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Oleynik, Gene Arnold, Ph.D.
The Ohio State University, 1987
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INCLUSIVE CHARGED D MESON PRODUCTION CROSS SECTION MEASUREMENT IN 800 GEV P-EMULSION INTERACTIONS

DISSERTATION

Presented in Partial Fulfillment of the Requirements

for the Degree of Doctor of Philosophy

in the Graduate School of The Ohio State University

By

Gene A. Oleynik, B.Sc., M.Sc.

**********

The Ohio State University

1987

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ACKNOWLEDGEMENTS

I would like to thank my wife Cindy, and my advisor Kurt Reibel for their patience and for keeping me on track. I would also like to thank the Fermilab Data Acquisition Group for their support in developing the online data acquisition system for this experiment. In this respect, Phil Yager, Winston Ko and the Stanford Linear Accelerator PEP-9 group were helpful in permitting me to rifle through their online data acquisition system to steal goodies. I would finally thank Ron Sidwell and Noel Stanton for their help and useful discussions on the analysis of the experiment’s data.

I dedicate this paper to my wife Cindy, for her help and support through the many years.
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"Lifetime of $D^0$ Charmed Mesons Produced in Neutrino Interactions" 

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Chapter I

INTRODUCTION

The experimental study of charm particle lifetimes and branching ratios has reached its maturity – current efforts are directed at high statistic studies and the observation of rare decay modes (see the review by Hitlin [1] for example). On the other hand, beauty lifetime studies, while rapidly advancing, still suffer from low statistics. In addition, up to the present time, all beauty lifetime measurements (but for one directly observed beauty pair in hadronic production [2]) have been determined indirectly through impact parameter methods. Hadronic beauty production is in much the same state that charm production was 10 years ago.

While the experimental study of the hadronic production of charm has made much progress in the last decade, the data accumulated is still unsatisfactory. Many cross section measurements suffer from large uncertainties due to the application of production model dependent large correction factors, measurements at the same energy but different targets do not seem to agree, significant results found by one group are nullified by another, and lastly, theorists have been hard pressed to explain some production features within the standard perturbative Quantum Chromo-Dynamic (QCD) framework. In brief, hadroproduction of heavy quarks is still an open field of study with many unanswered questions.

This paper describes the first running period of Fermilab experiment 653, a study of the decay properties of charm and beauty particles produced by high energy hadronic interactions using a hybrid emulsion-spectrometer. High resolution emulsion was used as the target for 800 GeV protons allowing the direct observation of the short lived charm and beauty particles. A high-resolution electronic spectrometer placed behind the emulsion selected "interesting" events,
Table 1: The ratio of charm to non-charm yields for various beams.

<table>
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<tr>
<th>Beam (interaction) type</th>
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<tr>
<td>Hadronic</td>
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</tr>
<tr>
<td>Electromagnetic (photon)</td>
<td>1/100</td>
</tr>
<tr>
<td>Weak (neutrino)</td>
<td>1/10</td>
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precisely located them within the emulsion, and provided information about the decay products.

Even though the charm to non-charm yield ratio of hadron beams is small relative to other possible beam types (see Table 1), a charged hadron beam was chosen for this experiment because of its superior rate of production. Aside from the higher rate, the study of the comparatively unexplored hadronic production dynamics provides sensitive tests of QCD processes – the production mechanisms of neutrino, photon and e^+e^- beams are relatively better understood.

The physics goals of this experiment were:

1. Direct lifetime and production cross section measurements of approximately 50 beauty pairs.

2. A high statistics (on the order of 10^3) direct lifetime measurement of charm mesons and baryons, and production cross section measurements.

3. The direct observation of the decay D_s \rightarrow \tau \nu_\tau \rightarrow other leptons.

4. The study of beauty and charm production dynamics (e.g. pair correlations).

The expectation of 50 beauty pairs for the first running period unfortunately appears to have been an over-estimate. A revised estimate of beauty yield for this experiment gives only a few beauty pairs for the first running period (The
original yield was based on a $\sigma(b\bar{b})$ cross section estimate of 50 nanobarns (nb) per nucleon. It appears that this was an over-estimate by roughly an order of magnitude. Recent measurements [2,3] in 320 GeV/c$^2$ $\pi N$ interactions yield a $\sigma(b\bar{b})$ on the order of 1-5 nb. Extrapolating to 800 GeV/c$^2$ $p N$ with the fusion calculated cross sections of reference [4] yields an estimate of 2-10 nb for this experiment.

Data collection started in earnest at the end of May 1985, and ended in mid-August of the same year. In this period, 32 liters of emulsion were exposed to approximately $3 \times 10^9$ protons from the Fermilab accelerator. This generated $5.4 \times 10^6$ recorded muon triggered events, corresponding to $1.1 \times 10^8$ interactions, of which about 70% were in the fiducial volume of the emulsion targets.

At the time of this writing (September 1987), 61% of the recorded data has been processed with emulsion scanning selection cuts, and the selected events sent to Japan for scanning. Emulsion scanning is now in progress there.

Based on the estimated small beauty yield, and the fact that a major portion of the data from the experiment is still being analyzed at the time of this writing, this paper will focus on charm production. A review of the experimental and theoretical aspects of hadroproduction of charm is presented followed by details of the experimental apparatus. The portions of the experiment in which the author was a major contributor, such as data acquisition, vertex analysis, and momentum analysis are discussed in some detail. Analysis performed to select muonic charm decay candidates and the Monte Carlo used in simulating the response of the apparatus are described in some detail as they were used for a preliminary, all electronic, determination of the inclusive cross section for the production of charged D mesons.
Chapter II
CHARM PARTICLE HADROPRODUCTION

2.1 Introduction

This chapter reviews the hadroproduction of heavy quarks with particular emphasis on charm production. Recent reviews [5,6,7,8,9] cover the current theoretical and experimental status in some detail. The approach here will be to first describe the "standard" theoretical leading order QCD description of heavy quark hadroproduction, then point out the agreements, and discrepancies, between theoretical and experimental results and relate attempts to resolve the discrepancies. An assessment of how this experiment can contribute towards the understanding of the hadroproduction of charm closes this chapter. The discussions that follow assume a familiarity with the rudiments of the parton and Quantum Chromo Dynamic (QCD) models.

2.2 QCD hadroproduction of heavy hadrons

Production cross sections for heavy hadron pairs by

\[ A + B \rightarrow C + \bar{C} \]  

where A and B are initial hadrons, and C and \( \bar{C} \) are heavy hadrons containing the heavy quark pair c and \( \bar{c} \) respectively (\( \bar{C} \) is not necessarily the anti-particle of C), are amenable to calculation in leading order in the QCD framework. This is accomplished by "factorizing" the production process into short distance constituent parton sub-processes with the three components in Figure 1:
Figure 1: Factorization of an hadronic interaction into interactions of its constituents.

- A parton (i.e. quark and gluon) description of content of the hadrons. Parton dynamical variables are usually taken as $x$ and $k_\perp$; where $x$ is the ratio of longitudinal (with respect to the hadron direction) component of the parton momentum to the total hadron momentum, and $k_\perp$ is the perpendicular component of the parton momentum. Each parton $a$ in hadron $A$ is assigned an $x$ distribution function, $G_{a/A}(x,\mu^2)$, where $\mu$ is the energy scale at which the interaction takes place (for heavy hadroproduction on the order of the heavy quark mass). The distribution of $k_\perp$ is usually parameterized as

$$K_{a/A}(k_\perp) = e^{-k_\perp^2/(\langle k_\perp^2 \rangle)}$$

but will be ignored in following discussions.

- A QCD formulation and calculation of the appropriate parton-parton subprocesses ($\sigma_{ab\rightarrow c\bar{c}}$ in the figure). For heavy quark pair production, the dominant short distance sub-processes are the "fusion" sub-processes in Figure 2 a). The flavor excitation subprocess in Figure 2 b) and the contributing
Figure 2: QCD contributions to heavy quark pair creation by annihilation and fusion (a), and flavor excitation (b). Individual flavor excitation contributions are shown in (c).
sub-processes c) have been included in addition to fusion by some, but as will be discussed, the fusion sub-processes already include these excitation sub-processes, so that adding them double counts the terms. At higher energies, the gluon fusion production mechanism dominates over quark annihilation production due to the highly virtual gluon in \( q\bar{q} \rightarrow g \rightarrow c\bar{c} \); the annihilation terms are therefore sometimes ignored.

- A “fragmentation” scheme, in which the heavy quark pairs “dress” themselves with other partons to form colorless hadrons, determining the final hadron species \( C, \bar{C} \). Fragmentation of a quark \( c \) into a final hadron \( C \) is described by the fragmentation function \( D_{c/C}(z) \), where \( z \) is the fraction of the quark energy carried by the final hadron \( C \). This is taken to be independent of the production method, and is only important when considering specific final state hadron species. For charm and heavier quark production, this is sometimes taken to be \( D_{c/C}(z) \propto \delta(1-z) \), where \( \delta \) is the Dirac delta function, which is zero unless \( z=1 \). This is based on the “Bjorken-Suzuki effect” \([10]\) that when a heavy hadron fragments, it carries off most of the heavy quark energy.

Combining these components, and ignoring \( k_\perp \) distributions and fragmentation\(^1\) yields the differential cross section:

\[
\frac{d\sigma(c\bar{c})}{dc_c dc_{\bar{c}}} \propto \sum_{ab} \int_0^1 dx_a \int_0^1 dx_b \times G_{a/A}(x_a, Q^2) \times G_{b/B}(x_b, Q^2) \\
\times \theta(\hat{s} - \hat{s}_{th}) \times \sigma_{a_b \rightarrow c\bar{c}}(\hat{s})
\]

where:

\[
\hat{s} = x_a x_b \hat{s} \quad \text{The squared center of momentum energy of quarks a and b} \\
\sqrt{s} = \text{The center of momentum energy of hadrons A and B} \\
\hat{s}_{th} = \text{The threshold energy squared}
\]

The \( a \) and \( b \) sum is over all partons in the incident hadrons. The \( \theta \) step function forces the condition \( \hat{s} \geq \hat{s}_{th} \). Results are very sensitive (to about an order of

\(^1\)Ignoring fragmentation simply gives the total yield regardless of the final hadron species.
magnitude) to the values of the parameters that enter the calculation:

- The heavy quark mass $m_c \sim 1.2 - 1.8$ GeV/c$^2$ for charm.
- The threshold energy squared $s_{\text{th}} \sim 4m_c^2$ to $4m_c^2$.
- $\Lambda_{\text{QCD}} \sim .2 - .5$ GeV

but the shape of the differential cross section, and the correlations between the heavy quark pair should not be. The factorization procedure depends on $\Lambda_{\text{QCD}}$ above through its expansion in the strong coupling constant $\alpha(\mu, \Lambda_{\text{QCD}})$. A thorough set of charm and beauty hadroproduction cross sections based on (3) are calculated in reference [4] for $\Lambda_{\text{QCD}} = .2$, $s_{\text{th}} = 4m_c^2$, and a range of masses for $m_c$.

Recently, Collins, Soper, and Sterman (CSS) [11] have reviewed the domain of validity of the factorization procedure (3) in some detail. Based on a careful analysis of the leading order QCD diagrams, they argue (but do not prove to all orders in perturbation) that to leading order the scheme is valid for heavy quarks for two reasons. Firstly, factorization ignores terms in $\mu/M$, where $\mu$ is a typical hadron mass scale, and $M$ the heavy quark mass. In addition, the perturbation is in $\alpha_s(M)$ — the strong coupling “constant” is evaluated at the scale of the heavy quark mass so that the expansion is expected to valid for $M \gg \Lambda_{\text{QCD}}$. They leave open the question of whether the charm mass is heavy enough. The interactions are found to be dominated by the short distance “fusion” processes, which already include the flavor excitation processes, so they should not be added separately. All multi-gluon diffraction processes, besides single gluon exchange, are found to cancel in all orders, and the single gluon exchange is already included in the fusion terms, so that pomeron-like (i.e. multi-gluon) diffraction should not be added separately. This domination by the fusion sub-processes has recently been confirmed to higher order by Ellis [12], who found the higher order $g + q \rightarrow c\bar{c} + q$ terms containing gluon diffraction and flavor excitation terms to be negligible. Though (3) is good for hard ($p_\perp^2 \geq M^2 \gg \Lambda_{\text{QCD}}^2$) production, the cross
section calculation is found to be valid in leading order for heavy quark production since the dominant integration region comes from $p_{\perp}^2$ on the order of $M^2$. Some predictions of (3) determined by CSS and others are:

1. Linear dependence on the atomic weight of the target ($A$) – this stems from the proportionality of (3) on the number of target quarks due to its short distance nature.

2. Central (i.e. small $x$) production of the heavy pairs with little in the fragmentation ($x \to 1$) tails.

3. Rapidity gap $|y_c - y_c'|$ correlations peaked near zero. The emerging heavy quark pair and heavy hadron pair tend to go in the same direction.

Neither 1) nor 2) above seem to agree with experiment for the hadroproduction of charm. Nonlinear $A$ dependence, and a "leading particle" effect, where hadroproduced charm hadrons containing valence quarks of the beam hadron are produced at anomalously high $x$, have been seen. Only one experiment has investigated correlations in the rapidity of charm pairs. Though their data is consistent with QCD calculations, it appears to fit better to a simple phase space model with no rapidity correlation.

More seriously, experimental charm pair cross sections have been found to be approximately an order of magnitude higher than those calculated with (3). This is generally attributed to the neglecting of higher order terms that may be important, or to the relatively low mass charm quark. As shall be seen, the charm

---

$^2$Rapidity is related to $x$ by:

$$x = 2 \times \left(\sqrt{p_{\perp}^2 + m^2/\sqrt{s} - 4m_p^2}\right) \times \sinh(y^*)$$

where:

- $p_{\perp}$ = The perpendicular momentum
- $m$ = The particle mass
- $\sqrt{s}$ = The center of momentum energy
- $m_p$ = The beam particle mass
- $y^*$ = The center of momentum rapidity
cross section discrepancy may not be as bad as originally thought. It is too early to tell whether beauty cross section measurements will lie closer to their QCD predictions.

The following section briefly covers the experimental evidence for the discrepancies 1) and 2) above, and relates attempts to explain them. A short discussion of measurements of charm correlations is also included as is a current listing of charm pair cross section measurements.

2.3 Experimental results and comparison to theory

Experiments must generally identify hadroproduced charm from a very large non-charm hadronic background before reliable cross sections can be calculated. This is accomplished in a number of ways:

- **Prompt lepton triggers.** "Prompt" charged leptons (i.e. leptons from particle decays of $\leq 10^{-12}$ sec.) from the decay of charm particles are separated from non-prompt leptonic decays (e.g., $\pi^\pm, K^\pm \rightarrow \mu^\pm \nu X$ for muons, or $e^+e^-$ pairs generated by $\gamma$-ray conversions from $\pi^0 \rightarrow 2\gamma$ decays for electrons). Neutrino beam dump experiments look for the neutrinos from the prompt leptonic decays of charm, usually eliminating the non-prompt background by an extrapolation to infinite target densities (where all non-prompt sources interact before they can decay leptonically). These experiments generally suffer from large backgrounds that are hard to control.

- **Mass peaks.** A fixed number of momentum analyzed charged tracks from an hadronic interaction are combined to calculate an invariant mass for a specific decay mode (e.g. all pairs of tracks are combined to form invariant masses for the $K^-\pi^+$ and $K^+\pi^-$ decay channels of $D^0/D^0$ charm meson decays – a peak at the neutral $D$ mass is searched for). In some experiments, additional trigger requirements (besides interactions) such as a muon trigger, are used to enhance the charm signal to background ratio.
These experiments are limited by the low charm branching ratios to simple all-charged states, and thus usually suffer from very large combinatoric backgrounds.

- Active target detectors. These detectors, mainly bubble chambers, streamer chambers, and emulsion, have the advantage of being able to visually identify charm production by event topology. They can, in principle, eliminate practically all background events. Supplementary triggers designed to improve signal to noise are used in some vertex detector experiments.

Experiments usually parameterize charm distributions by:

$$\frac{d\sigma}{dx dp_1^2} \propto (1-x)^n \times e^{-b p_1^2}$$

(4)

where the Feynman x variable $= p^*/p_{max}$, $p^*$ = the momentum of of the charm particle in the center of momentum frame, and $p_{max}$ = the maximum momentum it can have in this frame. The $(1-x)^n$ parameterization has its origins in the large x counting rules for hadron fragmentation of Gunion [13] and Brodsky and Blankenbecler [14]. Values of $n \sim 5$ are considered central and are typical for gluon fusion processes, while $n \sim 1-2$ are considered forward in x, or "diffractive-like".

Most experiments are performed with nuclear targets as opposed to exclusively proton targets (i.e. hydrogen) to take advantage of the higher rate of production. This has caused much confusion when results are compared. Results are usually presented as cross sections per nucleon, with a linear atomic weight (A) dependence $- \sigma/A$. As will be discussed, there is good evidence for a non-linear A dependence in the cross section ($A^\alpha$, $\alpha \approx 0.75$). Partly because of this, a number of p-hydrogen bubble chamber charm production experiments have been performed recently.

2.3.1 Atomic weight dependence

Fermilab neutrino beam dump experiment 613, using tungsten and Be targets, has measured the A dependence of prompt neutrinos produced by the decay of
charm particles. Using the form $A^\alpha$ they find $\alpha = 0.75 \pm 0.05$ for $x \geq 0.2$ [15]. This result has recently been corroborated by the WA78 group who measured the yield of prompt single muons from a 320 GeV/c $\pi^-$ beam incident on the target materials Al, Fe, and U [16]. They find $\alpha(\mu^+) = 0.76 \pm 0.08$ and $\alpha(\mu^-) = 0.83 \pm 0.06$ for $x \geq 0.4$.

The $A$ dependence has caused an annoying amount of confusion when the data from experiments with targets of different $A$ are compared. This confusion may not subside easily, particularly if the results of light flavor hadroproduction carry over into the production of charm. Atomic weight dependences in light flavor production (pions and Kaons etc.) has been studied in some detail with a variety of targets [17]. The \textit{nuclear} cross section can be represented by the empirical formula:

$$\sigma(A) = K_0 \times \sigma(p) \times A^\alpha$$

(5)

where $\sigma(p)$ is the cross section on protons, $K_0 \sim 1.5 - 2.0$, and $\alpha$ depends on $x$ and varies from 0.75 to 0.45 over the range of $x$ of 0-1. Cronin et al. [18] and McCarthy et al. [19] have shown that $\alpha$ also depends on $p_\perp$. The $p_\perp$ data not only exhibits shadowing effects ($\alpha < 1$) for low $p_\perp$, but anti-shadowing ($\alpha > 1$) for high $p_\perp$, which indicates some sort of collective nuclear excitation. The dependence of $\alpha$ on $x$ and $p_\perp$ can distort the $x$ and $p_\perp$ distributions from production on nuclear targets in an undetermined way.

The major source of confusion in comparing cross sections of various $A$ targets has been the fact that only a \textit{linear} $A$ dependence seems to match them to hydrogen cross sections (with $K_0 = 1$), which appears to conflict with the E613 and WA78 results. Macdermott and Reucroft [20] have recently investigated the charm production distribution data from two different targets and found that the data is consistent with (5), with $K_0 = 1.5$, $\alpha = 0.75$ for $x \geq 0.2$, but $= 1$ near $x = 0$.

These results indicate a nuclear "shadowing" effect that is not consistent
with the short distance perturbative QCD model (3). They are possibly attributable to fermi-motion, rescattering, coherent scattering, or final state interactions as the quarks fragment – all which could conspire to reduce the "transparency" of the nucleus. There must be a lower limit of $\alpha = 2/3 -$ a purely geometrical shadow dependence.

2.3.2 Total cross sections

Table 2 lists total cross section measurements of $A=1$ targets (to avoid complications due to the atomic weight dependence of the cross sections) for $x \geq 0$. The table totals up all measured contributions to the cross sections (mostly charged and neutral D mesons, which are thought to dominate, though this may not be the case) and compares them to QCD predicted total charm pair cross sections. The measured cross sections are not for pairs, but for single production and thus double count pair production, but this is compensated by the $x \geq 0$ requirement. The QCD predictions are for pair production at all $x$, and the range corresponds to the use of charm quark masses between 1.2 and 1.8 GeV/c$^2$. The measured cross sections are seen to be systematically high by a factor of about 2.5.

A word of warning: In a sense, all of these measured cross sections are from the same experiment– they all use the small LExan Bubble Chamber (LEBC), and somewhat of the same analysis techniques. The consistency of the data may reflect this fact more than anything else.

Table 3 (compiled in reference [7]) lists the average charm $p_{\perp}$ measured by a few experiments. Included in the table is the measured value of the parameter $b$ from fits to equation (4). All experiments are in good agreement on the transverse momentum distributions. Light hadron production has been noted for its subtle $p_{\perp}$ behaviour, as mentioned in the previous section. It is not known whether current experiments are insensitive to $p_{\perp}$ effects, or whether such effects are negligible for charm production.

I will close this section on total production with a rather exciting recent result. The WA75 group at CERN – a 350 GeV/c $\pi^-$-emulsion experiment, has
Table 2: Charm pair cross sections for $x_F \geq 0$.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Interaction</th>
<th>Species</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>$\sigma$(μb)</th>
<th>$\sigma$(μb)$_{QCD}$&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA16</td>
<td>$\pi^-p$</td>
<td>$D^\pm$</td>
<td>26</td>
<td>$4.5^{+2.2}_{-1.4}$</td>
<td>$7.7^{+7.2}_{-3.5}$</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>$D^0/D^0$</td>
<td></td>
<td>$12.2^{+7.6}_{-3.8}$</td>
<td>1-10</td>
</tr>
<tr>
<td>NA27</td>
<td>$\pi^-p$</td>
<td>$D^\pm$</td>
<td>26</td>
<td>$5.7\pm1.6$</td>
<td>$10.1\pm2.2$</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>$D^0/D^0$</td>
<td>$\Lambda^+_c/\Lambda^+_c$</td>
<td>$19.8^{+5.7}_{-4.0}$</td>
<td>1-10</td>
</tr>
<tr>
<td>NA16</td>
<td>p-p</td>
<td>$D^\pm$</td>
<td>26</td>
<td>$5.3^{+2.4}_{-1.6}$</td>
<td>$10.2^{+7.9}_{-4.3}$</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>$D^0/D^0$</td>
<td></td>
<td>$15.5^{+8.3}_{-4.6}$</td>
<td>1.5-12</td>
</tr>
<tr>
<td>NA27&lt;sup&gt;b&lt;/sup&gt;</td>
<td>p-p</td>
<td>$D^\pm$</td>
<td>27.4</td>
<td>$6.2\pm0.7$</td>
<td>$11.0\pm2.0$</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>$D^0/D^0$</td>
<td></td>
<td>$17.2\pm2.1$</td>
<td>2-14</td>
</tr>
<tr>
<td>E743</td>
<td>p-p</td>
<td>$D^\pm$</td>
<td>39.</td>
<td>$16.5\pm3.5$</td>
<td>$13.0^{+10.5}_{-6.6}$</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>$D^0/D^0$</td>
<td></td>
<td>$29.5^{+11.1}_{-7.4}$</td>
<td>4-20</td>
</tr>
</tbody>
</table>

<sup>a</sup> From reference [4], with $\Lambda_{QCD}=.2$ and a charm quark mass range of 1.2–1.8 GeV/c<sup>2</sup> for all $x_F$.

<sup>b</sup> Based on analysis of 27% of their data.
Table 3: Perpendicular momentum dependence in charm production.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Interaction</th>
<th>$&lt;P_\perp&gt;$ (MeV/c)</th>
<th>$b$ (GeV/c)$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>E595</td>
<td>$\pi^-\text{Fe} \to \mu$</td>
<td>700±150</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>$p\text{Fe} \to \mu$</td>
<td>920±140</td>
<td>—</td>
</tr>
<tr>
<td>NA11</td>
<td>$\pi^-\text{Be} \to D$</td>
<td>—</td>
<td>1.1±0.5</td>
</tr>
<tr>
<td>NA16</td>
<td>$\pi^-p \to D$</td>
<td>850±120</td>
<td>1.1±0.3</td>
</tr>
<tr>
<td></td>
<td>$pp \to D$</td>
<td>750±120</td>
<td>1.1±0.3</td>
</tr>
<tr>
<td>NA18</td>
<td>$\pi^-\text{Freon} \to D$</td>
<td>780±140</td>
<td>~1.1</td>
</tr>
<tr>
<td>WA42</td>
<td>$\Sigma^-\text{Be} \to A^+$</td>
<td>—</td>
<td>1.1±0.7</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td>802±26</td>
<td>1.1±0.09</td>
</tr>
</tbody>
</table>

recently reported an unexpectedly high rate of production of double associated charmed pairs (i.e. two pairs = 4 charm in a single event) at the level of 1% of charm interactions; they have seen 2 such events in 200 charm candidates. These events were observed visually in emulsion, and other interpretations are extremely unlikely.

2.3.3 **Feynman x distributions: leading particle effects**

Because of the possible dependence of the atomic weight parameter $\alpha$ on $x$, $x$ distributions obtained from charm production experiments using heavy nuclear targets must be treated as suspect; their distributions may be distorted by nuclear effects. It seems feasible that this may be the reason that the leading particle effects described below have taken so long to show up, and are still somewhat controversial.

2.3.3.1 **Forward baryons**

Evidence for the diffractive (large cross sections as $x \to 1$) production of the $\Lambda_c$ charmed baryon at an Intersecting Storage Ring (ISR) experiment was reported in 1981 [21]. This experiment measured a $(1-x)^n$, $n = .4$ production distribution.
This result is at variance with recent LEBC-EHS measurements that find central \( \Lambda_c \) production for 320 GeV p on hydrogen interactions [22]. A forward \( \Lambda_c \) production is however supported by a Serpukhov neutron on carbon experiment where \( n=1.5\pm0.4 \) has been measured [23], though the statistical significance of the mass peak used to select \( \Lambda_c \) baryons has been questioned [5]. Experiment WA42 has reported a forward production of the charmed strange baryon in \( \Sigma^-\text{Be} \rightarrow A^+ + X \), with \( n = 1.7\pm0.7 \). What is intriguing about this experiment is that the \( A^+ (\text{csu}) \) contains only one of the valence quarks (the strange quark) of the \( \Sigma^- (\text{dds}) \) beam, while the \( \Lambda_c (\text{udc}) \) contains two of the valence quarks of the proton (uud) and neutron (udd) beams.

### 2.3.3.2 Forward mesons

NA16, NA27, and E743 charm production studies using the high resolution LEBC bubble chamber have found leading particle effects in \( \pi^- p \rightarrow D \) mesons [6,24,25,26], but none in \( pp \rightarrow D \) mesons [27]. Neither NA27 nor NA16 \( \pi^- \) data fits well to a single \((1-x)^n\) distribution, but does to a two component distribution with a leading and central part. When the charm mesons are broken up into leading and non-leading components, the forward portion of the fit is seen come from the leading mesons, while the central is due to the non-leading mesons. NA27 obtains \( n = 1.8^{+0.8}_{-0.6} \) and \( 7.9^{+1.6}_{-1.4} \) for the leading and non-leading mesons, while NA16 finds \( n = 1\pm1 \) and \( 6\pm3 \) respectively.

The CFRS collaboration [28], and more recently E595 [29], have measured \( \mu^\pm \) production off an iron dump with \( \pi^- \) and p beams. Both groups have measured an excess of \( \mu^- \) over \( \mu^+ \) events with the \( \pi^- \) beam. No such asymmetry is seen in the proton beam data.

This can be interpreted as a leading particle effect as follows. Because charged charmed mesons decay leptonically to like signed leptons, and since the branching ratio for leptonic decay is larger for charged D mesons (\(~18.2\%)\) than for neutral D mesons (\(~7.0\%)\), one expects the decays of the combination \( D^0 - D^- \) to produce predominantly negative leptons, and \( D^+ - \overline{D^0} \) to produce net positive
leptons. $D^0 - D^- \text{ (quark contents } \bar{c}u \text{ and } \bar{c}d) \text{ both contain valence quarks of the }$

$\pi^- \text{ (quark content } \bar{u}d) \text{, and } D^+ - \bar{D}^0 \text{ (quark contents } c\bar{d} \text{ and } c\bar{u}) \text{ do not. In the case of the proton beam, the } \Lambda_c \text{ is the leading particle as it carries two of the protons valence quarks.}$

**2.3.3.3 Theoretical attempts to explain forward production**

Since the indications of forward $\Lambda_c$ from the ISR, there has been theoretical interest in explaining the forward behavior in terms of both perturbative and non-perturbative QCD frameworks.

The earliest attempts concentrated on making the charm quark distribution in hadrons "harder" (i.e. peaked at higher $x$). Most efforts centered on "boosting" the charm with the flavor excitation terms [30,31,32,33]. As already mentioned, these terms are already included in equation (3), and the reason they seemed to work is due to double counting. Diffraction by multi-gluon exchange is also ruled out by Collins, Soper and Sterman.

Brodsky [34,35] has put forward an "intrinsic" charm component in hadrons as a possible explanation (see Figure 3). Here, intrinsic means charm pairs bound to the hadron in a non-perturbative manner. The charm cannot be bound to the proton through perturbative means because the charm quark fluctuations are so far off their mass shell that their lifetime is much shorter than that of light quark fluctuations in the hadron, and thus they are not resolvable. Brodsky estimates the intrinsic charm in the proton to be on the order of 1%.

More recently, Ellis [12] has attempted to generate forward production within perturbative QCD by including higher order diffractive like terms, with no luck.

What all of the above fail to explain, is the apparent leading particle nature of the increase in forward production; they would increase forward production for any beam type. Apparently there is some kind of "recombination" of one of the charm quarks with a valence quark in the beam hadron. The data suggests that the charm quark need not be fast as the above attempts suggest – it combines with fast valence quarks of the beam particle. The fragmentation of the charm
Figure 3: Intrinsic charm in a proton.

quark appears to be dependent on the valence quark makeup of the beam; the beam valence quarks are not spectators.

2.3.4 Correlations between charm pairs

Only one experiment has produced correlation data at the time of this writing. The LEBC-EHS collaboration has measured $D\bar{D}$ correlations in 360 GeV/c $\pi^-p$ interactions [36]. They have investigated rapidity gap (the absolute difference between the rapidity of the two charm particles), $M(D\bar{D})$ (the invariant mass of the pair), $x$ of the pair, $p_T^2$ of the pair, and $\phi_\perp$ (the transverse angle the momentum of the pair makes with respect to the beam). Their data fits well to Monte Carlo generated events which used no correlation besides kinematics (a simple phase space model was used). All correlations are compatible with the QCD gluon fusion models (both the LUND and $\delta$ function fragmentation models were used) except for the $p_T^2$ distributions, which the fusion models underestimate at higher $p_T^2$ (they used the parton $k_\perp$ distribution form of equation (2) with $< k_\perp^2 > =$
The $\phi_{\perp}$ correlation, which is also sensitive to the parton’s $k_{\perp}$, is not fit well by the fusion models. An intriguing clustering of events around $\phi_{\perp} = 120^\circ$ shows up, though the statistics are low.

### 2.4 Limitations of this experiment for hadroproduction studies

Because of the multi-atomic nature of the target (see Table 4), protons incident on the emulsion will interact with nuclei with a variety of atomic weights (though silver is the largest contributor to the cross section). If a means of determining which nuclei the proton interacted with existed, this would be a blessing— the dependence of the cross section on atomic weight could be measured directly with a single target. Unfortunately no technique has been devised to accomplish this\(^3\). This means that such measurements as the pair production cross section per nucleon, $x$ distributions, rapidity gap correlations between the charm pair, and even leading particle effects are probably affected and perhaps smeared out or made meaningless by the nuclear $A$ dependence.

Cross section ratios (e.g. charged D to neutral D production) is not $A$ dependent however. In addition, unusual qualitative features of production can be looked for.

This paper presents a preliminary inclusive charged D meson cross section, launching the study of charm production in this experiment.

\(^5\)It was hoped that a relation could be found between the atomic weight of the interacting nucleus and the number of dark nuclear fragment tracks left in the emulsion. This was not borne out [37].
Chapter III

EXPERIMENTAL APPARATUS

3.1 Introduction to the apparatus

A high precision study of the hadronic production of charm and beauty particles and their subsequent decays required an instrument with excellent spatial resolution. In addition, the exponential character of particle decays required that the production target be placed as close as possible to this detector. The only feasible way to accomplish this without excessive losses was to make the detector the production target. The only present day detectors that satisfied these requirements were emulsion targets, streamer chambers, or bubble chambers. The higher precision emulsion target was chosen for this experiment.

The design of the target had to take into account the advantages and disadvantages of the use of emulsion in the context of a detector. On the one hand, emulsion could resolve particle trajectories as short as a few microns, and target blocks of emulsion up to a few centimeters were feasible – a range of four orders of magnitude. These distances corresponded to lifetimes in the range of $10^{-16}$ to $10^{-11}$ for the centrally produced particles in this experiment, more than adequate to detect charm and beauty decays. On the other hand, the price paid for this precision was a high density of material. While a high density would usually be considered a desirable target property, it would cause relatively large multiple scattering of particle trajectories and would produce secondary nuclear interactions that could “fake” particle decays. Ninety five percent of these secondary interactions could be eliminated as decays by visual inspection of the emulsion (see section 5.3), but 5% still would remain as a background. In addition, γ rays
from $\pi^0$ decays that convert into electron pairs in the emulsion generate a background that could fake decay vertices. A higher density of material would make such conversion more probable. Exposure of the emulsion to a charged hadronic beam would also generate a background of non-interacting beam tracks to search through for production and decay vertices. The final result of these considerations was an emulsion target module that had a high decay finding efficiency while at the same time presenting as little mass as possible to particles passing through it. These target modules were individually exposed to the beam with a precision target mover. This mover swept target modules horizontally and stepped them vertically across the beam at a variable rate that yielded a tolerable uniform density of beam exposure across the entire module.

