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A search for excited electrons in electron-proton collisions at HERA

Siedlein, Rupert V., Ph.D.
The Ohio State University, 1994
A SEARCH FOR EXCITED ELECTRONS IN ELECTRON-PROTON COLLISIONS AT HERA

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

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* * * * *

The Ohio State University

1994

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ACKNOWLEDGEMENTS

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CHAPTER I

Compositeness of $e^-$

The discovery of substructure in the electron would be a very important milestone in the development of modern physics. In analogy with systems of substructure spanning from molecular to atomic then hadronic classifications, one hopes to explain the well-ordered pattern of the fermionic spectrum with its three generations by a new layer of matter whose scale describes the dynamics of the excited particles. Compositeness can be invoked as a possible alternative to the conventional Standard Model description of electroweak symmetry breaking.

The existence of excited states would be the most unambiguous and characteristic signal for substructure in the fermionic sector. Indeed, if the known quarks and leptons are composite, they should be regarded as the ground state to a rich spectrum of excited states [1] [2]. The search for excited charged electrons has been systematically pursued for more than a quarter of a century now but has not met with any success so far [3] [4] [5]. This situation is not in conflict with the motivations behind the introduction of excited particles. Although the standard model correlates a large amount of experimental data, it is suspected that a threshold for new physics could be reached at the 1 TeV scale.

The production of spin-$\frac{1}{2}$ excited fermions can be studied assuming Magnetic
transitions between excited (*F*) and ordinary fermions (*f*). The transitions from \( f \rightarrow F \) were mediated by the gauge bosons \( \gamma, Z \) and \( W \). Such models for the production of excited leptons have been proposed in the framework of an effective Lagrangian [6] [7].

\[
\mathcal{L}_{\text{eff}} = \sum_{V=\gamma,Z,W} \frac{e}{\Lambda} \sigma^{\mu\nu} \bar{F}(c_{VF} - d_{VF} \gamma_5)f_{J} \partial_{\mu} V_{\nu} + \text{h.c.} \quad (1.1)
\]

where \( F \) and \( f \) denote the excited and ordinary fermions and \( V \) is the gauge boson to which the \( f \) and \( F \) couple. A model describing this new class of interactions between a standard lepton and its excited partner has to introduce two new types of parameters [6]. One is the compositeness scale \( \Lambda \), which describes the strength of the binding of the new constituent particles. The other is the new coupling strength between the standard leptons, the excited leptons and the gauge bosons. The magnetic nature of the interaction is expressed in terms of the tensor \( \sigma^{\mu\nu} \).

\[
\sigma^{\mu\nu} = \frac{i}{2}(\gamma^{\mu}\gamma^{\nu} - \gamma^{\nu}\gamma^{\mu}) \quad (1.2)
\]

Because of the \( \partial_{\mu} V_{\nu} \) structure the Lagrangian is not renormalizable and can only serve for first order calculations.

The couplings \( c_{VF} \) and \( d_{VF} \) of this phenomenological interaction Lagrangian are constrained by \( g - 2 \) experiments through high precision measurements of the magnetic moment and by the absence of electric dipole moments for electrons.

In this analysis the doublet model for the production of \( e^* \)'s was chosen [6]. In this particular model the excited fermions have spin and isospin 1/2. So both their
left-handed and right-handed components form weak isodoublets. For instance, in the case of the first generation leptons, one has:

\[ l_L = (\nu_e e)_L \quad e_R \]

\[ L_L = (\nu^*_e e^*)_L \quad L_R = (\nu^*_e e^*)_R \]

The Lagrangian describing the transition between excited fermions and ordinary fermions should respect chiral symmetry in order to protect the light leptons from acquiring a large anomalous magnetic moment which is ruled out by experiment [8]. This means that only the right-handed part of the excited fermions takes part in the generalized magnetic deexcitation. The latter is described in an SU(2)xU(1) invariant form by the following effective Lagrangian which can be derived from (1.1) under the above assumptions.

\[ L_{ff^*} = \frac{1}{2\Lambda} \overline{e} \sigma^{\mu\nu} [g f \frac{\tau}{2} W_{\mu\nu} + g' f' Y B_{\mu\nu}] f_L + h.c. \quad (1.3) \]

where \( g \) and \( g' \) are the usual weak coupling constants: \( g = \frac{e_0}{s_w} \) and \( g' = \frac{e_0}{c_w} \), where \( e_0 \) is the electron charge and \( s_w^2 = 1 - c_w^2 = \sin^2 \theta_W \approx 0.23 \). The factors \( f \) and \( f' \) are associated with the two gauge groups and can be interpreted as parametrizing different scales \( \frac{A_f}{f} \) and \( \frac{A_{f'}}{f'} \) for the two groups SU(2) and U(1) and the field tensors are given by

\[ W_{\mu\nu} = \partial_\mu W_\nu \quad (1.4) \]

\[ B_{\mu\nu} = \partial_\mu B_\nu \quad (1.5) \]
Then the couplings can be written in terms of $f$ and $f'$ as:

\begin{align}
    c_{\tau e^* e} &= \frac{-1}{4} (f + f') \\
    c_{Z e^* e} &= \frac{-1}{4} (f \cot \theta_W + f' \tan \theta_W) \\
    c_{W^+ e^* \nu} &= \frac{f}{2 \sqrt{2} \sin \theta_W} \\
    c_{W^- e^* \nu} &= \frac{-1}{4} (f - f') \\
    c_{Z \nu^* \nu} &= \frac{-1}{4} (f \cot \theta_W - f' \tan \theta_W) \\
    c_{W^+ \nu^* e} &= \frac{f}{2 \sqrt{2} \sin \theta_W}
\end{align}

Based on this Lagrangian the differential production cross section for $e p \rightarrow e^* X$ or $e p \rightarrow \nu^* X$ can be calculated. In this analysis though only the production of $e^*$'s is pursued. To calculate the production cross section of $e^*$ requires to model the proton with which the electron collides and which supplies the energy to produce massive $e^*$'s at HERA (also see section 5.2). The differential cross section for the production of $e^*$'s via photon exchange is then

\begin{equation}
\frac{d^2\sigma}{dW^2 dQ^2} = \pi \alpha^2 \left(\frac{f + f'}{\Lambda}\right)^2 K(M^*, Q^2, W^2)
\end{equation}

where $\alpha$ is the fine structure constant (here set at $1/128$), and $K$ is a function of $Q^2$ and $W^2$, which determine the kinematics of the process and contains the information about the structure of the proton.

### 1.1 Decay modes

The excited electron could decay into light leptons and gauge bosons

\begin{equation}
    e^* \rightarrow e \gamma, e Z, \nu W
\end{equation}
For $e^*$ masses below the $Z$ and $W$ mass its decay into final states has to occur either via the photon or via \textit{virtual} heavy gauge bosons. Due to the limited center of mass energy in previous direct searches for $e^*$'s, experiments have only been sensitive to $e^*$'s decaying into $e\gamma$. HERA does provide sufficient center of mass energy to extend the search region up to masses close to 300 GeV and look for decays via the $Z$ and $W$ for the first time directly.

The ratio of $f$ and $f'$ determines the widths $\Gamma(e^* \rightarrow lV)$ of the $e^*$ decay. The branching ratio into a particular mode can be calculated from

$$B(e^* \rightarrow lV) = \frac{\Gamma(e^* \rightarrow lV)}{\Gamma(\text{total})} \quad (1.13)$$

where the $\Gamma(\text{total})$ is the sum of all three widths.

The decay width of the $e^*$ is then given by [7]

$$\Gamma(e^* \rightarrow lV) = \frac{\alpha M^3}{4 \Lambda^2} 4 c_{V_{e\ell l}}^2 (1 - \frac{m_V^2}{M^2})^2 (1 + \frac{m_V^2}{2M^2}) \quad (1.14)$$

where $M_{e^*}$ is the mass of the $e^*$ and $m_V$ is the mass of the gauge boson indicated by $V = \gamma, Z, W$. The standard lepton into which the $e^*$ decays into is indicated by $l$.

The coupling parameters $c_{V_{e\ell l}}$ are given in equations 1.6-1.10.

Setting $f$ equal to $f'$ simplifies the expression for the partial cross section considerably. It fixes the branching ratio of the $e^*$ decay modes and only the mass of the $e^*$ is left as a free parameter. Figure 1.2 shows the branching ratios under this assumption. Under this assumption ($f = f'$) the excited fermions have very narrow widths up to large values of $M_{e^*}$. For masses above 200 GeV, the branching ratios become practically constant (see also figure 1.2). Table 1.1 lists the decay widths
Table 1.1: The total widths of the excited electron and their branching ratios (in %), for 100 and 200 GeV $e^*$'s and $\Lambda/f = 1$ TeV with $f = f'$

<table>
<thead>
<tr>
<th>$M_{e^*}$ (GeV)</th>
<th>$e^* \rightarrow e\gamma$</th>
<th>$e^* \rightarrow eZ$</th>
<th>$e^* \rightarrow \nu W$</th>
<th>$\Gamma_{\text{total}}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>72</td>
<td>1.2</td>
<td>26.8</td>
<td>2 \cdot 10^{-3}</td>
</tr>
<tr>
<td>200</td>
<td>34</td>
<td>10</td>
<td>56</td>
<td>4.6 \cdot 10^{-2}</td>
</tr>
</tbody>
</table>

for several $e^*$ masses. The decay tracks of $e^*$'s are therefore too short to be resolved experimentally.

In this analysis though the ratio of $f$ and $f'$ is not determined apriori and the limit on the coupling multiplied by the branching ratio is set as discussed in chapter 9.

With $\sigma_{IV} = \sigma_{\text{tot}} \frac{\Gamma(e^* \rightarrow IV)}{\Gamma(\text{total})}$ the partial cross section for one of the final states is then

$$\sigma_{IV} = B_{IV} \frac{|f + f'|^2}{4\Lambda^2} \pi \alpha^2 \sigma_0(M_*)$$

(1.15)

where $B_{IV} = B(e^* \rightarrow IV)$ and $\sigma_0(M_*)$ is the phase space integral over $K(M_*, Q^2, W^2)$. It should be noted that $B_{IV}$ is a function of $M_*$ and $f$ and $f'$. Figure 1.1 shows the total integrated cross section as a function of $M_*$ with the assumption of $f/\Lambda = 1$ TeV.

The angular distribution of the $e^*$ (spin 1/2) decay in its center of mass frame into a spin 1 and spin 1/2 particle is given by

$$\frac{d\Gamma}{dcos\theta} \sim 1 + cos(\theta)$$

(1.16)
where $\theta$ is the angle between the incoming and outgoing lepton. For $e^*$ masses above the energy of the incoming electron the $e^*$ moves in the direction of the incoming proton. The relativistic boost from the $e^*$ frame to the lab frame folds the angles of the boson as well as the lepton in the proton direction. The decay products, the boson and the lepton are being projected more towards the forward direction with increasing $M_e$.

1.2 Current limits

Currently the most stringent limits on the masses and couplings of $e^*$'s come from LEP100 data [4]. Direct searches for $e^*$'s can be performed at LEP in the $s$- and $t$-channel by looking for the reactions

$$e^+e^- \rightarrow Z \rightarrow e^*e^* \quad (1.17)$$

$$e^+e^- \rightarrow Z \rightarrow e^*e^- \quad (1.18)$$

Searches performed at all four experiments rule out $e^*$'s below the $M_Z/2$ mass using pair production. For masses above $M_Z/2$ the limit on the coupling depends on the mass of the $e^*$. The LEP limits become weaker with increasing $M_e$ and stop at the $M_e = M_Z$ and a coupling $\frac{\sqrt{A(t)+B}}{\Lambda} \sim 10^{-2}$ (GeV$^{-2}$). Figure 1.3 shows the current upper limits on the coupling as function of $e^*$ mass from LEP experiments.

$e^*$'s can also be directly produced in the $t$-channel reaction $e^+e^- \rightarrow e^*e^-$ or $e^+e^*$, in which one of the final state electrons escapes detection due to the $1/t$ behaviour of the cross section. In this search mode limits on the coupling for $e^* \rightarrow e\gamma$ were pushed
as low as $\frac{\sqrt{2}(f+f')}{\Lambda} = 3 \cdot 10^{-4}$ for masses close to the $Z$ mass. Feynman diagrams for the production of $e^*$ at LEP are shown in figure 1.4.

Since QED processes can be predicted with great accuracy, small deviations from standard physics arising from new phenomena can be detected in such processes. Furthermore limits derived from such calculations can go beyond the kinematic limit of single (or double) $e^*$ production in the direct mode, i.e. where the decay products of the $e^*$ can be observed directly.

In the indirect search mode one can extract limits on the $e^*$ mass-coupling parameters by looking for deviations of angular distributions from QED predictions in the process $e^+e^- \rightarrow \gamma\gamma$ where a $e^*$ would be exchanged in the $t$-channel [5]. Limits derived with this method are weaker though and only exclude the region for $\frac{\sqrt{2}(f+f')}{\Lambda}$ above $10^{-2}$, but the mass range of the $e^*$ can be extended up to 116 GeV. Figure 1.4 shows the limit on the coupling of $e^*$ as a function of mass from such considerations. The limit given in figure 1.5 can be converted to the more widely used (Hagiwara) limit by the conversion: $\lambda/m^* = \sqrt{2}c_{\gamma e^*e}/4\Lambda$.

Indirect limits can also be extracted from the $Z$ line shape [5]. Because of the high precision measurement of the $Z$ width at LEP, the total allowed width due to non-standard channels restricts the $e^*$ mass to be greater than 26 GeV, but it insensitive to masses above $M_Z/2$. The resolution of the $Z$ width accommodating the existence of new physics is becoming very small with the large data samples from recent LEP runs.

In nonaccelerator experiments limits on the coupling and mass of $e^*$ can be set
by considering the contribution of the excited fermion to the anomalous magnetic moment and the dipole moment of the electron [8]. High precision measurements of $g-2$ therefore constrain not only the chiral form of the model, but can also set bounds on the coupling-mass parameter space. Unfortunately present limit calculations have been made using different models for the production and decay of $e^*$ and are therefore difficult to compare. Present bounds on $\frac{\sqrt{2}(\ell+\ell')}{\Lambda^2} \leq O(10^{-3})$ give only an order of magnitude estimate. It also should be noted that bounds derived from virtual effects are quite sensitive to model dependent assumptions.