Estimates of charm pair production cross-sections by 800 GeV protons on emulsion yielded $1/1100$ charm pairs per interaction. Beauty production estimates were about a factor of 1000 smaller. Visually scanning for these “interesting” interactions in the emulsion would take a prohibitive amount of time (approximately 10 weeks to find 1 charm) even if good estimates of the interaction locations were known. Not only was a good estimate of position needed to save scanning time, but a method to improve the $1/1100$ signal to noise ratio needed to be devised. This required a knowledge of the products of the interactions and decays. An electronic spectrometer downstream (i.e. in the direction of the beam) of the emulsion provided this information.

The electronic spectrometer portion of the experiment was designed to aid in the location of events in the emulsion and to reduce non-interesting background by triggering on the semi-muonic decay modes of charmed and beauty mesons and baryons. This required the coming together of many state-of-the-art detector systems in order to more closely match the electronic apparatus to the precision of the emulsion target. The ability to quickly scan the emulsion for events required the spectrometer to efficiently predict vertices to within one microscope field of view. Decay vertices had to be resolved with a high degree of efficiency; they needed to be separated from the nearby primary nuclear interaction vertex in
particular. The spectrometer also needed precise charged particle tracking and two track separation to resolve the high multiplicity, relativistically collimated products of 800 GeV interactions. Also required was a large acceptance to pick up the slower, wider angle decay products of beauty and charm particles. The determination of which of the many decay modes and possible charm or beauty species were associated with an event required particle identifications and the precise determination of the momentum of charged particles. Finally, the selection criteria of a muon from the decay required a large geometrical acceptance for muon detection. A minimal path for pion and kaon decay in the length of the detector was required to reduce muon background from the muonic decays of these particles.

Figure 4 shows a layout of the experimental apparatus along with the coordinate system employed. The z=0 coordinate of the experiment was defined to be the front edge of the frame in the emulsion target mover that held the targets in place. The desired precision for vertex location required the introduction of the newly developing technology of solid-state microstrip detectors (SSDs) that could measure particle positions to less than 10 microns in one dimension. Sets of these detectors were placed on both sides of the emulsion target; the upstream (beam) set was used to measure beam tracks while the larger, higher precision downstream (vertex) detectors measured tracks from interactions and decays. These critical noise sensitive detectors, along with the emulsion target, beam scintillation counters, and associated low noise electronics, were surrounded by a radio frequency (RF) noise suppressing housing. A set of high precision drift chambers in conjunction with the vertex SSDs and a magnet separating them measured the momentum of charged particles. In addition, these chambers provided a link between the upstream vertex SSDs and the downstream components of the experiment. They also aided in rejecting spurious vertex SSD tracks. A time-of-flight system, lead-liquid-argon (LAC) electromagnetic calorimeter, and hadron calorimeter (HADCAL) provided limited particle identification and energy measurements. All particles but muons were ranged out by the upstream
Figure 4: Plan view of the experiment.
material, along with additional ranging steel, before they reached the most downstream portion where two walls of muon detection scintillators formed a muon trigger hodoscope. Two sets of drift chambers with a toroid magnet in between were placed immediately upstream of the hodoscope. This muon spectrometer could measure the trajectories of muons as well as their momentum, and was included to aid in performing muon perpendicular and total momentum cuts for an improved charm and beauty selection signal to noise ratio.

The experiment was triggered by a "clean" beam track giving rise to an interaction with 3 or more charged tracks, at least one of them a muon with an energy greater than approximately 5 GeV. A "clean" beam track was defined by halo and beam counters upstream of the target, while a thin scintillator directly following the target defined an interaction. A muon trigger required at least one hit in the front wall of the muon hodoscope in coincidence with at least one from the back wall.

Data from the experiment were read in a front end LSI-11/73 computer through FASTBUS and CAMAC data acquisition systems. After minor event assembly on this computer, events were transferred to a VAX 11/750 computer where an online system responsible for equipment monitoring, data monitoring, and event logging to magnetic tape resided.

3.2 Beam-line

Figure 5 depicts the Fermilab accelerator and beam-lines. Eight hundred GeV protons were delivered to the experiment at Lab-D through the NE beam line in a 10 second spill with a 60 second cycle time. Beam intensity at the lab was adjustable between $10^4$ and $10^7$ protons/second using a pyramid shaped movable tungsten attenuator far upstream of the experiment. The attenuator, along with other elements of the beam delivery system, could be monitored and controlled by the experimenters through the Fermilab EPICS (Experimental Physics Interactive
Figure 5: Fermi National Accelerator Laboratory main-ring and beam-lines.
Control System) beam-line control system which ran off a central PDP-11 computer. Typically, the intensity at the experiment was about $10^4$ protons/second ($10^5$ protons/spill).

The X and Y (horizontal and vertical) projections of the beam at the target along with the angular spread of the beam as measured by the beam measurement detectors (SSDs in conjunction with the drift chambers) are illustrated in Figure 6. The horizontal spread is seen to be 2 mm full width half max (FWHM), while the vertical spread is 2.5 mm FWHM. The angular spread along the X axis is 1.1 milliradian (mrad) FWHM, while the vertical angular spread is less than .2 mrad. As can be seen, the beam is angled upwards by 2 mrad with respect to the z axis. Both profiles show little halo in the beam. The large difference in the spread of the vertical and horizontal beam angles is due to different focusing in these directions, and the fact that the beam is redirected by magnets more in the horizontal direction. A beam spread within these limits did not significantly compromise the geometrical acceptance of the spectrometer for charged particles from interactions and decays.

### 3.3 Experiment front end: Radio frequency enclosure

Both beam and vertex solid state microstrip detectors (SSDs) were used to predict the location of primary nuclear interaction vertices in the emulsion target. The vertex SSDs were also used to select charm and beauty candidates by locating decay vertices with a muon track. The vertex SSDs in conjunction with the beam detectors were capable of predicting primary interactions to within 350 microns rms along the beam direction and 8 microns transverse to the beam. To achieve and preserve these resolutions required very accurate and stable relative alignments between the beam detectors, vertex detectors, and emulsion target. For this reason, all three components were placed on a 3.5 ton granite block.

The cable lengths to the read-out amplifiers from the vertex and beam SSDs were kept as short as possible to reduce noise; the readout amplifiers were on
Figure 6: Horizontal and vertical beam position and angular spreads at the target.
racks close to the detector. The granite block, SSDs, readout electronics and racks, and target mover were all placed in a radio-frequency (RF) hut designed to shield this critical upstream portion of the experiment from external noise. The RF hut had its own air-conditioning unit which kept the ambient temperature to 20 ± 3 degrees centigrade. Figure 7 depicts the layout of the upstream portion of the experiment in the RF hut.

3.4 Beam detector system

Precision beam tracking assisted in locating vertices in the emulsion by providing a constraint in assigning vertex SSD tracks to the primary nuclear interaction vertex (see appendix J). In addition to aiding in vertex fitting, the beam system rejected primary interactions occurring upstream of, or in, the beam detectors with a simple track count. The direction of the beam proton also provided information necessary for the study of charm and beauty production dynamics (e.g. Feynman x, charm and beauty perpendicular momentum).
The beam track measuring system was composed of a set of small drift chambers 500 cm upstream of the emulsion target along with a set of SSDs 27 cm upstream of the target.

3.4.1 Beam drift chambers (BDCs)

The drift chambers consisted of 18 planes of sense (signal detection) wires with 18 planes of field shaping wires glued to their back. Each sense plane had an active area of 9 cm × 9 cm and contained two sense wires. These planes were organized into pairs that had their sense wires parallel. Figure 8 illustrates a sense plane pair. The wires in one plane of the pair (un-primed in the figure) were offset from the corresponding wires in the other plane (primed in the figure) by one half of a wire spacing. As the figure indicates, this was done in a manner such that the planes in the pair could be interchanged by flipping them about their wire axis. The offset of the wires allowed a pair to resolve a beam track without left-right ambiguity.

The pairs were organized into three views: the X view with wires rotated 90 degrees about the z axis, and the U and V views with wires rotated ±30 degrees about z. Figure 8 illustrates the positioning of the chambers along the beam axis. The planes were held in place with six precision steel rods (Thompson rods) passing through the end-plates of an aluminum frame. A gas enclosure surrounded the frame and chambers.

The chambers were run with a half and half mixture of argon and ethane gas at one atmosphere. The 36 channels were pre-amplified and discriminated prior to being read out into LeCroy FASTBUS time-to-digital converters (TDCs). The resolution of the chambers was measured to be 150 microns per plane pair for 800 GeV beam tracks.
Figure 8: Beam drift chamber system and its sense plane structure.
3.4.2 Beam solid state microstrip detectors (beam SSDs)

The downstream portion of the beam detector consisted of 9 planes of commercially available SSDs\(^1\). These SSDs were the prototype models for the larger vertex SSDs.

Each plane in this detector contained a 2.4 cm × 3.6 cm wafer of silicon, 300 microns thick, with 1500 diode strips of 20 micron pitch (center-to-center spacing) and 10 micron width etched on it. This chip was mounted on a circular G-10 printed circuit board with readout pads from each diode alternating from one side of the chip to the other. This allowed the pads to be wire bonded to corresponding pads on the circuit board at an interval of 40 microns, well within the current limits of wire bonding technology. The signals from the diodes were pre-amplified with electronics mounted directly on these circuit boards.

Figure 9 illustrates the segmented instrumentation of the detector's strips. Only the central 12.42 mm of the planes were instrumented. The very central

\(^1\)Centronics, now Micron Semiconductor Limited.
4.74 mm of a plane had 80 strips instrumented at an interval of every three strips (60 micron spacing). The 3.84 mm regions on both sides of this central region had every 6 strips (120 micron spacing) instrumented for a total of 64 additional strips. This configuration led to 144 channels per plane and 1296 channels total of readout.

The planes were arranged in three views (the same as the drift chambers): X with the diode strips perpendicular to the horizontal, and U and V which had their strips rotated ±30 degrees from the horizontal. The circuit boards were mounted in an aluminum frame on three longitudinal Thompson rods for precision placement as illustrated in Figure 10. The resolution of these devices was measured to be 17 microns per plane for the central region, and 35 microns for the outer regions.

### 3.4.3 Beam track measurements

The large “lever arm” between the beam SSDs and drift chambers in conjunction with the precision of the microstrip detectors provided an rms position error for beam tracks projected to the target of approximately 10 microns in x and y and with an rms in slope of 20 microradians.

### 3.5 Emulsion target

The experiment exposed 49 target modules containing a total of 32 liters of Fuji ET-7B nuclear emulsion in its four months of running. The emulsion was poured immediately before exposure, and developed directly afterwards at a facility built at Fermilab to E653 specifications. This immediate processing avoided unnecessarily exposing the emulsion to cosmic-ray background tracks and improved the grain density. Each emulsion target was encased in an aluminum frame and was loaded into a target mover which exposed single target modules to the beam in such a manner that the typical density of beam tracks was uniform throughout the emulsion volume. The target mover was mounted on a granite block along
Figure 10: Beam solid state microstrip detector system.
Table 4: Composition of Fuji ET-7B nuclear emulsion.

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight % (W_i)</th>
<th>Atomic weight (A_i)</th>
<th>Atomic number (Z_i)</th>
<th>Number % (N_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>.3</td>
<td>126.90</td>
<td>53</td>
<td>.1</td>
</tr>
<tr>
<td>Ag</td>
<td>45.4</td>
<td>107.87</td>
<td>47</td>
<td>11.7</td>
</tr>
<tr>
<td>Br</td>
<td>33.4</td>
<td>79.90</td>
<td>35</td>
<td>11.1</td>
</tr>
<tr>
<td>S</td>
<td>.2</td>
<td>32.06</td>
<td>16</td>
<td>.2</td>
</tr>
<tr>
<td>O</td>
<td>8</td>
<td>16.00</td>
<td>8</td>
<td>11.3</td>
</tr>
<tr>
<td>N</td>
<td>11.7</td>
<td>14.01</td>
<td>7</td>
<td>5.9</td>
</tr>
<tr>
<td>C</td>
<td>20.6</td>
<td>12.01</td>
<td>6</td>
<td>2.0</td>
</tr>
<tr>
<td>H</td>
<td>39.6</td>
<td>1.01</td>
<td>1</td>
<td>39.6</td>
</tr>
<tr>
<td>Totals</td>
<td>100.0</td>
<td>&lt;A&gt; = 26.64</td>
<td>&lt;Z&gt; = 12.42</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Weighted sums

<table>
<thead>
<tr>
<th>Summation</th>
<th>2/3</th>
<th>.77</th>
<th>.8</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sum_i N_i \times A_i^x )</td>
<td>7.18</td>
<td>10.62</td>
<td>11.94</td>
<td>26.64</td>
</tr>
<tr>
<td>( \langle A \rangle_{eff} = \sum_i (N_i \times A_i^x)^{1/2} )</td>
<td>19.24</td>
<td>21.52</td>
<td>22.19</td>
<td>26.64</td>
</tr>
</tbody>
</table>

- \( a \) from \( N_i = \langle A \rangle \times W_i / A_i \)
- \( b \) from \( \langle A \rangle = 100\% / (\sum_i (W_i/A_i) \)
- \( c \) from \( <Z> = <A> \times \sum_i (W_i/A_i) \times Z_i \)

with the vertex and beam solid state microstrip detectors in order to preserve the relative alignment of these critical components.

### 3.5.1 Emulsion composition

Table 4 lists the atomic makeup of Fuji ET-7B nuclear emulsion along with the percent of each element weight and number [38]. The “average” atomic number weighted linearly with the number percent and atomic number is seen to be 26.6. This table also lists the “average” atomic number weighted linearly in the number percent, but by various powers of the individual atomic numbers. These weighted sums are relevant for cross section calculations, as there are indications
Table 5: Emulsion target module material properties.

<table>
<thead>
<tr>
<th>Material</th>
<th>Interaction length for protons (mm)</th>
<th>Radiation length (mm)</th>
<th>Density (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuji ET-7B nuclear emulsion</td>
<td>359</td>
<td>29.5</td>
<td>3.73</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>795</td>
<td>424</td>
<td>1.032</td>
</tr>
<tr>
<td>Lucite</td>
<td>697</td>
<td>338</td>
<td>1.20</td>
</tr>
<tr>
<td>Horizontal polystyrene spacer</td>
<td>10340</td>
<td>5523</td>
<td>.0793</td>
</tr>
<tr>
<td>Vertical honey-combed spacer</td>
<td>7962</td>
<td>3862</td>
<td>.105</td>
</tr>
<tr>
<td>Glassine paper</td>
<td>929</td>
<td>451</td>
<td>.9</td>
</tr>
</tbody>
</table>

that hadronic production of charm is not linear in its atomic number dependence. The various powers listed in the table reflect experimentally measured and theoretically predicted atomic number dependences as discussed in chapter II.

3.5.2 Horizontal and vertical module construction

Two types of target modules were employed; 24 of the 49 exposed modules were “vertical” and 25 were “horizontal”. The vertical modules had their emulsion sheet planes oriented perpendicular to the beam, while the horizontal modules were oriented parallel to the beam. Vertical modules were exposed uniformly at $1.5 \times 10^5$ protons/cm$^2$, while the horizontal were exposed at $.5 \times 10^5$ protons/cm$^2$. Figure 11 illustrates the construction of a vertical module, and Figure 12 shows the makeup of a horizontal module. Table 5 shows the relevant properties of materials contained in each type of module, while Tables 6 and 7 give their actual values for vertical and horizontal target modules respectively.

Both modules consisted of a main block of emulsion and an analyzing region made of spaced out vertical type emulsion sheets. The analyzing sheets assisted in the location of the decays of long lived particles, and were also used to improve the vertex predictions of the solid state microstrip detectors by providing precise tracking points near the main emulsion block. The analyzing regions were

$^2$Runs of densities between $.5 \times 10^5$ and $3 \times 10^5$ were performed however.
Figure 11: Vertical emulsion target module.
Figure 12: Horizontal emulsion target module.
Table 6: Vertical emulsion target module composition.

<table>
<thead>
<tr>
<th>Section</th>
<th>Item</th>
<th>Lengtha (mm)</th>
<th>Number</th>
<th>Total length (mm)</th>
<th>Int. lengths</th>
<th>Rad. lengths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>Emulsion sheet</td>
<td>.33</td>
<td>2 × 20</td>
<td>13.20</td>
<td>.038</td>
<td>.447</td>
</tr>
<tr>
<td></td>
<td>Polystyrene base</td>
<td>.07</td>
<td>20</td>
<td>1.40</td>
<td>.002</td>
<td>.003</td>
</tr>
<tr>
<td></td>
<td>Totals</td>
<td></td>
<td></td>
<td>14.60</td>
<td>.039</td>
<td>.451</td>
</tr>
<tr>
<td>Analyzer</td>
<td>Emulsion</td>
<td>.05</td>
<td>2 × 5</td>
<td>.50</td>
<td>.001</td>
<td>.017</td>
</tr>
<tr>
<td></td>
<td>Lucite base</td>
<td>.10</td>
<td>4</td>
<td>.40</td>
<td>.001</td>
<td>.001</td>
</tr>
<tr>
<td></td>
<td>Lucite base</td>
<td>.30</td>
<td>1</td>
<td>.30</td>
<td>.000</td>
<td>.001</td>
</tr>
<tr>
<td></td>
<td>Glassine paper</td>
<td>.03</td>
<td>9</td>
<td>.27</td>
<td>.000</td>
<td>.001</td>
</tr>
<tr>
<td></td>
<td>Honey-combed paper</td>
<td>1.52</td>
<td>5</td>
<td>7.60</td>
<td>.001</td>
<td>.002</td>
</tr>
<tr>
<td></td>
<td>Totals</td>
<td></td>
<td></td>
<td>9.07</td>
<td>.004</td>
<td>.022</td>
</tr>
<tr>
<td>Totals</td>
<td></td>
<td></td>
<td></td>
<td>23.67</td>
<td>.043</td>
<td>.473</td>
</tr>
</tbody>
</table>

Volume = .83 (main block) +.03 (analyzing region) = .86 liters total

a All lengths refered to are measured along the z axis.

Table 7: Horizontal emulsion target module composition.

<table>
<thead>
<tr>
<th>Section</th>
<th>Item</th>
<th>Lengtha (mm)</th>
<th>Number</th>
<th>Total length (mm)</th>
<th>Int. lengths</th>
<th>Rad. lengths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>Emulsion pellicle</td>
<td>20.0</td>
<td>1</td>
<td>20.00</td>
<td>.056</td>
<td>.678</td>
</tr>
<tr>
<td></td>
<td>Totals</td>
<td></td>
<td></td>
<td>20.00</td>
<td>.056</td>
<td>.678</td>
</tr>
<tr>
<td>Analyzer</td>
<td>Emulsion</td>
<td>.05</td>
<td>2 × 9</td>
<td>.90</td>
<td>.003</td>
<td>.030</td>
</tr>
<tr>
<td></td>
<td>Lucite</td>
<td>.30</td>
<td>9</td>
<td>2.70</td>
<td>.004</td>
<td>.008</td>
</tr>
<tr>
<td></td>
<td>Polystyrene paper</td>
<td>2.00</td>
<td>8</td>
<td>16.00</td>
<td>.001</td>
<td>.003</td>
</tr>
<tr>
<td></td>
<td>Totals</td>
<td></td>
<td></td>
<td>19.60</td>
<td>.008</td>
<td>.041</td>
</tr>
<tr>
<td>Totals</td>
<td></td>
<td></td>
<td></td>
<td>39.60</td>
<td>.064</td>
<td>.719</td>
</tr>
</tbody>
</table>

Volume = .47 (main block) +.04 (analyzing region) = .51 liters total

a All lengths refered to are measured along the z axis.
carefully designed to optimize beauty and charm yield with minimal losses due to multiple scattering and "fake" decays due to secondary interactions in the additional material. The following points were important considerations in the design:

1. There is an optimal emulsion thickness that is a compromise between a thicker emulsion for detecting the longer lived charm and beauty particles, and a thinner one to decrease the multiple scattering of charged particles that reduces vertex finding efficiency and resolving power. Extending the main block of the emulsion to pick up longer lifetimes in itself did no good because the longer the block, the less useful its most upstream portion due to the increase in multiple scattering from the additional material. This would worsen the efficiency and precision of locating vertices near the front of the stack. The introduction of more emulsion would also increase the chance of converting $\gamma$ rays from $\pi^0$ decays to electron pairs and would generate secondary nuclear interactions. Both occurrences would be indistinguishable from real decay vertices by the spectrometer, leading to a time consuming scanning for the events in the emulsion only to reject them in the end.

2. Secondary nuclear interactions produced heavily ionizing breakup fragments which left dark tracks in the emulsion easily distinguishing them from particle decays. On the other hand, non-active (i.e. non-emulsion) material in the target would provide a medium for the generation of secondary nuclear interactions that would be indistinguishable from decays. Additional spaced out emulsion sheets used as an analyzing region permitted the detection of the longer lived particles without the multiple scattering problems mentioned above, but required supporting framework to give them rigidity so that accurate position measurements could be preserved. This framework introduced non-active material into the target; the less massive this supporting material, the fewer the "fake" decays contaminating the charm and beauty samples. The horizontal target modules contained 9 analyzing
plates spaced out with a framework of polystyrene paper, while the vertical modules used honey-combed paper to space out its 5 analyzing plates.

3.5.3 Target mover and positional readout

The target mover was powered by an electrically and mechanically isolated motor which moved a target module back and forth across the beam. A PDP-11 computer controlled the movement and used real-time beam rate information obtained from an upstream scintillation counter to vary the horizontal sweep speed of the target mover so that the emulsion was exposed uniformly to the beam. At the end of each horizontal sweep, the target was moved vertically by 1 mm (the vertical beam width was 2.5 mm) so that the exposure density along the vertical axis was nearly uniform.

A position encoding system latched target mover X and Y coordinates with a precision of 1 micron whenever a pre-trigger occurred. A full trigger resulted in the read out of the X and Y information through the CAMAC system.

3.5.4 Emulsion alignment techniques

The relative orientation and position of the emulsion pellicles in the horizontal target modules were calibrated by exposing them to X-ray lines from a Toshiba EX-220GH X-ray machine placed upstream and to the side of the target mover. Targets were moved to a pre-selected position out of the beam, where they were exposed to two X-ray lines that were angled 45 degrees with respect to one another (see Figure 12). The mean line width of the X-ray beam was approximately 35 microns. The line edges were used to correct for the relative orientation of the emulsion pellicles. Variation in the edges was measured to be 2.5 microns rms. The relative alignment between the emulsion module and the spectrometer was determined by measuring 15 points along both X-ray lines in the vertical analyzing sheets in the target module. The calculated intersection of these two lines yielded rms errors in x and y of 1.3 microns and 3.8 microns respectively.

To determine the relative position between both types of modules and the
vertex and beam electronic detectors, a small portion of each target was exposed at a low beam track density. Match-up between the spectrometer and emulsion tracks proceeded quickly in this region. Once the beam track was found, the module could be aligned to the spectrometer with the 10 micron accuracy of the spectrometer beam track measurement. The emulsion modules also had each corner exposed to beam spots (i.e. the target mover remained stationary for hundreds of events). These spots permitted a quick rough alignment of 100 microns to be performed prior to the more refined low density alignment.

### 3.6 Charged particle spectrometer

The charged particle spectrometer was used to measure momentum with an upstream "arm" of 18 solid state microstrip vertex detectors (vertex SSDs) separated from a downstream arm of 10 drift chambers by an analyzing magnet. The SSDs were also used to locate primary nuclear interaction vertices (primary vertices) in the emulsion target immediately upstream of them. They also predicted decay vertex candidates which were used to select charm and beauty candidate events.

Both arms of the spectrometer were designed to precisely reproduce charged particle tracks in the high multiplicity, highly collimated environment of the 800 GeV interactions. This required not only excellent spatial resolution of tracks, but also the ability to separate nearly collinear pairs of tracks. The excellent spatial resolution of the detectors permitted the precise measurement of the angles of charged particles passing through both arms of the spectrometer. This allowed a precise determination of momentum to be performed.

The SSDs had an active area of 5 cm × 5 cm and had a transverse angular acceptance of 110 milliradians at the most downstream plane. These detectors could resolve single tracks to 8 microns rms in one dimension, and had a two track resolution of 50 microns. The set of 18 detectors, in conjunction with a beam track measurement, could predict primary vertices to 350 microns rms along the beam and 8 microns rms transverse to the beam. This resolution allowed the emulsion
scanners to isolate the event in one “mini-module” on the average, and about one microscope field of view. Decay vertices had poorer resolution on the average due to their lower multiplicity of charged tracks (2–4 compared to 9 for a primary interaction).

The downstream arm of the spectrometer consisted of 10 “vector” drift chambers – an equivalent of 50 conventional chambers because of their multiple sampling (5 samples per chamber = vector) along the beam direction. Multiple sampling in the chambers allowed left-right ambiguities to be resolved more easily using track vector (slope) information. The chambers had an active area of 1.7 m × 1.7 m and the most downstream plane yielded a transverse acceptance of 240 milliradians. The drift chambers could resolve a track’s position to 49 microns rms per chamber for beam tracks, but typically achieved a 62 micron rms error in the “busy” environment of 800 GeV interactions. Adjacent and nearly parallel particle tracks as close as 600 microns could be separated by these chambers.

3.6.1 Solid state microstrip vertex detectors (vertex SSDs)

A detailed discussion of these critical spectrometer components is contained in reference [41]. Only a brief description of construction and performance characteristics is described here.

The vertex SSDs consisted of 18 planes of detectors placed every 9mm along the beam line with the first plane approximately 71 mm downstream of the emulsion target. These detectors were developed by Micron Semiconductor Limited in conjunction with The Ohio State University.

Figure 13 illustrates a fully constructed detector plane. Each plane consisted of a silicon wafer with 1000 diode strips of 50 micron pitch and 35 micron width etched onto it. Readout pads from the strips were alternated from side to side so that each side had a pad every 100 microns. This wafer was mounted in a printed circuit board where readout lines were wire bonded to corresponding diode strips’ readout pads. Pre-amplifiers were mounted directly on this circuit board to prevent noise generation by the capacitance in the lengthy signal path
Figure 13: Vertex microstrip detector plane.
to the electronics racks. This permitted a signal to noise ratio of 20 to 1 to be achieved when the detectors were fully depleted. The detectors fully depleted at a reverse bias of 50 volts, and were maintained at this voltage during the run.

Since instrumenting all 1000 lines would not permit compact packaging and would generate cooling problems\(^3\), a graded readout scheme was implemented as depicted in Figure 14. The success of this scheme relied on the ability of the detectors to capacitively share charge via the floating lines in the regions where every line was not read out. This charge sharing capability allowed positions to be interpolated to less than the readout spacing. The scheme shown in the figure required the readout of only 384 lines per plane, corresponding to 48 8-channel pre-amplifiers and 7.2 watts per plane (864 pre-amplifiers and 130 watts total). Forty-eight pre-amplifiers could fit onto one circuit board compactly and could be cooled adequately.

The detectors were cooled with copper plates that had holes cut out to accommodate the pre-amplifiers and were mounted on the same side of the circuit board as the pre-amplifier casings as illustrated in Figure 13. The back of this plate had rectangular channels cut in it in which copper tubes (of rectangular cross section) were soldered. The ends of these tubes were connected to a water recirculation and purification system which carried off excess heat.

The total thickness of an entire detector package was 7mm. The detectors were mounted in an aluminum frame with precision Thompson rods providing accurate positioning. The wafers in the planes were sealed off from the outside environment by placing an o-ring around them. Plastic rings of a thickness slightly smaller than the o-rings were used to space out the detectors. The whole stack of detectors was compressed so that the o-rings would squeeze down to the plastic ring thickness, allowing for a uniform and accurate spacing while sealing off the wafers. Inert nitrogen gas was flowed through the portion of the detectors sealed off by the o-rings via small holes in the circuit boards. This prevented the

\(^3\)A pre-amplifier handling 8 channels required a total of 125 pre-amplifiers. At approximately .15 watt per pre-amp this yielded 19 watts per plane or 342 watts for the whole detector.
Figure 14: Vertex microstrip detector readout segmentation.
deterioration of performance due to the absorption of oxygen. The frame was sealed within an aluminum housing and was bolted to a pedestal resting on the granite block as depicted in Figures 7 and 15. Thin aluminum windows were placed in the front and back of the housing to allow particles to pass in and out of the detector with a low probability of interacting.

Figure 16 plots the residuals of tracks passing through each type of readout region in the detector. The central region of the detector achieved a resolution of 8.8 microns rms – better than the 14 micron resolution expected from the strip spacing alone. This was possible because charge was shared between adjacent lines somewhat by diffusion. The outer regions which capacitively shared charge had rms resolutions of 14.5, 15.8, and 26.1 microns for the every two, every three, and every fifth readout region respectively.

Performance of these detectors was trouble free throughout the run except for the loss of one plane due to a water leak. In addition, it was discovered during analysis that the spacing scheme discussed above had failed; the o-rings did not all compress down to less than the plastic ring thickness. This uneven spacing was calibrated out in the offline analysis. The detectors had an overall efficiency of 96%; the 4% inefficiency was mainly due to shorted or disconnected strips.

3.6.2 Analyzing magnet

The SCM-104 magnet (on loan to Fermilab from Argonne National Laboratory) was used to analyze the momentum of charged tracks in the experiment. Its dipole gap was set at 50.8 cm was supplemented with shaped pole pieces as shown in Figure 17. This allowed for a larger magnetic field without reducing the overall solid angle acceptance of the experiment. A disadvantage of this configuration was a very non-uniform field shape in the region of the pole tips. The magnet had symmetry only about the transverse (y-z) midplane, the pole tips destroyed any symmetry about the longitudinal (x-y) midplane, and a short in one of the windings in the lower coil destroyed symmetry about the vertical (x-z) midplane.

A detailed field map in a grid of 12.7 mm along the beam axis by a 25.4 mm
Figure 15: Vertex microstrip detector system housing.
Figure 16: Resolution in the vertex detector planes in the four readout regions.
Figure 17: The SCM104 analyzing magnet.
× 25.4 mm square transverse to the beam axis covering the central portion of
the magnet as well as 1 meter into the upstream and downstream spectrometer
detectors was recorded prior to the installation of the rest of the experimental
apparatus. Due to the physical construction of the field measuring device, field
points near the angled part of the pole tips could not be obtained but were
generated using a fit program with Maxwell field equation constraints. The total
\( \int B \times dl \) along the beam line was determined to be 11.2 kilogauss-meters with the
magnet running at 2400 amps. This yielded an effective transverse momentum
kick of .336 GeV/c.

Error analysis in the thin lens approximation yields a momentum measure-
ment error of:

\[
\frac{\delta p}{p} = \sqrt{(0.01)^2 + (0.00023p)^2} \quad (p \text{ in GeV/c})
\]

(6)

where the first term is estimated from multiple scattering errors in the track slopes
in both arms of the spectrometer, and the second term is due to measurement
errors in the slopes and is a measured quantity (18% error for beam straight
throughs of 800 GeV/c). The second term is consistent with the expected slope
measurement errors of approximately 70 microradians in the solid state microstrip
detectors and 30–35 microradians in the spectrometer drift chambers for beam
tracks, but is expected to be as high as \((0.0004p)^2\) for wider angle tracks pass-
ing through the poorer resolution areas of these detectors. Not included in the
first term are contributions from \( \int B \times dl \) variation, which is assumed zero in this
approximation.

First and second pass analysis, in which likely charm and beauty candidates
are chosen for emulsion scanning, used a thin lens approximation for momentum
determination. Third pass (detailed re-analysis) tracks were processed for
momentum with a Runge-Kutta iterative integrated fit using the measured field
map grid, and the thin lens momentum determination as a starting value. Mo-
mentum fitting is discussed in detail in appendix K.
3.6.3 Spectrometer drift chambers (SDCs)

The following description of the spectrometer drift chambers is based on the paper of reference [42], which may be referred to for more detail.

The downstream arm of the charged particle spectrometer consisted of 10 multi-sampling "vector" drift chambers. These chambers covered an active area of $1.7 \times 1.7$ square meters and were arranged in three views: the $X$ view measured along the horizontal magnet bend plane, and the $U$ and $V$ views were rotated $\pm 30$ degrees with respect to the horizontal.

The operational design of the chambers is illustrated in Figure 18. Five position samples were made at 1.02 cm intervals along the beam direction making vectors for the portions of the tracks in the chamber. As the figure shows, two different cell sizes were employed. Ten "fine" cells covered the central 50.8 cm of the detector where the track density was the highest and the slopes were typically less than 100 milliradians. Six "coarse" cells on each side of the central region covered the outer portion of the chamber, where track density was low, track
slopes were relatively large, and two track separation capability was not a major concern. The fine cells had a maximum drift distance of 2.54 cm and the five position samples were obtained by adding the signals from pairs of sense wires spaced at 5.1 mm intervals and separated by large diameter cathode wires. The coarse cells had a maximum drift distance of 5.08 cm. These cells were similar to the fine cells except they had only five non-paired sense wires spaced at 10.2 mm intervals. The combination of short drift distances along with the excellent transmission-line properties of the sense-cathode pairs and the signal summing of sense pairs yielded very short pulses (typically 25–30 nanoseconds full width base) of a quite uniform length in the fine cells. These uniform short pulses allowed for the inference of unresolved nearby tracks from the time over threshold (TOT) recording electronics.

Figure 19 displays the configuration of the wires in both the fine and coarse cells. The physical parameters of the chamber components, such as wire diameters, are described in Table 8. Sense wires were made of gold-plated tungsten,
Figure 19: Spectrometer drift chamber wire configuration in fine and coarse cells.
while all other wires were made of gold-plated aluminum. Voltages on the field shaping wires ($S'$, $S''$ and $F$ in Figure 19) were designed to give a uniform drift field. The large diameter of the cathode wires was chosen to keep the surface field low (8.7 kV/cm) minimizing problems with secondary emission.

Signals were amplified and discriminated with commercially available low-impedance amplifiers (LeCroy Research 2735A) prior to readout with LeCroy Research 1879 FASTBUS TDCs. These TDCs generated sparsified (i.e. data with below threshold times suppressed) leading and trailing edge times (LE and TE) for all pulses. The leading and trailing edge data preserved TOT information. The TDCs were not run at their maximum clock rate of 500 MHz, but at 334 MHz in order to accommodate the longer drift time of the coarse cells.