Also limits on the coupling and mass of $e^*$'s can be set from $\nu_\mu e \rightarrow \nu_\mu e$ reactions [9]. Again those limits are model dependent using one loop corrections to the Weinberg angle due to excited electrons (and muons). They go as high as 600 GeV with a cutoff scale for the loop calculations of 1 TEV.
Figure 1.1: Integrated cross section in pb GeV$^2$ of the $e^*$ as function of its mass without the coupling constant, i.e. for $\Lambda = 10^3$ GeV$^2$ and $f = f'$ the left scale would have to be multiplied by $10^{-6}$ GeV$^{-2}$. 
Figure 1.2: Branching ratios for $e^* \rightarrow e\gamma, eZ, \nu W$ as a function of the mass of the $e^*$. In this figure $f$ was set equal to $f'$ and $\Lambda/f$ was set to 1 TeV.
Figure 1.3: Current limits on the coupling constants of $e^+$'s as a function of mass from direct searches at LEP experiments [15]. The lines labeled with $ee\gamma$ are for $s$-channel production of $e^+$ and the lines labeled with $e(e)\gamma$ are the $t$-channel modes, where one of the electrons escapes through the beam pipe. The coupling $\lambda/m^*$ corresponds to $\sqrt{2}c_{ee\gamma}/\Lambda$. 
Figure 1.4: Current limits on the coupling constants of $e^*$'s as a function of mass from indirect processes [15]. In the channel $e^+e^- \rightarrow \gamma\gamma$ predictions from QED are compared to variations of the angular distributions due to $e^*$'s. The coupling $\lambda/m^*$ corresponds to $\sqrt{2}c_{ee^*}\gamma/\Lambda$. The $\lambda = 1$ curve is considered as an upper limit of the validity of the model. The intersection point is at 114 GeV, yielding the highest mass limit from LEP results.
In a search for new phenomena all the known processes in an experiment are considered to be background. In order to give the reader a better understanding of the two main sources of background in this study, Neutral and Charged Current Deep Inelastic Scattering (NC and CC DIS), the physics of $ep$ scattering will be shortly introduced in this chapter. It also should be kept in mind that the investigation of NC and CC DIS events was the main motivation for the construction of the HERA collider.

The physics of $ep$ scattering has been studied rather thoroughly over the last 40 years and many aspects of these interactions are well understood [10] [11]. It shaped our understanding of some of the most fundamental processes in subatomic physics and what has currently come to be known as the Standard Model. In the following sections I want to give a short overview of the known processes associated with $ep$ interactions.

By scattering electrons off nuclei one is able to probe the structure of the nuclei and the forces acting between nuclei and leptons. By increasing the energy of the leptons impinging on the target one is able to resolve the structure of the proton or neutron in more detail [12]. So far all lepton-hadron experiments have been fixed-
target experiments, i.e. a fixed target of hydrogen, iron or some other material was used and the protons and neutrons in it were essentially at rest [13]. Electrons and neutrinos have been used as probes, where the latter can interact only through the weak force. The measure for the resolving power or wavelength of the experiment is the quantity $Q^2$, where $Q$ is the four momentum of the “light” used to “see” into the nucleus (wavelength of the probe: $\lambda \sim 1/\sqrt{Q^2}$). At high enough energies and resolving power the constituents of the proton itself became visible. These partons were identified with quarks, which are the basic constituents of all matter and are bound together by gluons. The proton is currently understood to consist of three quarks (known as valence quarks, in this case $u$ and $d$ quarks) and a continuum of gluons, which can create more quark-antiquark pairs (sea quarks) of any of the six flavors ($u, d, c, s, (t), b$) [14].

2.1 Basic types of $ep$ interactions

When the vituality ($Q^2$) of the exchanged boson is high enough ($\sim 1$ GeV) to break up the proton then those interactions are called Deep Inelastic Scattering events (DIS). In the case where the exchange boson is a $\gamma$ or a $Z$ (Neutral Current DIS) the outgoing lepton is also an electron. Due to the large $Q^2$ value of the interaction it is then scattered into the detector. If the exchanged particle is a $W$ then the outgoing lepton changes into a neutrino which can not be detected, causing the event to be observed with net transverse momentum.

On the other hand at low enough values of $Q^2$ the exchanged photon is quasi-
real and \( ep \) collisions can be used to study all of photon-proton interactions, e.g. the structure of the photon with partons [15]. This branch of \( ep \) interactions is called photoproduction (\( \gamma p \)) physics. HERA is currently one of the best laboratories to investigate \( \gamma p \) interaction at a photon-proton center of mass energy of several hundred GeV's.

The total \( \gamma p \) cross section can be divided into an elastic, a diffractive and a non-diffractive part. In both elastic and diffractive \( \gamma p \) processes the photon couples to a vector meson (VMD: \( \rho, \omega, \phi \)) before scraping off the proton. In the elastic case the proton stays intact, whereas in the diffractive case the proton can turn into another baryon. The non-diffractive part of the \( \gamma p \) cross section on the other hand consists of VMD interactions and processes in which either all or some partonic constituent of the \( \gamma \) (direct and resolved processes) interact with the gluons and quarks of the proton.

Results from HERA confirm that the photon can act like a hadron (vector meson) and dijets from direct and resolved \( \gamma p \) processes were observed for the first time [16].

2.2 Kinematics of Deep Inelastic Scattering

To understand HERA physics one must understand the kinematics of \( ep \) scattering shown in figure 2.1. This figure gives the lowest-order diagram of the lepton-proton interaction. This corresponds to the simple parton model, in which the lepton interacts directly with one of the partons.

Here the incoming electron has momentum \( p_e \) and the scattered lepton, an electron in the case of Neutral Current interactions (NC) and a neutrino in the case of Charged
of the gauge bosons, the $W$ in the case of a CC interaction and either a $Z$ or a $\gamma$ in the case of a NC interaction. The initial hadron can either stay intact (elastic scattering) - small energy transfer - or fragment into new particles (inelastic scattering). The sum of all outgoing momenta on the hadronic side is denoted by $W$.

The four-vectors are given by:

$$p_e = (p_e, E_e) \quad p_e' = (p'_e, E'_e) \quad (2.1)$$

(throughout this paper we will use the metric $(1,1,1,-1)$). Then $q$ is defined as

$$q = p_e - p_e' \quad Q^2 = -q^2 \quad (2.2)$$

and the final hadronic state as

$$W = q + P$$

$Q^2$ is positive definite and runs between 0 and $s$. For sufficiently large $Q^2$ ($O(1 \text{ GeV}^2)$) the interaction becomes an electron-quark or electron-gluon interaction.

The center of mass energy $\sqrt{s}$ is given by

$$s = (p_e + P)^2 \sim 4E_eE_p \quad (2.3)$$

neglecting proton and electron masses (a safe assumption for the following analysis).

The Lorentz invariant kinematic variables (Bjorken variables) $x$ is defined as

$$x = \frac{Q^2}{2P \cdot q} \quad (2.4)$$

where $x$ is a measure of how much momentum the struck quark carries or the inelasticity of the event, i.e. at $x=1$ the event is elastic. In the proton restframe $x$ becomes
\( \frac{Q^2}{M_{p\nu}} \) where \( M_p \) is the mass of the proton and \( \nu \) the energy transfer \( E_e - E'_e \). The other Bjorken variable is \( y \) which is defined as

\[
y = \frac{P \cdot q}{P \cdot p_e} \quad (2.5)
\]

where \( y \) is a measure of the energy transfer in the proton restframe. In the proton restframe \( y \) becomes \( \frac{\nu}{E_e} \). The variables \( x, y \) and \( Q^2 \) are related by

\[
Q^2 = xys \quad (2.6)
\]

Any two of the three variables \( Q^2, x \) and \( y \) describe the kinematics of an inelastic event entirely. The invariant mass of the final hadronic system is given by

\[
W^2 = (P + q)^2 = Q^2 \frac{1 - x}{x} + M_p^2 \quad (2.7)
\]

\( W^2 \) and \( x \) are measures of the elasticity of the event, with \( x = 1 \) or \( W^2 = M_p^2 \) for a completely elastic event.

The simple parton model does not take into account the strong interactions of the quarks and gluons. In this approximation

\[
q + xP = F = p_{had}
\]

where \( F \) is the momentum of the struck quark and \( p_{had} \) is then the hadronic energy flow.

Table 2.1 shows how the kinematic range accessible at HERA compares to previous lepton-nucleon fixed-target experiments. Since less momentum has to be carried away by the center of mass of the system the maximum energy transfer is increased
Table 2.1: Kinematic region accessible at HERA

<table>
<thead>
<tr>
<th>Kinematic Variable</th>
<th>HERA</th>
<th>Pre HERA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s$ (GeV$^2$)</td>
<td>$10^5$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>$Q_{\text{max}}^2$ (GeV$^2$)</td>
<td>$8 \cdot 10^4$</td>
<td>400</td>
</tr>
<tr>
<td>resolution $\Delta$ (cm$^{-1}$)</td>
<td>$10^{-16}$</td>
<td>$10^{-15}$</td>
</tr>
<tr>
<td>$\nu_{\text{max}}$ (GeV)</td>
<td>$5.2 \cdot 10^6$</td>
<td>500</td>
</tr>
<tr>
<td>$x_{\text{min}}$ at $Q^2 = 10$ GeV$^2$</td>
<td>$10^{-4}$</td>
<td>$10^{-2}$</td>
</tr>
</tbody>
</table>

by two orders of magnitude. HERA is kinematically equivalent to a fixed-target experiment with an incident electron beam of 52 TeV. The $Q^2$ domain over which the $ep$ interaction can be measured is increased by two orders of magnitude.

2.3 Reconstruction of the kinematic variables

The key kinematic variables in $ep$ collisions ($x,y$ and $Q^2$) can be calculated from the measurement of the current jet and the scattered lepton in various ways [17]. The measurable quantities of the final state used to calculate the event kinematics ($x,y$ and $Q^2$) are shown in table 2.2.

Any two variables of the final state system ($E_e', \theta_e, E_{\text{had}}, \theta_{\text{had}}$) suffices to calculate the event kinematics. The coordinate system for $ep$ collisions is given in figure 2.3.

In the case where there is a final state electron one can use the angle and energy of the scattered electron to determine $x$, $y$ and $Q^2$ ("electron method").

$$Q_{el}^2 = 2E_e'E_e'(1 + \cos \theta) \quad (2.8)$$
Table 2.2: Measured kinematic quantities

<table>
<thead>
<tr>
<th>Kinematic Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_e'$</td>
<td>Energy of the final electron</td>
</tr>
<tr>
<td>$\theta_e$</td>
<td>Polar angle of the final electron</td>
</tr>
<tr>
<td>$E_{had}$</td>
<td>Energy of current jet(s))</td>
</tr>
<tr>
<td>$\theta_{had}$</td>
<td>Angle of current jet(s))</td>
</tr>
<tr>
<td>$E_i$</td>
<td>Energy of the initial electron</td>
</tr>
<tr>
<td>$E_p$</td>
<td>Energy of the initial proton</td>
</tr>
</tbody>
</table>

$\frac{x_{el}}{y_{el}} = \frac{E_e}{E_p} \frac{E_e' (1 + \cos \theta)}{2E_e - E_e' (1 - \cos \theta)}$ (2.9)

$y_{el} = 1 - \frac{E_e}{2E_e'} (1 - \cos \theta)$ (2.10)

The beam pipe removes a small fraction of the fiducial volume of the detector in the very forward ($\theta \leq 2.2^\circ$) and the rear direction ($\theta \geq 176.5^\circ$). The requirement of measuring the electron in the main detector is equivalent to a lower cut-off of the $Q^2$ region at $\sim 4 \text{ GeV}^2$. Therefore the region for Deep Inelastic Scattering (DIS) events at ZEUS extends from $Q^2 \geq 4 \text{ GeV}^2$ upward.

Figure 2.4 shows the contours of the measurable quantities in $x - Q^2$ space. It can be seen that the electron method is a precise estimator of the $Q^2$ variable in the high $Q^2$ region, where the energy and angle contours are very densely spaced. In the low $Q^2$ region, where the electron is scattered by a small angle and changes its energy by only a small amount ($\pm \sim 3 \text{ GeV}$), the estimation of $Q^2$ and in particular $x$ from the electron variables is poor. On the other hand combining the information of the angle of the electron and the current jet allows one to calculate the $x$ and $Q^2$ in this region.
It is also possible to calculate the kinematic quantities from the hadronic energy-flow alone [18]. In the case of NC events this provides redundancy and allows for systematic checks of the reconstructed variables. In the case of CC interactions though, where the neutrino escapes the detector, the measurement of the hadronic energy-flow is the only route to calculate the variables. Due to the undetected neutrino CC events have the signature of missing transverse momentum. Since the energy-flow along the beampipe can not be measured one has to rely on the transverse part of the overall momentum balance to reconstruct the kinematic variables of the event.

A method due to Jacquet-Blondel [19] calculates the kinematics of the event from the hadronic energy flow alone. It does not require the use of a jet algorithm as long as the transverse momentum of the dijet (proton remnant) can be neglected. The Jaquet-Blondel variables can then be derived from energy and momentum conservation.

\[
y_{JB} = \frac{\sum_i (E_i - p_{zi})}{2E_e} \tag{2.11}
\]

\[
Q_{JB}^2 = \frac{((\sum_i p_{zi})^2 + (\sum_i p_{zi})^2)}{1 - y_{JB}} \tag{2.12}
\]

\[
x_{JB} = \frac{Q^2}{s \cdot y_{JB}} \tag{2.13}
\]

where the sums run over all observed final hadronic states. Since in CC DIS events all visible energy is coming from the hadronic side, it is straightforward to sum over the final state hadrons.

For NC DIS events it suffices to subtract the energy of the electron out of the total sum over the calorimeter cells. This technique is most useful for good resolution.
in the kinematic region of \(0.01 \leq x \leq 0.05\), \(Q^2 \geq 100 \text{ GeV}^2\) and \(y \leq 0.03\) [21]. The Jaquet-Blondel method is particularly well suited to reconstruct the \(y\) variable.