The chambers were run with a gas mixture of 50%-49.5%-0.5% Argon-Ethane-Ethanol at 1 atmosphere. During operation, the high voltage supplies were ramped between beam spills. The gains of all the sense wires in a chamber remained uniform to ±15% when operated at the same voltage. Operation was relatively stable during the run, though the coarse cells had problems with electrical discharge.

TOT distributions for fine-cell hits from single beam track triggers and high-multiplicity interaction triggers are shown in Figure 20. The beam track TOT distribution has a spread of 13% rms, with negligible tails. Interaction tracks have spread of approximately 18%, with a long tail due to unresolved second hits. The analysis software generates a second hit from the trailing edge of the pulse if the TOT is more than 9 nanoseconds longer than the expected TOT value (arrow in Figure 20), corresponding to 0.47 mm in spatial separation. This cut increases the number of hits by 18%, half of which are real and appear on fitted tracks found by analysis software.

Figure 21 displays a typical reconstructed event in the drift chambers. The eight segment examples from one event in Figure 22 show how essential the trailing edge hits are for successful reconstruction. In each example, at least one track would be lost if not for the trailing edge information. This figure also illustrates
Figure 20: Spectrometer drift chamber time over threshold distributions for beam and interaction triggers.
Figure 21: Typical reconstructed event in the spectrometer drift chambers.
Figure 22: Eight segments of tracks from an event in the spectrometer drift chambers.
that crossing tracks are quite common. Figure 23 displays cleanly resolved nearly parallel tracks of an average separation of .64 mm.

Figure 24 shows the fine cell leading edge residuals of fitted straight three-dimensional tracks for the 10 chambers. The position resolution is 110 microns RMS per wire pair (49 microns per chamber) for 800 GeV beam protons, and 140 microns RMS per fine cell wire pair (63 microns per chamber) for tracks originating from interactions. No momentum selection has been made in the interaction residual plot so that multiple scattering errors are folded in. Trailing edge hits have a resolution about half as good as leading edge hits, as do the coarse cells (not shown). These fine cell residuals correspond to slope errors over the chambers of approximately 30–35 microradians for the fine cell beam tracks, and about 40–45 microradians for the fine cell interaction tracks. Coarse cell leading and fine cell trailing edge hits would have about double the error on the slopes.

3.7 Time-Of-Flight system (TOF)

The time-of-flight (TOF) system, along with momentum information from the charged particle spectrometer, was used to assign particle identifications to relatively low energy charged particles. This system was the only component of the experiment that could directly identify charged hadrons. The TOF system consisted of 48 38.1 mm × 38.1 mm × 1.68 meter long scintillators placed 4.1 meters downstream of the target and arranged side by side vertically in a UNISTRUT frame so that their total horizontal dimension measured approximately 1.88 meters. Figure 25 shows a beam’s eye and side view of the TOF setup. The scintillators were read out with Amperex XP2230 photomultiplier tubes from both ends. The tube signals were split in a 5:1 ratio; the larger signals were immediately discriminated, then delayed and recorded in CAMAC time to digital converters (TDCs), while the smaller portions of the signals were recorded in FASTBUS analog to digital converters (ADCs). The TDCs started from the edge of the trigger
Figure 23: Spectrometer drift chamber event illustrating resolution of nearly collinear tracks.
Figure 24: Resolution of spectrometer drift chamber fine cells.
Figure 25: Time-of-flight hodoscope.
counter S3 pulse, whose time resolution was approximately 600 picoseconds (ps). The time resolution of the time-of-flight counters was measured to be 150 ps per tube. Since the speed of light in the scintillators was measured to be $1.5 \times 10^8$ meters/second, the longitudinal position along the counter could be measured to about 2.25 cm using the time information from the tubes on both ends of the scintillator. A good start-time independent of the trigger was not recorded, but was fit from high momentum tracks in an event. The 150 ps resolution of the TOF counters gives an upper limit on the energy for separating particles for a two standard deviation (95% confidence level) separation in the flight time $t$ (i.e. $300\text{ps}$) of:

- pion-kaon separation $E = 2.26 \text{ GeV}$ (2 standard deviation in $t$)
- kaon-proton separation $E = 3.81 \text{ GeV}$ (2 standard deviation in $t$)

At energies above these, the particles cannot be unambiguously identified.

### 3.8 E653 calorimetry

Electromagnetic showers were produced by the conversion of incident $\gamma$ rays and electrons in lead sheets spaced out to form a lead-liquid argon calorimeter (LAC). The electrons in these showers ionized liquid argon in the interstitial space of the lead sheets. Charge from the ionization was collected on etched copper-clad G-10 boards immersed in the liquid argon between the lead sheets. The pad and strip read-out geometry of these boards permitted two dimensional shower localization. Shower shape and total collected charge allowed incident $\gamma$ ray and electron energies to be measured. Electrons could be identified from LAC shower position and energy deposition in conjunction with tracks from the charged particle spectrometer that matched in energy and position. Gamma ray pairs were used to reconstruct $\pi^0$s.

The hadron calorimeter (HADCAL) operated analogously to the LAC; hadrons generated cascade interactions in spaced out steel plates. Gas filled proportional
tubes, interleaved with the steel plates, collected charge from the ionization produced by hadrons passing through the tubes. Pad read-out in conjunction with the tube read-out allowed for the localization of the cascades transverse to the beam line. The total charge in a cascade provided a crude measurement of the incident hadrons energy. This calorimeter was the only element in the spectrometer that could directly detect neutral hadrons (besides $\pi^0$s which were detected with the LAC).

3.8.1 Liquid argon calorimeter (LAC)

The lead-liquid argon calorimeter of active area 1.625 meters $\times$ 1.625 meters centered on the beam line was placed 5 meters downstream of the emulsion target. The calorimeter could locate $\gamma$ rays and electrons with a resolution of about 1 mm rms and measured their energies with an accuracy of $12\% / \sqrt{E} + 2.5\%$. The readout geometry of the detector consisted of vertical (Y) and horizontal (X) strips alternated with pads of graded segmentation. Electron and $\gamma$ ray profiles were measured with a transverse strip segmentation finer than the shower widths. This allowed known shower shapes to be used to separate overlapping showers in the highly active central region of the detector where there were typically 6 showers per event. The pad positional and energy information permitted unambiguous match ups between the X and Y strips, making a 3-dimensional shower reconstruction possible.

The calorimeter consisted of three different sections along the beam direction as illustrated in Figure 26. The three sections differed in the makeup and number of the cells of which they were constructed. The front and middle sections were used for electron and $\gamma$ ray detection, while the back section was used primarily to reject hadronic showers. Only the front section was useful in separating overlapping showers by their transverse profiles. Figure 26 also illustrates the "generic" sandwich composition of a cell. There were 15 front cells consisting of 2.39 mm of lead, 2.54 mm of liquid argon, and two 1.59 mm thick back to
Figure 26: Lead-liquid-argon calorimeter inner core segmentation and cell structure.
back G-10 circuit boards followed by another 2.54 mm of liquid argon. The lead acted as the high voltage electrode of the cell, while the G-10 circuit boards were the low voltage electrodes. The middle section consisted of 18 cells identical in construction to the front’s cells. The back section contained 7 cells which were identical to those in the front and middle except the thickness of the lead was 4.67 mm, and the G-10 boards had a different read out geometry than that of the middle and front. The radiation lengths were 7.2, 8.6, and 6.2 for the front, middle and back sections respectively, yielding a total of 22 radiation lengths.

Charge was collected on the low voltage electrodes etched on the copper clad G-10 boards in the cells. These boards had 3 geometries: X strips, Y strips, and pad read-out. The X and Y strips were 5.1 mm by 1.63 meters long, but the central strips were split into a 163 mm x 163 mm region of 256 5mm x 20mm rectangular pads. Figure 27 shows the full pad geometry. All pads, including those in the central region of the strip readout geometry, were read out with copper strips on the back of the G-10 boards. The strips were electrically connected to the pads with soldered rivets which passed through the G-10 boards. The front and middle sections of the LAC had a X-PAD, Y-PAD, X-Y sampling, while the back section was read out entirely with pad boards.

The cells were held in place by uniform pressure on the front and back of the stack with steel springs welded on set screws tightened to a constant torque. Two steel pressure plates held the set screws in place. This arrangement rested on a steel plate that was suspended in a liquid argon cryostat by four thin walled steel pipes attached to the cryostat lid. The cryostat was built of stainless steel and was insulated with 23 cm depth of foam. The pressure plates and cryostat presented 2.88 radiation lengths to the beam. Purified argon was condensed in the cryostat and its oxygen content was monitored during the run.

The 3660 pad and strip read-out channels were read into LeCroy 1885 ADCs. All channels were calibrated weekly by injecting a fixed charge into all read out pre-amplifiers. Cross talk was measured to be 1-2 %, and the relative gains were

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4Boards made of a fiberglass-epoxy mix.
Figure 27: Lead-liquid-argon pad readout segmentation.
measured to a precision of 1-2%.

Figure 28 shows a typical shower in the LAC. X and Y strip pulse heights are plotted along the inner border. Pad hits are represented by circles whose diameter is proportional to the pad energy. The outer frame has fitted showers plotted along its axis. This LAC event illustrates the separation of two showers in the central region by the use of pad and shower shape information. Figure 29 shows the difference in position of 15 GeV electrons (determined by their showers in the LAC) and their spectrometer drift chamber tracks projected into the LAC. The electron’s position in the LAC was determined from its shower shape with a simple centroid algorithm and yields an rms error of 1.2 mm.

3.8.2 Hadron calorimeter (HADCAL)

This description of the hadron calorimeter is based in part upon a paper delivered at Fermilab in 1985. More details can be found in reference [43].

The hadron calorimeter was located between the liquid argon electromagnetic calorimeter and the muon detector and provided both positional and rough energy measurements for hadrons. The first few planes of this calorimeter also ranged out any electromagnetic showers that punched through the liquid argon calorimeter.

The HADCAL consisted of 16 planes of resistive plastic proportional tubes with pad readout interleaved with 16 iron plates. The tube and pad readout geometry covered an active area of 237 × 237 square centimeters with a varying degree of coarseness of segmentation, and allowed for unambiguous two-dimensional localizations of a hadron shower within single planes. The steel plates were 244 cm high by 305 cm wide by 5 cm thick and provided a total of 4.8 hadronic interaction lengths. Energy was measured by the proportional tube sampling, while position was resolved with both pad and tube readout. The high resistivity of the tubes allowed excellent spatial localization of a shower in the pads, but could result in high voltage trips from glow discharges in the tubes due to charge buildup. Trips were a problem at beam intensities greater than 20 kHz (over a beam spill time
Figure 28: Typical shower in the lead-liquid-argon calorimeter.
Figure 29: Position resolution for electrons in the lead-liquid-argon calorimeter.

Each active plane of the detector was made of three separate modules, the center module being more finely segmented than the two outer ones. Each module was constructed by epoxying 1.6 mm thick copper-clad G-10 boards on opposite sides of the plastic proportional tubes. The G-10 boards had identical patterns of rectangular pads etched in them on the sides adjacent to the tubes and the overlapping pads on both sides of the tubes were electronically ganged together. Readout lines were etched onto the other sides of the boards and were electrically connected to the pads by means of eyelets. Figure 30 shows the pad pattern for the center (a) and outer (b) modules. The tubes had an average resistivity of $10^4 \, \Omega \text{cm} \ (\pm 20\%)$, were strung with gold plated tungsten wire 51 microns in diameter, and were operated at 2100 volts in a gas mixture of 48.6% argon, 48.6% ethane, and 2.8% ethyl alcohol at atmospheric pressure. Alternate planes of the tubes were rotated 90 degrees so information was measured in two separate views. Pads were ganged 8 planes deep in each view for a total of 1016 readout channels, while
Figure 30: Hadron calorimeter inner and outer pad readout geometries.
tubes were ganged two planes deep in each view for a total of 1152 channels of readout.

3.9 Muon system

3.9.1 Overview

The layout of the muon system components is shown in Figure 31. The experiment used a muon hodoscope to trigger on semi-muonic charm and beauty decays. This hodoscope consisted of two walls of scintillators – one wall was imbedded in ranging steel while the second was located behind this steel. In addition to this hodoscope, a muon spectrometer consisting of two sets of six large drift chambers was placed on either side of a toroid analysis magnet. Part of the rationale for this spectrometer was to enable fast online data reduction using a cut on muon perpendicular momentum to enrich the charm and beauty samples over the background of light hadron muonic decays between the emulsion and muon chambers. Although no such online cut was ever made, the muon spectrometer information was used offline to reduce background. Muon spectrometer information was also used to reject muon triggers that did not have a link to upstream spectrometer tracks which pointed back to the vicinity of the emulsion. Both muon tracking and momentum information were used to link the muon candidates to upstream track segments of well measured momentum.

3.9.2 Muon hodoscope

The muonic trigger required at least one hit from both the front and back scintillation counter walls. This trigger was logically “anded” with a delayed pre-trigger from the upstream portion of the experiment. The mass of the apparatus upstream of the hodoscope amounted to 26 hadronic interaction lengths and 258 radiation lengths, virtually assuring that only muons could trigger the experiment. The upstream steel also ranged out muons below an energy of approximately 5 GeV.
Figure 31: Plan view of muon spectrometer and hodoscope.
The upstream scintillator wall was located 12.5 meters downstream of the target and consisted of 36 horizontal counters arranged in two vertical columns of 18 counters each, which covered an active area of 3.6 meters horizontal by 2.9 meters vertical. The downstream wall consisted of 40 counters of 1.7 meter in length arranged in two horizontal rows of 20 counters each, which covered an active area of 3.5 meters horizontally by 3 meters vertically and was placed 14.2 meters downstream of the target. The placement and area of both walls limited the angular acceptance for muon triggers to roughly 250 milliradians horizontally and 210 milliradians vertically.

Signals from the counters were split in a 2:3 ratio; 40% of the signal was intended for FASTBUS ADCs, and 60% of the signal was recorded in FASTBUS TDCs. For an unknown reason (possibly no gate) the split going to the ADCs failed to record the pulses, a fact which was not detected until after the completion of the run.

3.9.3 Muon spectrometer

The twelve 3 meter by 3 meter drift chambers measured the trajectories of the muons. These chambers were purposely oversized so that their centers lined up with the toroid center, which was offset with respect to the beam axis by approximately 1/2 meter to assure that the hole in its center was not along the beam line, where the majority of the muon tracks passed. This hole was 12 cm in radius - 1/2 % of the surface area of the toroid. The chambers were oriented in three views: one view was aligned vertically (Y), and two views (U and V) were rotated ±12 degrees with respect to the horizontal plane. The chambers were operated in an argon-ethane-ethanol mixture (50%-49.5%-0.5%) at one atmosphere.

Figure 32 illustrates the overall construction of these chambers, while Figure 33 shows a detail of a cell in a chamber. Each chamber had two 1.6 centimeter wide gaps separated by a central plane. The gaps were offset by one half of the

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*The chambers were run without ethanol during the later portion of the running period.*
Figure 32: Muon chamber structure.
Figure 33: Muon chamber cell and field shaping structure.
transverse cell size, 5.08 cm, relative to one another to resolve left-right ambiguities within each chamber. Copper field shaping strips of .25 cm width were etched onto G-10 boards and placed on each side of the central plane. Cathode and sense wires were made of gold plated tungsten of 50 and 30 microns in diameter and were strung to tensions of 100 and 60 grams respectively. The use of “HEXCEL” sheets, which were made of aluminum honeycomb sandwiched between thin aluminum sheets, enabled the chambers maintain mechanical rigidity while presenting little material to particle paths.

Figure 34 displays, for well collimated muon tracks, x and y residual distributions for upstream and downstream muon track segments projected to the toroid center for well. The projection spatial resolution is 400 microns rms on the average for the chambers.

A circular iron toroid 130 cm deep and 180 cm in radius was located 9.5 meters downstream of the target and was used to determine the momentum of penetrating muons (muons of less than 3.3 GeV/c were ranged out by upstream steel before reaching the downstream muon chambers). The momentum measurement provided an additional handle for linking to upstream spectrometer track segments. A field map generated with the CERN library POISSON program compared to Hall probe measurements of the toroid magnetic field to within 2%. A least-squares fit was used to determine the field as a function of the toroid radius and was utilized in a thin lens momentum determination. The field ranged 12% (19.5 ± 2.5 Kgauss) throughout the toroid, providing a perpendicular momentum kick of approximately .76 GeV/c. Momentum was determined by:

\[ p = 0.03 \times B(r) \times \theta \times \frac{\delta Z}{\delta \theta} \quad (\text{GeV/c}) \]  

(7)

where:

\[ B(r) = \text{fit field as a function of the toroid radius } r \text{ (in kilogauss)} \]

\[ \delta Z = \text{the toroid thickness (1.3 meters)} \]

\[ \delta \theta = \text{the angular deflection of the track in radians} \]
Figure 34: Muon chamber residual distributions.
The resolution was measured by looking at the difference in momentum as determined by the toroid and the upstream spectrometer (subtracting off an energy loss shift) for a well collimated sample of muon tracks. The result:

\[ \frac{\delta p}{p} = \sqrt{0.19^2 + 0.007p^2} \]  

(p in GeV/c) \hspace{1cm} (8)

has energy loss fluctuations folded in. The first term is due to multiple scattering in the toroid and errors in B field determination, while the second term comes from chamber measurement errors.

### 3.10 Trigger

The trigger of the experiment was defined by the coincidence of the beam, the interaction, and the muon tag, along with the anti-coincidence of a trigger veto. Scintillation counters defined the beam and vetoed any beam halo. The trigger veto was built from data acquisition hardware vetoes (e.g. when the hardware was "busy") in addition to the beam halo veto. The interaction portion of the trigger required at least 3 minimum ionizing charged particles exiting the emulsion target. Muons with energies greater than approximately 5 GeV that were in the geometrical acceptance of the apparatus could get to the rear muon counters and trigger the experiment.

Figure 35 is a detail of the front end of the experiment showing the locations of the beam defining trigger scintillator counters. The logical "or" of the three counters H0-H2 defined the beam halo veto. These counters were square scintillators with a circular hole cut in the middle. The halo tails of the beam were vetoed with H0 (note broken scale in the figure) which was a 508 mm × 508 mm square with a 66 mm diameter hole cut out in its center. H1 and H2 were 69 mm × 69 mm squares with 8 mm diameter holes, and overlapped the H0 hole. The three circular disk scintillator counters S1-S3 in coincidence defined the beam. The 10 mm diameter counters S1 and S2 overlapped the halo counters H1 and H2 holes respectively. The 5 mm disk S3 defined the maximum allowed beam deviation.
Figure 35: Detail of the upstream portion of the spectrometer including beam definition scintillation counters.
Table 9: Ranging parameters of the spectrometer.

<table>
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<tr>
<th>Spectrometer component</th>
<th>Density - thickness $\rho \cdot \delta z$ (g/cm$^2$)</th>
<th>Radiation lengths (mm)</th>
<th>Interaction lengths (mm)</th>
<th>Muon ionization minimum $I_\mu$ (MeV cm$^2$/g)</th>
<th>$\rho \cdot \delta z \cdot I_\mu$ (Gev)</th>
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<td>24.9</td>
<td>1.44</td>
<td>1.32</td>
<td>.285</td>
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<td>1.48</td>
<td>.932</td>
</tr>
<tr>
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<td>.498</td>
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<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.06</td>
</tr>
</tbody>
</table>

Minimum energy loss excluding muon steel = 3.28 Gev

The interaction counter was placed directly downstream of the emulsion, but upstream of the solid state vertex spectrometer. This scintillator was used as a minimum ionizing particle (MIP) threshold counter, the threshold being set to $> 3$ MIP for the data trigger. Nuclear interactions in occurring in this counter accounted for about 12% of the triggered interactions in the experiment.

The upstream part of the spectrometer played an active role in eliminating particles other than muons before they reached the muon hodoscope. The upstream steel (up to the muon back scintillator paddles) also ranged out muons with momentum less than 5 GeV/c. The muon trigger was the logical “or” of the front muon paddles in coincidence with the logical “or” of the back paddles. Table 9 lists the radiation lengths, interaction lengths, and muon energy loss for the various detector components in the spectrometer.

In addition to the halo veto, the experiment was also vetoed on the following:

1. Beam gate - the trigger was required to be in a time span consistent with the spill time of the accelerator.

2. CAMAC (i.e. host computer) veto - the experiment was not triggerable if
the computer was not ready to accept more triggers. This was the major source of the experimental dead time of 25 to 30 percent.

3. FASTBUS busy - triggers were disabled until all FASTBUS crates were ready to process a new trigger. A minor source of dead time.

4. FASTBUS full warning - triggers were disabled when the intermediate FASTBUS data buffer memories became full. This condition lasted until enough of the buffers were emptied by the computer in reading out events. A minor source of dead time at low beam rates.

The trigger logic of the experiment was broken up into two components: the fast pre-trigger, which included the beam counters, interaction counter, and beam halo counters; and the slower muon trigger. The pre-trigger started the gating of all detectors, but analog to digital conversion did not start until a muon was indicated by the muon logic. If there was no muon trigger in an allotted time, then all data acquisition modules were fast cleared (clearing prior to data conversion is much faster than during conversion - see sections 4.5.1), making the experiment triggerable again in as short a time as possible.

Table 10 displays the various triggers built out of the above components that were used in the experiment for data acquisition or calibration. As indicated in the table, some calibration triggers involved two additional components: the logical “or” of the time-of-flight scintillation counters and a more loosely defined beam in which the small S3 counter was not used.

3.11 Data acquisition and online systems

Events from the 10 second beam spills were recorded with two standardized data acquisition systems, CAMAC and FASTBUS. The data from a spill was buffered in FASTBUS bulk memories that were emptied into an LSI-11/73 front end computer over the longer accelerator cycle time of 60 seconds. The data was assembled
Table 10: Triggers used in the experiment.

<table>
<thead>
<tr>
<th>Triggers</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-I-M</td>
<td>Main trigger</td>
</tr>
<tr>
<td>B, B-I, B-T</td>
<td>Alignment and calibration of most of the apparatus</td>
</tr>
<tr>
<td>B-M, WB-T-M</td>
<td>Collimated muon beam for muon alignment and calibration</td>
</tr>
<tr>
<td>T-M</td>
<td>Wide parasitic muon beam for muon system calibration</td>
</tr>
<tr>
<td>WB, WB-T</td>
<td>Electron beam calibration of the Liquid Argon</td>
</tr>
</tbody>
</table>

Legend:  
- B beam (all beam counters and halo counters)  
- WB beam (no small S3 beam counter)  
- I interaction  
- T logical "or" of TOF wall  
- M logical "or" of the muon front counters in coincidence with the "or" of the muon back counters.  
- logical "and"  

Into events (i.e. structured in a specified format) on the LSI computer, then transferred to a VAX 11/750 computer over an electronic link. The VAX computer ran a sophisticated high speed data acquisition and monitoring online system. Besides the main responsibility of receiving events from the front end LSI computer and logging them to magnetic tape, the VAX online system monitored equipment hardware for failures and checked event data for corruption and other errors.

Overall throughput of the system was 300 events (averaging 26 kilobytes per event) per 60 second beam cycle during which data from the FASTBUS bulk memories could be processed through the entire online system and onto magnetic tape. This produced a tape of 5000 events about every twenty to thirty minutes.
Chapter IV
DATA ACQUISITION

4.1 Data acquisition introduction

Large, modern high energy physics experiments place demands on the design of online data acquisition (DAQ) systems that required much more sophistication than seen in the past. The large size and complexity of these experiments produce a huge data volume that demands continual real-time monitoring to assure that it is valid. In addition, most experiments need a substantial number of events to generate statistically meaningful results. This large number of events combined with the limited time available on accelerators implies very high data rates. Advancements in data acquisition hardware have been able to keep pace with rate demands to the point where computer readout is now the limiting factor.

E653 was a typical example of the above situation. Figure 36 plots the history of the integrated number of events recorded by E653 as a function of time. At an average of 26 kilobytes/event, E653 had a peak data rate of about 9 Gigabytes/day (for a total of 135 Gigabytes recorded). Even more data could have been recorded in the allotted running period if not for rate limitations imposed by the computers.

4.2 Overview of the data acquisition hardware and front end computer

Data was recorded with two “standardized” data acquisition systems: The older CAMAC (Computer Automated Measurement And Control) and the “state-of-the-art” FASTBUS (the name comes from its high speed “bus” – a multi-branched
Figure 36: Accumulated triggers as a function of time.

electronic connector). Ideally, one would want to run the experiment entirely with FASTBUS due to its high density (96 readout channels per DAQ module) and speed. However, FASTBUS time to digital converters (TDCs) with the time resolution desired for our time-of-flight system (~ 100 picoseconds) did not exist; CAMAC TDCs of the required resolution did. Since practically all of our remaining data volume was recorded with FASTBUS, we still took advantage of FASTBUS speed and density.

Both data acquisition standards were similar in their modularity of design. They consisted of "crates" into which a fixed number of standardized data acquisition modules could be placed. The crates supplied power for their modules, and allowed for module to module communication over a standardized backplane bus\(^1\). A special module for each crate, the "crate controller", arbitrated access to, and exercised control over, the other modules in the crate. Computers communicated with the data acquisition modules through their controllers. Crates

\(^1\)The FASTBUS system had an extra backplane bus, the auxiliary bus, into which special small modules, such as arbitration logic, could be placed.
could be linked together in a variety of architectures so that the host computer(s) could gain access to any module in any crate by the architecture's addressing scheme. All modules and crates were required to follow CAMAC or FASTBUS specification standards for power requirements, connection standards, communication timing and protocol, etc. This allowed for ease in interchanging modules and interfacing to computers.

A major difference between FASTBUS and CAMAC data acquisition systems was the higher speed of the FASTBUS. FASTBUS was capable of running at speeds of up to 8 MHz for 32 bit words, whereas the CAMAC top speed was 1 MHz for 16 bit words. In addition to higher speed, the FASTBUS communication protocol and design modularity standards allowed for the implementation of more flexible system architectures and for a much higher degree of intelligence within the system.

Events from the data acquisition modules were read into and pre-processed on a front end LSI/11-73 computer running the RSX11-M operating system, prior to transmission to a VAX 750, which ran VMS system software and contained the major portion of the experiment's online system. There were two reasons for using the LSI as the front end of the online system instead of basing it entirely on the VAX 750. Firstly, a DR11-W driver interface for communication between a VAX and FASTBUS 1821 controller did not exist, whereas we had an LSI driver for that purpose. Secondly, as will be discussed later, it was necessary to read the CAMAC data into the LSI computer. Since the dead-time of the experiment was then directly proportional to the time taken to handle the CAMAC data, it was advantageous to place the CAMAC system on its own processor. A sophisticated but user friendly LSI-based CAMAC data acquisition system already existed from the test run of E653, and had been used extensively after the test run not only for acquiring data via CAMAC, but also via FASTBUS with a CAMAC to FASTBUS interface. The readout of FASTBUS and CAMAC data was handled by separate programs running concurrently on the LSI computer, named RD1891 and RDCAM respectively. Although FASTBUS data was concurrently processed
on the LSI, it was arranged that the CAMAC data processing had highest priority during the accelerator spill when CAMAC readout was active.

4.3 Overview of the data acquisition process

Figure 37 depicts the data flow in the front end of the experiment. The FASTBUS data path is depicted with solid lines in the figure, while the CAMAC path is dashed. Upon receiving a trigger distributed to the remote crates (those close to the experiment’s detectors) by the CAMAC “super trigger module” (STM in the figure), analog pulses from the various components of the apparatus were read into FASTBUS and CAMAC data acquisition modules (DAMs). Signals from the SSDs, LAC, HADCAL, and muon hodoscope were converted into digital signals proportional to their integrated pulses by ADC modules. Discriminated time over threshold signals from the beam, spectrometer, and muon drift chambers, along with time information from the time-of-flight and muon hodoscope scintillation counters were converted into digital signals proportional to the time delay of the pulse by TDC modules.

Due to the high readout speed of FASTBUS compared to the readin speed of the LSI computer, the digitized data from the FASTBUS DAMs located in the remote crates was then buffered in high speed FASTBUS memories (1 and 4 megabyte LeCroy 1891s located in the “master” crate in Figure 37) during the data spill of 10 seconds, until they could be read into the LSI. This scheme required the 1891s to collectively hold at least one spills’ worth of data, and the LSI to empty the 1891 memories in one machine cycle of sixty seconds, otherwise the system could not keep up with the incoming data rate.

It was necessary to read CAMAC DAM data into the LSI (through a chain of crate controllers and a Kinetic Systems CAMAC to LSI interface as shown in Figure 37) only to immediately pipe the data back out to an 1891 memory through a special 2891 CAMAC module. This was the only means available at the time for getting the CAMAC data into an 1891 memory and in sequence
Remote crates in the experimental area

Figure 37: Hardware data flow.
FASTBUS data from an event. New triggers were vetoed via CAMAC from the trigger instant until the CAMAC pipe to the 1891 memory was initiated. This CAMAC veto, in conjunction with a FASTBUS veto from the trigger instant until the FASTBUS data was transferred to their 1891 memories, assured that the various 1891 records for a given event, including the CAMAC data, were stored in consecutive order in all of the 1891 memories (i.e. on an event by event basis). Once all of an event's 1891 records were read in through a DR11-W and assembled by the LSI front end, the event was transferred, via another DR11-W, to the ODIN online system on the VAX 750 computer. The ODIN system was responsible for final event assembly, detector monitoring, and logging the data to magnetic tape.

The following three sections discuss in detail the three major components of the DAQ system: the CAMAC and FASTBUS hardware, the LSI front end software, and the VAX ODIN online system. These sections are followed by a description of some of the software utilities available, then by a discussion of system performance limitations and planned future improvements for later runs of E653.

4.4 CAMAC hardware

Most CAMAC modules used in the experiment were standard (e.g. blind scalers, TDCs, data latches, etc.) and will not be discussed. Of special note however, is the Ohio State University built “super-trigger module” (STM) – a CAMAC module for generating computer controlled dead-times. This module, upon receiving a trigger input, would declare a CAMAC “look-at-me” (LAM) interrupt to inform the front end computer of the trigger, and held up a veto line disabling further triggers. All new triggers were ignored, and LAMs disabled until a command to re-enable was received from the front end computer. This logic permitted the computer to disable triggers until it was ready to process a new event.
Another CAMAC module of interest was the LeCroy 2891 CAMAC to FASTBUS module, that allowed for communication with 1821 FASTBUS "crate controllers". The 2891 modules accepted CAMAC protocol commands for manipulating 1821 registers and memories, and performed any FASTBUS functions with an appropriate table of CAMAC commands. Operating FASTBUS via the much slower CAMAC system is not a good practice in general, but as will be discussed, the 2891 provided access to remote 1821s that was not available through any other means.

4.5 FASTBUS hardware

Five types of LeCroy FASTBUS modules were employed in the experiment: the 1810 calibration and trigger (CAT), the 1879 multi-hit pipeline time to digital converter (TDC), the 1885 analog to digital converter (ADC), the 1891 multi-record buffer memory, and the 1821 processor module. Due to their relative newness as a DAQ tool, they will be described in the following sections, though more complex details of their operation are discussed in appendices. Following module descriptions, hardware data flow details will be discussed.

4.5.1 Calibration and Trigger Module (CAT) LeCroy 1810

The CAT module performed trigger and calibration functions for data acquisition modules (DAMs) residing in its FASTBUS crate via the crate's backplane. Each remote crate with DAMs contained one of these modules. Only the trigger capabilities relevant to data flow are discussed here.

Trigger logic was controlled with two loadable (via the 1821 processor in the same crate) registers: the clock and the measured pause interval. The clock, could be used as an external frequency reference for TDC modules in the crate, and was continuously programmable. The measured pause interval (MPI) allowed for a programmable fast-clear dead-time between the trigger instant and DAM conversions. Front panel inputs provided for a TDC stop signal, an ADC gate, and
a fast clear. A front panel busy output allowed for the veto of new triggers until the DAQ crate had established or re-established data acquisition mode. Trigger timing on a FASTBUS crate involving the CAT is described in appendix A.

For this experiment, the CAT clock was used for the TDCs' time reference instead of their internal clocks in order to assure a uniform clock time over all TDC modules in a given crate. The clock was set to 334 MHz, which provided 1.5 microsecond full scale, and a 3 nanosecond resolution for the TDCs, as described in the next section. An MPI setting of 3 microseconds provided ample time to process the muon trigger and fast clear unwanted (no detected muon) triggers.

4.5.2 Multi-hit Pipeline Time to Digital Converter (TDC) LeCroy 1879

This module accepted discriminated time over threshold signals and converted them to digitized time signals using a 512 bit (bin) pipeline shift register. The input signal was sampled at an internal or external (CAT) programmable clock rate, setting the upper bin of the 512 bin register to 0 or 1, depending on the state of the input signal, then shifting all bins in the register by one. Upon receipt of a TDC stop from either the front panel or backplane (CAT), the encoding and shifting of the register stopped, and a clock phase was recorded (to 1/2 the resolution of the TDC – 1 bin), thus freezing a 512 bin/clock rate history of the input state. Conversion of the input history consisted of executing a pattern recognition algorithm. This algorithm prevented electronic overshoot (after-pulsing) on the trailing edge of a real signal from generating “fake” signals, and reduced the history of the remaining “real” pulses to leading and trailing edge times. The pattern recognition circuitry checked for a programmable number “Z” of “leading zeros” prior to a hit candidate (series of 1’s). If fewer than Z 0 bins preceded a hit candidate, then the candidate was rejected as after-pulsing. If at least Z 0 bins preceded the hit candidate, then the hit’s leading and trailing edge bin count (first and last set bits positions) were recorded in separate internal 1024 by 32 bit memory buffers for later readout.
Time data from a hit was recorded in 10 bits of the lower half of the 32 bit data word. The upper 9 of these 10 bits recorded up to a 512 count TDC time. A phase latch recorded the state of the clock upon the receipt of a TDC stop signal to within half a bin width (1 bit). This phase bit was recorded in the least significant bit of the data word. The upper 16 bits of the data word were used to store address information. The address contained the TDC’s slot number in the crate and the channel number within the TDC that generated the signal. Leading and trailing edge data had to be read out of their respective memories separately, and since there was no tag distinguishing leading and trailing edge data, their order of readout was important for future retrieval.

An external (CAT) or internal clock could be used as a frequency reference. The maximum clock rate of 500 MHZ, could be divided down by a factor of 2,4,8, or 16. The internal clock was fixed at 500 MHZ, but the CAT clock actually used could be programmed continuously. Also programmable was the active time interval (ATI), the number of bins to be considered as interesting. The ATI was set to 512 bins for a full readout history. With an external CAT clock of 334 MHZ, the full scale time was 1.5 microseconds with a resolution (bin width) of 3 ns. The Z compacting parameter was set at 3, providing a two hit resolution down to \((Z+2)/\text{clock} = 15\) ns, and a 2 hit rejection of \((Z+1)/\text{clock} = 12\) ns.

4.5.3 Analog to Digital Converter (ADC) LeCroy 1885

The 1885 ADC module provided 12 bit dual range gated pulse integration for up to 96 analog input signals. A gate range of fifty nanoseconds to two microseconds was possible, with a relative time jitter of the gate edge receipt among all channels of no more than 5 ns.

The module could be programmed for three range modes: low, high, and automatic. The low range covered up to 200 picocoulombs (pc) ± 10% with a sensitivity of 20 counts/pc. The high range covered 1600 pc ± 10% with a sensitivity of 2.5 counts/pc. The automatic mode of operation selected the appropriate range for a given input signal and encoded whether the low or high range was
used in the range bit of the 32 bit data/address word. This bi-level range mode of operation extended the 12 bits (+ range bit) of data storage to an effective 15 bits of dynamic range.

Conversion (charge integration) and digitization of the analog inputs started ten microseconds after the leading edge of the gate when the internal MPI was used, but immediately after the trailing edge of an external (front panel) MPI if one was present. Complete conversion took less than 750 microseconds over all 96 input channels. A fast clear with a recovery time of 600 ns could be applied at any time.

As with all such charge integrating devices, a gated channel with no signal produced a non-zero output due to internal voltage baselines. Since these so called "pedestals" could vary from channel to channel and over time, they had to be calibrated (subtracted) out of the data. Pedestal data – gated runs with no signal – were periodically recorded on the LSI computer and downloaded to the remote 1821 processor modules that automatically subtracted them from incoming 1885 data in the manner described in the processor module section of this chapter.

4.5.4 Multi-record Buffer LeCroy 1891

The LeCroy 1891 FASTBUS modules were circular, singly linked memories. They stored variable-length records by chaining them together (hence linked) in a logically circular manner – they logically wrapped around the physical end of their memories. Records in the memory were accessed on a “first in/first out” basis, like a queue of people waiting in line for service; the first record written was the first read out. It was possible to protect these memories from being overwritten when they were close to being full; triggers could be disabled through a front panel “full-warning” output when a near full condition was internally detected. Details of the operation of these memories are discussed in appendix B.

Ten 1891 memories were used in the first run of E653; two with a four megabyte storage capacity, and eight with one megabyte of capacity.
4.5.5 Processor Module LeCroy 1821

The 1821 processor module was a fast Emitter Coupled Logic (ECL) intelligent FASTBUS "crate controller" capable of executing programmable FASTBUS protocol microcode with a 40 megahertz (25 nanoseconds/instruction) sequencer. This module was also equipped to sparsify an input stream of TDC and ADC data from modules in its crate. It performed this function by subtracting from the input data stream pedestal data which had been pre-loaded in internal pedestal memory. A threshold comparator circuit kept the resultant value as data only if it was above a pre-loaded threshold. The 1821 communicated either directly with a host computer via DR11-W communication hardware and an DEC/1821\(^2\) backplane interface, or indirectly through CAMAC with front panel connectors interfaced to a LeCroy 2891 CAMAC module. No arithmetic logic (except for subtractions and comparisons internal to the pedestal subtract and threshold comparison circuitry) was provided, so this module could not be used for event building or online cut operations.

The 1821 consisted of the following major sections:

- An input/output (I/O) section responsible for performing I/O between the 1821 registers, internal memories and external devices.

- A pedestal subtraction and comparison section which subtracted pedestals from data and applied a threshold cut on the resultant values. This was accomplished in a four stage pipeline acting on the input stream of data words at a clock rate of 100 nanoseconds/stage (.4 microsecond/32 bit data word total).

- A 40 MHZ sequencer which executed 64 bit instructions from one of 8 internal random access/read only (RAM/ROM) memory chips.

- Eight internal RAM or ROM 256 × 64 bit loadable/programmable memories.

\(^2\)Digital Equipment Corporation (DEC) is the manufacturer of the LSI and VAX line of computers.
• An externally loadable pedestal memory for lookup of pedestals by the pedestal subtraction circuitry. This memory was capable of storing pedestal information for up to thirty-one 128 channel modules.

• A data memory of \(4096 \times 32\) bits for storage of (sparsified) data for I/O operations.

Two threshold registers were available for low or high range ADC threshold comparison and suppression. Pedestals and threshold registers were downloaded from the LSI computer to the 1821 processors in FASTBUS crates on the floor of the experiment. The only path possible for this downloading operation was through 2891 CAMAC to FASTBUS interfaces. The data from the 1891 memories in the master FASTBUS crate was transferred with the much faster DR11-W interface. One 1821 processor resided in each of the remote crates and ran microcode designed to sparsify and pipe data recorded from the experimental apparatus by the DAMs to the master crate 1891 buffer memories via ECL connections and a DEC/ECL interface on the 1821 backplane (see Figure 37). The 1821 residing on the master crate ran microcode to read these buffered events from the 1891 memories in its crate into internal memory for retrieval by the LSI front end computer.

A major limitation (for this experiment) of the 1821s was their internal memory limit of 4096 data words; writing more than 4096 words of data resulted in wrap around of the memory, and hence consequent corruption of data. This did not present a problem for the remote 1821s, as they piped data to the 1891 memories word by word, whereas the master crate 1821 stored 1891 memory data in its internal memory for readout by the LSI computer. As there is effectively no limit (1–4 Mbyte) of how much data could be stored in an 1891 memory record, there was a real possibility of wrapping the data around the 1821 memory during 1891 to 1821 transfers. This situation could be avoided by careful distribution of data acquisition modules throughout the remote FASTBUS crates (and hence 1891 modules since there was a one to one correspondence between them) so
that the likelihood of more than 4096 words/event for a given 1891 memory was remote. This was not as successful as desired in the first run of the experiment due to a limited number of FASTBUS crates. About 5% of the events were discarded at the LSI front end (i.e. read in but not sent to the VAX) due to wrap around in the 1821 on the master crate.

### 4.6 FASTBUS data flow

The transfer of data from the remote FASTBUS data acquisition modules to the LSI computer was built upon two essentially independent operations. A “write” operation transferred data from the DAMs in the remote crates to the 1891 buffer memories on the FASTBUS master crate. The “read” operation read an event into the LSI from the 1891 memories by way of the master crate 1821 processor’s internal memory over a DR11-W link between the 1821 and LSI.

In the “write” operation, the DAM data words were piped to their 1891 memory through the 1821 on the remote crate with its microcode; once a data word from one of the DAMs was transferred to the remote crate’s 1821 and passed through its pedestal subtraction and suppression circuitry, microcode transferred it to the associated 1891 on the master crate via an 1821/ECL interface. When all DAMs were emptied of their data in this manner, the 1891 was strobed with a “write completion” signal; the totality of the DAMs’ data then constituted a record in the 1891 memory.

The “read” operation was initiated by the 1821 processor on the master crate in response to a read request from the LSI computer (via a DR11-W link and 1821/DEC interface card). The read transfer proceeded in analogy to the “write” operation with the replacement of “DAM” with “1891” and “remote 1821” with “master crate 1821” in the description. There was one major difference: The records from the 1891 memories were not piped word by word as on the remote crates. The records associated with the event being read (i.e. the oldest record in each 1891 memory) from a group of 1891 memories were moved from the 1891s to
the local memory of the master crate 1821 processor. They were then transferred to the LSI computer from the 1821 memory as a block in direct memory access (DMA) mode over the DR11-W link. The size of an 1891 record, or group of 1891 records, could exceed the 4096 by 32 bit word memory size of the 1821. When this occurred, the records would wrap around the 1821 memory as previously described. Because of this, the number of 1891 memory records transferred to the master crate 1821 in one transfer was limited by the 1821's memory size. This number was determined by the LSI computer when performing a "pre-read" (see section 4.8.2) of the 1891s to calculate their record lengths. The group of 1891 records thus determined were transferred to the 1821 for readout by the host LSI over the DR11-W link. This procedure was continued until all 1891 memories were emptied of their records for the event being read.

All 1891 records associated with a trigger formed a pre-assembled event. The association of 1891 memory records with a trigger was by record sequence number only; if a record got out of sequence in an 1891, all of its following records would also be out of sequence with their trigger. Records in the memories got out of sequence if the remote crate associated with the 1891 either failed to see a trigger, or received multiple triggers when there was only one. In the first case, the 1891's records were one behind the other 1891's records, while in the second case, the the records were ahead of the other 1891's records. Out of sequence spills occurred at the 5% level near the beginning of the first running period, but were reduced to near 0% for most of the rest of the run. Recovery from sequence errors is discussed in the LSI section of this chapter.

4.7 CAMAC data flow

Discussion of CAMAC hardware data flow unavoidably involves some of the CAMAC-LSI software, as it played such an active role in the trigger processing. The CAMAC driver on the LSI front end provided two different paths for executing a set of CAMAC tables upon the receipt of a CAMAC "Look-At-Me"
(LAM) interrupt. In the first method, a task that had requested notification of a LAM interrupt would wait asynchronously for a message from an installed LAM servicing task to LAMSRV) that would indicate that the specified LAM interrupt had been signaled by the CAMAC hardware. When the CAMAC driver notified LAMSRV of a LAM, LAMSRV would notify any task that had requested notification of this LAM by sending the task a message that it was waiting for. Upon receipt of this message, the task could act on the interrupt by executing sets of CAMAC tables – a list of basic CAMAC functions to be executed as a unit, but serially, by the CAMAC driver. For instance, if the LAM indicated a trigger, the task could read in data from CAMAC modules via a CAMAC table before re-enabling triggers at the end of the table. However, because of the significant time lag in getting the LAM message to a task, this method incurred significant dead-time before triggers could be re-enabled by the task. The advantages of this method were the ability of tasks to process multiple LAM interrupts and the ability of multiple tasks to run CAMAC concurrently by requesting unique LAMs.

In the second path of LAM processing, a special “fast” LAM was requested by a task. This LAM was waited for directly in a CAMAC table, eliminating the time taken by the LAMSRV notification scheme.

In this experiment, the LAMSRV path was used to receive the end of spill (EOS) and beginning of spill (BOS) LAMs that were necessary for the synchronization of the RD1891 and RDCAM online software programs. Time critical data triggers were processed with the fast LAM method. Following the satisfaction of the fast LAM wait, the CAMAC trigger table read out the CAMAC TDC data. It was then safe to re-enable the previously disabled trigger logic of the STM in the CAMAC table before starting to pipe the data to CAMAC's 1891 FASTBUS memory via the 2891 CAMAC module.

BOS LAMs were used to re-enable all logic for data acquisition and had

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3A task in the LSI RSX11-M operating system is simply an executable program. An installed task is permanently memory resident.
no data associated with them. The BOS LAM interrupt was generated about 1 second before the machine spill started. EOS LAMs were generated 1 second after the machine spill ended. The RDCAM task disabled data acquisition logic upon an EOS, and read in end of spill data consisting of blind scaler and scanning digital voltmeter information. This data was not piped to CAMAC’s 1891 module until the RD1891 task signaled that all events from the spill had been read out and that the 1891 memories had been reset (readout complete – ROC). This assured that the EOS data would not follow any events that had caused the records in the 1891 memories to get out of sequence. When the ROC was confirmed, the EOS data was piped to CAMAC’s 1891, and all 1821s on the floor were given a “fake” readout trigger (i.e. a trigger with no gate). This fake trigger was necessary to assure that a record (only a four word header in this case; the DAMs had no data because there was no gate) was written to all 1891 modules along with the EOS data to CAMAC’s 1891, so that the records in the memories remained in sequence.

4.8 The LSI front end computer

The portion of the online software that resided on the LSI front end consisted of: the task “RD1891”, the “RDCAM” task, the global memory region “DATCOM”, FASTBUS and CAMAC drivers, and the inter-process and inter-processor communications driver (CD) and its associated FORTRAN interface software (CD-PACK). The task “RD1891” read in events from the 1891 memories on the master FASTBUS crate, performed minor event formatting such as setting up the event’s directory structure and filling run statistic counters, and sent the events to the VAX online system. The “RDCAM” task was responsible for handling machine spill interrupts (EOS and BOS LAMs), providing a pipeline of CAMAC data through the LSI to a reserved 1891 memory, and performing error protection and recovery functions through a communication link with the RD1891 task. The RD1891 task created the global region DATCOM in order to extend its data
address space for double buffering up to 64 Kbyte events; by allocating enough space to store two events, one could be read from FASTBUS into half of this space, while a previously read event was being transferred to the VAX from the other half. The Fermilab supplied CD and CDPACK software [44,45] was used for communications between the LSI and VAX portions of the online through a physical DR11-W hardware link, and between the RD1891 and RDCAM task on the LSI via a "virtual" CD link — a pathway in the CD software that permitted programs on the same computer to communicate in the same manner as programs on different machines.

The RDCAM and RD1891 tasks had a number of similar features. Both were "event" driven (event in the sense of something happening on the computer system — not to be confused with data events) to handle asynchronous input from multiple sources\textsuperscript{4}. This enabled the tasks to actively process information while at the same time waiting for the occurrence of a number of events. It also permitted a natural partitioning of the tasks into routines tailored for processing these asynchronous system events. Both tasks accepted commands either from the VAX online system (via CD and CDPACK) or from the terminal. Commands from both sources were formatted into packets and were executed by a set of common routines. RD1891 and RDCAM could be run independently of the VAX ODIN system by requesting so when starting them up.

\textbf{4.8.1 The RDCAM LSI task}

The task "RDCAM" was mainly responsible for reading CAMAC data into the LSI computer, and piping it back out to its 1891 memory as quickly as possible during the beam spill. Immediately after the beam spill, non time-critical CAMAC data — blind scaler counters, digital voltmeter readings, and other monitoring information — was read out as a special end of spill trigger. The RDCAM

\textsuperscript{4} Using RSX11-M operating system's event flag setting and waiting services to signal and wait for system events avoided deadlocks and race conditions that would ensue from any serial method of processing system events.
task was also responsible for synchronizing the entire online system with the accelerator cycles through CAMAC LAM interrupts that were arranged to occur immediately prior to (BOS), and immediately after (EOS), the beam spill.

Triggers were disabled by RDCAM starting from the EOS and lasting until the RD1891 task had read out of all of the 1891 memories for the spill (i.e. ROC). End of spill data was not piped out to the 1891 memory until ROC. The ROC condition was signaled to RDCAM by the RD1891 task over the virtual CD link. This signal was the end of a hand shake cycle that started with RDCAM signaling RD1891 that an EOS had occurred. The EOS condition was used by RD1891 to define the ROC condition – no data in the 1891s along with an EOS.

The execution flow of RDCAM is described in Figure 38. As indicated, there were two separate “wait states” for the task. These states were mutually exclusive, and were implemented by switching event flag wait masks prior to entering the wait state. While in the data acquisition mode (between BOS and EOS), all possible system events were waited for: unsolicited terminal input, unsolicited commands from the VAX portion of the online, EOS and BOS LAM interrupts, fast data trigger LAM completion, and unsolicited messages from RD1891 over the virtual CD link. Upon receipt of an EOS LAM, EOS data was read in, triggers were disabled, an EOS message was sent to the RD1891 task over the CD link, and the wait mask was switched to wait for unsolicited input from the terminal, VAX online, or RD1891 task before the wait state was entered. This allowed the task to wait for the ROC from RD1891 without the interference of CAMAC LAMs, but permitted intervention by operators (e.g. to shut down the online system). The receipt of a message from the RD1891 task signaled a ROC and the wait masks were once again exchanged.

Unsolicited commands (e.g. begin run, end run, pause, etc.) originating at the LSI or VAX online terminals took precedence over other system events in either wait state to prevent the operators from being locked out by other system events.
Figure 38: LSI RDCAM CAMAC task flow chart.
4.8.2 The RD1891 LSI task

The RD1891 task read events from the FASTBUS 1891 memories, performed minor event formatting upon them, then sent them to the VAX computer for monitoring and eventual writing to magnetic tape. In addition, the events were processed for occurrences of some anticipated errors.

Events up to 64 kilobytes (kb) were processed; those exceeding this limit were read in and discarded (or "flushed"). Two 64kb buffers were used to overlap the transfer of events to the VAX with the reading in of events from FASTBUS. Accessing this amount of memory space on the LSI under the RSX11-M operating system was a problem since tasks were limited to a total size of 64 kb. A global 128 kb memory region DATCOM was created by RD1891 to overcome this restriction. The RD1891 task then mapped a 32 kb common block to this memory region through a 32 kb "window" that could be moved about the region to access any 32 kb portion of it. Details of this scheme and other memory storage saving techniques are described in appendix C.

Figure 39 displays the main flow of the RD1891 program. The task waited for the occurrence of an unsolicited terminal or VAX command, an EOS message from the RDCAM task over the virtual CD link, or for the FASTBUS data flag. As with the RDCAM task, unsolicited commands always took precedence. The task needed to poll the 1891 memories with a "pre-read" (briefly described below) to determine if they had any data, as FASTBUS interrupts were not available. To avoid the excessive use of Central Processing Unit (CPU) cycles (computer time) imposed by any synchronous polling scheme (e.g. a tight CPU bound wait loop), a FASTBUS data flag in conjunction with the system mark time directive was used to asynchronously poll the 1891s at a fixed time interval. As long as the 1891 memories were found to have events, the FASTBUS flag was left set so that there would be an immediate return from the wait state and a consequent processing of the next event. If an event read failed because there was no data, then the FASTBUS flag would be cleared, all mark time requests cancelled, and a mark time request to set the FASTBUS flag in 1/6 of a second (10 LSI clock
Figure 39: LSI RD1891 FASTBUS task flow chart.
ticks) would be queued to the system before the RD1891 wait state was entered. Then, in 1/6 of a second, the system would set the FASTBUS flag satisfying the wait state, execution would continue, and an attempt to read the 1891s would be performed again. Polling would continue until data was again available. When a no-data condition was detected by RD1891, it checked an internal end of spill (EOS) flag to see if the RDCAM task had signaled an EOS condition. If so, then RD1891 would enter a read out complete (ROC) routine. Since the 1891 memories were then empty and no more data was expected for a while (triggers were disabled between spills), then it was safe to reset all 1891 memories in the master crate, and to perform a general end of spill cleanup. Resetting the 1891 memories assured that they would start recording at the physical beginning of their memory in the next spill. This restricted “sequence” errors to within one spill. RD1891 also determined if there were any sequence errors in the last spill from the now “frozen” 1891 memories’ write pointers – the 1891 record sequence counters imbedded in these words should all have been the same. If a sequence error was detected, it was signaled to the VAX online. In addition to the error checking and recovery in this routine, spill statistics were printed out to a terminal. Before returning, this routine signaled a read out complete to the RDCAM task and set the internal EOS flag off.

Additional error recovery in RD1891 consisted of:

- The discarding of events greater than 64 kb. These events were read in pieces to the same location in memory (to avoid excessive memory mapping overhead) until the whole event was read. It was then discarded.

- Discarding events if any 1891 memory’s record length exceeded 4096 32 bit words. These events had wrapped around in the master crate 1821 as described in section 4.5.5.

- Checking with a timed loop, before each event was read out, the FASTBUS master crate to see if it was busy. If it was still busy after a fixed amount of
attempts, it was assumed locked up. Additionally, if a pre-read (to determine if there was data) returned no data, then the master crate was locked up. Data acquisition could not proceed without some kind of intervention. If a lock up was detected, the entire master crate was reset. This destroyed any data in the 1891 memories, but data acquisition could usually proceed without human intervention.

- Tagging "framing" errors. In about 3% of the transfers of 1891 memory record(s) to the 1821 processor memory, spurious words were inserted by the hardware (usually a few duplicated words). This corrupted the directory structure of the event.

A "pre-read" of the 1891 memories' registers was performed in each polling cycle to determine if they contained data. This consisted of reading out the current record's starting and ending addresses for all of the 1891s as well as checking address validity as illustrated in the algorithm in Figure 53 of section 4.5.4. The data thus read out formed a natural directory structure of the event as indicated in Figure 40. As the figure and algorithm show, the starting and ending addresses of the records in the various 1891 memories were used to make pointers to the corresponding variable length 1891 data in the buffer. A fixed section of LSI counters and run statistic data (e.g. number of discarded events, number framing errors, etc.) was appended to the directory and event data prior to sending the partially structured event to the VAX computer.

4.9 VAX ODIN system

This section discusses the VAX ODIN\(^5\) component of the online software. A general discussion of design and implementation considerations is followed by a brief description of the specific means of implementation. Descriptions of the major components then follow.

\(^5\)Major software components of the VAX portion of the online system were named after Norse gods
Figure 40: RD1891 event directory structure.
4.9.1 Philosophy of design and implementation

Two related issues arose in the consideration of the design and implementation of the VAX online system for E653: the definition of features for monitoring and recording the data, and the implementation of these features in an environment where the demand for resources such as Central Processing Unit (CPU) time and memory would in many instances exceed the resource availability. Design goals for online system were:

- **Efficiency** – The system needed to be as fast as possible given host computer limitations.

- **Ease of use** – Simplified commands and a help facility, control of entire system from one terminal.

- **Self-contained data acquisition environment** within the online program – the user should not have to exit the program to perform any acquisition related functions.

- **Ease in addition of new components** (modularity).

- **Self-monitoring displays** of the entire data acquisition software and hardware system.

- **Continual writing of events** without the need to halt data acquisition between tapes (i.e. automatic tape switching on a full tape volume) and requiring as little user intervention as possible. – This would allow the concurrent recording of events in the emulsion and onto tape.

- **Real-time monitoring** of critical components of the experimental apparatus such as magnet currents, high voltage supplies, etc.

- **Quick event displays** of experimental apparatus. – The ability to look at the experiment as a whole in limited detail with the option to look at any particular component in greater detail.
The ability to independently monitor, and develop software for, the various components of the apparatus. This would allow the "experts" of a given component to develop their monitoring software independently of, but in parallel with, the development of other components. This implies that a standard "package" of uniform, easy-to-use routines for monitoring functions – histogramming, plotting, statistics, etc. – and commands to execute them should be made available to these experts.

The major concern in implementing these goals was to maximize the use of two major resources of the computer: free memory space and CPU cycles (computer time).

The VAX/VMS operating system is an "open" system – most specialized system routines are available to VAX users. These routines are made available in all languages as either system services, modules in run-time libraries, or as executive or kernel routines (though the higher access mode executive and kernel routines were not used by the online programs). These well tested and highly optimized VMS routines were used in the implementation of the online programs wherever possible.

The VAX/VMS process scheduler was recruited to optimize CPU usage. The online system was divided into a number of tasks (e.g. data collection, monitoring, data writing, user command input processing), that operated asynchronously. The main process\(^6\) that controlled the entire online system created sub-processes to execute these tasks. The sub-processes were event-driven – they were placed in a wait state by the scheduler until needed. This assured that CPU cycles were available to a task upon demand. If a number of the sub-processes had work to do simultaneously, they were scheduled on a "round-robin" (i.e. rotated) basis (references [47] pp. 183–207 and [48] pp. 287–293 discuss VAX/VMS scheduling in detail). All processes and sub-processes in the online data acquisition system were run at a higher process priority than most other processes on the VAX. This allowed other processes to be run on the system with no degradation in data

\(^6\)A process on a VAX computer system is a memory resident, executable program.
acquisition performance.

The division of the online system into separate tasks (sub-processes) also fit in naturally with the VMS process ownership and context (i.e. total environment) concepts (see for instance references [48] p. 259 or [47] pp. 3–5). The online sub-processes, in general, handled all functions that had to be performed in their context under the VMS operating system. For instance, since the data writing sub-process wrote events to tape, it had to “own” the tape and the file on the tape. It was therefore responsible for mounting and dismounting tapes and for opening and closing files on the tapes as well as writing the events to tapes. Similarly, the event gathering sub-process was set up to be the only process with a link to the LSI front end computer; all communications to the LSI had to be processed in its context.

Although the sub-processes could operate “simultaneously” and independently, they needed to communicate information to one another (e.g. much of the “parallel” processing was on different events; these events needed to be passed on to the next sub-process for its particular processing). Introducing multi-tasking and scheduling into the online system, while providing optimal CPU sharing, complicated matters by necessitating the introduction of inter-process communication. The VAX/VMS operating system provided a wide variety of support for this purpose; VMS shared image data structures\textsuperscript{7}, event flag services, and mail-boxes, were used to implement inter-process communication.

Memory was allocated and deallocated in variable length blocks from a memory-ordered circular list of free blocks of memory. A “manager” sub-process allocated portions of this pool of memory to itself and other sub-processes as needed, deallocating the blocks for re-use when they were no longer needed. Memory blocks used to buffer events were passed between online sub-processes through shared memory queues (linear lists of items for which all insertions are made at

\textsuperscript{7}In VAX jargon, an image is the representation in memory of an executable program, or set of non-executable data structures such as a shared image.
one end of the list, while all removals are made at the other end). Online processes pulled events off of their associated queue, processed them, then passed them to another online process by pushing them onto its queue. This memory management scheme not only maximized use of the memory pool, but also fit in with the partitioning of the online system into separate tasks via the event queueing mechanism.

Because E653 recorded on two media – data onto tape, and tracks onto the emulsion – some synchronization was needed to avoid recording on one medium while the other was not able to record. Since tapes had to be changed about every 20 minutes, while emulsion modules typically were replaced every 12 hours, it was important not to interrupt the emulsion exposure while changing tapes. With this in mind, automatic tape switching was made an integral part of the online system design.

Event monitoring was implemented through detached processes (i.e. processes independent of the main online system). These processes could access events in real-time through a common queue which was filled by the online system. Events were pulled off this queue, copied to buffer space within the process, then returned to the online system for re-use. All of this was accomplished through interface routines that were transparent to the user. These analysis processes contained all the rudiments necessary to monitor and display information from events – histogramming, plotting, and statistics functions were built in as well as commands to access and display this information. Analysis and displays could be tailored to specific components of the experiment through user defined subroutines.

Most of the approximately 15000 lines of VAX online code was written in VAX/VMS extended FORTRAN 77. The only exception was the shared code section, which needed to be re-entrant (i.e. simultaneously accessible by more than one process – reference [48], p. 132, discusses re-entrant code) and thus was

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8 Of this size, 8000 lines belonged to the ODIN DAQ system, while 7000 belonged to the NORN analysis system super-structure.
written in VAX assembler language⁹.

4.9.2 ODIN online implementation

Figure 41 depicts the normal data flow throughout the online system. The VAX/VMS ODIN online system consisted of: the shared image ODINSHARE, the process ASGARD, three ASGARD sub-processes and their associated queues, and the free queue. The shared image ODINSHARE included a memory pool, the FREELIST, for buffering events for analysis. The user interface process, ASGARD, accepted unsolicited commands from a terminal and controlled the entire online system, including the LSI processes. Three ASGARD created sub-processes HUGIN, THOR, and MUNIN processed events in three phases: acquisition and assembly, cutting and monitoring, and writing to tape respectively. Events were asynchronously made available to two of these sub-processes and to detached NORN analysis processes through three queues. The CTQ, MTQ, and ANQ queues (cut, magnetic-tape, and analysis queues) were supplied events from HUGIN, THOR, and MUNIN respectively. The “consumers” of events from these queues were THOR, MUNIN, and NORN(s) respectively. These queues also had the effect of statistically smoothing the incoming data rate. A fourth queue, the FRQ (free queue), was used as a trash bin for processed events, and was periodically emptied into the FREELIST to replenish the memory pool. All ODIN processes ran at elevated process priority so that other processes on the system could not interfere with data acquisition.

Full analysis and detector monitoring was implemented through the NORN system. NORNs were normal priority detached processes that competed for events in the ODIN analysis queue. The NORNs could be tailored for individual detector analysis through simple user interfaces, and had online histogram and graphics packages built in.

Detached, normal priority processes called LOKI could execute a restricted subset of ASGARD commands, and thus allowed minimal monitoring of the online

⁹FORTRAN is not re-entrant because it uses local process memory to store information.
Figure 41: ODIN online system data flow.
system from remote locations.

All ODIN processes and sub-processes along with the NORN and LOKI processes linked in with the shared image ODINSHARE which made available to them shared data structures and routines.

4.9.3 ODINSHARE shared image

The ODINSHARE shared image was a non-executable set of routines and data structures installed in the VAX's memory that could be shared by any processes that were linked with it. When any of the shared image's data structures or routines that were being accessed by a process were not in physical memory, they were brought into memory from the image's disk file. When the shared image's physical memory pages were no longer in use by any process, they were copied back to the disk image file. Thus all data stored in the shared image global data structures (e.g. in FORTRAN common blocks) by linked processes was saved for future access by processes 10. This property allowed ODINSHARE to be used as a database. In addition to shareable data structures, ODINSHARE contained re-entrant routines that could be transparently accessed by any process linked to the ODINSHARE image.

Shared data areas and routines in ODINSHARE included the memory pool used to buffer events, the FREELIST used to manage the pool, a set of interface routines that accessed the pool through the FREELIST, event queues to distribute the events to the various online processes, shared FORTRAN commons that shared information among the processes in the online system, and an error message section that defined message formats for anticipated online system errors. A number of shared service routines were also supplied for general use.

The database capability of the FORTRAN common blocks was used in monitoring critical voltages of the experimental apparatus (e.g. magnet current, RF

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10Re-linking the shared image after making changes to its routines or data structures would destroy this information however.
hut temperature etc.). Scanning digital voltmeter data extracted from the CA-MAC data in incoming events was compared to acceptable limits defined in shared FORTRAN commons.

The various sections contained in the ODINSHARE image are described in detail in appendix D, including more details of the voltage monitoring scheme.

### 4.9.4 ASGARD user interface process

The ASGARD process was the portion of the online most visible to the user. The terminal from which it was invoked accepted commands that controlled the entire online system. ASGARD was responsible for bringing up the rest of the online system, namely its sub-processes HUGIN, THOR, and MUNIN. All anticipated error messages from these sub-processes and the LSI portion of the online were routed to ASGARD for display at its terminal with a warning bell.

ASGARD provided a self-contained environment for data acquisition and needed to be started only once for a series of data runs; commands that changed the online configuration such as setting up data writing modes, beginning and ending a run, mounting/dismounting tapes, etc. could be given at the ASGARD terminal. Lengthy series of commands such as selecting the writing mode etc. were stored in a standard set of command files, which could be invoked using the indirect command-file processing feature:

```
@FILENAME
```

This would serially process the commands in the file in a fashion similar to VAX DCL indirect command processing. A typical terminal session for beginning a
run consisted of:

\begin{verbatim}
ASGARD >  @LOG
\( \text{!setup standard writing mode} \)
\( \text{!via the command file LOG.COM} \)
ASGARD >  MOUNT 1
\( \text{!mount a tape on device 1} \)
ASGARD >  MOUNT 2
\( \text{!mount a second tape on device 2} \)
ASGARD >  BEGINRUN
\( \text{!for auto tape switching} \)
\( \text{!begin a run} \)
\end{verbatim}

Here ASGARD> is the prompt displayed by the unsolicited input routines when the user starts typing at the terminal, and the exclamation point precedes comments.

Some typical informative ASGARD monitoring commands were: SHOW DEVICE, which displayed available devices for event writing; SHOW SYSTEM, which displayed ODIN system characteristics such as pool usage, CPU usage etc.; and SHOW SCALERS, which displayed blind scaler information.

Details of the ASGARD process are discussed in section E.1 in appendix E.

4.9.5 ASGARD sub-processes

Though the three ASGARD created sub-processes did most of the data acquisition work, none could write information to a terminal directly (this was reserved for ASGARD), but all had log and error files that were used for debugging purposes. All had a number of common features, for example, the way they processed commands from ASGARD, the way they responded to errors, and they manner in which they started up. Details of the common features of the ASGARD sub-processes are contained in section E.2 of appendix E.
4.9.5.1 HUGIN event receiver and builder sub-process

The ASGARD sub-process HUGIN was the only process that directly communicated with the LSI front end computer, and hence was responsible for receiving and allocating space for incoming events or error messages from the LSI, and for funneling portions of ASGARD BEGINRUN and ENDRUN commands to the appropriate tasks on the LSI computer. LSI error messages were processed then passed on to ASGARD for display, while, after minor formatting, events from the LSI were pushed onto the cut queue for further processing by THOR. A non-live “playback” mode could be selected to read events from disk or tape instead of the LSI front end.

HUGIN was the manager of the memory pool FREELIST, and was thus responsible for allocating space for the events it received from the front end LSI computer, as well as deallocating space back to the FREELIST from events that had been fully processed and written to tape. The memory management techniques used by the HUGIN process are described in appendix F.

4.9.5.2 THOR minimal monitoring and cut sub-process

The THOR sub-process, second in the chain that processed events, was originally intended to perform online cuts of the data to reduce the data (tape) volume produced by the experiment. Cut processing interfaces in HUGIN were made, but were never implemented. Without the cut processing, THOR was used to perform all calculation intensive event processing for the ODIN system (HUGIN and MUNIN being data input-output intensive). Small amounts of data were extracted from events by THOR for minimal real-time detector and event monitoring functions. These functions included accumulating run by run event statistics: 1891 memory module record lengths, EOS blind scaler counts and ratios, equipment voltage monitoring via scanning digital volt meter data, and LSI error counts (number of framing errors, spills out of sequence in 1891 records, etc.). These statistics were stored in shared FORTRAN commons for display by
ASGARD upon user request.