Taking advantage of regions of validity for both methods, one can define the mixed method:

\[
y_{\text{mix}} = y_{\text{JB}} \quad (2.14)
\]

\[
Q_{\text{mix}}^2 = Q_{\text{el}}^2 \quad (2.15)
\]

\[
x_{\text{mix}} = \frac{Q_{\text{JB}}^2}{s \cdot y_{\text{JB}}} \quad (2.16)
\]

In the discussion of the DIS NC and CC events as background for the exotics search only the \(y_{\text{JB}}\) was used.

A third method of reconstructing the event kinematics in the case of NC DIS is through a measurement of the angle of the scattered electron (\(\theta\)) and the angle of the struck quark (\(\gamma\)).

\[
y = \frac{\sin\theta(1 - \cos\gamma)}{\sin\gamma + \sin\theta - \sin(\theta + \gamma)} \quad (2.17)
\]

\[
Q^2 = 4E_e^2 \frac{\sin\gamma(1 + \cos\theta)}{\sin\gamma + \sin\theta - \sin(\theta + \gamma)} \quad (2.18)
\]

\[
x = \frac{E_e \sin\gamma + \sin\theta + \sin(\theta + \gamma)}{E_p \sin\gamma + \sin\theta - \sin(\theta + \gamma)} \quad (2.19)
\]

The polar angle \(\gamma\) of the current jet can be obtained with the Jaquet-Blondel method:
This method has the advantage that it suffers less from the uncertainties in calorimeter energy calibration. In the region $x \geq 10^{-4}$ the double angle method is the best estimator of the $x$ variable.

2.4 Cross sections in Deep Inelastic Scattering

A look at the ep cross section as a function of $Q^2$ and energy transfer $\nu$ reveals the general characteristic of the target constituents and their distributions. If one increases $Q^2$ from low values the coherent proton scattering dies away and the incoherent elastic scattering from individual constituents of the proton becomes progressively more important. Increasing $Q^2$ is equivalent to decreasing the wavelength or increasing the resolution of our probe and at sufficiently large $Q^2$ one begins to see quarks rather than the entire proton.

If lepton-quark scattering is truly pointlike, then the Simple Parton Model (SPM, see also figure 2.1) predicts that at large enough values of $Q^2$ and fixed $x$ the quark distribution functions and therefore the proton structure functions should not change with increasing $Q^2$. This assumption is known as the Bjorken scaling hypothesis [20]. If in the limit as $Q^2 \to \infty$ and $\nu \to \infty$ the quark distributions stay finite, they can only depend on the ratio of those two quantities, which was defined to be $x = \frac{Q^2}{2M\nu}$. Note that $x = \frac{Q^2}{2M\nu}$ is also dimensionless and therefore does not set a mass or length
scale, hence the term scale invariance.

The cross section in the deep inelastic region of phase space has to take this structure of the proton in terms of structure functions $F_{1,2,3}(x,Q^2)$ into account. Where $F_{1,2}(x,Q^2)$ arise from the electromagnetic current and $F_3(x,Q^2)$ from the weak current. These structure functions can be written in terms of the quark distribution functions [21], which measure the probability of the lepton scattering off one of the quarks carrying a momentum fraction $x$ via an interaction of order $Q^2$.

The NC and CC differential cross sections are given by:

\[
\frac{d^2\sigma_{NC}(e^\pm, P)}{dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4} (y^2 x F_1(x, Q^2) + (1-y)F_2(x, Q^2))
\]

\[
\frac{d^2\sigma_{CC}(e^\pm, P)}{dx dQ^2} = \frac{G_F^2}{2\pi} \frac{M_W^2}{(M_W^2 + Q^2)^2}(y^2 x F_1(x, Q^2))
\]

\[
+ (1-y)F_2(x, Q^2) \pm (y - \frac{y^2}{2}) x F_3(x, Q^2)
\] (2.8)

where $\alpha$ is the fine structure constant, $M_W$ is the mass of the $W$ and $E_e$ is the energy of the incident electron.

The NC cross section has a pole at $Q^2 = 0$ due to the photon propagator in the scattering amplitudes. The CC cross section on the other hand approaches a constant value as $Q^2 \to 0$ due to the $W$ propagator. At $Q^2 = M_W^2$ the differential cross sections $\frac{d\sigma_{NC}(e,P)}{dQ^2}$ and $\frac{d\sigma_{CC}(e,P)}{dQ^2}$ have the same magnitude and with increasing $Q^2$ the differential CC cross section falls off slower than the differential NC cross section. This behaviour was demonstrated experimentally for the first time at HERA.

Figure 2.2 shows the cross sections for NC and CC scattering as a function of $x$ and $Q^2$. 
Due to the $1/Q^4$ dependence of the NC DIS differential cross section, the total integrated NC cross section is very sensitive to $Q^2$ cutoff. Since the majority of NC DIS events scatter the electron at a small angle from the incident direction, the measurement of the NC cross section depends on how well one is able to observe those low $Q^2$ electrons.

With HERA it is possible to measure those structure functions in a region of phase space, that was previously not accessible [22]. The structure functions measured in previous experiments were extrapolated to the kinematic regions of HERA. At low values of $x$ ($\sim 10^{-4}$) the predictions for the $x$ dependence of the structure functions vary considerably. Models underlying those evolution techniques of the structure functions can be tested at HERA [23].
Figure 2.1: Feynman diagram of $ep$ scattering. $p_e$ is the 4-momentum of the incoming electron and $p'_e$ the 4-momentum of the outgoing electron. $q$ is the four momentum of the exchanged boson ($\gamma, Z, W$). $F$ is the 4-momentum of the scattered quark. $W$ is the sum of the four momenta of all hadrons coming from the proton (current jet and remnant).
Figure 2.2: The left distribution shows the cross section in $nb$ for NC scattering at HERA in bins of $x$ and $Q^2$. The right distribution shows the the cross section in $pb$ for CC scattering. The two numbers given in each bin correspond to two different structure functions (MTB1 (fat) and MTB2 (slim)).
Figure 2.3 ep scattering variables in the lab frame, where

\[ p_e = (\vec{p}_e, E_e), \text{(initial electron)} \]
\[ p'_e = (\vec{p}'_e, E'_e), \text{(scattered proton)} \]
\[ P = (\vec{P}, E_P), \text{(initial proton)} \]
\[ F = (\vec{F}, F), \text{(hadronic energy)} \]
CHAPTER III

The Electron-Proton Collider HERA

The Hadron Electron Ring Accelerator (HERA) [24] is the first electron-proton collider in the world. It is built in a tunnel of 6.3 km circumference and located 20-30 m underground at the DESY laboratory in Hamburg, Germany. The tunnel contains two separate synchrotron rings. One accelerates and stores a proton beam, the other an electron beam. Figure 3.1 shows the layout of the DESY accelerator system including HERA, and a cross section through the HERA tunnel. The two beams are not continuous, but consist of bunches of particles circulating in the rings in opposite directions. The two rings have the identical circumference and the proton ring lies above the electron ring with a separation of 80 cm. At two of the four interaction points on opposite sides of the tunnel the rings intersect each other such that the two beams are brought into collision to provide $ep$ interactions for the two detectors H1 and Zeus. The North Hall houses the H1 detector [25], while the ZEUS detector [26] occupies the South Hall. These multipurpose detectors built for the measurement of particles produced in the $ep$ collisions are described in detail in chapter 4. The analysis detailed in this thesis was performed within the ZEUS collaboration. The main HERA parameters are summarized in table 3.1
Table 3.1: Some design parameters of the HERA collider

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Proton</th>
<th>Electron</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal energy</td>
<td>820</td>
<td>30</td>
<td>GeV</td>
</tr>
<tr>
<td>c.m. energy</td>
<td></td>
<td></td>
<td>GeV</td>
</tr>
<tr>
<td>$Q^2$</td>
<td></td>
<td></td>
<td>GeV</td>
</tr>
<tr>
<td>Luminosity</td>
<td>98400</td>
<td>1.5 • 10^{31}</td>
<td>cm^{-2}s^{-1}</td>
</tr>
<tr>
<td>spec. Lumi</td>
<td>15 • 10^{29}</td>
<td></td>
<td>cm^{-2}s^{-1} mA</td>
</tr>
<tr>
<td>Number of interaction points</td>
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<td>mrad</td>
</tr>
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<td></td>
<td></td>
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<tr>
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</tr>
<tr>
<td>number of quads</td>
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<td>580</td>
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</tr>
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<td>58</td>
<td>mA</td>
</tr>
<tr>
<td>total number of particles</td>
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<td>0.8 • 10^{13}</td>
<td></td>
</tr>
<tr>
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<tr>
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<tr>
<td>time between crossings</td>
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<td></td>
<td>ns</td>
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<tr>
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<td>filling time</td>
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<tr>
<td>lifetimes</td>
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<td>2-15</td>
<td>h</td>
</tr>
</tbody>
</table>

3.1 Beam energies

With a proton beam energy of 820 GeV and an electron beam energy of 26.7 GeV
HERA can provide ep collisions with a center of mass energy an order of magnitude
higher than it was previously possible. The proton beam energy is limited by the
strength of the magnetic field provided by the HERA superconducting dipole magnets.
which keep the proton beam on its 6.3 km orbit. The magnets are able to contain a proton beam of up to 1 TeV. The maximum electron beam energy is determined by the superconducting radio frequency (RF) accelerator cavities which replenish the energy lost by the electrons through synchrotron radiation. Enough power can be supplied by the cavities to store an electron beam of up to 35 GeV. During the running in 1993 not all RF (radio frequency) cavities were installed, leading to a reduction of the electron beam energy that was supplied for luminosity running. Polarized electrons are not scheduled to be utilized until 1997.

Electrons in storage rings can become transversely polarized by the emission of synchrotron radiation. The amount of polarization is limited by the depolarization effects due to magnet misalignments and orbit errors. Utilizing special orbit corrections, polarization values of over 60% (maximum theoretical polarization is 92.4%) have been achieved by HERA.

3.2 Beam Fills and Running conditions

The HERA proton beam requires a longer filling time and has a longer life time than the electron beam. Therefore the proton beam is filled before the electron beam. After tuning the beams for luminosity at the interaction points (see section on luminosity measurement) data is taken. A consecutive series of events collected in one of the detectors is called run. Runs are sequentially numbered for identification. A run may continue for as long as the lifetime of the electron beam, but conditions prevailing at the ZEUS experiment may require a run to be prematurely ended and a new run to be started within the same beam fill. After the electron beam has decayed and
provides insufficient luminosity, the current ZEUS run is ended, the electron beam is
dumped and a new electron beam is filled. Similarly, once the proton has decayed,
the current ZEUS run is ended, the electron and proton beams are dumped and new
beams are filled. The beam conditions within a fill, and therefore during a ZEUS run,
are considered stable. Beam conditions across fills, and therefore across ZEUS runs,
may vary.

In order to reach the design integrated luminosity of 100 pb$^{-1}$ per year HERA has
to fill 220 buckets, spaced 96 ns apart. A bucket is the site of a single bunch and the
buckets are evenly spaced. For the experiments this means that they must be able
to deal with bunch crossing rates of over 10 MHz. This is two orders of magnitude
higher than at LEP and only four times smaller than the LHC design. It is presently
the machine with the highest crossing rate worldwide. In addition to bunches that
cross an opposing bunch at the center of both experiments, there are "pilot bunches".
The pilot bunches are buckets that do not have an opposing bucket from the other
beam. They pass the detector without any physics interactions and therefore they
can used to estimate the background rates from beam interactions (see next section).

3.3 Backgrounds at HERA

Beam induced backgrounds

Beam particles can collide with gas remnants in the the vacuum of the ring. If
these collisions occur close enough to the detector, they can create background events
underlying the real physics events from beam-beam interactions. Collimators both
upstream and downstream are installed to reduce triggers from such backgrounds.

This background for the HERA experiments induced by the beams, can be separated into backgrounds from the electron beam (e-background), and more importantly backgrounds from the proton beam (p-background).

e-backgrounds consists of synchrotron radiation and collisions of electrons with some remnant nuclei in the beam pipe (electron-gas) Background from the synchrotron radiation is minimized by several collimators (C3,C4,C5) [27] [28]. e-background deposits a fairly small amount of energy in FCAL, in contrast to real ep events. Electron-gas background, however, forms significant background for the luminosity measurement for the electron. In order to estimate the effects of the e-background on the luminosity counting rate a pilot electron pilot bunch is included in the beam, this is an electron bunch that is not matched by a proton bunch. The rate resulting from the pilot can be used to adjust the measured ep counting rate. At low luminosities the contribution from electron-gas interactions can exceed the ep-bremsstrahlung rate and thereby introduce a large uncertainty in the luminosity measurement.

The largest background comes from collisions of beam protons with gas that remains in the beam pipe. Since the total proton-nucleon cross sections are very large at HERA energies such interactions can lead to high background rates. These so-called "beam gas interactions" have a $E_t$ spectrum which falls off very rapidly and their $p_t$ distribution is balanced in the transverse direction. Although most beam gas events are easily separable from real events in the offline analysis, they increase the
trigger rates by orders of magnitude and made a multi level trigger system necessary. The rate of beam-gas induced triggers depends on the beam current, both electron and proton, and the vacuum in the beampipe. At design luminosity the beamgas trigger rate has been estimated to be $O(100kHz)$. Again proton bunches that were not matched by electrons could be used to estimate the amount of background due to beam-gas interactions. Obviously though, no statistical subtraction of event rates is possible in the case of triggered events as it is the case of the $e - background$.

3.3.1 Other backgrounds

The actual bunches can be approximated with a Gaussian distribution in the $x,y$ and $z$ directions and beam particles can therefore scrape off the beam wall, magnets, inner side of the collimators or other elements in the beam line.

$p - background$ created far upstream of the detector can produce muons which travel almost parallel to the beam line. The so called halo muons are several meters displaced from the beam axis.

The background coming from cosmic ray muons is independent from the beam intensity. Cosmic ray muons are produced in air showers at large heights when high energetic (up to many TeV) cosmic particles collide in the atmosphere and create particle showers, including muons. They easily penetrate 25 meters deep into the hall and can trigger the detector. Cosmic rays that occur in coincidence with real $ep$ events are difficult to identify and remove.