When THOR had finished with an event, it was pushed onto the magnetic-tape queue, and the event flag associated with that queue was set. The MUNIN process could then extract the event from the magnetic-tape queue and write it to tape or disk.

4.9.5.3 MUNIN tape writing and run logging sub-process

The MUNIN sub-process was responsible for: writing events to magnetic-tape or disk, mounting and dismounting tapes, monitoring output tape and disk devices for errors, the automatic switching of tapes when full, and keeping a run by run disk file log (RUN.LOG) of tape mounting, file opening, and any user input (e.g. operator, emulsion-id, etc.). File structuring, internal record structuring, and event structuring are discussed in section 4.9.9.

MUNIN could be set up in a writing or no-writing mode. In the no-write mode, events were not written to any output file, but were immediately pushed onto the next queue in the chain. The automatic switching mode was also selectable. If not selected, a run would terminate upon encountering a full tape volume. The auto-switch mode allowed continuous running if a second device was kept ready with a tape volume mounted on it. Upon reaching the end of the volume on the current device, its file was closed and it was dismounted. A file was then opened on the second device, a tape header was written to it, and data writing continued on the new volume. The magnetic-tape switching algorithm is discussed in more detail in appendix G.

After MUNIN had written an event to tape or disk, the event was pushed onto the next queue in the chain (almost always the analysis queue for processing by the NORNs), and the appropriate queue flag was set to notify the users of that queue.
4.9.6 NORN detached analysis processes

NORNs were normal priority, detached processes that performed real-time analysis on incoming live events copied from the analysis queue (ANQ) of the ODIN system into internal buffers for processing. NORNs were designed to be easily tailored for analysis and display of specific components of the experiment. The main components of a NORN were:

1. User transparent interfaces that copied events from the ODIN ANQ into an internal buffer.

2. User transparent LOCK_XXXX routines that:

   (a) Assured the NORN was run in the same group account as the ODIN system (to access the group-global flags and the VMS lock manager group locks correctly).

   (b) Assured the NORN was running below a set base process priority so as not to interfere with data acquisition processing.

   (c) limited the total number of NORNs and LOKIs on the system to an ODIN specified parameter and assigned to each NORN a unique process name.

3. User interface routines EVINIT, EVPROC, and EVEXIT. These routines initialized a NORN, processed an event, and processed results respectively. EVINIT was mainly used to set up histograms, EVPROC to unfold events and histogram/display pertinent information, and EVEXIT printed histograms and results upon exit.

4. A standard set of commands for program control, histogram functions, and graphics functions. Command parsing was performed by the same set of routines that parsed ASGARD commands - CMD_XXXX. Unsolicited terminal commands were accepted through a terminal mailbox with the SRV_XXXX shared memory routines.
5. Histogram and graphics implemented by a reduced set of the CERN HBOOK routines dubbed MINI-HBOOK. MINI-HBOOK routines had the same call structure as the corresponding full CERN HBOOK routines though not all HBOOK routines were implemented in MINI-HBOOK, and internal histogram storage was handled differently. The MINI-HBOOK graphics routines were interfaced to the internal MINI-HBOOK histogram storage via the NORN display commands, and had such features as a continuously updating display mode and scatterplots. Restriction of HBOOK routines and reorganization of its internal storage were necessary in order to reduce memory usage, since each online NORN kept a copy of the histogram package in memory.

6. A NORN help library to provide help information on NORN commands and other items pertinent to operating a NORN which could be accessed in NORN command mode.

7. An exception and signaled error condition handler as in the ASGARD process.

8. An exit handler to do NORN specific cleanup on image exit.

More than one online NORN could be run concurrently, but the total number of NORNs allowed in the system at any one time could not exceed an ODIN system parameter that restricted the total number of NORN and LOKI processes in the system\textsuperscript{11}. This number was set to 5–6 for normal running. Typically, a standard monitor NORN along with two or three detector specific NORNs were run concurrently during data acquisition. A “live” event display generated online by a NORN analysis process is shown in Figure 42.

\textsuperscript{11}There was also an upper limit of 10 concurrent online NORNs due to the limited availability of group-global event flags.
Figure 42: NORN analysis generated event display from the first running period.
4.9.7 LOKI data acquisition "spy" processes

Detached LOKI processes executed a subset of ASGARD commands for remotely monitoring the online system from distant locations over the ETHERNET network. Only ASGARD commands such as SHOW could be executed; commands that could affect the running of the online data acquisition process (e.g. BEGIN-RUN, ENDRUN) were not included for use by these processes. More than one LOKI could be active at any instant, but their number could not exceed an ODIN system parameter which limited the total number of online NORNs plus LOKIs.

4.9.8 Command processing

The ASGARD, NORN and LOKI processes all used VAX/VMS COMMAND DEFINITION UTILITY based command definition and execution routines to provide a simple and uniform command environment for the user. Details of the command system syntax, parsing, and implementation are given in appendix H.

4.9.9 File and event structures

Data was written with standard VAX RMS macros as binary 32 bit integers. A fixed-length record size of 3840 bytes was chosen to conform to the maximum record size on a CYBER computer (512 60 bit words). A block size of 30720 was chosen to minimize the amount of inter-block gaps generated on tapes (i.e. maximizing the number of events per tape – a maximum of 30720 was chosen to keep the block size compatible with the maximum 16 bit field allowed on IBM machines while at the same time requiring it to be an integral number of records). As the variable event lengths practically always exceeded the record length, internal record formatting was required. This was implemented with one 32 bit word per record to store event structure information as depicted in Figure 43. Algorithms for reading (writing) events by stripping (generating) these record formatting words quickly (i.e. with no bulk memory moves) were used and proved quite satisfactory in speed and CPU usage. This form of record formatting also
BYTE OFFSET

| 0     | RN = Record # this event (0 — N - 1) |
| 1     | RR = Remaining records (N - 1 — 0)   |
| 2-3   | BC = Byte count of data to follow in this record |
| 4-?   | BC Bytes of event data               |

GARBAGE
(In general, all records full except last of event)

NOTE THAT RN + RR + 1 = N
= NUMBER OF RECORDS THIS EVENT
AND THAT RN = 0 = FIRST RECORD
OF THE EVENT, RR = 0 IS THE LAST RECORD

Figure 43: Internal record formatting for event tape writing.
allowed for quick error checking and recovery from corrupted records and "out of sequence" event records.

The events themselves were structured internally as depicted in Figure 44. The modularity of the FASTBUS hardware configuration (a one-to-one correspondence between 1891 modules and DAQ crates) drove the design of the event format (see section 4.8.2). The main body of the event directory, and the data itself were filled on the LSI front end, while a fixed length portion of the event was filled on the VAX in event space reserved for it.

Tapes were pre-labeled in ANSI standard format and multiple files per tape were permitted, though in practice, only one file was generated per tape (exceptions were, for example, calibration tapes). Tape labels were required to conform to the Fermilab specified \(^{12}\) format "WWnnnn", where WW is a two character string, and nnnn is a 4 digit run number.

The ODIN system extracted the run number from the tape label, and automatically generated unique file-names from this information as follows:

- the first file on the tape is RnnnnA.DAT
- the second is RnnnnB.DAT
- ...
- with wrap around on RnnnnZ.DAT

If a fatal write error occurred, and a secondary tape volume WWmmmmm was mounted and ready, then the first volume was dismounted, and the file "Rmmmm1.DAT" was opened on the secondary volume. Event writing continued on the new volume until the sum length of data written to both volumes equaled the length of data that would fit onto one tape. The "1" instead of "A" in the new volume filename distinguished it as an error continued file, while the summed length requirement permitted later merging of the two tapes into one.

For normal running, each tape began with a header "event" containing various calibration information, and ended with an end of spill event. Error continued

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12 Tapes vaulted at Fermilab with labels in this format could be automatically retrieved by the Fermilab tape retrieval system.
Figure 44: Structure of an online event.
tapes did not have headers written to them in keeping with the merging scheme already mentioned.

4.9.10 Device database

Up to eight output devices could be specified for the ODIN system by simply defining in the ODIN login procedure the group logical names ODIN$DEV1... ODIN$DEV8 to the appropriate device names. ASGARD initialized the device database at startup time by translating the logical names to the device names. The devices could then be selected for use with the ASGARD INITIALIZE/DEVICE command. This scheme allowed for easy redefinition of devices without the need to recompile or re-link the online system.

Each device had four bits reserved in a 32 bit word (hence the maximum of eight devices) which describe the static state of the device:

1. The select bit was set when the device had been selected with the INITIALIZE/DEVICE command. Devices had to be selected before they could be used.

2. The ready bit was set when the device was ready for file opening and data writing. Disk devices were always ready, but tape devices needed to be software enabled via the ASGARD MOUNT command.

3. The tape bit was set if the device was a tape drive, otherwise it was cleared.

4. The fourth bit was reserved for future expansion.

The ASGARD SHOW DEVICE command displayed the above information for all available devices along with any currently opened input or output device and file names.

Three 6250 bytes/inch, 75 inches/second, Systems Industries tape drives were configured on the massbus of the VAX computer. In principle, only two drives were needed to implement auto-switching, but three were necessary in practice since one was usually in a state of repair.
4.10 Online utilities

A number of utility programs were generated to augment testing of the front end DAQ hardware and to provide support for the online system and offline analysis. Support utilities included:

- LSI front end programs which loaded microcode and/or pedestal data to remote 1821 modules via CAMAC front port connections. Microcode was selected to either enable the 1821s for data acquisition or to perform module testing.

- A pedestal file generating program. This utility generated a file in a format for loading pedestal data in remote 1821s for subtraction and zero suppression of the data. In addition to the pedestals, one standard deviation fluctuations due to noise were also calculated and saved for later offline signal processing. Pedestal runs were performed once per day. This was typically done during machine down periods since pedestal acquisition was incompatible with data acquisition.

- Utilities to test the front end DAQ hardware by writing bit patterns to various points in the DAQ system, and reading back the patterns at the same point or further downstream in the system. These tests could locate latched or discontinuous bits, and reveal bad memory locations.

- An LSI/VAX utility (SENDFB/GETFB) that transferred the recorded pedestal run data from the LSI to shared FORTRAN commons in the ODINSHARE shared image on the VAX. These pedestal values were then available to the online system, and were written as part of the tape header for each tape.

- A VAX/VMS DIGITAL COMMAND LANGUAGE (DCL) command extension program OCOPY, that copied ODIN formatted tapes or disk files. This command provided some simple cut options (e.g. it copied only a range or list of event numbers) and could generate output files or tapes of different formats (i.e. differing record or block size combinations).
4.11 Performance limitations and planned future improvements

Two constraints limited the system throughput to approximately 300 events (averaging 26 kilobytes per event) per 60 second beam cycle: overflow of the smaller 1 megabyte 1891 buffer memories and the non-overlapping on the LSI front end of the 1891 data read with the data write to the VAX system. Dead-time on the system – essentially a measure of the inefficiency in the use of the emulsion – was 30%-35% and was limited by two rate dependent and one rate independent factors. Reading CAMAC into the LSI to pipe it to the 1891 resulted in a 25%-30% dead-time at the rates used (completely masking the 10% dead-time from FASTBUS DAQ hardware). Running at higher rates resulted in a large dead-time contribution due to “full warning” vetoes from the smaller 1891 memories which prevented them from being over-filled. This was kept to a minimum at the sacrifice of throughput by reducing the beam rate. The source of rate independent “effective” dead time was the discarding of 5% of the incoming events by the LSI data acquisition software because of event size limitations. This occurred when an event exceeded the maximum buffer length of 64 kbytes on the LSI, or when the spectrometer drift chambers produced too large an amount of data in one 1891 memory record for storage in the 1821 processor memory, resulting in wrapping the data around the 1821 memory.

4.11.1 RD1891 and FASTBUS

The “RD1891” program proved to be the major software throughput limitation of the online system. Its software was set up to double buffer events so that computer bus cycles for reading in data from the 1891 memories could overlap with those for writing out events to the VAX ODIN system by performing QIO\textsuperscript{13} DMA “writes” with no wait from one buffer while performing DMA “reads” into

\textsuperscript{13}queue input/output request – the means by which Digital Equipment Corporation computers schedule input/output requests from processes
the other. During the middle of the run it was discovered that the DR11-W driver, which reads events from FASTBUS into the LSI, performed the entire DMA transfer at driver interrupt priority level without any interrupt servicing. This blocked any other driver activity during these DMA cycles and prevented any overlapping. It was not known whether putting DMA completion interrupt servicing in the driver, so that DMA could proceed below driver interrupt level, would drastically affect the performance of the system by allowing overlap, or have no effect at all. Tests showed that there was little effect; it appeared that the LSI bus arbitration logic cycles had a latency time that did not allow for the hoped for DMA overlap.

The only software improvement for the second and later runs was the implementation of a list driven driver. This allowed for the elimination of some QIOs, but did not seem to improve the throughput significantly. An additional FASTBUS crate for the spectrometer drift chamber readout allowed its TDCs to be split into two crates, each of which would produce less than 4096 32 bit words of data. This eliminated the 5% of effective dead-time due to the discarding of events with 1821 memory wrap around that was present during the first run. Also, all one megabyte 1821 memories were replaced by 4 megabyte memories so that full memory warnings (at above 250-300 26 Kbyte events/spill during the first running period) are no longer a throughput limitation.

4.11.2 RDCAM and CAMAC

The “RDCAM” task not only contributed the major portion of the dead-time of the experiment during the first data run, but also commanded the LSI front end for the first 10 seconds of the 60 second accelerator cycle. This could reduce the throughput of the online by approximately twenty percent. All CAMAC processing was moved to smart CAMAC crate controllers for the second and later runs. This reduced the dead-time from the 30% of the first run to approximately 10% (FASTBUS overhead), and increased the throughput of the system by 20%. During the first run the system was not run at its full capability of approximately
350 events/cycle because both the 1 megabyte 1891 memories full warnings and the rate dependent CAMAC overhead yielded an unacceptable dead-time before this rate was achieved. The beam intensity was adjusted to keep the total dead-time to below 25–30%. Later runs of the experiment will have neither the full warning nor the CAMAC overheads, allowing the system to be run at its full capability.

4.11.3 VAX ODIN system

During the first run, the ODIN online system used approximately forty percent of the available CPU time on the VAX for processing between 250–300 26 Kbyte events per 60 second cycle, corresponding to 80–95 millisecond/event (3–3.7 microsecond/byte). Of this time it was determined that each of the three ASGARD sub-processes consumed 1–2 milliseconds per event in overhead due to queuing and event flag servicing algorithms. The process THOR contributed an additional 2–3 milliseconds per event in obtaining and processing monitoring information from the events. The remaining CPU cycles were due to servicing event I/O from the LSI and to the output tapes and from system overheads such as process scheduling.

Absolute limits were placed on system throughput by the CPU usage of the ODIN system and by the tape drive speed of 75 inches per second. The CPU usage amounted to an upper limit of 650 to 750 events per 60 second cycle. Since approximately 5000 26 Kbyte events were written to 2300 feet of tape at a density of 6250 bytes/inch, the tape drive speed limit was reached at a rate of about 700–800 events/cycle. The ultimate limit is thus determined by the CPU usage – 650–750 events/cycle.

The only planned change in the ODIN system for later runs is the modification of its front end to solicit fixed length (64 Kbyte) event reads from the LSI front end. In the first run, the HUGIN process was aware of pending unsolicited LSI transfers via an asynchronous system trap, and did not perform a read until the variable length of the transfer was known and space was allocated for it from
the memory pool. While this method allowed optimal use of memory by allocating only what was needed, it did not allow for QIO overhead to be overlapped with other functions as the QIO was serial in the read process. It was originally thought that memory space restrictions would be severe, but careful coding and system organization overcame such restrictions. It was thus deemed appropriate to re-design the HUGIN front end to optimize throughput by performing read QIOs with no wait prior to data transfer.

A possible option for later runs is the placing of the 1891 driver directly on the VAX, as was originally envisioned for the experiment. A driver on the VAX would practically double the system throughput to the above mentioned CPU limit, but no dependable VAX-1821 DR11-W driver is yet available.
Chapter V
DATA ANALYSIS

This chapter describes the basic analysis and calibration performed on the spectrometer data to select charm and beauty candidates for emulsion scanning. The selection criteria, along with their contribution to the reduction of background, are discussed. Only those pieces of apparatus that were included in the analysis at the time of this writing are covered - the time-of-flight and hadron calorimeter are not.

5.1 Event analysis

This section describes the basic analysis performed to generate data necessary for the selection of events for emulsion scanning. The use of this data in making selection decisions is described in the next section.

The resolving capabilities of each component of the spectrometer have already been discussed in the chapter describing the apparatus; a summary of these resolutions is included in Table 11 for reference.

5.1.1 Beam track measurements

The beam track was reconstructed independently in the beam drift chambers and beam solid state detectors. These results were then combined to form a single higher precision beam track measurement with a global $\chi^2$ describing the fit. Events were rejected if the $\chi^2 > 6$, or if there were fewer than 3 solid state detector planes (out of 9 possible) participating in the fit\(^1\). Interactions originating in the

\[\text{---}\]

\(^1\)Studies found that almost all events with $< 3$ beam SSD hits were poorly measured though the $\chi^2$ did not reflect this.
Table 11: Spectrometer resolution summary.

<table>
<thead>
<tr>
<th>System</th>
<th>Quantity</th>
<th>Units</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emulsion</td>
<td>Position Angular</td>
<td>μm</td>
<td>1-10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>mrad</td>
<td>1-10</td>
</tr>
<tr>
<td>Beam SSD</td>
<td>Position/plane</td>
<td>μm</td>
<td>17-35</td>
</tr>
<tr>
<td>Combined</td>
<td>Position/plane</td>
<td>μm</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>Position (z=0) Angular</td>
<td>μm</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>μrad</td>
<td>20</td>
</tr>
<tr>
<td>Vertex SSD</td>
<td>Position/plane</td>
<td>μm</td>
<td>8-24</td>
</tr>
<tr>
<td></td>
<td>Position (z=0) Angular</td>
<td>μm</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>μrad</td>
<td>70</td>
</tr>
<tr>
<td>Spectrometer DC</td>
<td>Position/plane</td>
<td>μm</td>
<td>50-60</td>
</tr>
<tr>
<td></td>
<td>Angular β</td>
<td>μm</td>
<td>35</td>
</tr>
<tr>
<td>Primary vertex</td>
<td>Position (z)</td>
<td>μm</td>
<td>300-400</td>
</tr>
<tr>
<td>Second vertex</td>
<td>Position (x,y)</td>
<td>μm</td>
<td>6-10</td>
</tr>
<tr>
<td></td>
<td>Position (z)</td>
<td>μm</td>
<td>550-750</td>
</tr>
<tr>
<td></td>
<td>Position (x,y)</td>
<td>μm</td>
<td>11-18</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>Position (x,y)</td>
<td>mm</td>
<td>1.2</td>
</tr>
<tr>
<td>Calorimeter</td>
<td>Energy (δE/E)</td>
<td>%</td>
<td>12/√E + 2.5</td>
</tr>
<tr>
<td>Charged particle</td>
<td>Momentum δp/p</td>
<td>p in Gev/c</td>
<td>√((.01)^2 + (.00023p)^2)</td>
</tr>
<tr>
<td>spectrometer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muon spectrometer</td>
<td>Momentum δp/p</td>
<td>p in Gev/c</td>
<td>√((.19)^2 + (.007p)^2)</td>
</tr>
</tbody>
</table>

a Does not include momentum dependent multiple scattering contribution.
b The resolution varies approximately as the square root of the charged particle multiplicity.
c Based on √10/3 × resolution of the primary. The average multiplicity of the primary is about 10, while the secondary is assumed to be a three prong decay.
beam system, or upstream of it, were rejected if the count of hits in the beam
detector was greater than 20.

5.1.2 Vertex solid state microstrip detector track and vertex fitting

The high multiplicity, relativistically collimated tracks provided difficult track
pattern recognition problems for the whole spectrometer. This was particularly
true for the vertex SSDs that were close to the point of production where tracks
were separated by distances on the order of 10–100 microns.

Due to charge sharing and diffusion processes, a track passing through these
detectors generally left charge pulses on more than one line – usually the two
closest to the track’s path. The raw ADC “hits” on the detector lines thus had
to be organized into clusters corresponding to the charges left by single tracks.
These clusters of ADC hits were used by charge sharing and diffusion algorithms
to determine a track’s position in the detector to better than the detector’s strip
spacing. These positions were used by a track finding algorithm to reconstruct
the three dimensional particle trajectories. All components of the track finding
algorithm required that the tracks originate in a cylinder of 2.5 mm radius cen­
tered on the beam track and bracketed by the upstream emulsion edge and the
interaction counter in the z direction. Tracks were built view by view (6 planes
per view, 3 views: x,u, and v) using a cone of angular acceptance to locate hits in
the successive planes of a given view. These plane to plane “links” were used to
generate full segments for each view. The segments for a particular view that were
generated in this manner could share linked hits, and were appropriately weighted
by how many hits they shared. The segments from all views were combined to
make 3-dimensional track candidates via a $\chi^2$ fit which generated fit values for the
candidate’s x and y projection slopes, intercepts, and error estimates for each of
these. Track candidates were rejected if their $\chi^2$ was greater than 5. The resulting
tracks were kept only if they made an acceptable link to a drift chamber track at
the midplane of the analyzing magnet; acceptance was defined by a link $\chi^2$ of less
than 9. The remaining reconstructed 3-dimensional tracks were then refit under
the assumption that the original fit was close enough to the best so that a small cylinder centered on the track would contain all hits that the particle generated in passing through the detector. This cylinder was used to locate additional hits that were missed in the first fit. If additional hits were found, then the track was refit with the new information.

A fringe field of about 1 kilogauss near the back of the SSD stack biased the x slopes of the measured tracks by bending the particle trajectories. A momentum and charge dependent correction was applied to the x slopes of tracks in order to improve their quality for vertex reconstruction. This correction was applied only after linking to drift chamber tracks, as the correction worsened SSD–SDC track linkage.

Vertices were separated into three classes: primary (production) nuclear interaction vertices, secondary muonic decay vertices, and non muonic decay vertices. Individual but similar algorithms were used to fit these classes of vertices. These algorithms are described in appendix J. Only events with primary interaction vertices in the fiducial volume of the emulsion were kept for emulsion scanning and further analysis. Events with muonic vertices made up the major category of muonic charm and beauty decays.

5.1.3 Spectrometer drift chamber track fitting

The use of leading and trailing edge times to detect overlapping or crossing tracks and other aspects of drift chamber analysis have already been discussed in chapter 3 section 3.6.3. Drift times in the drift chamber were immediately converted into positional offsets from the chamber wires. Tracks were then fit in a manner similar to that in the vertex SSDs\(^2\), but the additional track vector information was used to help make "roads" of acceptance for the tracks as well as to resolve left-right ambiguities (i.e. reject image hits in a chamber). Three dimensional tracks were reconstructed with a \(\chi^2\) fit. Tracks were refit in the same manner as the vertex

\(^2\)A similar linking of hits was used to make vector segments at the cell (5 wire vector) level. The linking code common to the SSD's and SDC's analysis was actually developed for the SDC analysis.
SSD tracks.

5.1.4 Track linkage in the SCM104 magnet: momentum determination and overall track finding efficiency

Vertex SSD and spectrometer drift chamber (SDC) tracks were linked at the "bending" midplane\(^3\) of the analyzing magnet. A \(\chi^2\) measure of the goodness of fit was based on the measurement and multiple scattering errors of the two tracks making the link, and was used to select acceptable links (\(\chi^2 < 9\)). The requirement of a good link rejected spurious (i.e. fake) tracks from both detector systems. The thin-lens approximation was used to determine the momentum of the tracks in the early stages of analysis. More sophisticated momentum analysis was used in later stages (i.e. prior to kinematic fitting). Both methods are described in appendix K.

The overall efficiency for locating charged particles produced in the emulsion was calculated by determining the fraction of emulsion tracks with slopes less than 120 milliradians (i.e. well within the spectrometer acceptance) that were matched with linked spectrometer tracks. This was found to be 86\%, but may be a slight under-estimate since some of the missed tracks may not have passed through both arms of the spectrometer due to their low momentum. Monte Carlo simulations yielded an efficiency of 87\% in agreement with this measurement. Assuming that the SSDs and spectrometer drift chambers have equal efficiencies, this yields a 92\% efficiency for each. By comparing the summed energy of the charged particles in events to the 800 GeV beam energy, it was determined that we were missing some high momentum charged particles. These particles were probably not resolved in the highly collimated central region of the detector.

\(^3\)The \(z\) plane where upstream and downstream track projections crossed. The \(z\) of this midplane was adjusted for non-linear, momentum dependent corrections that were due to the non-uniform magnetic field.
5.1.5 Muon tracking and linkage to upstream track segments

Muon analysis is treated in detail in references [49,50] and will be only briefly discussed here.

Muon tracking in the downstream chambers proved to be more difficult than originally anticipated due to hadron cascade “punch through” from the hadron calorimeter. In 60% of the triggered events, the upstream muon chambers were swamped with charged hadrons exiting from the hadron calorimeter. It was very difficult to find the upstream muon segment in this environment, and sometimes only a downstream muon segment could be found. This led to the following three-fold muon link classification scheme:

1. Up-down muon link. – The muon track was located in both the upstream and downstream muon chambers, and was linked to a SDC track in both momentum and position\(^4\).

2. Down-only muon link. – The muon track was located in the downstream chambers only, but its projection linked to a SDC track at the toroid mid-plane and was consistent in momentum with the SDC track.

3. Up-down unlinked muon. – The muon was seen in both chambers, but did not make a link with any SDC tracks.

Upstream spectrometer chamber tracks used for muon linking were required to match with a vertex SSD track. Muon detector tracks linked to upstream spectrometer tracks in 35% of the triggers. Some of the loss was due to inefficiencies caused by hadron punch through in the front chambers, while the majority had no link because the muons were from the decay of K\(^\pm\)s and \(\pi^\pm\)s between the upstream spectrometer and muon chambers. Muons could link to more than one SDC track; in this case, the link with the best \(\chi^2\) was used. This could affect charm and beauty selection since a muon linking to the wrong SDC track could

\(^4\)The average momentum loss was subtracted from the upstream momentum measurement before comparison. A \(\chi^2\) measure of goodness of fit was built from both the position and momentum differences.
lead to its being assigned to the wrong vertex. In addition, though rare, more than one muon could link to a single spectrometer drift chamber track.

Table 12 contains the overall efficiency of the muon system, with a breakdown of the contributions from the various components in the system and the methods used to obtain them. The estimated errors given in the table correspond to the limited statistics in determining the quantities.

The front muon paddle inefficiency was determined with events from a beam · interaction data tape (no muon trigger requirement) as the ratio of events in which front paddles did not respond, but in which there was a fit muon track in the chambers, over the total number of fit muon tracks in the chambers. The efficiency of the trigger, the logical “and” of the front and back muon paddles, was taken to be the square of 1 minus this inefficiency.

The chamber fitting efficiency was determined as the fraction of events with a fit muon track in the chambers when the muon paddles indicated there should be a track there. The linking efficiency of muon tracks to upstream spectrometer drift chamber (SDC) tracks is shown in Figure 45. This figure plots, as a function of
of muon momentum ($p_\mu$), the ratio of fit muon chamber tracks linked to an upstream track segment (an SSD-SDC linked track) to fit muon chamber tracks. Since the source of the muons was predominantly $\pi \rightarrow \mu \nu$, the low efficiency indicated by the figure for $p_\mu < 10$ GeV/c is due to the low efficiency for detecting the pion tracks that decay in the spectrometer drift chambers; the muon can make an angle with respect to the pion of greater than 3 milliradians below a pion momentum of 10 GeV/c (see the discussion in section 5.3). Since charm particles decayed before reaching the spectrometer drift chambers, the efficiency for linking the muons from their decay was taken to be the constant dashed line of 0.56 in the figure, which is the average of the data between 10 and 50 GeV/c. This factor includes the SSD-SDC linking efficiency since SDC tracks not linked to an SSD track were not included. "Unfolding" the SSD-SDC linking efficiency of 0.86 yields a muon to SDC linking efficiency of $0.56/0.86 = 0.65$.

The efficiency for muons from charm particle decay to be accepted by the geometry of the muon hodoscope and to pass all analysis cuts, and thus make

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**Figure 45**: Muon to upstream spectrometer link efficiency as a function of muon momentum.
Figure 46: Monte Carlo generated muon geometrical and DST cut efficiency as a function of Feynman $x$.

it to a DST tape, is shown as a function of the Feynman $x$ variable in Figure 46. The solid line through the data points is meant to guide the eye, and is not a result of a fit to the data. The total efficiency factor of $\sim 0.25$ is half due to losses below $x = 0$, and half to an overall factor of 0.5. This efficiency was determined by Monte Carlo simulation of charm particle production and decay in the apparatus as described later in this chapter, and includes losses due to inefficiencies in SSD-SDC track linkage, SSD and SDC track reconstruction, and vertex reconstruction. The muon chambers and hodoscope paddles are assumed to have 100% efficiency. The error bars in the figure are due to limited statistics.

5.1.6 Lead-liquid argon calorimeter $\pi^0$, $\gamma$ ray, and electron identification

Electron candidates were spectrometer tracks whose position and momentum matched up with the position and energy deposition of showers in the lead-liquid argon calorimeter as formulated in a $\chi^2$ based on the position and energy match
Table 13: Major non-leptonic charm meson inclusive "neutral" decay modes.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Branching ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^{\pm} \rightarrow \pi^0 X$</td>
<td>27</td>
</tr>
<tr>
<td>$D^{\pm} \rightarrow \overline{K}^0/K^0 X$</td>
<td>33</td>
</tr>
<tr>
<td>$D^{\pm} \rightarrow \overline{K}^0/K^0\pi^0 X$</td>
<td>20</td>
</tr>
<tr>
<td>Total excluding overlap</td>
<td>40</td>
</tr>
<tr>
<td>$D^0/\overline{D}^0 \rightarrow \pi^0 X$</td>
<td>37</td>
</tr>
<tr>
<td>$D^0/\overline{D}^0 \rightarrow \overline{K}^0/K^0 X$</td>
<td>29</td>
</tr>
<tr>
<td>$D^0/\overline{D}^0 \rightarrow \overline{K}^0/K^0\pi^0 X$</td>
<td>16</td>
</tr>
<tr>
<td>Total excluding overlap</td>
<td>50</td>
</tr>
<tr>
<td>$D^{0*}/\overline{D}^{0*} \rightarrow D^0/\overline{D}^0\pi^0$</td>
<td>54</td>
</tr>
<tr>
<td>$D^{0*}/\overline{D}^{0*} \rightarrow D^0/\overline{D}^0\gamma$</td>
<td>54</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
</tr>
<tr>
<td>$D^{\pm\ast} \rightarrow D^{\pm\pi^0}$</td>
<td>34</td>
</tr>
<tr>
<td>$D^{\pm\ast} \rightarrow D^{\pm\gamma}$</td>
<td>17</td>
</tr>
<tr>
<td>Total</td>
<td>51</td>
</tr>
</tbody>
</table>

along with the front/total energy ratio in the LAC\(^5\). No events were cut based on LAC analysis. The electron tracks were tagged in the data summary tapes to aid emulsion scanners in rejecting $e^+e^-$ pairs as two-prong decay vertex candidates. Table 13 lists the inclusive branching ratios of charm mesons to neutral hadrons, and illustrates the importance of $\pi^0$ reconstruction from the $\pi^0 \rightarrow 2\gamma$ decay. This table also illustrates the relative importance of tagging $\gamma$ rays for the reconstruction of $D^{\pm\ast}$, $D^{0\ast}$, and $\overline{D}^{0\ast}$ mesons.

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\(^5\)Electron showers deposited most of their energy in the front of the LAC, while hadron showers deposited most of their energy in the back. The front/total ratio ($f/t$) was compared to its expected mean value for electron showers to determine if it was within its expected error: $\chi^2_{f/t} = (f/t - \bar{f}/\bar{t})^2/\text{(expected error)}^2$ where $\bar{f}/\bar{t} \approx .85$. Including this ratio in the $\chi^2$ had the effect of rejecting hadronic showers.
Table 14: "Non-physics" cuts on the data sample.

<table>
<thead>
<tr>
<th>Module type</th>
<th>Framing errors (cut)</th>
<th>Upstream interactions (cut)</th>
<th>Bad beam (cut)</th>
<th>Fiducial X-Y loss (cut)</th>
<th>&quot;Good&quot; triggers (kept)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>3.2</td>
<td>10.2</td>
<td>5.8</td>
<td>28.0</td>
<td>59.4</td>
</tr>
<tr>
<td>Vertical</td>
<td>2.9</td>
<td>17.3</td>
<td>13.7</td>
<td>0.0</td>
<td>69.9</td>
</tr>
</tbody>
</table>

a Based on 25143 triggers  
b Based on 17450 triggers  
c Spurious words inserted by hardware that corrupted the event structure.  
d Poor beam fit: $x^2 > 6$, SSD hits < 3, or no fit.  
e Beam track not in the fiducial X-Y boundaries of target.

5.2 Charm and beauty emulsion scanning event selection

Events were "filtered" through three analysis passes to enhance the beauty and charm sample over background events. The first was performed for purely engineering purposes with "loosened" second pass cuts and will not be discussed. The second performed cuts that selected charm and beauty candidates for emulsion scanning. The third pass identified electrons in the remaining events. Both the raw and summarized events that passed the cuts were written to Data Summary Tapes (DSTs) for distribution to Japan for scanning. DSTs and their associated routines and formats are described in appendix I.

Prior to the application of a set of "physics" cuts, fiducial volume and other "across-the-board" cuts were performed to filter non-useful events from the data sample. Table 14 lists the results of these cuts. Entries in this table are based upon the remainder left after all cuts to the left in the table have been performed.

6The trigger sample for this table already excluded the non-analyzable non-data trigger events (i.e. tape header and end of spill events). These "events" amounted to about 1% of the initial sample of $5.42 \times 10^6$ events.

7Differences in the number of upstream interactions and bad-beam measurements between the horizontal and vertical targets listed in this table are due to the difference in the ratio of their interaction lengths to the number of interaction lengths upstream of the emulsion – the vertical
Table 15: Classes of “physics” cuts on the data sample.

<table>
<thead>
<tr>
<th>Cut variable</th>
<th>Class 3</th>
<th>Class 2</th>
<th>Class 1</th>
<th>Class 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{\mu}$ (Gev/c)</td>
<td>8.000</td>
<td>8.000</td>
<td>8.000</td>
<td>0.000</td>
</tr>
<tr>
<td>$p_{\perp \mu}$ (Gev/c)</td>
<td>0.200</td>
<td>0.800</td>
<td>0.250</td>
<td>0.000</td>
</tr>
<tr>
<td>Impact parameter of muon (microns)</td>
<td>50</td>
<td>100</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>$p_{\text{hadrons}}$ (Gev/c)</td>
<td>5.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Impact parameter of hadrons (microns)</td>
<td>0.050</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Decay length (mm)</td>
<td>2.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Invariant mass (Gev)</td>
<td>0.250</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

*a All cut variables had to be greater than the tabled value to survive.

As the table indicates, the sample of events left for further processing after these cuts—“good” triggers—were on the order of 60–70% of the data—approximately $3–3.5 \times 10^6$ events.

Table 15 lists the four classes of “physics” cuts performed on the sample of “good” triggers. The table lists the event classes in order of their priority: the leftmost class cuts were performed first, if an event failed the cut, it was passed on to the cut to the right, otherwise it was kept as a candidate event. Class 3 cuts were the main physics cuts and selected events with secondary muonic vertices that passed the muon $p_{\perp}$ (unless otherwise noted, $p_{\perp}$ will refer to the momentum component transverse to the beam proton direction), $p$, associated hadronic momentum and impact parameter, and decay length cuts. Class 2 cuts selected high $p_{\perp}$ muons from beauty decays from the events that failed the class 3 cuts. Class 1 cuts were kept because they contained muonic “kink” events (i.e. emulsion produced fewer interactions than the horizontal relative to those produced upstream of the emulsion.)
Table 16: Second pass “physics” cuts applied to typical data sample.

<table>
<thead>
<tr>
<th># events before cut(s)</th>
<th>Applied cut(s)</th>
<th>% of events cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>17450</td>
<td>Non physics cuts for “good” triggers</td>
<td>30.1</td>
</tr>
<tr>
<td>12093</td>
<td>Require good muon link to spectrometer</td>
<td>71.3</td>
</tr>
<tr>
<td>3469</td>
<td>No primary vertex</td>
<td>3.0</td>
</tr>
<tr>
<td>3364</td>
<td>&lt; 2 tracks from primary</td>
<td>1.0</td>
</tr>
<tr>
<td>3331</td>
<td>Z of primary ≤ -12mm</td>
<td>1.9</td>
</tr>
<tr>
<td>3268</td>
<td>Z of primary &gt; emulsion edge</td>
<td>12.8</td>
</tr>
<tr>
<td>2849</td>
<td>No secondary vertices found</td>
<td>39.1</td>
</tr>
<tr>
<td>1735</td>
<td>Muonic secondary vertex cuts (^b)</td>
<td>89.7</td>
</tr>
<tr>
<td>178</td>
<td>Muon physics cuts and mass cut (^c)</td>
<td>41.0</td>
</tr>
<tr>
<td>105</td>
<td>Number of class 3 events left</td>
<td></td>
</tr>
</tbody>
</table>

Number of events passed for all classes of cuts.

<table>
<thead>
<tr>
<th>Class 3</th>
<th>105</th>
<th>Class 2</th>
<th>23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>116</td>
<td>Class 4</td>
<td>113</td>
</tr>
</tbody>
</table>

\(^a\) Based on data from vertical emulsion modules.

\(^b\) Z of secondary in bounds and decay length > 2mm.

\(^c\) p, p\(_\perp\), and impact parameter of muon cuts along with invariant mass cut.

decays with only one charged track—the muon). This class will probably not be scanned by the emulsion groups. The fourth class picked up the relatively low background (besides \(K_S\) decays) set of charm and beauty decays that occurred in the vacuum between the emulsion and interaction counter. Table 16 lists the sequential effects of these cuts on vertical target data\(^8\). Cuts higher in this table were performed first and preempted later cuts. The events left after all cuts in the table were class 3 events. Events failing class 3 cuts were processed with class 2 cuts, those failing these were processed with class 1 cuts, and those failing class 1,3, and 2 were then processed with class 4 cuts. The results (remaining events) of these cuts are also listed in the table.

\(^8\)Horizontal data agreed with this vertical data to within 1%.
The effects of the physics cuts were studied in detail with Monte Carlo generated charm and beauty pair and background events [51], and were designed mainly to enhance the semi-muonic beauty decay sample relative to the background from the muonic decays of charged pions and kaons.

5.3 Background estimates

Three major categories of background were identified for the events selected for emulsion scanning:

1. Spectrometer reconstructed muonic vertices from small angled "kink" decays of the charged pions and kaons produced by secondary nuclear interactions. Selected events in this category could only be rejected after emulsion scanning.

2. Identification of secondary nuclear interaction vertices as decay vertices by emulsion scanners. Five percent of secondary nuclear interactions occurring in the emulsion (explained below), and all those occurring in non-active target material (e.g. the emulsion stack frame) fell in this category.

3. Background when looking for the associated charm partner. The previous item (2) also belongs in this category as do $e^+e^-$ pairs produced by $\gamma$ ray conversions from $\pi^0 \rightarrow 2\gamma$ decays ($e^+e^-$ pairs were usually identified in the emulsion by their small opening angle).

The first of these background categories will be discussed in some detail since it determined the final charm data sample. The second and third will be discussed briefly.

The main background in the muonic and semi-muonic decay trigger comes from the decay of charged pions and kaons in the volume of the apparatus. Table 17 lists the major contributing decay modes. The upper limit on the muon's momentum in its parent's rest frame – $p_{\text{max}}$ – placed a limit on the angle that
Table 17: Pion and kaon decay modes contributing to muon background.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Branching fraction</th>
<th>$p_{\text{max}}^a$ (Gev/c)</th>
<th>$c\tau$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^\pm \rightarrow \mu^\pm \nu$</td>
<td>100.0</td>
<td>.030</td>
<td>780.4</td>
</tr>
<tr>
<td>$K^\pm \rightarrow \mu^\pm \nu$</td>
<td>64.0</td>
<td>.236</td>
<td>370.9</td>
</tr>
<tr>
<td>$K^\pm \rightarrow \pi^0 \mu^\pm \nu$</td>
<td>3.2</td>
<td>.215</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ For the two body modes, $p_{\text{max}}$ corresponds to the momentum of either particle in the center of momentum frame; for the three body mode, it corresponds to the maximum momentum of any of the particles in that frame.

The muon made with respect to the parent direction which is approximately given by:

$$\theta < \frac{p_{\text{max}}}{p}$$

where $p$ is the momentum of the parent. As an example, a $10 \text{ GeV/c} \pi^-$ decaying into $\mu^- \nu$ will have the muon “kink” with respect to the $\pi^-$ direction with an angle of less than 3 milliradians. For muonic kaon decays, an energy of $>78 \text{ GeV/c}$ is required to restrict the muon angle to $<3$ milliradians. These decays generated narrowly deflected muons between the target and the muon spectrometer that looked like muons coming from the target; the muon measured in the muon spectrometer would most likely be linked to the spectrometer track of its pion or kaon parent. This background depended on the flux of pions and kaons decaying in the volume of the spectrometer.

The $p$ and $p_\perp$ cuts placed upon the muon were designed to reduce this background without corresponding losses to charm and beauty muonic decays. A qualitative understanding of the effect of these cuts can be obtained by considering the decay energy available to the muon, and the energy available to the muon’s parent from production dynamics. Since the relatively light pions and kaons were usually produced with a high energy and thus relatively small angle with respect to the beam axis, the $p_\perp$ of a muon from the subsequent decay was still on the
order of the \( p_{\text{max}} \) for the decay mode. The momentum requirement of 8 GeV/c on the muon and the \( p_\perp \) cut of .250 GeV/c thus eliminated most of the muon background from pion and kaon decays. On the other hand, the energy required to produce heavy charm or beauty pairs left less available kinetic energy, and the resulting heavy mesons or baryons made a relatively large angle with respect to the beam. In addition, because the heavy charm and beauty quarks decayed into much lighter quarks, their decay muon usually had a larger center of mass momentum than one from pion or kaon decay, and thus had a larger \( p_\perp \) on the average. Class 2 cuts were designed to take advantage of this.

A study of the muon background from pion and kaon decay was performed for this experiment's proposal [51] using CERN Intersecting Storage Ring [52] pion and kaon production data. The resulting muon flux per meter of decay length from pions and kaons that passed the muon \( p \) and \( p_\perp \) cuts was determined to be \( 1.55 \times 10^{-3} \) m\(^{-1} \) and \( 7.0 \times 10^{-4} \) m\(^{-1} \) respectively. Monte Carlo studies revealed that the flux from secondary nuclear interactions was down by a factor of approximately .13 from that of primary nuclear interactions\(^9\). Since our sample consisted of secondary vertices with a muon (presumably decays), the background per interaction was given by:

\[
\text{BG/INT} = P_{\text{INT}} \times \langle \text{Mult} \rangle \times \delta D_{\text{EFF}} \times \text{(muon flux)} \times .13
\]

\[
= (10\text{mm}/444\text{mm}) \times 12 \times 6.5\text{m} \times 1.55 \times 10^{-3}\text{m}^{-1} \times .13
\]

\[
= \frac{1}{2825}
\]

where:

\( P_{\text{INT}} \) = The probability of a nuclear interaction.

\( \langle \text{Mult} \rangle \) = Average multiplicity from nuclear interaction.

\( \delta D_{\text{EFF}} \) = Effective decay path.

\( ^9 \)This can be understood as follows: .5 of the .13 factor is due to the lower energy of the particle producing the secondary interaction—reducing the multiplicity of the secondary interaction by a factor of 2. The rest is due to fewer of the lower energy muons passing the \( p \) and \( p_\perp \) cuts.
The contribution from the lower flux of kaons was ignored in the calculation. The probability of interaction was based on half of the emulsion thickness — 10 mm — with an effective secondary interaction length of 444 mm\(^{10}\). The average multiplicity of hadrons from the primary interaction capable of producing secondary nuclear interactions was taken to be 12 — 10 charged hadrons\(^{11}\), about 90% of which were pions, and two long lived neutral hadrons (the remaining 5 or so \(\pi^0\)s decayed to 2 \(\gamma\) rays). The effective decay length of 6.5 meters corresponded to the distance between the emulsion and the front end of the hadron calorimeter.

The background per interaction ratio must be multiplied by the interaction per trigger ratio (\(\approx 20\)) to obtain the ratio of background/trigger since all of this muon background is accepted by the trigger. This background corresponded to about 35 events per data tape (at 4800 recorded events per tape) or about 37000 events over the entire running period. More useful is the background per "good trigger" — the background seen in our reduced data sample per tape — which must be multiplied by the factors in Table 14. This yields on the order of 20–25 background events per DST tape or 24000 DST background events over the entire running period.

All but 5% of the muonic secondary interaction background could be eliminated by visual inspection of the vertex in the emulsion. Ninety percent of nuclear interactions left heavily ionizing "dark" tracks in the emulsion easily distinguishing them from decays [54]. Half of the remaining background — so called "white stars" — could be rejected on charge non-conservation grounds: they appeared not to conserve charge due to multiply charged spallation nuclei fragments and slow ions from the nuclear breakup that did not leave visible tracks. Therefore, all but 1200 of the background in the run (about 1-2 events per DST tape) could be

\(^{10}\)The effective interaction length for secondary hadrons in the emulsion was based on measurements by the emulsion scanners in this experiment.

\(^{11}\)The average number of relativistic charged particles (nuclear breakup fragments excluded) produced in p-emulsion interactions was measured to be 19 in the test run of the experiment. The majority of these were produced at low rapidity (i.e. large angle) [53] and were outside of the angular acceptance of the spectrometer. The estimate of 10 charged particles agrees with the average number of charged tracks assigned to the primary vertex by the spectrometer analysis.
eliminated after visual inspection of the emulsion. The rest had to be eliminated by kinematic fitting.

Secondary nuclear interaction vertices also contributed to the background in scanning for the associated charm or beauty particle decay. Most of this background could be visually eliminated as discussed above. Electron-positron pairs from $\gamma$ conversion also contributed to this background, and were eliminated with the help of the lead-liquid argon calorimeter electron identifications. Electron pairs could also be independently identified visually by the typical small opening angle between the electron and positron in the emulsion.

Other minor sources of background were mainly due to pattern recognition problems:

- Muons that were accidentally associated with the wrong SSD tracks and hence were assigned to the wrong vertices (class 3), or to no vertex (possibly class 2).

- Muons from primary produced charged $\pi$ or $K$ decays that were accidentally associated with other tracks to form a secondary vertex (our vertex programs worked real hard to make secondary muonic vertices) that ended up as class 3 events.

- A poorly measured beam track that caused tracks from the primary vertex to have exaggerated impact parameters and $p_\perp$. This could generate class 2 event background from muons associated with primary $\pi$ and $K$ decays.

- $K_S$ decays between the emulsion and interaction counter that ended up as class 4 events (this background was used for engineering purposes – $K_S$ mass resolution).
5.4 Spectrometer calibration

Since the drift chamber parameters — drift velocity, start times, etc. — that were used to fit tracks were very sensitive to the gas mixture (particularly the spectrometer drift chambers), they needed to be calibrated on a run by run (tape by tape) basis because instabilities\textsuperscript{12} in the equipment that mixed the argon-ethane gases for all of the drift chambers resulted in mixtures that varied with time in an unpredictable manner. The relative alignment between various components in the experiment were also determined on a run by run basis as part of the calibration software package. Low multiplicity events on a tape were used to get corrections to the calibration data from the previous calibration run. Since a single tape provided a limited amount of statistics, statistical fluctuations needed to be smoothed out. This was accomplished by averaging the tape by tape calibration data over emulsion modules, which consisted of about 25 tapes per module.

The solid state detectors in the experiment were stable over time, and only needed one set of calibration data for dead-lines, noise pedestal widths\textsuperscript{13}, and the relative pulse height response of each line to minimum ionizing particles. The variation in response to minimum ionizing particles over the channels in these detectors was due to amplifier and pre-amplifier gain variations; the detectors themselves had a fairly uniform response. This variation was corrected by normalizing each line's response to minimum ionizing particles\textsuperscript{14}. Dead lines due to discontinuous connections, shorted lines, and dead amplifier channels were mapped out for the detectors. Pedestal noise sigmas that were recorded for each live channel were stored for later use in track finding.

The central portion of the lead-liquid argon calorimeter was calibrated with electron beams of various energies. This calibration data, in conjunction with

\textsuperscript{12}The microprocessing system that regulated the mix was not reliable. In addition, there were gas flow problems due to the freezing of the regulator on one of the gas bottles.

\textsuperscript{13}Pedestal noise and pedestal drift variations were eliminated prior to data recording by the FASTBUS hardware pedestal subtraction circuitry; pedestal data runs were performed regularly during the run to eliminate variations over time.

\textsuperscript{14}For example, all channels in the vertex SSDs were normalized using the Landau peaks from the minimum ionizing signals of muons.
pulsar calibration data for the entire detector, was used to extrapolate the electron calibration to the outer regions of the detector.

As already described in section 3.6.2, the spectrometer magnet was calibrated by measuring the magnetic field strength over the volume of the magnet in a fine spatial grid. Even though the relative field strengths in this grid were measured accurately, systematic rotations and offsets of the entire map were possible. These systematics were eliminated by moving the field map until the best momentum fits (using the Runge-Kutta momentum fitting algorithm) were achieved.

The muon system toroid magnet was constructed with a small transverse slit through its side which allowed a Hall-probe to be inserted to measure the radial dependence of the magnetic field. These measurements agreed well with the CERN library POISSON magnetic field program fit used in the analysis as discussed in section 3.9.

5.5 Monte Carlo simulation

The CERN library GEANT3 program was used as a basis for the simulation of the experiment by Monte Carlo techniques. This program allowed a systematic definition of the geometric and physical properties of the experimental apparatus, and provided particle tracking, interactions and decays. What it did not provide was an event generator\(^{15}\); it could fully simulate the development of an event after its generation, however.

A naive event generator was used to produce nuclear interactions whose products were charm meson/baryon pairs and a “background” of pions. Charm pairs were generated with a \((1-x)^n\) Feynman x distribution and \(e^{-bp_\perp^2} p_\perp^2\) distribution. The parameters \(b\) and \(n\) were adjustable, and were nominally set to \(n=4\) and \(b = 1\), in rough agreement with experiment (discussed in chapter 2). The

\(^{15}\)A later version does provide an interface to the LUND Monte Carlo event generator. Plans of incorporating this into the experiment Monte Carlo are in progress.
generated pairs were completely uncorrelated; the distributions were sampled independently for both charm particles. Experimental data [36] tends to support uncorrelated production (aside from kinematic correlations from energy and momentum conservation), but theoretical QCD calculations [11] yield a correlation in the difference between the rapidity of the charm pair about 0. A correlation in the rapidity difference of the charm pair could skew the Feynman x distributions of the associated charm particles (i.e. the charm particle of the pair that did not trigger the experiment) towards the forwardly biased distribution of the trigger charm particles.

The pion background was generated with triangular rapidity and exponential \((e^{-x^2}) x^2\) distributions based on ISR p-p interaction data. These distributions ignored nuclear effects and did not conserve energy or momentum (they were independently sampled for each pion generated). This had the effect of generating too small a multiplicity and at the same time too few high rapidity (i.e. high energy) pions in the (ignored) rapidity distribution tails. The average number of charged pions was taken to be 12, in order to agree with the observed charged multiplicity associated with the primary nuclear vertex, and was distributed according to Poisson statistics. This background was sufficient for determining track finding and vertex fitting efficiencies, but not for simulating the muon trigger background from pions (or kaons) decaying into muons, since the pion rapidity and \(p_x\) distributions were not accurately represented.

Hadronic and electromagnetic secondary interactions were permitted, and particles were multiply scattered with GEANT Moliere scattering routines. Decays of unstable particles were generated using user specified lifetimes and branching ratios. The choice of values for the branching ratios and lifetimes are detailed in reference [41]. Since only specific decay modes of the associated (non-trigger) charm will be considered, the only set of branching ratios relevant are those of the muonic trigger charm decay modes. These branching ratios are listed in Table 18.

Solid state microstrip vertex detector and spectrometer drift chamber tracks
Table 18: Charm muonic decay branching ratios used in Monte-Carlo.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th># charged prongs</th>
<th>Branching ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^\pm \rightarrow K^0/K^0\mu^\pm\nu$</td>
<td>1 prong 7.4%</td>
<td></td>
</tr>
<tr>
<td>$D^\pm \rightarrow K^0*/K^0*\mu^\pm\nu$</td>
<td>1 prong 2.0% 3 prong 3.9%</td>
<td></td>
</tr>
<tr>
<td>$D^0/D^0^* \rightarrow K^\mp\mu^\pm\nu$</td>
<td>2 prong 4.1%</td>
<td></td>
</tr>
<tr>
<td>$D^0/D^0^* \rightarrow K^{\mp*}\mu^\pm\nu$</td>
<td>2 prong 3.8%</td>
<td></td>
</tr>
<tr>
<td>$\Lambda^\pm \rightarrow \Lambda\mu^\pm\nu$</td>
<td>1 prong 1.1%</td>
<td></td>
</tr>
<tr>
<td>$\Lambda_c^\pm \rightarrow p/pK^\mp\mu^\pm\nu$</td>
<td>3 prong 1.8%</td>
<td></td>
</tr>
<tr>
<td>$\Lambda_c^\pm \rightarrow K^0/K^0\mu^\pm\nu$</td>
<td>1 prong 1.6%</td>
<td></td>
</tr>
</tbody>
</table>

were digitized using the inverse of the algorithms used to interpret the data; the vertex detectors diffusion and charge sharing algorithms were applied in reverse to generate charges on the SSD lines from Monte Carlo tracks, while drift chamber algorithms were similarly applied in reverse to generate drift times from the tracks. Simulated noise fluctuations of the equipment and associated recording electronics were added to the hit data and the results were written to data files along with Geant vertex and tracking information.

These Monte Carlo generated files were then passed through the experiment's offline analysis program. The digitized information for the SSDs and spectrometer drift chambers were analyzed with the same routines as real data\textsuperscript{16}. Muon and LAC systems were not digitized, but were derived directly from the Monte Carlo generated events. For LAC analysis, electron tracks were ignored, but $\gamma$-rays from $\pi^0$ decays were not; $\gamma$-rays were projected to the LAC from their Geant vertex, and were stored as "perfect" LAC $\gamma$-ray hits in the appropriate offline analysis buffers. Muons were projected to the muon system from the Geant track segment near the most downstream spectrometer drift chamber, so that multiple scattering prior to this chamber was taken into account. Muon track

\textsuperscript{16}Aside from the unpacking of ADC and TDC data into hits.
information was stored in the appropriate offline buffers, and if it had a momentum greater than the cut of 8 GeV/c, then the spectrometer drift chamber track was tagged as a muon. Muon tracking and linking to spectrometer drift chamber tracks was thus 100% efficient, as was LAC γ-ray detection. A DST tape was made with this information. Monte Carlo vertices and charged tracks originating in the emulsion were recorded as emulsion tracks and vertices in the DST format. Any Geant vertices that were closer than 2 microns were coalesced into one.
Chapter VI
INCLUSIVE CHARGED D MESON CROSS SECTION

A charged D meson mass peak from the decay modes $D^{\pm} \rightarrow K^\mp \pi^\pm \pi^\pm$ was searched for in the invariant mass distribution of exclusive 3 prong decays. Since one of the produced charm pair necessarily decayed with a neutral product (the neutrino from the muonic decay of the “trigger” charm particle) the charm mesons selected in the mass peaks were “associated” (i.e. non-trigger) charm particles.

All possible combinations of 3 charged tracks were used to form candidate vertices. These were constructed with the routines described in appendix J modified to generate vertices for all combinations of tracks satisfying the 3 prong count and a summed charge of $\pm 1$. The fitting routines returned fit vertex $x$, $y$, and $z$ positions, error estimates for these positions, and a $\chi^2$ goodness of fit measure. The tracks forming the hypothetical decay vertex, along with the assumed masses of the particles that generated the tracks, were used to calculate the invariant mass of the decay’s parent. The background from combinatorics, secondary interactions, etc., was reduced by the cuts listed in Table 19 (the kaon cuts in the table are applied to the 2 prong $K \rightarrow \pi^+ \pi^-$ decay mode). These cuts were designed to select good decay vertices and to reduce non-charm background by, for example, using the known decay times for the $D^\pm$ to reject secondary interactions and the long lived decays of non-charm particles. The invariant mass spectrum in Figure 47 illustrates the power of this technique in isolating neutral kaon decays by their invariant mass (the cuts listed in Table 19 were used to generate this figure). This figure indicates about a 4 MeV/c$^2$ width for the kaon mass, corresponding to a mass resolution of approximately .9%.
Table 19: Cuts applied for invariant mass fits.

<table>
<thead>
<tr>
<th>Applied cut</th>
<th>rel.</th>
<th>K⁰</th>
<th>D±</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay length (mm)</td>
<td>&gt;</td>
<td>2.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Vertex $\chi^2$</td>
<td>&lt;</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Decay length/$\sigma_{\text{decay length}}$</td>
<td>&gt;</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Vertex z error (mm)</td>
<td>&lt;</td>
<td>10.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Z decay (mm)</td>
<td>&gt;</td>
<td>0.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Z decay (mm)</td>
<td></td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Momentum of all tracks (GeV/c)</td>
<td>&gt;</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Momentum asymmetry ($P_{\text{min}}/P_{\text{total}}$)</td>
<td>&gt;</td>
<td>0.12</td>
<td>0.06</td>
</tr>
<tr>
<td>Momentum asymmetry ($P_{\text{max}}/P_{\text{total}}$)</td>
<td>&lt;</td>
<td>0.80</td>
<td></td>
</tr>
<tr>
<td>$p_\perp$ balance (GeV/c)</td>
<td>&gt;</td>
<td>0.10</td>
<td>0.42</td>
</tr>
<tr>
<td>$p_{\perp X}/\sigma_{p_{\perp X}}$</td>
<td>&lt;</td>
<td></td>
<td>6.0</td>
</tr>
<tr>
<td>$p_{\perp Y}/\sigma_{p_{\perp Y}}$</td>
<td>&lt;</td>
<td></td>
<td>6.0</td>
</tr>
<tr>
<td>$p_{\perp}/\sigma_{\perp}$</td>
<td>&lt;</td>
<td></td>
<td>2.75</td>
</tr>
<tr>
<td>Proper lifetime (picoseconds)</td>
<td>&gt;</td>
<td></td>
<td>0.30</td>
</tr>
<tr>
<td>Proper lifetime (picoseconds)</td>
<td>&lt;</td>
<td></td>
<td>2.2</td>
</tr>
<tr>
<td>Decay momentum (GeV/c)</td>
<td>&gt;</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>(Impact parameter)/$\sigma_P$ all tracks</td>
<td>&gt;</td>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>Number of SSD-SDC linked tracks</td>
<td>&lt;</td>
<td></td>
<td>28</td>
</tr>
<tr>
<td>No class 4 events allowed</td>
<td></td>
<td></td>
<td>√</td>
</tr>
</tbody>
</table>
Figure 47: $K^0 \rightarrow \pi^+\pi^-$ invariant mass plot.
An extremely powerful "right sign" muon cut was also applied to the candidate decays. Assuming no flavor changing neutral current decays to $\mu^+\mu^-$, conservation of charge implies that the decay of the charm producing the trigger muon must follow

\[
\begin{align*}
    c & \rightarrow \mu^+X \\
    \bar{c} & \rightarrow \mu^-X
\end{align*}
\]

where $c$ and $\bar{c}$ are the charm and the anti-charm quark respectively. The associated charged charm mesons must then be

\[
\begin{align*}
    \bar{c} & = D^- \\
    c & = D^+
\end{align*}
\]

since it is the anti-particle of the trigger charm. The associated charged charm meson must therefore have the opposite sign of the trigger muon. The kaon sign must be the same sign as the muon for the Cabibbo favored $K\pi\pi$ mode; one need only require:

- Kaon sign from $K\pi\pi$ decay = muon sign of trigger decay
- Kaon sign from $K\pi\pi$ decay = $-\$ charged charm meson sign

as illustrated in Figure 48. Since non-charm background should have half "wrong sign" and half "right sign" muons, the cut should reduce the background by half without reducing any of the charm signal.1

### 6.1 Efficiencies and the determination of the cross section

There were a number of experimental efficiencies that had to be corrected for in determining the cross section:

1This assumes that one of the recorded charm decayed with a muon and triggered the experiment. If the charm signal was not associated with the trigger muon at all, then the charm signal would be reduced by $1/2$ too.
Figure 48: Schematic of model used in Monte Carlo simulation of \( \mu \) triggered charm pair production.

- Geometrical acceptance for particle detection – the experiment did not cover a full solid angle (i.e. can not see particle trajectories at all angles). The acceptance efficiency depended on the dynamics of the interaction, and was partially determined by simulating the interaction and experiment by Monte Carlo techniques.

- Efficiencies of the various components of the apparatus for detecting particles – the detectors were not 100\% efficient at detecting what they were designed to. This was particularly important for the trigger detectors. These efficiencies were determined from data.

- Experimental live-time – the experiment was not "live" for recording data all of the time due to the finite response times of recording electronics and computers, and other factors that effectively resulted in the failure to record "usable" trigger data. The trigger efficiency could also be considered a live-time factor with this loose live-time definition, as could the efficiency for
recording non-corrupted data. These live-time efficiencies were determined from data.

The formula for determining the cross section for producing charged D mesons\(^2\) using the invariant mass technique for the \(K\pi\pi\) decay mode, with efficiency correction factors included, is given by:

\[
\sigma(D^{\pm}) = \frac{A}{N_0} \cdot \frac{1}{[\epsilon_1 BR_{\text{eff}}]_{\text{MC}}} \cdot \frac{N_{\text{inv}}}{[\epsilon_2 N_{\text{beam}} \rho t]_{\text{NMC}}} \quad \text{(linear in A)} \quad (13)
\]

where:

- \(N_{\text{inv}}\) = Observed charged meson mass signal
- \([\epsilon_1 BR_{\text{eff}}]_{\text{MC}}\) = Trigger charm species dependent efficiency factors
  - \(\times\)effective muonic branching ratio of the trigger
  - \(\times\)the branching ratio of \(D^{\pm} \rightarrow K^{\mp} \pi^{\pm} \pi^{\pm}\)
- \([\epsilon_2 N_{\text{beam}} \rho t]_{\text{NMC}}\) = Target module type dependent efficiencies
  - \(\times\)Incident number of beam particles \(\times \rho \times t\)
- \(A\) = Atomic weight of the target
- \(N_0\) = Avagadro's number
- \(\rho\) = The target density (in g/cm\(^3\))
- \(t\) = The target thickness (in cm)

The equation has been broken up into a factor independent of the type of target and the Monte Carlo simulation, a portion with factors dependent on Monte Carlo results or on the trigger charm species \([...]_{\text{MC}}\), and a factor either dependent on the target type (horizontal or vertical) or independent of Monte Carlo methods \([...]_{\text{NMC}}\). In particular, the muon efficiency has been split between these factors.

\(^2\)The cross section quoted is for the production of both \(D^+\) and \(D^-\) mesons. The notation used is thus: \(\sigma(D^{\pm}) = \sigma(D^+) + \sigma(D^-)\).
6.2 Estimation of the incident beam, beam dependent factors, and non Monte Carlo efficiencies

For the cross section determinations, \( N_{\text{beam}} \) was estimated by:

\[
N_{\text{beam}}/\text{module} = \text{Emulsion area} \ (\text{cm}^2) \times \text{Exposure} \ (\text{protons/cm}^2) \quad (14)
\]

using the constant emulsion surface area and the known exposures for each module. The effective exposure area of the emulsion was determined for a few target modules of horizontal and vertical type by calculating the total beam they were exposed to and dividing by their known exposure. The area determined in this manner was found to be \( 544 \pm 7 \, \text{cm}^2 \) for vertical targets – an accuracy of about 1%, and \( 265 \pm 15 \, \text{cm}^2 \) for horizontal targets – an accuracy of 6%. The effective area and exposures were then utilized to determine the total number of protons incident on the emulsion for the sample data used in determining the cross section. This yielded \( 1.17 \times 10^9 \) protons for the vertical emulsion, and \( 3.18 \times 10^8 \) for the horizontal.

The cross section term including all target dependent factors is given by:

\[
]\[\varepsilon_2 N_{\text{beam}} \rho t]_{\text{NMC}} \sum_{i}^{V,H} N_{\text{beam}} \cdot \varepsilon_{i}^{\text{NMC}} \cdot (\rho t) ; \quad (15)\]

\[
= (1.17 \times 10^9)(.260)(5.11) + (3.18 \times 10^8)(.235)(7.79)\]

\[
= 2.14 \pm .16 \times 10^9 \quad (\text{grams/cm}^2)
\]

where the sum is over vertical and horizontal modules (V and H). Contributions to the total "non Monte carlo" efficiencies (\( \varepsilon_{i}^{\text{NMC}} \)) are listed in Table 20. The density and thickness for the target modules were taken from Table 6 for the vertical modules, and Table 7 for the horizontal.

6.3 Dynamical model and Monte Carlo determined efficiency factors

Figure 48 illustrates the simple dynamical model used for Monte Carlo simulation of the production of charm pair events. As already mentioned in section 5.5 of the
Table 20: "Non Monte Carlo" efficiency correction factors.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Value</th>
<th>Estimated Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live time:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical</td>
<td>.68</td>
<td>.02</td>
</tr>
<tr>
<td>Horizontal</td>
<td>.73</td>
<td>.06</td>
</tr>
<tr>
<td>&quot;Non Physics&quot; cuts(^a):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical</td>
<td>.699</td>
<td>.006</td>
</tr>
<tr>
<td>Horizontal</td>
<td>.594</td>
<td>.005</td>
</tr>
<tr>
<td>&quot;Non-flushed&quot; events(^b):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical</td>
<td>.966</td>
<td>.001</td>
</tr>
<tr>
<td>Horizontal</td>
<td>.957</td>
<td>.005</td>
</tr>
<tr>
<td>Fraction of sample analyzed (readable data tapes)</td>
<td>.96</td>
<td>—</td>
</tr>
<tr>
<td>Muon efficiency(^c)</td>
<td>.59</td>
<td>.05</td>
</tr>
<tr>
<td>Total factors:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical</td>
<td>.260</td>
<td>.022</td>
</tr>
<tr>
<td>Horizontal</td>
<td>.235</td>
<td>.028</td>
</tr>
</tbody>
</table>

\(^a\) From table 14.

\(^b\) Flushed (discarded) triggers are discussed in section 4.8.2.

\(^c\) From the bottom of table 12.
Table 21: Monte Carlo generated acceptance factors.

<table>
<thead>
<tr>
<th>Species:</th>
<th>$D^0/\bar{D}^0$</th>
<th>$D^\pm$</th>
<th>$\Lambda_c/\bar{\Lambda}_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$ trigger geometrical and DST cut acceptance</td>
<td>$0.258\pm 0.011$</td>
<td>$0.306\pm 0.013$</td>
<td>$0.103\pm 0.008$</td>
</tr>
<tr>
<td>$K\pi\pi$ invariant mass acceptance</td>
<td>$0.073\pm 0.012$</td>
<td>$0.079\pm 0.012$</td>
<td>$0.053\pm 0.017$</td>
</tr>
</tbody>
</table>

previous chapter, both charm particles of the pair were generated independently according to the distributions of equation (4) on page 11, and were not correlated. The trigger side of the pair, the charm particle that decayed to a muon, was taken to be a mix of charm particle species produced in fractional ratio $f_i$, where $i = D^0/\bar{D}^0$, $D^\pm$, or $\Lambda_c/\bar{\Lambda}_c$. The charm species fractions used were:

\[
f_{D^\pm} = 0.30; \quad f_{D^0/\bar{D}^0} = 0.50; \quad f_{\Lambda_c/\bar{\Lambda}_c} = 0.20
\]

in rough agreement with NA27 $\pi$-p and p-p data (see Table 2).