In the chapter on the triggering the weapons which are available against backgrounds will be explained.
3.4 Luminosity measurement

The $ep$ bremsstrahlung process

$$ep \rightarrow ep\gamma$$

is used to measure the luminosity. It is based on the coincidence measurement of the electron and the photon in the luminosity monitor (LUMI). The cross section for this process is purely electromagnetic and can be calculated with great precession (as matter of fact it one of the processes that is calculable with the highest accuracy in physics) using the Bethe-Heitler [29] approximation.

LUMI consists of two separate detectors, one for the electrons and one for the photons. Figure 3.2 shows the layout of the LUMI.

The photon detector of LUMI is located 107 m from the interaction point. It consists of an air-filled Cerenkov counter and a lead-glass calorimeter. A carbon filter is placed in front of the photon detector to shield against the low energetic synchrotron radiation. Since the filter converts a fraction of the photons into $e^-e^+$ pairs a Cerenkov counter is placed between filter and calorimeter so as to veto the counting rate due to such conversions.

Electrons that are scattered by a small angle are deflected by the beam magnets and can reach the electron detector, which is located 34.7 m from the interaction point and 30 cm off the beam axis on top of the electron beam pipe. The electron detector is a lead-scintillator calorimeter.
Table 3.2: Upper limits on physics rates at design luminosity

<table>
<thead>
<tr>
<th>Class</th>
<th>Type</th>
<th>Rate [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photoproduction:</td>
<td>VMD</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Boson-gluon fusion</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>$(M_{qar{q}} \geq 3 \text{ GeV})$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>QCD Compton</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>$(M_{qq} \geq 3 \text{ GeV}, p_t \geq 2 \text{ GeV})$</td>
<td></td>
</tr>
<tr>
<td>DIS:</td>
<td>Neutral Current $(Q^2 \geq 100 GeV^2)$</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Charged Current $(Q^2 \geq 100 GeV^2)$</td>
<td>0.001</td>
</tr>
</tbody>
</table>

The luminosity is obtained from the LUMI counting rate $N_{LUMI}$ with

$$\mathcal{L} = N_{LUMI}/\sigma_{e\gamma}A_{LUMI}$$

where $\sigma_{e\gamma}$ is the theoretical $e\gamma \rightarrow e\gamma$ cross section and $A_{LUMI}$ is the experimentally measured acceptance. The systematic errors in the measurement of the luminosity are due to the energy calibration, the photon acceptance and the uncertainty of $N_{LUMI}$ because of e-gas background in one or both LUMI detectors.

### 3.5 Physics Rates

Table 3.2 shows the expected event rates for the design luminosity. Those numbers are upper limits since detector performance and acceptance will lower them.

### 3.6 Performance in 1993

The 1993 proton beam energy, $E_p=820 \text{ GeV}$, and electron beam energy, $E_e=26.7 \text{ GeV}$, provided $e\gamma$ collisions with center of mass energy, $\sqrt{s} = 296 \text{ GeV}$. In 1993
HERA was operated with 86 bunches in each beam plus 6 electron pilot bunches and 10 proton pilot bunches generating a typical beam current of 12-15 mA for the electron and proton beam.

In 1993 HERA performed exceedingly well in delivering the luminosity, that was planned for this year. Luminosity was accumulated continuously over a period of 6 months. HERA accumulated a total of 1088 nb\(^{-1}\) and ZEUS was able to collect 608 nb\(^{-1}\) online and 554 nb\(^{-1}\) offline. This corresponds to 11 hours of continuous running at design luminosity. The uncertainty of the luminosity measurement for the 1993 data will add up to 6.5% total systematic error. The difference between delivered and collected luminosity is due to deadtimes necessary to configure the detector (closing the calorimeter and ramping up of the high voltage of the tracking detectors) and data acquisition and hardware failures (power trips and/or large backgrounds). Figure 3.3 shows the integrated luminosity during the 1993 running of the machine.

In 1993 a small fraction of the particles in the proton bunches were separated from the main bunch and moved into a “satellite”. The reason for this behaviour of the beam is currently under investigation. The satellites advance the main bunch by \(~8\) ns, therefore a 60 cm cut on the vertex eliminates events from interaction with the satellite bunch. The contribution to luminosity from those bunches is estimated to be less than 5% as measured from the beam rate counters (C5 counters as explained in 4.1.2).

During the luminosity runs in 1993 for ZEUS and H1 no efforts were made with respect to the polarization of the beam by the HERA machine group and zero polar-
Table 3.3: Comparison of performance parameters for the 1993 HERA runs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1993</th>
<th>design</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>e beam energy</td>
<td>820</td>
<td>820</td>
<td>GeV</td>
</tr>
<tr>
<td>p beam energy</td>
<td>26.6</td>
<td>30</td>
<td>GeV</td>
</tr>
<tr>
<td>c.m. energy</td>
<td>296</td>
<td>314</td>
<td>GeV</td>
</tr>
<tr>
<td>$Q^2$</td>
<td>87248</td>
<td>98400</td>
<td>GeV</td>
</tr>
<tr>
<td>Luminosity</td>
<td>0.01</td>
<td>1.5</td>
<td>$10^{31} \cdot \text{cm}^{-2}\text{s}^{-1}$</td>
</tr>
<tr>
<td>spec. Lumi</td>
<td>3-6</td>
<td>3.4</td>
<td>$10^{29} \cdot \text{cm}^{-2}\text{s}^{-1} \text{mA}$</td>
</tr>
<tr>
<td>e circulating current</td>
<td>12-15</td>
<td>26</td>
<td>mA</td>
</tr>
<tr>
<td>p circulating current</td>
<td>12-15</td>
<td>20</td>
<td>mA</td>
</tr>
<tr>
<td>$N_e$/bunch</td>
<td>2</td>
<td>3.6</td>
<td>$\cdot 10^{10}$</td>
</tr>
<tr>
<td>$N_p$/bunch</td>
<td>2</td>
<td>10</td>
<td>$\cdot 10^{10}$</td>
</tr>
<tr>
<td>number of bunches</td>
<td>84 +6 (+10)</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>time between crossings</td>
<td>96</td>
<td>96</td>
<td>ns</td>
</tr>
<tr>
<td>e bunch length</td>
<td>1</td>
<td>0.8</td>
<td>cm</td>
</tr>
<tr>
<td>p bunch length</td>
<td>30</td>
<td>11</td>
<td>cm</td>
</tr>
<tr>
<td>z vertex width</td>
<td>14</td>
<td>6</td>
<td>cm</td>
</tr>
<tr>
<td>z vertex mean</td>
<td>-6</td>
<td>0</td>
<td>cm</td>
</tr>
<tr>
<td>e filling time</td>
<td>20</td>
<td>15</td>
<td>min</td>
</tr>
<tr>
<td>p filling time</td>
<td>20</td>
<td>20</td>
<td>min</td>
</tr>
<tr>
<td>e lifetimes</td>
<td>2-15</td>
<td>$\geq 5$</td>
<td>h</td>
</tr>
<tr>
<td>p lifetimes</td>
<td>10-500</td>
<td>$\geq 10$</td>
<td>h</td>
</tr>
</tbody>
</table>
Figure 3.1: Layout of the HERA accelerator system (top figure) and a cross section through the HERA tunnel (bottom figure).
Figure 3.2: Top view of the luminosity detector. The electron luminosity detector (LUMIE) and the photon luminosity detector (LUMIG) are shown with respect to the beam line and magnets. The x and z axis are not on the same scale. The B magnets focus the beam and the Q magnets bend the beam. Electrons scattered within a very small angle and with only a fraction of the electron beam energy are deflected by the bending magnets out of the outgoing electron beam pipe into LUMIE. Photons produced in the electron beam direction remain in the proton beam pipe until the pipe and the proton beam curve upward, at which point the photons exit the pipe into LUMIG. The scattered electron ($e'$) and emitted photon ($\gamma$) of a Bethe-Heitler bremsstrahlung event, $ep \rightarrow e'\gamma p$, are shown entering LUMIE and LUMIG, respectively.
Figure 3.3: Integrated luminosity (online) written to tape by the ZEUS detector in $n\text{b}^{-1}$ during the 1993 running.
CHAPTER IV

The ZEUS experiment

The physics experiment can be broken up into four stages:

- the observation of charged and neutral particles in the detector components.
- the formation of the trigger and subsequent readout of the measured quantities to a storage device (DAQ).
- the reconstruction of the event and preliminary selection
- the extraction and analysis of selected events according to different physics topics.

4.1 The ZEUS detector

The ZEUS detector is a multipurpose detector to make use of the wide variety of physics available at HERA. Construction of the ZEUS detector started in 1988, the detector was commissioned in 1992. It is approximately 18 m long, 11 m wide and 9 m high and weighs about 3600 tons and is located in the South Hall at the HERA ring. Figure 4.1 shows a cut away view of the detector along the xy plane and the yz plane.
The following criteria controlled the design of the detector.

◊ The center of mass is boosted in the forward (proton) direction and thus a asymmetric detector is required, i.e. more interaction lengths of detector in the forward (boost) direction.

◊ NC DIS events have high energetic electrons scattered into the fiducial volume of the detector. The detector must therefore detect electrons well, requiring a high resolution electromagnetic calorimeter. Important for heavy quark physics and some of the exotic particle searches are excellent identification of charged leptons ($e^\pm, \mu^\pm$) in the vicinity of hadronic jets. This calls for a combined effort of tracking, calorimetry and muon detection.

◊ In CC DIS events the neutrino escapes undetected. Those events stand out through their large missing transverse momentum. Therefore the detector has to be as hermetic as possible, to be confident that missing momentum is the result of an escaping neutrino and not of charged or neutral particles escaping detection.

◊ In order to measure the current jet(s) as well as possible a well segmented high resolution hadronic calorimeter is required.

◊ Measuring the momentum of charged particles from the tracks requires a central tracking device surrounded by a strong magnet in order to bend the tracks of highly energetic particles. This tracking chamber in combination with a central vertex detector enables one to calculate the true vertex of the events very precisely.

◊ To measure the luminosity and tag electrons which were only deflected by a small
angle electron and photon detectors far downstream from the interaction point are necessary.

HERA beam structure imposes tough technological constraints on the design of the detector. Very short bunch crossing times, high background rates and high levels of radiation require a fast detector response and read-out, online calibration capabilities and an excellent trigger system.

4.1.1 ZEUS coordinate system

The commonly used coordinate system for Zeus is right handed. The positive $z$ axis points in the proton or forward direction, the positive $y$ axis points up and therefore the positive $x$ axis points towards the center of the HERA ring. The origin of the detector is at the nominal interaction point. The standard cylindrical coordinates are the $z$, the radial distance to the beam pipe $r = \sqrt{x^2 + y^2}$ and the azimuthal angle $\phi$ perpendicular to the beam axis starting at positive $x$. The standard spherical coordinates consist of $\phi$ and $z$, the polar angle $\theta$ measured from the positive $z$ direction and the distance from the origin $\rho = \sqrt{x^2 + y^2 + z^2}$. Figure 4.2 shows the ZEUS coordinate system.

4.1.2 Detector components

Only the components relevant to this analysis will be described.

The interaction region and beam pipe elements [30]. The beam pipe in the detector area consists of four parts and has two vacuum pumps at both ends to ensure proper beam conditions. This part of the beam pipe is water cooled to get
rid of the heat dissipated by RF power losses. Several collimators and masks reduce the high background from synchrotron radiation, beam-gas interaction and the beam scraping off beam elements. The C5 collimator surrounds about 3/4 of the beampipe and is located at $z=-3.15$ m. This device is equipped with silicon counters to provide information on beam performance and timing.

◊ The vertex detector (VXD) is placed between the outer radius of the beampipe and the inner wall of the Central Tracking Detector (CTD) [31]. Its inner cylinder radius starts at 10 cm and its outer is 16 cm. It consists of a high precision drift chamber with its wires running parallel to the beam axis. The main purpose of the VXD, besides increasing the precision with which the interaction vertex can be measured, is the detection of short lived particles and the improved momentum and angular resolution of the charged tracks.

◊ The CTD is a cylindrical drift chamber covering the angular range between 15° and 164°. It contains 24192 wires, of which 4608 are sense wires, arranged in nine superlayers. The axis of the CTD lies right on the ZEUS $z$ axis, the centre of the CTD is at $z=2.5$ cm and it is 2.5 m long. Five of the superlayers have wires parallel to the chamber axis, four layers are stereo layers which have wires with a small angle with respect to the beam, which are used to determine the $z$ coordinate of the hits. The $z$ resolution achieved by $z - by - timing$ equals 4 cm. The resolution via the FADC is considerably better ($O(mm)$), i.e. the $z$ vertex can be reconstructed within several mm, which is the most important aspect of the CTD for this analysis. The position resolution in the $r - \phi$ plane is 260 $\mu$m. The chamber measures $dE/dx$
with an accuracy of better than 10-11%. The measurement of $dE/dx$ improves the ability to identify particles. The momentum resolution in the $x-y$ plane $dp_t/p_t$ is $(0.003 + 0.006)p_t$. Figure 4.3 shows several reconstructed tracks in the CTD.

◊ The magnet coil (COIL) A superconducting coil with 0.9 radiation length thickness and an inner radius of 92.5 cm provides a 1.4 Tesla magnetic field parallel to $z$-axis and pointing in the forward direction. In order to correct the influence of this field on the beam a compensating magnet is installed behind RCAL.

◊ The high resolution uranium calorimeter (CAL) [32] [33] [34] The calorimeter consists of three sections: Forward, Barrel and Rear (FCAL, BCAL and RCAL). Except for the beam holes the calorimeter hermetically surrounds the interaction region. CAL is a compensating sampling calorimeter with depleted uranium as an absorber and plastic scintillator as active material. In a sampling calorimeter only a fraction of the total energy of a particle or jet is "sampled". This fraction is called the visible energy and is measured by the ionization loss of shower particles traversing active (scintillator) layers. The ratio of visible to total energy (sampling fraction) depends on the type of particle in the shower. In order to minimize the energy resolution due to variations of the sampling fraction the calorimeter was made compensating. In a compensating calorimeter the response to hadronic showers is equal to the response to electromagnetic showers ($e/h$ ratio) so that event-to-event fluctuations, the factor dominating hadronic energy resolution, is minimized. An $e/h$ ratio of $1.00 \pm 0.05$ and was obtained in beam tests. The hadronic energy was shown to have a resolution of $\sigma(E)/E = 35%/\sqrt{E} \pm 2\%$ and the electromagnetic energy
resolution is $\sigma(E)/E = 18%/\sqrt{E} \pm 2%$. In order to measure the energy resolution of the calorimeter, individual modules of the device were exposed to a test beam of well calibrated particles. The response of the calorimeter to those test particles of known energy and type could therefore be measured and the calorimeter thereby calibrated.

The structure of FCAL, BCAL and RCAL is similar. They are divided longitudinally, i.e. in the direction of $r$, into two parts. The inner part is the electromagnetic calorimeter (EMC) with a depth of $\sim 25$ radiation lengths ($X_0$) that is read out as one section (for uranium $X_0 = 0.32$ cm). The outer part is called the hadronic calorimeter (HAC). It varies in depth from $\sim 126 \, X_0$ in the very forward direction to $\sim 63 \, X_0$ in the rear. In FCAL and BCAL the HAC is read out in two sections, in RCAL it is read out in only one section. Figures 4.4 show the segmentation of the ZEUS calorimeter. It displays a side view of all three sections and frontal views of the rear and forward sections.

The light from the plastic scintillator is read out via wavelength shifter guides to photomultiplier tubes that convert the light into an electrical pulses [33]. Each subsection of the calorimeter (tower) is read out on the left as well as the right side, enabling an excellent time measurement of the event from the calorimeter. That pulse is then sent to the front end electronics that sit directly on the individual calorimeter modules. The resolution within which the time of the different towers can be measured is on the order of 1 ns.

The performance of the calorimeter for both time and energy measurement is
continuously monitored. For calibration purposes the uranium noise \(O(20\,MeV)\) of
the calorimeter cells, charge injections into the read out electronics and light injected
into the PMT's are used. The calibration procedure is done at least every 8 hours
and the correction constants have then to be applied on- and off-line [35].

◊ The return yoke and backing calorimeter (BAC) The iron yoke for the
return of the magnetic flux has the shape of an octagonal cylinder and surrounds the
entire calorimeter. The yoke has three sections: the clam shells that can be opened
and a bottom yoke which is fixed. The yoke itself is instrumented with proportional
tubes and as such forms the backing calorimeter. It can be magnetized for an indepen­
dent measurement of the momentum of muons in the Barrel region. BAC measures
the energy leakage out of the main calorimeter, as well as the trajectories of muons.
Very high energetic particles can also develop showers that are not entirely contained
in the volume of the calorimeter and some to their energy escaped detection in CAL.
This fraction can then be recovered in the BAC.

◊ The Barrel and Rear Muon detector (BMUON,RMUON) In the barrel
and rear detector regions limited streamer tubes chambers are located behind the iron
yoke. They measure the position and angle of muons with a momentum resolution of
20\% for momenta of 20 GeV. In the region of the bottom yoke muons are detected
with the help of three layers of the backing calorimeter instrumented with additional
position read-out.

◊ The forward muon detector (FMUON) detects muons in the forward
direction. This detector consists of a toroidally magnetized iron region, i.e. $\vec{B}$ points in the $\phi$ direction, interleaved with sections of drift chambers, limited streamer tubes and time of flight counters. It allows for an independent measurement of the muon momenta up to 100 GeV down to very small forward angles.

4.2 The ZEUS Trigger and Data Acquisition

The ZEUS trigger [36] and data acquisition system [38] recognizes data from "good" $ep$ collisions in any given bunch crossing and writes them to a storage medium. The design of the ZEUS trigger was driven by the following performance criteria:

- The background rates can be as high as $O(100kHz)$
- The rate of physics events written to storage medium is $O(Hz)$. Therefore a reduction factor up to $O(100000)$ is necessary.
- The time between bunch crossings is 96 ns. A trigger decision can not be reached in this time period with electronics, which is presently available. The data has to be pipelined in order to be able to read out the detector at each bunch crossing.

Because of the high bunch crossing rate (96 ns) the trigger has three levels where each level can only make decisions on events accepted by the previous trigger level. The trigger thereby minimizes the trigger rate from background events in real time and the time available for processing the events becomes larger at each level.

Figure 4.5 gives an overall layout of the trigger system.
4.2.1 The First Level Trigger

The first level trigger (FLT) [37] is a parallel pipelined processor. Each detector subcomponent (calorimeter, tracking chamber, muon chamber etc) stores the data from 58 bunch crossings in a separate analog pipeline. The trigger electronics for each component are pipelined as well. After a step the data is moved to the next step for further processing, and data from the next bunch crossing is read in, where each step is repeated every 96 ns. This avoids any deadtime and ensures that every crossing can be processed. Each FLT component has a total of 2.5 μs - broken up in 26 steps - available to process an event and pass the results to the Global First Level Trigger (GFLT). The GFLT has then 2.0 μs to process the results of the subcomponents and send the final GFLT decision to the data buffer whether to accept or abort the event. Based on the information of the subcomponents GFLT generates 64 subtriggers where each subtrigger is a logical yes/no decision. The subtrigger bit are set depending on how the various local FLT results compare to programmable thresholds. The most prominent subtriggers are based on calorimeter FLT (CFLT) information. The final GFLT decision is made from the logical OR of all 64 subtriggers. For subtriggers which have trigger rates, that are too high to be acceptable to the next level it is possible to prescale them by a programmable factor.

After an event is accepted, the pipelined data is transferred to a holding buffer, where full width digitization is initialized. This transfer can take up to 10 μs and is the most significant source of deadtime in the trigger system. During this time period no new beam crossings can be accepted. This deadtime is also handled by GFLT,
by not counting luminosity during deadtime. The output rate of each local FLT is not supposed to exceed 1kHz, otherwise additional deadtime can be generated. The GFLT trigger rate, including FAST CLEAR can not exceed 1kHz.

4.3 The Fast Clear

The Fast Clear (FC) [41] is a processor that reanalyzes the CALFLT data during the digitization of the data, that has been accepted by GFLT. It ensures that the effective FLT rate (including FC) does not exceed 1 kHz. FC has been integrated into the trigger system, but has not been used for background rejection during the 1993 runs.

The FC processor is described in detail in the appendix.

4.4 The Second Level Trigger

The data is read out from the pipeline and after its digitization is stored in separate buffers for each subcomponent. These buffers are several events deep depending on the component, they belong to. The Second Level Trigger [42] components calculate their results based on the high resolution data in those buffers. The data is also more complete than at the first level at the first level, eg. information on the time measurements of the calorimeter data is now available. Similar to the FLT design the results of the SLT components are sent to the Global Second Level Trigger GSLT, which then makes the final GSLT trigger decision. A large part of of the SLT hardware is implemented with a transputer network, giving SLT a high degree of flexibility.

The GSLT output rate should not exceed 100 Hz and therefore SLT has to achieve a reduction factor \(\sim 10\).
4.5 The Event Builder

After the GSLT decision is made the data of a specific event is still distributed over several subcomponent buffers. The Event Builder (EVB) [39] collects all the data from different components carrying the same event number and "builds" an event. EVB formats the event in the ZEBRA structure [43]. It distributes the "raw" event, which contains the complete data of an event in $\sim 140$ kB, to one of the Third Level Trigger (TLT) branches. The EVB hardware is based on a transputer network for the subcomponent interfacing and a customized crossbar switch to link any of the detector subcomponents to any branch of the TLT.

4.6 The Third Level Trigger

The TLT [40] has to be able to reduce the data rate from GSLT of about 100Hz to about 3 Hz. It is implemented with a farm of thirty 4D35 SGI computers, each working on a different event. Since TLT has more processing time and the full information is available for each event, it can perform a more sophisticated analysis and achieve the required background suppression to reduce the trigger rate to a level acceptable for data storage. The code running on the TLT computers is standard FORTRAN analysis code, some of it derived from offline analysis code. In addition to being flexible, TLT is therefore user friendly. Code which was developed offline for calculation of certain quantities and is needed to reject background is used in the TLT. Also adaption to unforeseen hardware conditions can easily be implemented.
4.6.1 TLT strategy

The TLT has two stages, one for the rejection of data (TLT VETO) and one for the classification of physics events. Figure 4.6 shows the TLT trigger scheme. Only events that pass the TLT VETO can be chosen by one or several of the physics classes. The criteria for the first stage are general data quality checks, reducing trigger rates from background events. All events that have been selected by at least one physics class can be written out to mass storage. This differs from the strategies of the other triggers, that were designed to minimize background by rejecting bad events opposed to selecting "interesting" events. Physics classes are categorized according to specific physics interest, like Photoproduction or DIS. Those classes are flexible, new classes can be added or existing ones modified according to changing off- and online requirements. The TLT has two bypass branches, through which a small and fixed ratio of events can pass without having to satisfy the TLT data requirements. One of the bypasses avoids TLT entirely and the other one only the physics class selection. The purpose of having a fixed fraction of events bypassed is to have a sample of minimum bias events.

4.7 Storage of Data

The data is transported from the TLT processors to multiple destinations via a crossbar switch. Different processors can concurrently transfer data at a rate of about 20 MB/s to the DESY mainframe computer onto cartridge tape, to a local equipment computer for online monitoring and to online workstations. The upper limit on data
transfer to the cartridge tapes is .5 MB/s, yielding an upper limit of 4-5 events/s that can be written to long-term mass storage. Starting with the cartridge tapes the offline analysis chain begins.

4.8 Reconstruction and the analysis environment

Every event that is written to tape passes through the ZEUS reconstruction program ZEPHIR [44]. This program reconstructs either real or Monte Carlo (see chapter 5) quantities for further physics analysis. In the case of the various tracking detectors (VXD, CTD, FTD, RTD, F/B/RMUON) these objects are tracks and track elements and for the calorimeter calibrated energies and energy clusters.

The reconstruction of physics events will run through three phases:

(1) Reconstruction of individual components: tracking chambers, compensating calorimeter, backing calorimeter and luminosity monitor.

(2) Global track matching, global cluster finding in CAL and BAC, matching of tracks and clusters.

(3) Particle identification, e.g. by combining measurement from CTD ($dE/dx$) and CAL.

**Track Reconstruction**: During data taking the digital signal processors (DSP's) extract the drift time and pulse size from the Flash Analog to Digital Converters (FADC's). The results of the pulse train analysis are stored in a database (ADAMO tables). The $z - by - timing$ system measures the difference between the time of arrival of a pulse at the forward end of the chamber and its arrival time at the rear end of the chamber. These timing values are also stored. Then the measured drift
times are matched with hits found in the $z$–by–$t$iming system (where applicable). So the drift distances from a particular wire together with the hits are stored as ADAMO tables.

The next step is to run a pattern recognition algorithm on the space points. First seed tracks are found in the outer layers of the CTD. These seed tracks are then extended inwards. Points on the track are added as wire layers are crossed. After the pattern recognition phase the tracks are fitted accounting for the time of flight and signal propagation delays. The final fitted track parameters are then stored in ADAMO as TCTRAK.

The track reconstruction in VXD starts either from a small track segment in the outmost region of the VXD or by following a reconstructed CTD track. Here pattern recognition and fitting are done simultaneously. Since VXD alone can not resolve the left-right ambiguity by itself, the problem has to be untangled by track-matching with the neighboring component.

During the global reconstruction vertex finding is performed utilizing information from all components.

**Calorimeter Reconstruction:** The calorimeter event output consists of the energies in the left and right photomultiplier tubes, based on the charges which are reconstructed by the DSP's and the information on the time of the pulse. Accounting for the geometry of the detector this information is stored after zero suppression as raw data in the ADAMO table (CTENE).

The raw data is corrected using information gained by the calibration of the
calorimeter. Test beam data was used to set the absolute energy scale and the gain variations are monitored with various sources. This corrected data is written into the CALTRU tables which are the most commonly used tables in ZEUS data analysis. Then local clusters are identified based on a nearest neighbor algorithm finder (condensates). Electrons and gammas usually correspond to a single cluster whereas hadrons can be split between two or more condensates. In the global reconstruction phase various jet algorithms (SLCT, JADE and UA1) are run on the CALTRU data globally, i.e. matching objects between CAL regions.

The reconstructed data is then run through a number of filters to select the events that are of interest to specific physics research topics and writes a bit pattern into the header of the event accordingly. The data after reconstruction and event selection is then saved and is known as the “reconstructed event”.

An introduction to the ZEUS analysis environment is given in [45]. The statistical analysis is usually done within the EAZE framework, which lets the user develop his or her own code to analyze the data and choose packaged routines from a pool of analysis routines (e.g. matching track in CTD with clusters in the calorimeter). With the help of EAZE a subset of the analyzed events can be written out to personal disk or tape. The event statistics can be stored with the CERN HBOOK package and are then interactively analyzed using the CERN PAW package.

Two event display programs allow the user to scan and view selected events. The viewing of the event is possible for raw as well as reconstructed data. Due to the low rate of interactive scanning by an individual only final selected events (O(100)) can
be investigated with this method. GAZE provides a 3D representation, while LAZE specializes in 2 dimensional projections of the event.
Figure 4.1: Cut-away view of the ZEUS detector. The top figure shows the detector cut in $x - y$ plane looking in the positive $z$ direction.
Figure 4.2: Cut-away view of the ZEUS detector. The figure shows the detector cut in the $y-z$ plane.
Figure 4.3: The ZEUS coordinate system.