The associated charged D mesons were required to decay exclusively into $K\pi\pi$ in the Monte Carlo, while the trigger side charm was required to decay inclusively into muons. Events were generated for the three species of trigger charm enumerated above. The generated events were then run through the charm selection analysis programs to generate a DST of selected events. The events on the DSTs were then passed through the invariant mass $D^\pm$ selection program to obtain the final sample of events – those passing all of the cuts listed in Table 19 and having an invariant mass of $1869\pm 50$ MeV/$c^2$. This procedure determined the efficiency factors $\epsilon_{DST_i}$ and $\epsilon_{INVMI_i}$ respectively, where $i$ indexes the trigger charm particle species. These efficiencies, along with the statistical errors due to the limited number of events generated, are listed in Table 21.

The effective inclusive branching ratio for the trigger charm particle to decay into a muon times the branching ratio for the associated charged charm meson to decay into $K\pi\pi$, including trigger charm species dependent Monte Carlo generated
Table 22: Charm particle branching ratios and masses used for cross section.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Branching ratio (%)</th>
<th>Assumed mass (MeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D^± → μ^±X</td>
<td>18.2 ± 1.7</td>
<td>—</td>
</tr>
<tr>
<td>D^0/D^0 → μ^±X</td>
<td>7.0 ± 1.1</td>
<td>—</td>
</tr>
<tr>
<td>Λ^± → μ^±X</td>
<td>4.5 ± 1.7</td>
<td>—</td>
</tr>
<tr>
<td>D^± → K^±π^±π^±</td>
<td>11.4 ± 1.1</td>
<td>1869.3 ± 0.6</td>
</tr>
</tbody>
</table>

The inclusive branching ratios to muons, the exclusive Kππ branching ratio, and the assumed mass used for the charm particles are from reference [40], and are listed in Table 22. The εINVMi efficiencies are trigger species dependent because class 4 DST events were discarded by the invariant mass program cuts; the 3
trigger species produce differing proportions of accepted class 4 events over total accepted events in passing through the DST analysis programs.

As discussed in the previous chapter, a \((1-x)^n, n=4\) distribution was used for both the trigger and associated charm. Varying \(n\) by \(\pm 1\) unit resulted in deviations in \(\epsilon_{\text{DST}}\) of less than 1% and in \(\epsilon_{\text{INV}}\) of less than 5%. Changing the fractions for the trigger species within the errors of the NA27 \(\pi-p\) data yields deviations in the final result of equation (16) of up to 30%. The branching ratio errors, and the statistical errors in determining the efficiencies contribute a 17% error. The overall estimated uncertainty of (16) is approximately 35%.

Combining equations (13), (15), and (16) yields a charged D meson cross section per nucleon (linear in \(A\)):

\[
\sigma(D^\pm) = 3.36 \pm 1.20 \times N_{\text{INV}} \quad \text{(in microbarns-\(\mu\)b)}
\]

### 6.4 Charged D meson mass peak signal and cross section

Figure 49 is the invariant mass spectrum for charged D mesons after passing through the cuts of Table 19. The background was estimated by examining three 100 MeV/c\(^2\) bins on either side of the 1869\(\pm 50\) MeV/c\(^2\) signal, and yielded 13 counts. The signal is 21 counts, a statistical significance of 5.8\(\sigma\). The charged D meson mass determined from the events in the 1869\(\pm 50\) MeV/c\(^2\) range of this plot is 1877 \(\pm 17\) MeV/c\(^2\).

Figure 50 shows the effect on the signal of requiring a) the right muon sign, and b) the wrong muon sign. Using the same background estimation technique as in the total signal, the right sign signal is 14 counts over a background of 6 corresponding to a significance of 5.7\(\sigma\), while the wrong sign signal is 7 counts over a background of 7 corresponding to a significance of 2.6\(\sigma\).

The observed muonic signal is taken to be the right sign signal of 14 \(\pm 5\) counts, where the error is from Poisson statistics. The wrong sign signal is most probably due to accidental trigger by charm particles decaying through the decay chain:

\[\text{Charm} \rightarrow K^\pm X \rightarrow \mu^\pm \nu X\]
Figure 49: Charged D meson invariant mass plot.
Figure 50: Charged D mass plot with a) right μ sign, and b) the wrong μ sign.
The muonic right sign signal must be corrected for predominantly right signed trigger background from:

\[ \text{Charm} \rightarrow \pi^\pm X \rightarrow \mu^\pm \nu X \]

This background was estimated to be 16% of the right sign signal by Monte Carlo simulation, so the corrected charged meson signal becomes \( 12 \pm ^5_4 \). Also, from the interaction lengths in Tables 6 and 7, approximately 8% of the interactions in the volume of the emulsion occur in the lucite and polystyrene emulsion backing. The final signal is thus \( 11 \pm ^5_4 \), and corresponds to charged D meson cross sections per nucleon (by equation (17)) of:

\[
\begin{align*}
\sigma(D^\pm) &= 37^{+17}_{-13} \pm 13 \text{ \( \mu b \)} \quad (A^1 \text{ dependence}) \\
\sigma(D^\pm) &= 92^{+42}_{-24} \pm 33 \text{ \( \mu b \)} \quad (A^{.77} \text{ dependence}) \\
\sigma(D^\pm) &= 62^{+28}_{-22} \pm 22 \text{ \( \mu b \)} \quad (1.5 \times A^{.77} \text{ dependence})
\end{align*}
\]

where the non-linear atomic weight dependence correction factor comes from Table 4. The statistical errors come from the Poisson distribution of the invariant mass signal, while the systematic errors come from the efficiency factors, branching ratios, and incident beam estimates.

### 6.5 Discussion of results and comparison to other experiments

A major uncertainty in the cross section measurement is whether the muon that triggered the experiment actually comes from the decay of a charmed particle. Muons that triggered the experiment from pion and kaon decays not coming from a charm decay vertex could be associated with a charm particle vertex and thus pass through the analysis cuts. In addition, the estimate of a 16% contribution to the right sign signal from pions coming from charm decay may be an underestimate. These types of events should not be included in the cross section calculation, and would yield an overestimate. Though the occurrence of this type of background is estimated to be small, evidence that this may be happening at some level is indicated by a possible signal with muons of the wrong
Table 23: Inclusive D meson cross sections for $x > 0$ and various A dependences.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>A</th>
<th>$\alpha A$</th>
<th>$\alpha A^{-77}$</th>
<th>$\alpha 1.5A^{-77}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA27</td>
<td>27</td>
<td>H (1)</td>
<td>11.2±2.3</td>
<td>24.4±8.1</td>
<td>16.3±5.4</td>
</tr>
<tr>
<td>CHERM</td>
<td></td>
<td>Cu (64)</td>
<td>9.4±3.1</td>
<td>27.0±3±5</td>
<td>18±2±3</td>
</tr>
<tr>
<td>E595</td>
<td></td>
<td>Fe (56)</td>
<td>10.7±1.1±1.8</td>
<td>17±17±11</td>
<td>31±11±11</td>
</tr>
<tr>
<td>E613</td>
<td></td>
<td>W (184)</td>
<td>7.8±1.7</td>
<td>25.9±5.6</td>
<td></td>
</tr>
<tr>
<td>E743</td>
<td>39</td>
<td>H (1)</td>
<td>16.5±3.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E653</td>
<td>39</td>
<td>Em. (27)</td>
<td>18.5±5±6</td>
<td>46±17±17</td>
<td>31±11±11</td>
</tr>
</tbody>
</table>

* Cross sections covering all Feynman $x$, including that of this paper, have been converted to $x > 0$ cross sections by division by 2.

sign. The only way to assure that this is not a major contribution to the right sign signal is to visually confirm that the muon is associated with a charm decay by scanning the candidate events in the emulsion. This will be done in the near future, and the quoted inclusive charged D meson cross section is to be considered preliminary until then.

The only other cross section measured at the same center of mass energy as this experiment is from the LEBC p-p Fermilab 743 experiment listed in Table 2. They find an inclusive charged D meson cross section of $\sigma(D^+) = 33 \mu b$. The cross section measured here appears to agree well with the LEBC result if a linear A dependence is assumed. If an $A^{-77}$ dependence as measured in the beam dump experiments [15] and [16] is assumed, there is agreement within error only if an additional proportionality factor is included (1.5 is used for illustration here). Other nuclear charm production cross sections near this energy also seem to agree best with hydrogen cross sections with a linear A dependence as illustrated in Table 23 (compiled from the reviews of references [6,7,8]).
6.6 Implications for further analysis of this experiment

An estimate of the yield of muon triggered charm in the fiducial volume of the emulsion contained in the data summary tapes can be made from the observed charged D signal of $11 \pm 4$. In the notation used in the cross section calculation, the number of associated charged D mesons that must be on the data summary tapes of the sample is given by:

$$N_\pm = \frac{11 \text{ counts}}{\text{BR}(D^\pm \rightarrow K\pi\pi) \cdot \sum_i f_i \cdot \epsilon_{INVMI}}$$

$$= \frac{11}{0.114 \times 0.071} \approx 1400 \pm 500$$

where the error is statistical only. Since this represents about 61% of our data, we expect our full data sample to contain $2300 \pm 800$ associated charged D mesons. Assuming a charged D meson production fraction of 0.3 yields $7700 \pm 2800$ associated charm particles, or pairs, total. We will not be able to reconstruct all of these charm particles of course; approximately one half will be traveling backwards in the center of momentum frame, and the decay products will not be in the acceptance of the apparatus, while others, such as single prong decays with small kink angles, though accepted, will be difficult to reconstruct.
Chapter VII

CONCLUSIONS

The all electronic portion of a hybrid emulsion-spectrometer experiment triggered on the muons from charm particle decay was used to determine an inclusive charged D meson production cross section for p-emulsion interactions at a center of mass energy of $\sqrt{s} = 39$ GeV. From a signal of $11^{+5}_{-4}$ charged D mesons obtained from 61% of the experiment’s first run data, the cross section per nucleon was measured to be:

$$\sigma(D^{\pm}) = 37^{+17}_{-13} \pm 13 \text{ } \mu b$$

where the dependence on atomic weight (A) was taken to be linear. An uncorrelated charm pair production model was used in a Monte Carlo simulation to determine geometrical acceptances and software reconstruction efficiencies. This result is preliminary, since the charged D meson candidates will be scanned in the emulsion to visually reject any background at a future date, and the remaining 39% of the first run data will be processed.

The best agreement with p-p data at the same center of mass energy is achieved if a linear atomic weight dependence is assumed. The two results are approximately one standard deviation apart if an $A^{-77}$ dependence is used.

The size of the charged D meson signal presented in this thesis implies that the first run data should contribute on the order of 1000 reconstructed charm pairs to the total yield of the experiment, which is now in its second running period.
Appendix A

Trigger timing on a FASTBUS crate

Figure 51 schematically depicts trigger timing on a crate for the cases of a full and fast cleared trigger. A trigger "event" – the earlier of a TDC stop or ADC gate leading edge – started the measured pause interval (MPI), and brought down the busy line. TDC stops and ADC gates were applied during the MPI. However, if a fast clear was received by the CAT during the MPI, data acquisition mode was re-established in essentially zero time, and the busy line was brought up to re-enable trigger receipt. A fast clear after the start of conversion (end of the MPI) took approximately five microseconds if there were any TDCs in the crate since they needed to be digitally cleared to re-establish data acquisition mode (ADCs could be fast cleared at any time and took ~ 0.6 microseconds to clear). For a trigger that was not fast-cleared, the trailing edge of the MPI started data conversion in all DAMs on the crate. Readout of the DAMs was performed by microcode in the 1821 in the crate upon its receipt of a delayed (after completion of data conversion) trigger. Once readout was complete, the CAT busy was freed by the 1821 microcode, and data acquisition could resume.
Figure 51: Hardware trigger timing on a FASTBUS crate.
Appendix B

LECROY 1891 MEMORY OPERATION

Data was recorded in the 1891 memory modules as variable-length records. The records were managed with five internal registers: the next transfer address (NTA), the auxiliary write pointer (AWP), the end of memory (EOM), the full warning offset (OFS), and the end of block (EOB). The NTA contained the address of the header for the next record to be read, while the AWP contained the next “writable” address in memory. Overwriting of unread records was prevented by the EOM register, which pointed to the logical end of the memory. A judicious choice for the value of OFS register prevented memory full conditions from occurring by supplying a veto to synchronize “read” and “write” operations. Read completion detection was performed using the EOB register.

Each record in the memory had a header as its first 32 bit word. Bits 0–19 of this header constituted the LINK, which contained the address of the header of the next record stored in the memory. The LINKS of the records in memory chained together all records; in principle, any one could be accessed by sequencing through the LINKS. The last record in memory had its LINK pointing to a “null” header; the null header’s LINK pointed to itself indicating the logical end of available records (see Figure 52). The null header was also the location the AWP pointed to – the next location to write to in memory. Bits 20–27 of the header formed a record sequence counter modulo 256, and bit 30 was the data valid bit. Upon a read operation, a valid record’s LINK was not equal to the NTA and its valid bit was set. A non-valid record had either its LINK equal to the NTA (the “null” header), or its valid bit cleared. Since the NTA was the starting address of the record being read, and the LINK the ending address + 1 (i.e. the
Figure 52: FASTBUS 1891 bulk memory logical structure.
location of the next record to be read), the length of the record:

\[ \text{LINK} - \text{NTA} - 1 \quad \text{(appropriately masked to bits 0–19)} \quad (19) \]

was negative if the event had wrapped around the physical memory. In this case, the size of the record was:

\[ \text{LINK} - \text{NTA} - 1 + \text{MEMORY SIZE}. \quad (20) \]

Figure 53 describes the LSI polling and length calculation algorithm based on these facts.

Microcode internal to the "crate controller" (e.g. the 1821 processor module) provided "read" and "write" operations for the memory. The read operation loaded the LINK of the header pointed to by the NTA (i.e. the address of the end of the current record) into the EOB register and started the transfer of data. Each word transferred incremented the NTA address, so that it pointed to the next record when readout was completed (NTA register equaled the EOB register). The EOM register was then loaded with the NTA so the logical end of memory was always defined to be the address of the next record to be read. The receiver (1821) was then strobed with an end of transfer signal. Write operations were somewhat more passive; the 1891 would accept any write request as long as a full condition could not ensue. A full condition was determined by:

\[ \text{AWP} = \text{EOM} \quad \text{(AWP was auto-incremented during a write)} \quad (21) \]

When the full condition was reached, the 1891 locked up and the memory full line was latched. The memory full condition could only be freed by resetting the memory, which destroyed any data that was present. The OFS register prevented memory full conditions by allowing a full-warning veto to be latched whenever the condition:

\[ \text{AWP} + \text{OFS} > \text{EOM} \quad (22) \]

occurred. When a write operation created a full warning condition, an external full warning line was latched up so that additional triggers, and hence writes,
Simplified LSI data valid and length calculation
(data pre-read) algorithm

Notation:

\(<n:m>\) = word masked to bits n through m
(i.e. all other bits cleared)
\(\land\) = bit-wise or
\(\cdot\) = bit-wise and
\(i\) = 1891 index

Length = 1891 record length
Nta = 1891 next transfer address
Link = 1891 link pointer to next record
Memsize = Total size of 1891 memory

\(i = 1\)
READ NTA,LINK,AWP of all 1891 modules
If( read failed) go to HUNG

CLOOP:
Length(\textit{i}) \leftarrow \text{Link}(\textit{i})<0:19> - \text{Nta}(\textit{i})<0:19>
Bit30 \leftarrow \text{Link}(\textit{i})<30:30>
If( Bit30 = 0 \land \text{Length}(\textit{i}) = 0) go to NOVALID
Length(\textit{i}) \leftarrow \text{Length}(\textit{i}) - 1
If( \text{Length}(\textit{i}) < 0 ) \text{Length}(\textit{i}) \leftarrow \text{Length}(\textit{i}) + \text{Memsize}(\textit{i})
If( \text{Length}(\textit{i}) < 0 ) go to NEGERR
If( i > N1891 - 1) go to READ
\(i \leftarrow i + 1\)
Go to CLOOP

NOVALID: Poll – set up next pre-read poll in N ticks of clock
(mark time request for data flag). Exit and wait for
mark time completion or other asynchronous interrupts.

NEGERR: Fatal error – negative length – stop

HUNG: Reset and poll – reset master crate. Reset all 1891
modules (destroys any data!). Set up next pre-read
in N ticks of clock. Exit and wait for mark time
completion or other asynchronous interrupts.

READ: Perform minimal event structuring – set up for data
read of all 1891s. Read out 1891s into buffer location
following pre-read ”directory” data.

WRITE: Wait for last write to VAX completion. Write to VAX and
exit if no error, otherwise recover from error if
possible, bomb out on an unrecoverable error.

Figure 53: LSI 1891 bulk memory polling “pre-read” algorithm.
could be vetoed. Upon removal of the full warning condition on a read (the EOM had increased to point to the next record to be read, the NTA), the full warning line was lowered, and data acquisition could resume. A conservative value (e.g. $2-5 \times$ the expected maximum record length) had to be loaded into the 1891 OFS register prior to data acquisition, since this method of memory protection left a window of vulnerability – too small of an OFS could be chosen. OFS was set to 8192 32 bit words for normal experimental running conditions. If the memory was writable (i.e. there was no full condition), then the content of the address pointed to by the AWP was cleared, and data was allowed to be transferred to the 1891 by strobing the sender. Transfer terminated when an end of record (EOR) was strobed by the sender, or a full condition was reached. After transfer terminated, the header for the record was loaded with its LINK pointing to the “null” header, its valid bit set, and its record ID set to the ID of the last written record + 1 modulo 256.

All full, full warning, and write lines were front panel emitter coupled logic (ECL) inputs. Reads were performed over the FASTBUS backplane; the 1891 was intended to be read out via a FASTBUS controlling module (e.g. 1821) in the same crate that conforms to its protocol. The controlling module was also used to read and load 1891 registers.
Appendix C

RD1891 task memory mapping and overlaying

A global 128 kilobyte (kb) memory region DATCOM was created by the RD1891 task to overcome the 64kb task size restriction on the LSI running the RSX11-M operating system. The RD1891 task could then map a 32kb FORTRAN common block to the region through a 32 kb movable “window” with RSX system services. Figure 54 illustrates this window mapping by the RD1891 task to regions of the LSI's physical memory. As indicated by the figure, global FORTRAN clusters of routines were also mapped to with a separate 16kb window. This saved much needed space as a large memory resident FORTRAN library was accessed with only 16kb of the task. After these mappings, only 16kb was left for the mainline RD1891 program. It was not possible to fit the necessary programming directly into this 16kb, so some overlaying of non time-critical code was necessary\(^1\). Even then, keeping the program within the available space required restricting the amount of diagnostic code placed in the program. Only 50–100 words of additional space for coding was left after stripping the program down to essential, functional code.

A consequence of using memory mapping was that events with a length between 32 and 64 kb needed to be sent in two packets to the VAX since a window remap had to be performed to access past the first 32 kb. This resulted in a slight degradation in the throughput due to the time taken in setting up the extra transfer.

\(^1\)In an overlay, independent routines shared the same physical memory space. These routines were swapped in and out of memory to disk as needed. This could be used only for non time-critical code because of the time taken to swap the routines.
Figure 54: RD1891 task mapping to DATCOM memory region and FORTRAN cluster libraries.
Appendix D

ODINSHARE SHARED IMAGE SECTIONS

This appendix contains detailed descriptions of the ODINSHARE shared image sections of the VAX ODIN online system described in the data acquisition chapter of this paper.

D.1 EVQ global data structure section and its access routines

The event pool and queueing system utilized by the online processes consisted of the following ODINSHARE data structures:

1. The FREELIST - This was a singly linked, circular memory ordered list of unused blocks of contiguous virtual memory that provided a pool of memory to buffer events for the ODIN and NORN systems. The shared routines EVQ_XXXX provided for allocation and deallocation of virtual memory blocks from the list, and allowed access to information about the list for statistical displays of pool usage.

The structure of the FREELIST and the “free blocks” (i.e. blocks of unused, available space) in this list and in queues is depicted in Figure 55 (lists and queues are described in references [46] pp. 228–293, 435–455, and [47] pp. 42–47). The free blocks in the list were “chained” together through address “links” contained in an internal header supplied by each block; a specific free block could be reached by sequentially searching through the links of all blocks in the list with a lower address. A free block’s header consisted of the first four 32 bit words in the block, and was reserved for
Figure 55: ODIN online system circular memory list – the FREELIST.
use by allocation, deallocation and queuing algorithms. The first word, the forward link (FLINK), pointed to the next free block's memory location, the second was reserved for queuing algorithms, the third contained the inclusive byte count of the block (aligned up to an 8 byte boundary), and the fourth word was reserved for possible future use.

The FREELIST initially consisted of one free block the entire length of the list. When a block of memory was requested, the FREELIST was searched linearly in its forward links until a block at least equal to the requested length, or a negative link, was found. A negative link indicated the end of the list had been reached; upon such an occurrence the requestor was notified that there was no space of the requested length available. If a large enough block was located, then it was truncated to the requested size, and the links of the previous and next free block were patched around this truncated block. The block of memory was then out of circulation as far as the list was concerned. Any space left over from the truncation was patched back into the list as a free block (or part of an existing free block). The address of the requested block was then passed back to the requester as a return argument. Once a block had been allocated, only its address and byte count (the length in bytes—the third word in the header) needed preservation. The first two words in a block's header were modified when the block was pushed into a queue as shown in Figure 55. An event in a queue had the FLINK pointing to the next block in the queue, while the second word in the header, the backwards link (BLINK), pointed to the previous block in the queue. The byte count of the block had to remain unmodified until it was deallocated.

Deallocation consisted of searching the FREELIST in its forward links until a link with an address greater than that of the block to be deallocated, or a negative link indicating the end of the list, was reached. The block was then patched into the list after this link. If the patched block was contiguous with either of its free neighbors, then they were coalesced to make a single,
larger block. Whenever all blocks were deallocated back to the FREELIST, it once again was a single block the size of the entire list.

There was no method for multiple processes to access the list in a synchronized manner, so that only one process, the “pool manager” HUGIN, could access the list. This method of access was chosen to avoid event by event CPU and real-time overhead that would occur in any implementation of a synchronized access scheme.

2. The three doubly linked queues: the CTQ, MTQ, and ANQ (cut, mag tape, and analysis queues). These queues, in conjunction with group-global event flags associated with them, provided access to buffered events for the processes THOR, MUNIN and NORN(s) respectively. The pool manager, HUGIN, after allocating space from the FREELIST for an event and reading the event into that space, “pushed” the address of the event into the CTQ, and set the CTQ flag telling the next process in the chain, THOR, that there was an event in its queue. THOR then “popped” the event address off the CTQ, processed the event, and then placed it in the MTQ, setting the MTQ flag to notify MUNIN that there was an event for it to process, etc. (see Figure 41). These queues were synchronized and could be accessed by any process. The list heads for these queues were located in the shared image EVQ data section.

3. The FRQ (free queue). This queue was essentially a trash-bin for used blocks of memory. It permitted processes besides the pool manager to return a block to the FREELIST in a synchronized manner – they would push the block onto the FRQ, which the pool manager periodically flushed to the FREELIST (which only it could access) to replenish the list.

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1 Synchronization was achieved using the VAX interlocked queuing instructions INSQHI, INSQTI, REMQHI, and REMQTI to push or pop events to or from the queues. Once an event was pushed onto (popped from) a queue, any (no) process could access it, and since pushing and popping were hardware interlocked, synchronization was assured.
D.2 Shared FORTRAN commons section

Block data common object modules that were linked in with the shared image could be referenced transparently (i.e. as any FORTRAN common is referenced) by any process linked to the shared image. Unlike the storage of normal process specific FORTRAN common blocks, the shared image FORTRAN common data was stored in a global location in physical memory and could be accessed as a common set of data not only among the various routines in a process, but also among processes on the VAX system. In the ODIN system, these commons were mainly used to share semi-static information among the online processes (e.g. device database information), though some system switches (e.g. a common variable limiting the maximum number of active online NORNs) were initialized in the shared image block data. The usage of shared common switches allowed parameters affecting system performance to be changed by relinking the shared image with the modified block data – other processes in the system did not need to be re-linked.

Most shared commons were used to convey information collected by ASGARD sub-processes to ASGARD for display. No synchronized access to the commons was provided for; synchronization was by protocol only and care had to be taken when accessing the commons. Some volatile information required no synchronization as the current updated value was desired.

A FORTRAN common buffer of approximately 40kb was maintained in the ODINSHARE image for the purpose of storing the most current pedestal run information for every channel of each detector component. A special utility process GETFB linked to ODINSHARE was run to receive pedestal data from the LSI.

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2For example, THOR, upon receiving an end of spill event, extracted blind scaler data, performed a cumulative sum, and updated the results in shared common for access by an ASGARD display command. If the display command were to simply write the information to the terminal directly from the common variables (which takes about 2-3 seconds), there would be a risk that THOR would update the common data during this time, and some of the displayed information would be from the last update, and some from the one in progress. A modicum of synchronization was used to avoid such occurrences. The data was first copied to a local buffer (taking only micro-seconds), then was displayed from the local buffer.
over the DR11-W link between the computers. As soon as all data was verified, it was copied to the shared FORTRAN common, and the process exited. Any process accessing the data in the common after the GETFB update would get the new pedestal information. In particular, pedestal data was written to each data tape as part of the tape header by the online system.

The database property of the shared image was also used to store information and switches for processing the CAMAC scanning digital voltmeter measurements. A set of acceptable voltage ranges and activation switches were initialized in shared image block data common statements. These settings could be modified at run time via the ASGARD SET/VOLTS command. The process THOR read the scanning DVM voltages from end of spill events, and compared them to the acceptable ranges for any activated channels. If a voltage was out of range, then it was signaled to the ASGARD process, which put an error message along with a warning bell to the terminal.