Figure 4.4: Reconstructed tracks in the CTD in the $x - y$ plane. The CTD consists over 9 superlayers and each superlayer is partitioned in cells with 8 sense wires.
Figure 4.5: Layout of the calorimeter and its segmentation. The figure (a) shows a longitudinal cut along the beam axis in the $y-z$ plane. FCAL goes from $373 \geq z \geq 222$ cm, BCAL goes from $-123 \leq z \leq 230$ cm and RCAL from $-148 \leq z \leq -234$. FCAL, RCAL and BCAL have a depth of 7.1, 5.3 and 4.0 absorption lengths respectively. FCAL covers a polar angle $2^\circ \leq \theta \leq 37^\circ$, BCAL covers $37^\circ \leq \theta \leq 129^\circ$ and BCAL covers $129^\circ \leq \theta \leq 177^\circ$. The longitudinal segmentation into EMC and HAC section is shown, as is the transverse segmentation of typically 5x20 cm$^2$ for FCAL and BCAL EMC cells, 10x20 cm$^2$ for RCAL EMC cells, and 20x20 cm$^2$ for HAC cells. The 32 BCAL modules were designed, assembled and tested by the US collaborators.
Figure 4.6: Layout of the calorimeter and its segmentation. In the bottom figures (b,c) a transverse cut perpendicular to the beam pipe is shown displaying the segmentation of the EMC sections for FCAL and RCAL. The outer EMC cells, shadowed by BCAL, have the same segmentation as the HAC cells.
Figure 4.7: Layout of the ZEUS trigger system. The data flows from top to bottom starting from the detector components and being selected for mass storage at the bottom. The entire detector has to be read out every 96 ns, only 3-5 events can be written to tape, making a multilevel pipelined trigger system necessary.
Figure 4.8: Layout of the third level trigger (TLT). Data which is not bypassed (only 0.1%) has to pass data quality cuts and then be selected by at least one of the physics groups. Bypass branches enable the acquisition of a small number minimum bias events.
Simulations of interactions between elementary particles are performed with Monte Carlo techniques. The programmer plays God and generates events according to distributions of the kinematic variables of a specific process. These can be calculated from known theoretically cross sections. The events generated with Monte Carlo programs are the predictions of what should happen in the interaction and how it will be measured in the experimental device. They are necessary to estimate acceptances or efficiencies ("how much do we see?") and biases ("are we seeing correctly?").

The generated events have to be run through the detector simulation and then be reconstructed (see chapter 4.8 and 5.1). For this Monte Carlo production a farm of approximately 40 computers (Funnel) [46] was used, on which the detector simulation as well as the reconstruction of the events was performed. Our working group was extremely fortunate as to be able to utilize a second farm of 20 dedicated computers at the Ohio State University to perform simulation and reconstruction.

5.1 The Simulation of the experiment

In order to compare the event shapes and distributions predicted by models (standard and exotic) one has to simulate the experimental environment entirely and run the
predictions of the model through a full simulation of the experiment.

In a search for new particles all known physics processes, although interesting, are considered as "background". It is important for this analysis that the simulation of the background processes enables one to see whether a new process beyond the Standard Model has occurred, by comparing the data against the Standard Model predictions. This necessitates to have a good understanding of the background processes.

In order to measure a cross section or to search for new processes, one has to understand the response of the detector and of the trigger system to the phenomenon which is to be measured. The detection efficiency of the experiment (without any further cuts in the analysis chain) is called acceptance in this study. The detector will also smear and distort the experimental signals to some degree, i.e. even a very sharply peaked signal (in the limiting case a $\delta$ distribution) will have a finite width due to detector effects. Furthermore the detector might shift the mean of signals by various amounts ("migration"). The size of these effects is given by the resolution of the detector and can be studied by running Monte Carlo events through a simulation of the experiment.

### 5.1.1 The simulation of the detector

The Monte Carlo for Zeus Analysis, Reconstruction and Trigger (MOZART) [26] makes use of the CERN GEANT [47] program package to track the particles through the detector. It simulates the signals of the active components of the detector. Physics processes such as particle decay and interaction, secondary particle generation, energy loss in dead (non-active) and active material, multiple scattering, wire hits and
calorimeter energy deposits are taken into account by MOZART.

5.1.2 The simulation of the trigger

ZGANA [48] simulates the trigger response to the data (either real or simulated), which is read out by the detector (raw data). Therefore ZGANA can be run on generated events after they have been processed by MOZART or on real raw data in order to study the effects of the trigger system on the acceptance of a specific class of events. Presently ZGANA only includes the simulation of the first level trigger. Since the SLT had only a negligible effect on the data selection beyond FLT and TLT in 1992 and 1993 runs for this analysis, it was safely neglected in the trigger simulation. The effects of the TLT were simulated by each of the physics working groups separately, since the second stage of the TLT was tuned according to different physics interests.

Due to the outstanding signature and high energies involved in the decay of $e^*$ events the trigger efficiency is above 99% for the $e^* \rightarrow e\gamma$ and $eZ$ and above 88% for $e^* \rightarrow \nu W$ at the lowest mass point considered in this search. At higher masses the trigger efficiencies increase.

5.2 The $e^*$ event generator

The $e^*$ events were simulated with the HEXF generator [49]. HEXF is a Monte Carlo program which generates excited fermions in $ep$ interactions, based on the model specified in the chapter 2.

The differential cross section can be divided into three kinematic regions, each
calling for a different description of the structure of the proton. These can be described as:

- elastic region: $W^2 = M_P^2$
- quasielastic region: $W^2 \geq (M_P^2 + M_n^2), Q^2 \leq 5.0 \text{ GeV}^2$
- deep inelastic region: $W^2 \geq (M_P^2 + M_n^2), Q^2 \geq 5.0 \text{ GeV}^2$

In the elastic region the structure function can be described by the electric and magnetic form factors [50]. A phenomenological parametrization from Brasse et al. [51] is used to characterize the structure functions in the quasielastic region. The structure function MRSD0 [52] from the PYSTFU library [53] were used to describe the deep inelastic region. At the kinematic limit of $M_{e^*} = 297 \text{ GeV}$ approximately 100% of the total integrated cross section comes from the elastic interactions (see figure 5.1), i.e. interactions in which the proton does not break up. This fraction decreases with decreasing mass of the $e^*$. At the maximally available energy for the production of $e^*$ ($M_{e^*} = 297 \text{ GeV}$) the production is exclusively elastic. The dependence of the cross section on the structure function parametrization is weak and is given in section 8.

The effects of the initial state radiation from the incident electron is taken into account via the Weizsäcker-Williams approximation [54]. The dominant contribution to radiative corrections is assumed to come from the emission of a photon collinear to the electron. The energy distribution of the emitted photon is given by

$$f_\gamma = \frac{\alpha}{\pi} \frac{1 + (1 - z)^2}{z} \log\left(\frac{E_z}{m_e}\right)$$
where $z$ is defined to be $E_\gamma/E_e$, $E_\gamma$ is the energy of the emitted photon and $E_e$ is the energy of the incident electron. $z$ has to lie between $z_{\text{min}}$ and $z_{\text{max}}$, where $z_{\text{min}}$ is an infrared cutoff to protect against the pole at $z = 0$ and $z_{\text{max}} = 1 - M^2_e/s$ is the upper limit on the energy of the photon in order to produce an excited fermion with mass $M^2_e$. The center of mass energy is denoted by $s$ and the mass of the electron by $m_e$.

To render $f_\gamma$ integrable, $f_\gamma$ is set constant to $f_0$, for $0 < z < z_{\text{min}}$ subject to the condition

$$\int_0^{z_{\text{max}}} f_\gamma(z)dz = \int_0^{z_{\text{min}}} f_0dz + \int_{z_{\text{min}}}^{z_{\text{max}}} f_\gamma(z)dz = 1$$

Therefore the energy of the incident beam electron is replaced by $E'_e = (1 - z)E_e$ on a event by event basis. The generator then needs three random variables, which have to be thrown in order to determine its three independent kinematic variables $W, Q^2$ and $z$. The cross section for bremsstrahlung events peaks at very small angles, therefore the radiated $\gamma$ escapes down the rear beam pipe. Hence it is not explicitly simulated except for its effect on the available energy in the collision.

The initial and final state parton showers are simulated by LEPTO 6.1 [55] and the hadronization by JETSET 7.3 [56] (see next section).

The elastic cross section and kinematics were also compared with two elastic $e^*$ generators, written independently by myself and N. Roocroft [57] and found to be in agreement.
5.3 Background events for the search signal

Since the various decay modes of $e^*$ can leave signatures, that have very different topologies in the detector, almost all $ep$ processes had to be checked as possible contributions to the background of the search signal. The three most important backgrounds are from NC and CC deep inelastic scattering and Compton scattering. Photoproduction events also had to be considered, but their contributions were vanishingly small after the final analysis cuts (see chapter 7). The modelling of the $ep$ interaction [60] is described in the following sections.

5.3.1 Modeling of $ep$ events

Figure 5.2 gives a schematic picture of Monte Carlo event generation in $ep$ processes. The central part of the event generation consists of the simulation of the hard scattering process, where partons $p_i$ and $p_j$ scatter and produce partons $p_k$ and $p_l$. This part can be calculated perturbatively. After the hard scattering, the final partons $p_k$ and $p_l$, as well as the electron and proton remnants, must fragment and decay in order to produce the stable final state particles. In DIS processes the particle coming from the electron line is a direct boson and the hard scattering is always electroweak, at lower $Q^2$ the photon can be resolved and behave as a hadron or as a $q\bar{q}$ pair and produce a remnant.

5.3.2 Perturbative QCD phase

The hard scattering description plus the fragmentation of the outgoing partons are not sufficient to describe $ep$ data. When modelling processes that involve strong inter-
actions, the effects of the hard process are smeared by fragmentation and hadroniza-
tion effects. The initial and final state partons can radiate soft gluons and thereby
change the hadronic final state. In general different models use either of two basic
classes of QCD calculations to describe those corrections [58].

Within Fixed order QCD models the matrix elements of these radiative correc-
tions are calculated exactly up to order $\alpha_s$ or $\alpha_s^2$, which is the highest order available
so far. Although matrix elements are exact, their practical usefulness is limited by
the lack of higher order corrections. A cutoff against collinear and soft gluon emis-
sion, usually in terms of a minimum invariant mass of the parton pair, $y_{\text{min}} = \frac{M_{jj}}{E_{cm}}$ is
applied to insure against unphysical cross sections.

QCD shower models or QCD cascades are based on calculations which derive prob-
abilities for gluon emission and decay by summing the leading (and sometimes also
next to leading) logarithms of the perturbative series to all orders. Depending on
the total center of mass energy of the reaction and on the cutoff parameter of
the gluon emission, such models can generate large numbers of secondary quarks and
 gluons. These models however, do not include the full fixed order matrix element for
parton splitting. Some of the QCD shower models may correct for this deficiency by
a probabilistic reweighting method according to the first order matrix element at the
$q \to qg$ vertex.

An alternative approach to QCD cascades is given by the Colour Dipole Model
(CDM). In DIS, the scattered quark and the remnant diquark form a colour dipole,
which acts as a colour antenna and emits further partons, in analogy to electromag-
netic radiation from a conventional antenna. The radiated parton can then in turn form dipoles with other partons and thereby produce a dipole cascade.

5.3.3 Hadronization Phase

The transition of the final state quarks and gluons into final hadrons are described in hadronization models. Only phenomenological models are available for this phase. The model used in most generators at ZEUS is the LUND string hadronization model [59] implemented in JETSET. Colour strings are formed between the colour charges and gluons, and each string then fragments into several $q\bar{q}$ pairs, out of which colourless hadrons are formed. Dynamical effects on the overall distribution of hadrons which are predicted by this string picture were first observed in 1980 by the JADE collaboration at the PETRA $e^+e^-$ storage ring. String models are used both within QCD shower and fixed order QCD models.

5.3.4 Decays of unstable hadrons

The last step to generate final state particles that can be run through the detector is to let the unstable hadrons that were produced in the hadronization phase decay according to known branching ratios. This is done by implementing simple decay tables which are available e.g. from the particle data book [3].

The various stages of hadronic decays are shown in figure 5.3 for $e^+e^-$ collisions at LEP energies.
5.3.5 *ep* Generators

The modeling described above is implemented in various generators. For the main background in this analysis, NC and CC DIS, two different generators were used to have a better estimate of the systematic error. The ones that were used in this analysis are described below.

**HERACLES**

HERACLES [61] generates NC and CC deep inelastic scattering events taking into account electro-weak radiative corrections to first order. These include interference of leptonic and quarkonic radiation, and the complete one-loop virtual corrections. The program is accurate over phase space regions where $y(1 - x)^2 \geq 0.004$. Inelastic Compton events are also generated by HERACLES, whereas the elastic Compton scattering can not be described because of a low $W^2$ cutoff, where inelastic versus elastic indicates whether the proton was broken up or not.

HERACLES itself generates events at the parton level. For the hadronization of the event an interface with a hadronization and fragmentation package is needed. The DJANGO program [64] provides an interface to LEPTO[63], ARIADNE [65] and JETSET[55].

**LEPTO**

LEPTO is a complete generator providing modelling of the hard scattering process and hadronization. First order QCD matrix elements for gluon radiation $\gamma q \rightarrow qg$
and boson-gluon fusion $\gamma g \rightarrow q\bar{q}$ are implemented and higher order QCD radiation is treated using parton showers. This gives the best of all worlds: exact calculations of the first order processes, which are treated with the matrix element method (e.g. hard gluon radiation), plus an additional softer parton shower for higher than first order processes in the leading log approximation. Hadronization is performed using the Lund string model.

**ARIADNE**

ARIADNE [65] is a program for the simulation of QCD cascades, implementing the colour dipole model. It is not a complete event generator, but needs an interface to another program like LEPTO for the simulation for the hard scattering and to JETSET for the fragmentation of the partons into final state leptons.

**HERWIG**

HERWIG [62] is a general purpose event generator. The generator can also describe hadron-hadron and lepton-lepton processes. QCD corrections for the lepton-hadron mode are performed by either parton shower or by $O(\alpha_s)$ QCD matrix element. Covering not only hard lepton-hadron, but also soft hadron-hadron collisions HERWIG is particular well suited to generate photoproduction events.

**COMPTON**

COMPTON2.0 [66] is a special purpose generator, dedicated to produce elastic and inelastic QED Compton events. It is interfaced with HERWIG and JETSET for the description of the hadronization and fragmentation. The inelastic Compton events
from HERACLES and COMPTON2.0 were compared and found to agree reasonably well.

Since some of the processes have large integrated cross section, it is advantageous to limit the phase space over which one integrates only over those regions which are populated by signal events which are being investigated. This can lead to significant reductions in Monte Carlo production of background events. Since the generation of Monte Carlo events can take up to 4 minutes per event even using RISC chip machines, this reduction can significantly improve the efficiency with which Monte Carlo events are generated. Care has to be taken to estimate the systematic error introduced by those “generator level cuts”. One has to estimate the number of events that would have been moved in phase space enough due to experimental effects, such that they had been detected in the signal region although generated outside of it. The generator level cuts that were used in this analysis were all tuned such that such effects of this sort were minimized ($\leq 2\%$). The classes of events that were generated for this analysis are listed in table 5.1.
Table 5.1: Background processes and their Monte Carlo events used in this analysis.

<table>
<thead>
<tr>
<th>Process</th>
<th>Generator</th>
<th>Structure</th>
<th>Hadronization</th>
<th>Events</th>
<th>Cuts</th>
<th>L (pb^-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIS NC</td>
<td>Heracles+ Ariadne</td>
<td>MRSD0</td>
<td>Dipole Cascades</td>
<td>68000</td>
<td>$E_t \geq 14.\text{GeV}$</td>
<td>3.1</td>
</tr>
<tr>
<td>DIS NC</td>
<td>Lepto Heracles+ Ariadne</td>
<td>ELHQ1</td>
<td>ME + PS</td>
<td>20000</td>
<td>$E_t \geq 30.\text{GeV}$</td>
<td>3.2</td>
</tr>
<tr>
<td>DIS CC</td>
<td>Lepto Heracles+ Ariadne</td>
<td>ELHQ1</td>
<td>ME + PS</td>
<td>1000</td>
<td>No Cuts</td>
<td>14.</td>
</tr>
<tr>
<td>DIS CC</td>
<td>Compton</td>
<td>Compton2.0</td>
<td>Brasse Jetset</td>
<td>500</td>
<td>No Cuts</td>
<td>7.1</td>
</tr>
<tr>
<td>$\gamma P$ dir</td>
<td>Herwig</td>
<td>MRSD0</td>
<td>Jetset</td>
<td>100000</td>
<td>No Cuts</td>
<td>0.51</td>
</tr>
<tr>
<td>$\gamma P$ res</td>
<td>Herwig</td>
<td>MRSD0</td>
<td>Jetset</td>
<td>85000</td>
<td>$E_t \geq 20.\text{GeV}$</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25000</td>
<td>$E_t \geq 20.\text{GeV}$</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Figure 5.1: Fraction of $e^*$ cross section in which the proton does not fragment (elastic production). The cross section becomes entirely elastic at high masses, since there is enough energy to break up the proton. Since elastic events leave a clean signal in the detector, the increase in the elastic fraction at high mass improves the detection efficiency in the kinematically most interesting region.
Figure 5.2: Schematic model of ep interactions. FSPS are the Final State Parton Showers and ISPS are the Initial State Parton showers. $x_{1,2}$ are the momentum fractions of the scattering partons corresponding to the momenta $p_{i,j}$, whereas $p_{k,l}$ are the momenta of the partons after the hard scattering process. The hard subprocess can be calculated perturbatively. The initial and final state parton showers have to be treated phenomenologically. The fragmentation of the partons into hadrons is done within the LUND or HERWIG model.
Figure 5.3: Stages of hadronization of jets [53]. QCD plus hadronization models which are typically used to model hadronic final states in $e^+e^-$ annihilation. The typical momentum scale where hadronization sets in is given at the bottom axis (taking LEP energies as an example).
CHAPTER VI

The Trigger and Data Selection

6.1 Zeus Trigger in 1993

The design and layout of the ZEUS trigger system was described in chapter 4.4-4.6. The Zeus trigger system was completely operational in 1993 and nearly of all the components in the design specifications were fully implemented [67]. Since HERA only ran a fraction of the design luminosity, the background rate from beam interactions was sufficiently low that it was possible to keep the good physics without utilizing the full power of the trigger system. Each of the trigger levels was therefore run at a significantly lower rate than they were designed for.

The time averaged rates for the three trigger levels for 1993 were:

- FLT output: 117 Hz
- SLT output: 40 Hz
- TLT output: 3.6 Hz

In the following sections timing cuts as well as cuts on the longitudinal energy variable are commonly used, they are explained in detail in chapter 7.1.
6.1.1 FLT

The FLT reads data in at every beam crossing (10 MHz). It made use of the information from the calorimeter, the muon chambers, the lumi detectors, the C5 beam monitor counters, the Vetowall and the CTD. The calorimeter first level trigger (CFLT) is the most important of these. It ran at about 110-120 Hz. The CFLT quantities used for the FLT trigger decision were based on the information of the electromagnetic and hadronic regions and subregions of the calorimeter. During the initial phase of the 1993 operation the FLT configuration were modified and tuned, but most of the data was taken with a stable configuration. The FLT acceptance rate for events with $Q^2 \geq 10 \text{ GeV}$ is above 96%. This was a logical OR of the following trigger classes.

**CAL trigger:**

Cal-E: total energy in the calorimeter $\geq 15 \text{ GeV}$

EMC-E: total energy in the electromagnetic section of the calorimeter (EMC) $\geq 10 \text{ GeV}$:

$E_t$: total transverse energy $E_t \geq 11.5 \text{ GeV}$; where $E_t = \sum_i \sqrt{E_{x_i}^2 + E_{y_i}^2}$ and $i$ runs over all calorimeter cells (scalar sum)

BEMC-E: energy in the electromagnetic section of the barrel calorimeter (BCAL EMC) $\geq 3.4 \text{ GeV}$

REMC-E: energy in the electromagnetic section of the rear calorimeter excluding towers directly adjacent to the beam pipe (RCAL EMC) $\geq 2 \text{ GeV}$
**REMC-th:** RCAL EMC including a scaled energy contribution from the towers directly adjacent to the beam pipe (REMC threshold sum) $\geq 3.75$ GeV. The scaling is done in order to keep some sensitivity to low $E_t$ events without increasing the trigger rates too much. This setting allows for the study of resolved photoproduction events, where the low $E_t$ photon remnant is deposited in the rear part of the detector.

**LUMI tagged:**

Energy deposited in LUMIE detector by an electron $\geq 5$ GeV $\cdot$ AND ($\cdot$REMC-E $\geq 0.5$ GeV $\cdot$ OR $\cdot$ REMC - th $\geq 1.25$ GeV)

**Muon trigger:** Various FMuon triggers: a track in forward muon detector and B-RMUON triggers: a track in Barrel or Rear muon detector. All Muon triggers require calorimeter energy and a CTD FLT track.

Although an event could be triggered in any of the above categories, all $e^\ast$ events were triggered in $CAL - E, EMC - E, E_t, BEMC_E$. The trigger efficiencies are very high in all decay modes of the $e^\ast$, $e\gamma$: 100%, $eZ$: $\geq 99\%$ and $\nu W$: $\geq 88\%$. 
6.1.2 SLT

The SLT rejected events based on timing cuts and spark criteria. Sparks can occur in the photomultipliers of the calorimeter, when a large amount of charge has built up and suddenly discharges. Those discharges can fake large energy deposits in the calorimeter. They can be recognized because of energy deposits which are too large as to come from \( ep \) interactions and because of large asymmetries between left and right cells. The times from all photomultipliers (PMT) with energy above 500 MeV were averaged in each section of the calorimeter (FCAL, BCAL and RCAL) separately. Only events with time measurements of less than 8 ns for each section were triggered. This reduces the trigger rate due to beam gas background and in particular due to sparks, since sparks are not correlated to the beam timing. The main reduction was achieved through RCAL timing (52\%). Total SLT reduction rate was between 60-85\%.

6.1.3 TLT

The TLT rejected events based on timing cuts, spark criteria and cosmic rejection. Timing was calculated from all cells that had a left-right imbalance of less than 20\% and each photomultiplier had more than 200 MeV. If \( T_{FCAL} - T_{RCAL} \) or \( T_{GLOBAL} \geq 8 \) ns, then the event was rejected. Figure 6.1 shows the timing distributions for a run in 1993. The effectiveness of the timing cuts at TLT can clearly be seen. The C5 beam pipe monitors measure the electron and proton bunch pass-through times -3.15
meters downstream of the nominal interaction point. Events with C5 times which are inconsistent with ep interaction were rejected. The timing cuts reduce the background due to beam-gas significantly (see also next section on timing requirements). The TLT rejection rate from data quality requirement (TLT VETO) was \( \sim 45\% \).

Events that were not vetoed had to either fall into at least one of the Physics categories or have a "passthrough" flag, i.e. a fixed ratio of one out of 100 events is passed on irrespective of TLT veto. One out of every 60 events that pass the TLT veto is passed through irrespective whether it is selected by one of the categories. To enhance the sample of passthrough events with a good vertex, also one out of every 60 events that pass the TLT veto and have a good vertex is passed through. The overall reduction rate of TLT (VETO and PHYSICS SELECTION) was \( \sim 90\% \).

There are five physics categories available for the triggering of events:

- Deep Inelastic Scattering
- Soft Photoproduction
- Boson Gluon Fusion (hard photoproduction)
- **Exotic Physics**
- Muon Physics

Each of those categories had several subtriggers. The TLT category motivated by the exotic search interest has several subtriggers which are described here.

**Exotic Physics**

NC: NC DIS like events as indicated by \( E - P_z \geq 20 \).

CC: CC DIS like events with missing transverse momentum, has to be above 9
GeV, where transverse momentum is calculated as \( \sqrt{(\sum_i E_{x_i})^2 + (\sum_i E_{y_i})^2} \) without including any cells in the inner ring of FCAL in the sums.

**HiEt**: Events with scalar transverse energy \( E_t^{\text{no\ ring}} \) has to be greater than 30 GeV, where the scalar sum \( E_t^{\text{no\ ring}} \) does not include any cells in the inner ring of FCAL \( \cdot \) \( \text{AND} \) a TLT vertex. At TLT level the track and vertex reconstruction is done using only z-by-timing in SL 1,3,5.

**NCHiEt**: Events with scalar \( E_t^{\text{no\ ring}} \) \( \geq 8 \text{ GeV} \) \( \cdot \) \( \text{AND} \) \( E - P_z \geq 20 \text{ GeV} \) \( \cdot \) \( \text{AND} \) a TLT vertex

**Lone Pair**: Events that have two or more Island clusters \( \cdot \) \( \text{AND} \) (a TLT vertex \( \cdot \) \( \text{OR} \) \( 90\% \) of the energy of the Island clusters are in the EMC part of the calorimeter).

The Island finder is based on calorimeter information alone. It is a nearest neighbor algorithm that identifies clusters by considering the energy gradient between adjacent towers [68].

**IslandEt**: Events with \( E_t \geq 20 \text{ GeV} \) \( \cdot \) \( \text{AND} \) a TLT vertex. The calculation of \( E_t \) is based on all Island clusters except those in the FCAL with \( r \leq 30 \text{ cm} \).

**Muons**: Events with hits in one of the muon chambers \( \cdot \) \( \text{AND} \) a track in CTD \( \cdot \) \( \text{AND} \) a TLT vertex

The Exotics category, \( i.e. \) a logical OR of all of the above categories, had a trigger rate between 1-2 Hz, but only between 5-15 \% of all TLT triggered events were unique exotics events. The DIS categories (NC and CC) used by the exotics group are the same as of the DIS groups. The NC and CC categories are the two most important
triggers in this search. Since events with a well identified electron and a $\Sigma E - p_z$ value (see section 7.1) that is consistent with the scatter of an electron into the detector or large missing transverse momentum are certainly selected in the DIS category, but are also the essential criteria of a large number of exotic signatures.

**Recorded data**

The 7 million events that were triggered and recorded correspond to 554 nb$^{-1}$. All events were written to tape for further processing. The contamination from non $ep$ physics is estimated to be of the order of 10%. This data roughly divides into the following sample of physics events.

For the final analyses $\leq 1$ million events will be used:

- Soft photoproduction 700 k events
- Hard photoproduction 100 k events
- DIS 50 k events

**6.2 Reconstruction and Selection**

Events that pass the three trigger levels are fully reconstructed on a farm of high performance workstations, based on multiprocessor Silicon Graphics computers. Following the reconstruction part of the program, the events are analyzed by a series of physics filters defined by the different physics analysis groups. Based on these filters the reconstructed events can be selected to be stored on the common usage disk (zarah disks). At this point of the data flow each selected event has a trigger word, identifying it as a candidate of one or more of the physics groups, written into its
header. This allows for fast selection of the events at a later time. Figure 6.1 shows the layout of the data acquisition and selection chain for this analysis.

For this analysis only events that were selected by the "Exotics Analysis" group are used. The cuts for this class are described here.

6.2.1 Data quality cuts

Beam-Gas and cosmic event suppression with timing cuts

At a vacuum of $10^{-9}$ Torr and an effective sensitive length downstream of the detector of 100 m the rate from collisions between the proton beam and the rest gas would be $O(100 \text{ kHz})$. Such non-physics collisions occurring in front of the detector deposit energy in the rear calorimeter, where they enter from the rear side as compared to good $ep$ events. The energy deposited from such beam gas events can exceed what is allowed for $ep$ events.

The arrival times of the particles created in beam gas events are very different from the ones in $ep$ events. In beam gas events the energy is deposited before the actual bunch crossing occurs, whereas the energy in $ep$ events must be deposited after the bunch crossing or interaction time. Figure 6.2 shows the difference between the timing from a beamgas event and an $ep$ event. The time when the energy is deposited in the calorimeter can be measured by the timing of the individual pulses in each photomultiplier tube (PMT) with excellent precision. The FCAL, BCAL or RCAL times $t_F$, $t_B$ and $t_R$ are then given by a suitable average over the cells in FCAL, BCAL or RCAL respectively. The time measured with the calorimeter is offset by the
time it takes a highly relativistic particle to reach a particular cell in the calorimeter. After accounting for the time of flight from the nominal interaction point (NIP) to the calorimeter cell the $ep$ events have then $t_f = 0$ ns and $t_r = 0$ ns. On the other hand when beam gas events deposit energy in RCAL, then $t_R$ differs from $t_f$ by the time it takes particles to travel the distance RCAL-FCAL which is approximately 11 ns. For beam-gas events with energy in RCAL, we expect therefore $t_R = -11$ns, where the minus sign indicates that the signal is too early. Therefore beamgas events are clearly distinguishable from $ep$ events in the $t_R - t_F$ vs. $t_R$ plane. Figure 6.3 shows the distribution of the signal time measured in the RCAL versus the difference $t_f - t_R$ between signal times seen in FCAL and RCAL.