D.3 Error message section

All error messages in the ODIN and NORN systems were encoded in the standard VAX error message format using the VAX MESSAGE UTILITY. VAX error messages consisted of a facility name, a severity type (informative, warning, error, or fatal), the error message name, and text describing the error. Standard VAX/VMS signaling routines parsed the encoded error and printed out the message in the format:

```%Facility-Severity>Error name, Informative text```

An error message object module was generated by the MESSAGE utility from a message definition file, and was linked in with the ODINSHARE shared image. Since all error message symbols were declared universal in the link, any process could access the error message information for a given error by (transparently) vectoring into the message table in the shared image. Placing the rather lengthy (due to the message's text portion) table into the shared image provided memory...
savings since each process did not need to keep its own copy of the table in memory.

### D.4 Shared routines section

There were four categories of shared routines in the ODINSHARE image:

1. **EVQ.XXXX** routines provided access to the event pool FREELIST and the four queues used by the online system.

2. **MBX.P.XXXX** routines used the VAX MAILBOX facility to provide an ASGARD initiated timed "handshaked" command cycle with one of its sub-processes.

3. **MBX.E.XXXX** routines were used by ASGARD sub-processes to send unsolicited error messages to ASGARD via the VAX MAILBOX utility.

4. **SRV.XXXX** routines performed general interest service functions for any process linked to ODINSHARE. In particular, terminal unsolicited command input and control-c interrupt handling routines fell in this category.

All shared routines were written in re-entrant VAX assembler code. Using shared routines saved on memory usage as only one copy of the routine needed to be in memory to service all users. A greater advantage was obtained in maintainability of the shared code due to the vectoring nature of accessing it. With a little care, a shared routine could be modified and the shared image re-linked without the need to re-link all processes that referenced the routine; the caller would be correctly vectored to the modified routine in the shared image.

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3. Control-c software interrupts (asynchronous system traps) were handled in a different manner than normal terminal input.
4. The program sequencing in memory was redirected to the memory location of the shared code by a jump instruction located where the routine call would normally be.
5. The vectoring resulted in a minimal additional cost in execution time due to an extra jump instruction when the routine call reference was (transparently) vectored to the shared routine via a dispatch table created when linking the shared image to the calling process.
D.5 ODINSHARE organization and read/write global data protection

The VAX/VMS linker permitted virtual memory (memory locations that appear contiguous to the user, but are mapped to non-contiguous portions of physical memory) arrangement of object modules into sections when linking them to make a shared image. The linker, when used to link a shared image into a process, would place the shared image sections at the end of the processes virtual address space. Figure 56 depicts the arrangement of the ODINSHARE image and its placement in a process linked with it.

NORN analysis processes did not allow the user to access an event in the EVQ system directly, but had a user-transparent interface that copied an event from the EVQ pool into a local memory buffer, then immediately pushed the original onto the free queue. As this interface was part of the NORN process and had to have the ability to access any address in the EVQ pool, the NORN process needed to link in the entire ODINSHARE image. Since FORTRAN did not provide protection against array boundary overflows due to coding errors, there existed the possibility that an array overflow on a write operation could overwrite part of the EVQ event pool, thus corrupting events that were in use by other processes in the system. To avoid this type of corruption, the shared image was organized so that its writable EVQ data sections were preceded by read only code as in the figure. If, for example, a NORN wrote past one of its arrays in a do loop, the program, as illustrated in the figure, would stop with an access violation when it tried to access past the read only section. This scheme did not protect against a direct write into the EVQ section however, but such an occurrence would be unlikely. The possibility of corruption of the EVQ data by NORNs could be completely avoided by compiling and linking the NORNs in VAX debug/check mode prior to online use. This would catch any array boundary overflows and other memory access violation errors before they could do any harm.
Figure 56: Online process virtual memory map with ODINSHARE shared image mapped onto it.
Appendix E

Program details of ASGARD and its sub-processes

E.1 The ASGARD process

When ASGARD was started up, it initialized the rest of the online system through the following steps:

1. Established its condition handler to process errors.

2. Established its exit handler to do image cleanup upon exit.

3. Disabled the system’s ability to swap it out of memory.

4. Checked that another ASGARD process was not running by attempting to rename itself to ASGARD, and exited with an error message if one was.

5. Assured that there were no online NORNs running on the system, as the memory pool would be initialized. If NORNs were permitted online when the pool was initialized, then subsequent pool corruption could occur. If any online NORNs existed, their names and terminals were listed at the ASGARD terminal, a message was broadcast to each such NORN’s terminal telling it to log off, and ASGARD exited with an error message.

6. The EVQ event pool system was initialized.

7. All data structures and data-bases (e.g. the device data-base) were initialized.

8. The sub-processes HUGIN, THOR and MUNIN were created and initialized.
9. The terminal unsolicited input mailbox was created, and unsolicited terminal input was initialized.

10. The command message and sub-process error message mailboxes were created and initialized.

11. The group-global common event flags used for command/error mailbox and queue access synchronization were created and initialized.

12. ASGARD then waited for its three sub-processes to signal that they had initialized themselves and were ready but paused.

ASGARD was normally in a wait state for one of two events: unsolicited terminal input or unsolicited error messages from its sub-processes. Unsolicited commands were accepted from the terminal via the SRV_USI shared code and were processed with a standard set of routines, CMD_XXXX, which parsed the commands and dispatched them. Unsolicited error messages were broadcast to the terminal. Hardware exceptions or internally signaled errors were put to the terminal via ASGARD’s condition handler. This handler also unwound all routine calls up to the main level of the program (i.e. to the level where the handler was established). Execution then continued at the next instruction after the routine call in the main program.

Portions of ASGARD commands requiring sub-process action or intervention were signaled to the sub-process in a “handshaked” cycle. In the first half of this cycle, the ASGARD command execution routine sent a coded message to the sub-process’s mailbox and waited for a reply in the ASGARD mailbox. The cycle was completed when the sub-process, after parsing and executing the command message, returned a status to the ASGARD mailbox. Both ends of the cycle could time out and abort the command cycle. If a bad status was returned to the ASGARD mailbox, it was put to the terminal with a warning bell. All statuses were formatted as standard VAX error message packets, and either were VAX/VMS system defined status codes, or were defined by the VAX/VMS SET MESSAGE
DEFINITION UTILITY and stored in the ODINSHARE shared image message section.

Since sub-processes were not automatically deleted by the VMS operating system when their creator exited, an exit handler was established which used system services to force exits on ASGARD's sub-processes. This exit handler was invoked by VMS whenever the establishing image (i.e. ASGARD) exited, even if for a fatal error. This assured that all sub-processes disappeared from the system along with ASGARD. This handler performed other cleanup operations such as renaming the process from ASGARD back to its original name, stopping all queue activity by clearing all queue flags, and setting all other flags to their initial non data acquisition states.

E.2 ASGARD sub-processes

The three ASGARD sub-processes HUGIN, THOR, and MUNIN had a number of features in common. Each sub-process executed a similar initialization routine when it was created. This routine:

1. Initialized the ODIN group event flags so that they could be accessed.

2. Opened the sub-processes mailbox to receive ASGARD commands.

3. Opened a channel to the ASGARD mailboxes so that command return codes and unsolicited errors could be sent to ASGARD.

4. Accessed all pages (512 byte memory blocks) of the EVQ pool system to bring them into the sub-processes working set; paging overhead was thus incurred at initialization time instead of run time.

5. Sent a message to ASGARD indicating that it was ready but paused.

The sub-processes all had nearly identical condition handlers which first signaled the error or exception to ASGARD, then either unwound calls and continued on
non-severe errors, or re-signaled severe errors causing a fatal exit. These sub-processes were all event driven, and were normally in an event-flag wait state for unsolicited messages from ASGARD or activity on their event queue. The exception was HUGIN, which also waited for events and error messages from the LSI computer. System events were signaled by the setting of one of a set of group-global event flags shared among all processes in the ODIN and NORN systems.

None of the sub-processes could write information to the terminal directly (this was reserved for ASGARD), but all had log and error files that were used for debugging purposes.
Appendix F

Hugin memory management

In its live mode, HUGIN became aware of unsolicited data from the LSI through the posting of a user mode asynchronous system trap (AST) that executed on any attempted unsolicited writes by the LSI. The AST set the appropriate flag (event vs error message) upon which HUGIN was waiting. HUGIN then used a CD routine, CDSTAT, to determine the length of the pending incoming data, allocated space for it, and only then performed the data read transfer from the LSI to the VAX. The allocation scheme was somewhat more complicated than thus described – it had to take into account the case when not enough space in the pool was available to read in the event. When unable to obtain space for an event from the FREELIST, HUGIN:

1. Purged the FRQ (and possibly the ANQ) to the FREELIST in an attempt to get space. The FREELIST was then searched again for a block of space large enough.

2. On failure to get a large enough block, the HUGIN wait mask was switched to wait for the logical "or" of its unsolicited command flag, the LSI unsolicited error message flag, the endrun control flag, and the FRQ (and possibly the ANQ) flag, and the not-done bit was set into a mode word of the HUGIN process. Note that the LSI data flag was not waited on – HUGIN waited for either a command, error message, or for an event consumer to release pool space to the FRQ (or possibly the ANQ).

3. If the wait state was satisfied by the FRQ (or possibly the ANQ) flag and the not-done bit was set in the mode word, then the previous wait mask
was restored, the not-done bit cleared, and another purge to free space was attempted starting at step one above.

4. This process continued until a large enough block of space was available for the event, or the write from the LSI timed out.

Three modes of purging the FRQ and ANQ queues could be specified with the ASGARD INITIALIZE/HUGIN command:

1. Purge the analysis queue anytime. When HUGIN performed a purge to replenish the FREELIST, both the FRQ and ANQ were purged. This mode favored data acquisition, and assured that the NORN analysis process saw “fresh” events, as older ones were purged.

2. No purge of the analysis queue. HUGIN purged only the free queue. This mode favored NORN analysis processes. It could only be used for preliminary equipment testing, or when no events were passed to the analysis queue. If the analysis queue did receive events, and if this mode was chosen, then the consumption rate of the NORN analysis processes determined the throughput of the entire online system. If the NORNs did not consume events as fast as they came in, then the online system could incur fatal time-outs at the front end.

3. Purge the ANQ only on FRQ purge failure. HUGIN first attempted to obtain space by purging the free queue; the analysis queue was purged only if purging the free queue failed to free enough space. This mode was a compromise between 1 and 2 above.

During the first half of the run, the first purging mode was used. The second half used the third mode. Very little difference in performance was noted between these two modes.
Appendix G
Automatic tape device switching

At approximately 1 spill's length of data from the end of the current tape, the MUNIN process decided what action to take at the next CAMAC end of spill event. If the auto-switching mode was enabled (via the ASGARD INITIALIZE/DEVICE command), and an additional tape drive was available and ready, then MUNIN sent a message to the LSI CAMAC task RDCAM via HUGIN's CD link. This message specified that the trigger type for the next end of spill event should be overwritten by the software with the special end of run (EOR) trigger type. As this EOR event propagated through the system, it initiated particular responses in each task or process to set up for the next run (tape). The LSI FAST-BUS task RD1891 cleared its run by run counters. The ODIN process HUGIN inserted a tape header event in the CTQ directly following the EOR event upon encountering it. The THOR process dumped out a statistical summary to the line printer for the last tape upon receiving the EOR event followed by a tape header. Lastly, MUNIN, upon seeing the new tape header, closed the file on the old device, dismounted it, opened a file on the new device, and wrote the tape header to it. This method assured that each tape started with a header, and ended with an end of spill event.

If however, auto-switching was not enabled, or a second device ready, then the endrun procedure was quite different. In contrast, the message sent to the LSI specified that RDCAM should disable triggers when the end of spill event was received. HUGIN sent a tape trailer\(^1\) following the EOR event instead of a tape header, and MUNIN upon seeing the tape trailer, initiated a shutdown of

\(^1\)A "pseudo-event" identified by a bit set in the event mode word. These pseudo-events were not written to tape; their only purpose was for synchronizing the endrun sequence.
the entire online system by signaling HUGIN to shutdown. This method assured that all of the events that were in the system prior to the disabling of triggers were written to tape before shutdown.
Appendix H
ASGARD and NORN command structures and definitions

ASGARD and NORN system commands were defined using the VAX/VMS COMMAND DEFINITION UTILITY. Each command required an entry in a Command Language Definition file (CLD file) which specified the syntax of the command, and a routine to execute the command (the execution routine name was also specified in the CLD file). Command execution routines could use VAX command language interpreter (CLI) routines to parse the command, allowing tailoring of the command in the same manner as VAX Digital Control Language (DCL). The commands were dispatched for execution through a user transparent interface to the VAX CLI dispatcher. Linking the CLD and command execution routines into a process was all that was needed to make the command available to the ODIN or NORN systems. The command syntax format of the ODIN and NORN commands was essentially identical to that of VAX DCL commands since the VAX CLI routines were used to parse and execute the commands. The basic syntax format was:

<verb> [/<Qualifier>...] [ <Parameter> [/<Qualifier>...]...]  

Here angled brackets denote a user specified mnemonic, brackets denote optional items, and ... a possible list. Qualifiers were separated by slashes, and parameters by spaces or commas. Qualifiers could be assigned values or names:

/ <Qualifier> = <value or name>

and could be either global (following the verb and applying to all parameters) or local (applying only to the parameter they follow). VAX supplied CLI routines
used in the command execution routines could check for the presence of qualifiers and parameters in the command, and could extract any (assigned) values.

In addition to command definition interfaces, the following support was available to ASGARD, NORNs and LOKIs:

- Shared image routines for unsolicited terminal input and (control-c) command cancelation.

- Non-sharable transparent basic command routines for processing and dispatching commands in a VAX DCL type of environment such as:
  - Indirect processing of sets of commands from disk files.
  - The DCL command to spawn a DCL sub-process.
  - Symbol definition, deletion, and display. Symbols allowed command abbreviations to be easily defined.
  - A HELP command that interfaced to the VAX HELP UTILITY and supplied help information to a running process (e.g. NORNs, ASGARD, LOKI) for help on, for example, commands available to the process.
  - Logical definition assignments and deassignments.
  - Set/No set verify.
  - Command line continuation for long commands.
  - Prompt string specification.
  - Other typical VAX DCL features.
Information about charm and beauty candidate events did not come together all at once\textsuperscript{1}, and measurements were expected to be improved and thus needed periodic updating. Therefore, one wanted this information stored in a random-access data-base that would lend itself to quick access and updating. The large volume of information generated by analysis that needed to be saved did not permit the use of relatively low capacity random access devices however. For this reason, a “pseudo” data-base type of environment was designed for mass storage on magnetic tapes.

Both raw event and summary event information were written to Data Summary magnetic Tapes (DSTs) in the format of binary encoded 32 bit integers\textsuperscript{2}. The sequencing of events on these DSTs was raw-event – summary-event – raw-event–etc. The raw event was simply copied from the raw production tape, while the summary data was formatted and written to the DSTs with a standard set of DST routines and a fixed summary event format. Each major component of the experiment was represented by a “module” in the summary event. A module consisted of a variable number of records that represented, for example, fit tracks. Each record had a fixed format for the information it contained and was fixed in length\textsuperscript{3}. “Get” and “put” routines allowed the floating-point information generated by the analysis to be transparently stored as scaled integers or retrieved as

\textsuperscript{1}Emulsion measurements were added after spectrometer measurements.

\textsuperscript{2}Binary encoded “twos complement” 32 bit integer format was the easiest format to decode for the various types of computers used.

\textsuperscript{3}The summary event code was written in a modular manner that easily allowed items to be added to the end of records and permitted the changing of the maximum number of records per module, the number of modules, etc. in a backwards compatible, user transparent manner.
Table 24: Summary "event" modules and their parameters.

<table>
<thead>
<tr>
<th>Summary module</th>
<th>Maximum # of records</th>
<th>Record length (32 bit words)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Header</td>
<td>1</td>
<td>18</td>
</tr>
<tr>
<td>Vertices</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Emulsion tracks</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>Spectrometer</td>
<td>100</td>
<td>42</td>
</tr>
<tr>
<td>Lead-Liquid-Argon calorimeter</td>
<td>30</td>
<td>18</td>
</tr>
<tr>
<td>Hadron calorimeter</td>
<td>10</td>
<td>19</td>
</tr>
<tr>
<td>Inferred tracks</td>
<td>10</td>
<td>17</td>
</tr>
<tr>
<td>Muon tracks</td>
<td>5</td>
<td>40</td>
</tr>
<tr>
<td>Kinematic fits</td>
<td>50</td>
<td>15</td>
</tr>
</tbody>
</table>

floating-point values. These summary routines were designed as far as possible to interface with the DSTs as if they were modifiable databases. Of course, when an events information was changed on a DST, a whole new DST tape needed to be generated.

Table 24 lists the modules in a DST event along with some of their parameters. The vertex module allowed entry of records for both spectrometer generated vertices and those found by emulsion scanning. The spectrometer module records contained both upstream (SSD) and downstream (SDC) measurements. Information about the beam track was also stored as a record in the spectrometer module. Track information for particles passing through the various components of the detector were internally cross-referenced. The inferred track and kinematic fit modules were not generally used until feedback from the emulsion scanners was available.

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4Each module had an integer scaling factor specified for each item in its format list.
Appendix J

Vertex fitting algorithms

The assignment of particle tracks to vertices, and the precise location the of these vertices was absolutely crucial for the successful outcome of the experiment. The correct assignment of muon tracks to vertices was particularly important for the tagging of semi-muonic charm and beauty decays. A precise determination of the location of vertices was necessary in order to avoid lengthy emulsion scanning.

Combining the tracks in an event to form vertices was a difficult task. In the first place, the problem was inherently recursive. To determine a charged track's x and y position at a vertex required a knowledge of the z position of the vertex. In addition, a track measured in the downstream SSDs projected back to a vertex in the emulsion had a position error that depended on how far into the emulsion the vertex was located. The conventional use of track error estimates to weight the tracks in vertex location fitting thus depended on the vertex location itself. Therefore, an iterative approach which used initial vertex position estimates to generate better ones was required. Secondly, because of the short lifetimes of charm and beauty mesons, a good fraction of the decays occurred quite close to their production point. Since the trajectories of the particles were measured about 150 mm downstream of the interaction point, SSD slope measurement errors, though small, amplified into significant position errors when projected back to the vertices. In addition, multiple scattering in the SSDs, interaction counter, and the emulsion all contributed to track position errors in the range of 10–20 microns at their vertex. These factors created a "region of confusion" about the

1The difficulty in the design of a multi-vertex fitting algorithm will not be adequately reflected here. Many techniques were tried and rejected before settling on the algorithm described here.
primary vertex where decay vertices blended in with the primary, becoming undetectable. Lastly, because of the high energy of the products of the interactions and decays, most tracks came out in a narrow solid angle; angles with respect to the beam axis were small – typically less than 25 milliradians. A precise (8 micron) position measurement orthogonal to the beam axis was possible. The resolution along the beam direction was worse than the transverse measurement by a factor of the average track slope – more than an order of magnitude (350 microns). Unfortunately, the longitudinal beam measurement is the most important for separating decays from their production point.

The algorithms described here attempted to address the above considerations. The fitting of primary nuclear interaction vertices will be discussed first. A similar algorithm used to find decay vertices containing a muon is described next. This algorithm played a key role in the selection of events for emulsion scanning. An algorithm that found any remaining secondary vertices is then briefly discussed.

### J.1 Primary nuclear production vertex fitting

Only well measured vertex SSD tracks linked to spectrometer drift chamber tracks at the magnet midplane were used to reconstruct vertices. This selection criterion was used for two reasons: to reject spurious tracks, and to correctly weight tracks using multiple scattering error estimates, for which a momentum estimate was required. In addition, since muons were assumed to originate at semi-muonic decay vertices, tagged muon tracks were not used in the construction of primary vertices.

Figure 57 depicts the flow of the primary vertex fitting algorithm. As already indicated, the nature of the problem dictated that a preliminary vertex position estimate be supplied (this preliminary estimate will be discussed in some detail later). As Figure 57 shows, this estimate was performed twice, rejecting tracks in between the estimates based on the new position information from the
Good Beam?

Kill bad (large $\chi^2$) or unlinked SSD tracks.

Kill tracks identified as muons.

One or more SSD tracks left?

Yes

Preliminary vertex estimate

VSVXGT preliminary $x,y,z$ vertex estimate (kills some tracks temporarily and some permanently)

Set expected $x,y,z$ errors to 10,10,350 microns.

VSVIMP "box" cuts. Reject tracks if $> 4 \sigma$ of expected error.

VSVXGT again

Pass = 1

$\chi^2$ Vertex fit

VSVIMP again

Main $\chi^2$ fit using vertex estimate from last pass or VSVXGT

Convergence (change in $x,y,z$ from last pass $< 1$ micron) or pass = 5

Yes

Done

No

Pass = Pass + 1

Figure 57: Production vertex fit flow chart.
first estimate. The result was then perturbed upstream by 1 mm in an attempt to "un-bias" the important class of events with decay vertices in close proximity to the primary vertex\(^2\). The resulting vertex position estimate was the initial input into an iterative \(\chi^2\) fit. The \(\chi^2\) fit was repeated until either convergence\(^3\) or five iterations was achieved. Each iteration recalculated the track errors (and hence the track's weight in the fit) and the track's x and y projections at the z of the vertex based on the vertex location estimates of the previous iteration. The x and y projections of a track at the vertex were related to the z of the vertex by:

\[
\begin{align*}
  x_i &= x_{0i} + (dx/dz)_i \times (Z - Z_{REF}) \\
  y_i &= y_{0i} + (dy/dz)_i \times (Z - Z_{REF})
\end{align*}
\]

where:

- \(x_i\) = x of track i at the z of the vertex
- \(y_i\) = y of track i at the z of the vertex
- \(x_{0i}\) = measured x of track i at z = \(Z_{REF}\)
- \(y_{0i}\) = measured y of track i at z = \(Z_{REF}\)
- \((dx/dz)_i\) = measured x slope of track i
- \((dy/dz)_i\) = measured y slope of track i
- \(Z\) = z of the vertex
- \(Z_{REF}\) = reference z for SSD measurements

In addition, vertex location error estimates (1 standard deviation) were calculated each iteration\(^4\) to reject tracks with a "box" cut about the vertex with the VSVIMP (Vertex SSD-Vertex IMpact Parameter) routine. Tracks not passing through a box centered on the vertex location with sides 4 times the size of

\(^2\)Secondary vertices close to the primary tended to blend in with it. This had the effect of pulling the position of the primary downstream towards the secondary. The 1 mm backwards bias tended to suppress the assignment of these secondary tracks to the primary vertex yielding a better primary vertex position estimate and sometimes allowing the location of an otherwise lost secondary vertex. This perturbation did not affect interactions with no secondary vertices; the vertex sprung back to its initial estimate in this class of events, indicating that we did not bias decay lengths.

\(^3\)The X, Y, and Z fit to the vertex were all required to differ from the last iteration by less than 1 micron.

\(^4\)Initially, the errors were taken to be \(\delta x, \delta y = 10\) microns, and \(\delta z = 350\) microns.
these errors in quadrature with the track's error (i.e. 4 standard deviations) were rejected for the next iteration (only).

Figure 58 is the flow chart of the VSVXGT (Vertex SSD Vertex GeT) routine that calculates the intial vertex estimate prior to $\chi^2$ analysis. The input to this routine was a "special" track about which other tracks are clustered to make a vertex. This track was forced into the fit and could not be rejected. For primary vertex fitting, this track was the beam track, which by its nature is associated with the production vertex. This special track was used to reject candidate tracks as coming from the vertex it was associated with. Two estimates of the Z location of the vertex, $Z_X$ and $Z_Y$, were made using the special track and each candidate track. $Z_X$ was calculated by setting the x position of the two tracks equal, then solving for the Z where this occurred. $Z_Y$ was computed in the same manner from the y projection of the track. The quantity $Z_X - Z_Y$ was compared to its expected error to determine if it differed from zero. If it was not consistent with 0 within 3 standard deviations, then the candidate track was permanently rejected from the vertex. If it was not consistent with 0 within 2.5 standard deviations, but was within 3, then it was rejected for the current VSVXGT pass only. This procedure was very-effective in rejecting secondary vertex tracks as well as poorly measured ones from the primary vertex. A Z vertex estimate was made with the weighted sum of the $Z_X$ and $Z_Y$ of the two tracks. If this estimate was greater than 1000 mm upstream of the target, then the candidate track was rejected$^5$. A final Z estimate was made from the weighted $Z_X$ and $Z_Y$ sums of all acceptable tracks. As previously mentioned, 1 mm was subtracted from this value.

Using this Z estimate, weighted X and Y estimates were calculated from only those tracks found acceptable in the Z estimate (i.e. the same set).

This procedure was repeated once more after the "box" cut was performed on tracks. The final X, Y and Z estimate was used as input into the $\chi^2$ fit.

$^5$This rejected spurious vertex estimates made from pairs of tracks with a small opening angle.
Get candidate track

Calculate ZX, ZY estimate from candidate and "special" track

Kill candidate track permanently for this vertex.

Yes

ZX-ZY consistent with 0 within 3 \sigma

No

ZX-ZY consistent with 0 within 2.5 \sigma

Mark as candidate for this estimate.

ZE = weighted sum of ZX and ZY

Yes

ZE < -1000 mm?

No

Use ZX and ZY to accumulate weighted Z estimate.

Decrease Z estimate by 1 mm

X-Y loop

Marked as a candidate?

No

Make weighted sum for X and Y estimates.

Last candidate?

No

Exit with X,Y,Z vertex estimate

Yes

Figure 58: Flow chart of initial vertex finding algorithm: VSVXGT.
The $\chi^2$ was calculated from:

$$
\chi^2 = \sum_i [(x_i - X)^2/\sigma_{ix}^2 + (y_i - Y)^2/\sigma_{iy}^2]
$$

where:
- $x_i =$ $x$ of track i at $z=Z$
- $y_i =$ $y$ of track i at $z=Z$
- $\sigma_{ix} =$ $x$ error estimate for track i at $z=Z$
- $\sigma_{iy} =$ $y$ error estimate for track i at $z=Z$

$(X, Y, Z) =$ vertex position estimate input

The $x$ and $y$ track error estimates here depend on the $X$, $Y$, and $Z$ of the vertex as previously stated. The minimization of (24) presumably yielded better $X$, $Y$, and $Z$ estimates as well as the error estimates: $\delta X$, $\delta Y$, and $\delta Z$. These error estimates were used as input into the "box" track trimmer that was performed every iteration.

A primary nuclear interaction vertex was found in 97% of all events. Figure 59 illustrates the location of primary interactions in vertical emulsion. Included is a blow-up of the distribution in the $z$ direction. These figures are essentially a map of the hadronic interaction length "density" of the material in the beamline. The main emulsion block, analyzing plates, and interaction counter clearly stand out. Analysis of these figures was consistent with the expected vertex error of $\delta Z = 300$ microns. Figure 60 displays the difference between the beam track $x$ and $y$ projections at the vertex and the $x$ and $y$ of the vertex. These plots are biased because the beam track was included in the fit. A better idea of the match up between vertex SSD tracks and the beam track is given by Figure 61. The momentum of the SSD tracks in this figure were greater than 50 GeV/c, and had been associated with the primary vertex. Comparison of these figures illustrates the importance of the beam track in vertex fitting.

The best way to illustrate the ability to locate decay vertices is with a display of a charm pair candidate event. Figure 62 displays the $x$ projection of tracks fit in 3 dimensions for one such event. The fit primary vertex is outlined with a square box whose sides correspond to its expected error. Tracks reconstructed
Figure 59: Primary interaction vertex position distributions in vertical emulsion.
Figure 60: Difference between beam and vertex x and y projections – beam in fit.
Figure 61: Difference between beam and high momentum SSD tracks at the primary z position.
Figure 60: X view of event 2333-4839 in the vertex microstrip detectors.
by the vertex solid state detectors are represented by solid lines in the figure. The dotted lines correspond to tracks located by scanning in the emulsion. A three prong decay vertex outside of the emulsion is outlined by a triangular box. That this is a decay is clearly visible; a charged emulsion track’s dotted projection passes directly through the decay vertex, but the track is not seen in the SSDs. A neutral two prong decay vertex within the emulsion is circled in the figure.

J.2 Semi-muonic decay vertex fitting

The tracks used in reconstructing semi-muonic decay vertices included any hadrons passing the impact parameter and momentum cuts listed in Table 15. Tracks originally assigned to the primary vertex were recycled and could be assigned to a muonic vertex. The “special” tracks used in fitting these vertices were muons with a momentum greater than 8 GeV/c. After this track selection, vertex fitting proceeded along the lines described for primary vertex fitting. An exception was the following: If a vertex fit was not acceptable (in $\chi^2$ and decay length), then candidate tracks were dropped off the candidate list one by one until either an acceptable fit occurred, or the track candidate list was exhausted. This was done to pick up all possible charm candidates; semi-muonic decay vertices could be contaminated with badly measured tracks or tracks from other vertices. An acceptable fit was defined to be: $\chi^2 < 6$, and a decay length $> 2$ mm.

J.3 Other secondary vertices

After looping over all muon tracks to get muonic vertices, an attempt was made to pick up any remaining supposedly non-muonic vertices. Track candidates were tracks not yet associated with any other vertices. Here the “special” tracks were any that had a momentum greater than 1 GeV/c and that were not yet associated with any vertex. Candidate tracks were not dropped on failure and refit as with

---

6Poorly measured primary vertex tracks that were rejected by the primary vertex fit did not generate fake secondary vertices as the ZX-ZY technique was also utilized in secondary fitting.
the semi-muonic muon vertices. A fit was defined to be acceptable if its $\chi^2 < 6$, and its z position $+ 2$ standard deviations in its error was greater than the primary vertex z.
Appendix K

Momentum fitting algorithms

The precise determination of the momentum of the charged decay products from charm and beauty particle decays was necessary to determine the momentum and mass of the decaying particle. A precise determination of mass enabled the identification of the particle species (i.e., D, D*, Λc etc.). The high-resolution tracking of the upstream solid state detectors and downstream spectrometer drift chambers in conjunction with the high field SCM104 analyzing magnet separating them provided this ability.

The thin lens approximation:

$$p = q \int B \times dl / \delta s$$

(25)

where: $B =$ magnetic field strength.

$dl =$ element of path length.

$q =$ charge of the particle trajectory.

$\delta s =$ change in track slope between upstream and downstream measurements.

$p =$ the total momentum of the particle

and $\int B \times dl$ is taken constant.

was used to determine momentum in first and second pass event analysis, in which charm and beauty candidates were selected for emulsion scanning. This method was quick and hence suitable for use on the large volume of triggers recorded by this experiment. The precision of the momentum determined in this manner
was not good enough for the kinematical fitting of the good charm and beauty candidates returned by the emulsion scanners. A slower, more precise momentum fitting method could be used on this reduced set of events. The rest of this section will describe the more precise method used for the kinematic and later stages of E653 analysis.

**K.1 Runge-Kutta momentum fitting program**

A fourth order (fifth in error) Runge-Kutta [55] integration technique was used to numerically "ray trace" particle trajectories through the SCM104 magnetic field (B field) from initial conditions. This method integrated the equations of motion through the magnetic field in fixed length steps in the direction of the particle’s trajectory (i.e. z, the direction of the beam). The initial conditions were varied until the generated path fitted well to the hits in the detector planes left by the particle’s traversal. Since the generated path depended strongly on the initial charge/momentum used, this method resulted in a good momentum estimate. Details of Runge-Kutta integration and the Newton-Raphson iteration technique as applied to particle trajectory fitting in magnetic fields can be found in references [56,57,58].

The Newton-Raphson iteration procedure minimized the \( \chi^2 \) of the residuals between the fit coordinates and those of the up and down stream spectrometer detectors [56,57]. Five \( \chi^2 \) parameters were fit: \( x, y, dx/dz, dy/dz \) – all at the first upstream solid state microstrip detector (SSD), and \( q/p \) (where \( q = \) the sign of the particle’s charge, and \( p = \) momentum of the particle in GeV/c).

The Runge-Kutta integration is comparable in speed and accuracy to its major competitor, the quintic-spline fitting method, but is more straight-forward since the propagated values of the coordinates and slopes for one integration step depend only on their values at the last step [56,59]. It performs an integration from initial conditions as opposed to the quintic-spline method which fits a trajectory, is self starting, and can be used not only to fit trajectories, but also to
ray-trace particles from specific initial conditions. This is not the case for the quintic-spline method; it can only fit a complete trajectory. Five routines were developed for fitting/ray-tracing:

1. MOMINI.FOR – selected options (e.g. fit vs. ray-trace) and convergence criteria (e.g. $\chi^2$ cutoff), and/or read in the survey data for the detectors and set up translations and rotations between local SSD, MAGNET, and spectrometer drift chamber (SDC) coordinates.

2. MOMFIT.FOR – the fitting or ray-tracing routine.

3. MOMRKF.FOR – the workhorse Runge-Kutta integration routine.

4. BREAD.FOR – read in the approximately .6 Megabyte B field grid file.

5. BFIELD.FOR – interpolated the B fields from the grid.

In addition, the following three auxiliary files were needed:

1. MOMSET.TXT – include file.

2. MOMFLD.TXT – include file.

3. ICNFLD.DAT – the binary integer B field grid file.

All routines were self-documented as to arguments etc.

K.2 Experimental coordinates and weights

Experimental coordinates and inverse covariances (weights) were passed to MOMFIT via the hit and weight arrays:

$$XUP(25) \ WUP(25,25) \text{ for upstream SSDs}$$

$$XDN(15) \ WDN(15,15) \text{ for the downstream SDCs}$$
The dimensions of these arrays were inflated to allow for future expansion of the detectors. The coordinates passed via these arrays were offset corrected X,U, and V coordinate detector hits. They were compared to the fitted (propagated) x and y coordinates — $x_{\text{fit}}$, $y_{\text{fit}}$ — as follows:

$$u_{\text{fit}} = x_{\text{fit}} \times \cos(\theta) + y_{\text{fit}} \times \sin(\theta)$$

where $u_{\text{fit}}$ is the fitted coordinate for the specified plane, and $\theta$ is the rotation angle of the plane as determined by survey. For the spectrometer drift chambers, only one measurement per chamber — fitted over the five wires — was used; the weight for these chambers corresponded to the fit over the five wires. To turn off a chamber or SSD with respect to the fitting, the weight for that chamber or SSD was set equal to zero.

**K.3 Fitting technique and approximations used**

For minimizing the $\chi^2$, the coordinates and slopes were taken to be linear in the $\chi^2$ parameters (only for error matrix determination, not for integration):

$$x_{\text{fit}} = x_0 + \left(\frac{dx}{dz}\right) \times (z - z_0) + \left(\frac{q}{p}\right) \times XX(z)$$

$$y_{\text{fit}} = y_0 + \left(\frac{dy}{dz}\right) \times (z - z_0) + \left(\frac{q}{p}\right) \times YY(z)$$

where:

- $q/p$ = charge/momentum (GeV/c$^{-1}$)
- $dx/dz$ = the measured x track projection slope.
- $dy/dz$ = the measured y track projection slope.
- $x_0$ = the x position at the first SSD plane.
- $y_0$ = the y position at the first SSD plane.
- $z_0$ = the z position of the first SSD plane.

The variables: $q/p, dx/dz, dy/dz, x_0, y_0$ are the $\chi^2$ parameters used in fitting the track. The (unknown) functions $XX$ and $YY$ are taken to depend on the $z$ coordinate only (dependence on all $\chi^2$ parameters — in particular $q/p$ and track
slopes – was ignored). These functions represent all magnetic field bending information. This approximation was good for large momentum, but broke down (i.e. converged more slowly) at lower momentum.

Figure 63 describes the flow of the fitting procedure. The Newton-Raphson technique was used to reduce the $\chi^2$:

$$\chi^2 = \sum_j \sum_i (u_i - f_i)(u_j - f_j)/\sigma_{ij}^2 \quad (29)$$

where: $u_i = \text{measured coordinate for plane } i$

$f_i = \text{ray traced (fit) coordinate for plane } i$

$\sigma_{ij}^2 = \text{covariance between planes } i \text{ and } j$

In this method, perturbations to the $\chi^2$ parameters that will reduce the $\chi^2$ are determined from the minimization requirements:

$$[\partial\chi^2/\partial\xi_i]_{\text{next}} = [\partial\chi^2/\partial\xi_i + \sum_j (\partial^2\chi^2/\partial\xi_i\partial\xi_j) \times \delta\xi_j + \ldots]_{\text{cur}} = 0 \quad (30)$$

where: $\delta\xi_j = \text{the perturbation to add to the } \chi^2 \text{ parameter } \xi_j$

$\partial\chi^2/\partial\xi_i = \text{the (partial) rate of change of the } \chi^2 \text{ with respect to the } \chi^2 \text{ parameter } \xi_i$

$\partial^2\chi^2/\partial\xi_i\partial\xi_j = \text{the "weight" matrix}$

and cur denotes values of the current iteration

next denotes requirements for the next iteration

All dependence on the $\chi^2$ parameters $\xi_i$ is contained in the fit coordinates $f_i$ through equations 27,28 and 26. Inverting the above equation yields the desired $\chi^2$ perturbation:

$$\xi_j = \sum_i V_{ji} \times \partial\chi^2/\partial\xi_i \quad (31)$$

where: $V_{ji} = [\partial^2\chi^2/\partial\xi_i\partial\xi_j]^{-1}$

= the inverse of the weight matrix – the "error" matrix

These perturbations were then added to the $\chi^2$ parameters (which are also ray-tracing initial conditions), and a new ray trace – fit cycle was made. These
Ray-traced through the entire magnetic field and all detector planes?

- No
- Yes

Calculate residuals between the physical track and ray-traced track. Generate "weight" matrix for later use.

- No
- Yes

Initial values and chi-square parameters from thin-lens approximation

Ray-trace (one Runge-Kutta step) the particle track through the magnetic field in the SCM104 magnet and detectors

Figure 63: Momentum fitting program flow.
steps were repeated until signs of acceptable convergence or no convergence at all were detected.

The Runge-Kutta method required the B fields to be determined at three points for each integration step along the particle trajectory. The third B field calculation for a step was approximately equal to the first for the next step. This near equivalence was used so that only two of the time consuming B field calculations were performed per step (except for the first step, which required three calculations). Both methods were tested, and no significant differences in results were detected (except for the difference in execution times of course).

K.4 Convergence criteria for the fit

After each Runge-Kutta integration iteration, the values of the $\chi^2$ parameters that would lower the $\chi^2$ for the next iteration were determined as described above. In addition, an estimate of the $\chi^2$ for the next iteration was calculated. This $\chi^2$ estimate ($\chi^2_{nxt}$) was found to be accurate only if the current $\chi^2$ ($\chi^2_{cur}$) was less than 10. Using $\chi^2_{nxt}$ for a convergence criterion allowed a reduction of one in the number of iterations to be performed. Iterations stopped if the logical “or” of the following conditions was satisfied:

- $\chi^2_{nxt}$ less than $\chi^2_{cut}$ ($\chi^2_{cut}$ default = 2) and $\chi^2_{cur}$ less than 10.
- $|\chi^2_{nxt} - \chi^2_{cur}| / (\chi^2_{cur} + 1)$ less than $\chi^2_{stable}$ (the $\chi^2_{stable}$ default was 0.01). This was a so called “stable-solution” which occurred for $\chi^2 > 2$ if too coarse of a step size was used. This condition was avoided as far as possible.
- The maximum number of iterations MAXITR was reached (the MAXITR default was 6).

$\chi^2_{cut}$, $\chi^2_{stable}$, and MAXITR had the default values mentioned, but could be re-defined with a MOMINI subroutine call. Fit detector coordinates were returned from MOMFIT, but because of the $\chi^2_{nxt}$ cutoff, the fit coordinates returned were from the next to last iteration (the last never being performed). An option in
MOMINI existed that forced one more iteration to get fit coordinates for that iteration, but it was only used if coordinate fits were important as it took more time. Monte Carlo tests showed that the above convergence criteria yielded fits identical to those with one additional iteration (i.e. the additional iteration made no significant changes to the $\chi^2$ parameters, and the average $\chi^2$ remained at 1.). The Monte Carlo fits took about 1–2 iteration from 10–800 GeV/c, 2–3 around 5 GeV/c, and 3–4 around 1 GeV/c. This simple Monte Carlo ignored multiple scattering, and did not include any fringe magnetic fields in the detectors themselves. Therefore, the above iteration counts do not hold for real data at lower momentum.

K.5 Execution time optimizations

Two problems arose when using uniform steps along the $z$-axis in the low momentum regime:

1. The number of iterations was rather large for tracks below approximately 2 GeV/c when the error matrix was only calculated and inverted on the first iteration. At low momentum, a small change in the $\chi^2$ parameters varied the trajectory by a large amount. It was therefore not surprising that the first iteration approximation to the error matrix was not good.

2. For lower momentum and larger step sizes, the $\chi^2$ tended to stabilize at large values; the larger the step, the greater the tendency to stabilize. This was most likely due to the fact that the errors in track propagation were on the order of the detector measurement errors for low momentum and large step sizes.

To counteract these problems, an automatic mode was implemented. In this mode:

1. A fixed step size of 200 mm was used since at above 250–300 mm steps, stable high $\chi^2$ solutions started to appear at lower momentum. This step
size corresponded to approximately 7 Runge-Kutta steps through the magnet. This was equivalent to 14 quintic spline steps since the Runge-Kutta integration evaluates the magnetic fields at the middle of a step as well as at the ends.

2. For momentum greater than 2 GeV/c, the error matrix was calculated and inverted only on the first iteration, but was used for all iterations. Below 2 GeV/c, the error matrix was calculated and inverted for every iteration. This actually took less time on the low momentum tracks since fewer iterations were performed due to faster convergence.

The automatic mode was always used to fit tracks; the manual uniform step mode, was used only for optimization tests.
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