The timing can further be affected by the displacement of the bunches and the length of the individual bunches. For beam gas events $t_f - t_R$ is independent of the proton bunch length, whereas for $ep$ events $t_f - t_R$ is smeared by both electron and proton bunch length. Since the electron bunch is much shorter than the proton bunch the width of $t_f - t_R$ mainly depends on the proton bunch length and introduces an uncertainty of $\sim 1$ns. A systematic displacement of the bunches can be corrected by another overall shift of the timing constants.

The timing resolution is a function of energy. The resolution of the time measurement of one calorimeter cell is $0.4 + 1.4/E^{0.65}$ ns. The global time for the calorimeter is determined from the time reconstructed in the individual channels by forming an energy weighted average over the channels in R, F and BCAL. Channels with insufficient energy or channels that have fired due to sparks are not included in the
averages.

The calorimeter timing can also be used to reject events from interaction of cosmic particles in the detector. Since those particles, mainly muons, enter the detector from the outside the difference of the the upper and the lower half of the calorimeter $t_u - t_d$ is one way to identify those type of events. Future plans on background suppression include the use of times from 16 different regions of the calorimeter for the trigger, i.e. to consider $t_i - t_j$ where $i$ and $j$ run over all regions.

Thus in order to reduce background the timing cuts for the 1993 data were set in the following way:

\[-6\text{ns} \leq t_F \leq 6\text{ns}\]
\[-6\text{ns} \leq t_R \leq 6\text{ns}\]
\[-8\text{ns} \leq t_G \leq 8\text{ns}\]
\[-6\text{ns} \leq t_F - t_R \leq 6\text{ns}\]
\[-8\text{ns} \leq t_u - t_d \leq 8\text{ns}\]

Figure 6.4 clearly shows the effectiveness of the above cuts to reduce beam-gas background.

Events with a time measurement from the C5 counters that is inconsistent with an $ep$ collision were rejected. Events which had little energy ($\leq 1$ GeV) in the whole calorimeter except for one cell with a dead PMT were rejected. This is an effective protection against spark triggers.
Exotic Subcategories

In addition to the above data-quality-cuts the events have to be in one of six exotic subcategories in order to be selected. These slots have a similar structure as the TLT categories, but with tighter cuts.

NC: \( E - P_z \geq 25 \) and at least one electron above 4 GeV. Events with isolated muons are rejected to reduce background due to cosmics. Electrons are identified by the LOCAL, ELEC5 or EEXOTIC electron finder. ELEC5 and EEXOTIC use a similar algorithm which is described in section 7.1. LOCAL is based on the ISLAND algorithm [68]. An "island" cluster is checked for its transverse size, electromagnetic to hadronic energy ratio and energy distribution in order to identify it as an electron.

CC: The transverse momentum (without including any energy in the inner ring of FCAL) has to be above 8 GeV \( \cdot AND \) cosmic ray rejection.

HiEt: transverse energy (without including any energy from the inner cells of the calorimeter) has to be greater than 30 GeV \( \cdot AND \) a vertex has to be found based on CTD and VXD tracks or hits (TC or VC vertex) \( \cdot AND \) cosmic ray rejection.

NCHiEt: \( E - P_z \geq 20 \) GeV \( \cdot AND \) \( E_t \geq 8 \) GeV \( (E_t \) calculated as above) \( \cdot AND \) good VC vertex \( \cdot AND \) cosmic ray rejection \( \cdot AND \) an electron above 4 GeV (same electron identification as in NC category).

IslandEt: \( E_t \) based on the Island cluster finder \( \geq 20 \) GeV \( \cdot AND \) good VC or TC vertex \( \cdot AND \) no isolated muons
**Jet:** Events with jets with transverse momentum above 15 GeV \( \cdot \) AND \( \cdot \) good TC or VC vertex. Jets are identified based on the UA2 algorithm, that searches the calorimeter for clusters with a fixed \( \eta - \phi \) cone.

**Lone Pair:** A pair of Island clusters with either large electromagnetic to hardronic energy ratio \( \cdot \) OR \( \cdot \) a VC or TC vertex

**TauB:** Special category designed to save flavour changing leptoquarks, \( E_t \) (island) \( \geq 30 \) GeV \( \cdot \) AND \( \cdot \) \( p_t \geq 10 \) GeV \( \cdot \) AND \( \cdot \) \( E - p_z \geq 20 \) \( \cdot \) AND \( \cdot \) no isolated muons \( \cdot \) AND \( \cdot \) a VC or TC vertex

**Muons:** Track in one of the muon detectors \( \cdot \) AND \( \cdot \) matching track \( \cdot \) AND \( \cdot \) good TC or VC vertex.

The trigger word that is written into the event header contains the information within which of the exotic subcategories the event was selected. Analyses that search for exotic phenomena can then select events with only the bit pattern, that fits their specific search pattern.

All background and signal Monte Carlo events were run through a simulation of this selection process. The efficiencies with which the \( e^+ \) Monte Carlo events pass a logical OR of the above slots is listed in table 6.1. The efficiencies for all masses and all decay modes are above 83 \%.
Table 6.1: Acceptance of $e^* \rightarrow e\gamma, eZ$ and $\nu W$ signal Monte Carlo through storage disk selection (ZARAH). This constitutes the experimental acceptance due to detector and trigger effects.

<table>
<thead>
<tr>
<th>decay</th>
<th>$e\gamma$</th>
<th>$eZ$</th>
<th>$\nu W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass</td>
<td>50</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>250</td>
<td>290</td>
</tr>
<tr>
<td>efficiency %</td>
<td>99</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

6.3 The excited fermion search sample

From all the events, that were written to storage disk as exotic events only the subset that is relevant for the search for excited fermions was further analyzed in this study. Events that were in any of the above categories except Lonepair or TauB, and fulfilled further cuts were selected and written to the local OSU user disks for convenient access as the excited fermion search sample.

- $E - P_z \leq 75 \text{ GeV}$
- $E_{total} \leq 900 \text{ GeV}$
\begin{align*}
\text{\vert vertex \vert} \leq 75 \text{cm} & \quad \text{AND} \quad \begin{cases} 
N_{\text{electron}} > 1 \\
\text{OR} \\
p_t > 8 \text{GeV} \\
\text{OR} \\
(E_t \geq 20 \text{ AND } (E - p_z) \geq 20) \\
\text{OR} \\
(E_t \geq 50 \text{ AND } (E - p_z) \geq 10)
\end{cases}
\end{align*}

All events were checked for the bunch crossing numbers, in order to ensure that
the event is due to an ep crossing. Events which were taken during runs in which the
calorimeter or machine performance was downgraded were also rejected.

A total of 84078 events were written out to excited fermion search sample and
used in this analysis (preselected events). At this level the integrated luminosity of
the data sample those exotic candidates were selected from corresponds to 554 nb^{-1}.

The cumulative effects of TLT, ZARAH and PRESELECTION cuts on the search
signal can be found in tables 6.2.
Table 6.2: Efficiency of $e^* \rightarrow e\gamma, eZ$ and $\nu W$ signal Monte Carlo through PRESELECTION. The efficiencies do not include the experimental acceptances (detector and trigger).

<table>
<thead>
<tr>
<th>decay</th>
<th>$e\gamma$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>mass</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>efficiency %</td>
<td>96</td>
<td>97</td>
</tr>
<tr>
<td>decay</td>
<td>$eZ$</td>
<td></td>
</tr>
<tr>
<td>mass</td>
<td>125</td>
<td>150</td>
</tr>
<tr>
<td>efficiency %</td>
<td>98</td>
<td>99</td>
</tr>
<tr>
<td>decay</td>
<td>$\nu W$</td>
<td></td>
</tr>
<tr>
<td>mass</td>
<td>125</td>
<td>150</td>
</tr>
<tr>
<td>efficiency %</td>
<td>99</td>
<td>100</td>
</tr>
</tbody>
</table>

The $e^* \rightarrow e\gamma$ efficiency decreases slightly with increasing mass, since the electron and photon are boosted more forward. This can lead to the loss off one or both decay products through the forward beam hole. The slight dip at $M_{e^*} = 50$ GeV is due to the kinematics of the production mechanism. For masses below 53.2 GeV (twice the beam energy) the $e^*$ is produced in the backward direction and in asymmetric decays the more energetic one of the the two decay products can escape through the rear beam hole. If one or both decay products are lost, the event can be rejected because of either insufficient energy and $E - P_z \leq 25$ GeV or missing vertex.

In the $eZ$ channel both decay products are produced in the forward direction for all masses. For mass points just above the $Z$ mass the lepton has almost no energy and the detection efficiency is low. Since the region up to 100 GeV has been
thoroughly searched by previous experiments [3] [4], the current search starts above 100 GeV. Due to the wider showering of the $Z$ the efficiency in this channel remains higher than in the $e\gamma$ channel up to the kinematic limit.

The $\nu W$ channel is less efficient at all masses due to the escaping neutrino, this is particularly true at high masses where one of the $e^*$ decay products decays escapes through the forward beam hole. If the $W$ partially escapes then the event cannot be triggered. For the leptonic decays (30% branching fraction) the folding of the decay products in the forward direction makes the detection efficiency of this mode more sensitive to this kinematic effect.
Figure 6.1: The difference between FCAL and RCAL time measurements are plotted versus RCAL times. The times are measured by the calorimeter and are available with full width digitization at the second level trigger stage (see figure 4.5). This shows the capability of TLT to reject beam gas events based on timing cuts at TLT level. $ep$ events must occur at $T_{FCAL} \sim 0$ and $T_{FCAL} - T_{RCAL} \sim 0$. The other peak is due to beam gas events occurring upstream of the detector.
Figure 6.2: Schematic view of the timing differences between an $ep$ event and a beam gas event as viewed in the detector. Beam gas events that occur close to the nominal interaction point (within $\sim 150$ cm) cannot be rejected based on timing considerations.
Figure 6.3: Schematic layout of the data chain down to the 'Excited Lepton Selection' data. The data flows from top to bottom. The strategy of TLT is shown in figure 4.6.
CHAPTER VII

The hunt for e*'s

Excited electrons always decay to either an electron (or a neutrino) and a gauge boson. Figure 7.0.1 shows the Feynman diagram for the production and decay of an e*. Since the heavy gauge bosons have either four or five decay modes (W or Z), the signatures of the e* vary considerably. The various decay modes of the e* fall into two broad categories though. Events that are of the neutral current type (NC) and of the charged current type (CC), as listed in table 7.1. The signature of the NC sample is a well identified electron and no missing transverse momentum, as the scattered electron is detected and balances the jet from the struck hadronic system. The main characteristic of the CC sample is missing transverse momentum due to the neutrino escaping the detector. It should be pointed out that CC interactions are generally high $Q^2$ events, in comparison to the production of e*'s which dominate in the low $Q^2$ region, i.e. the same topology can be interpreted as the result of two very different kinematic processes. Although the NC cross section peaks at low $Q^2$, the final event selection in the NC-like modes will also be dominated by high $Q^2$ events. With a set of base cuts clean NC and CC samples were established. This is explained in detail in section 7.1. These agree well with Monte Carlo predictions. The search for any signals which disagree with the standard model predictions are based on those two
Table 7.1: $e^*$ decay modes

<table>
<thead>
<tr>
<th>$e^*$ decay</th>
<th>boson decay</th>
<th>final state</th>
<th>BR % (boson)</th>
<th>Topology</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^* e\gamma$</td>
<td>$e\gamma$</td>
<td>100.</td>
<td>2 em clusters</td>
<td>NC</td>
<td></td>
</tr>
<tr>
<td>$e^* eZ$</td>
<td>$ee$</td>
<td>$eee$</td>
<td>3.3</td>
<td>3 em cluster, high $E_t$</td>
<td>NC</td>
</tr>
<tr>
<td>$e^* eZ$</td>
<td>$\tau\tau$</td>
<td>$\tau\tau$</td>
<td>2.3</td>
<td>1 em cluster, high $E_t$</td>
<td>NC</td>
</tr>
<tr>
<td>$e^* eZ$</td>
<td>$\nu\nu$</td>
<td>$\nu\nu$</td>
<td>20.</td>
<td>1 em cluster, missing $p_t$</td>
<td>CC</td>
</tr>
<tr>
<td>$e^* eZ$</td>
<td>$q\bar{q}$</td>
<td>$e$ hadrons</td>
<td>70.</td>
<td>1 em cluster, high $E_t$</td>
<td>NC</td>
</tr>
<tr>
<td>$e^* \nu W$</td>
<td>$\tau\nu$</td>
<td>$\nu\nu\nu$ hadrons</td>
<td>6.6</td>
<td>missing $p_t$, jets</td>
<td>CC</td>
</tr>
<tr>
<td>$e^* \nu W$</td>
<td>$q\bar{q}$</td>
<td>$\nu$ hadrons</td>
<td>68.</td>
<td>high $E_t$, missing $p_t$, jets</td>
<td>CC</td>
</tr>
</tbody>
</table>

samples.

The channels which are considered in this analysis are listed in table 7.1. The $\tau$ channel in $W$ and $Z$ decay modes were not searched for separately, but are included by the hadronic search modes of the $W$ and $Z$. The maximally detectable fraction of the $eZ$ decay mode with the NC sample is 75% and 20% with the CC sample and of the $\nu W$ decay mode with the CC sample it is 75%.

The decay modes of $e^*$ via the $Z$ and $W$ into the final state $e\nu\nu$ can not separated. Candidates found in this channel are included in the $eZ$ search mode. Since this channel increases the acceptance in the $\nu W$ by only 10%, the $W \rightarrow \nu e^-$ mode was not included in the $e^* \rightarrow \nu W$ search.
7.1 The final analysis samples

The cuts that were applied to establish the NC and CC fiducial samples are described here.

Timing

Events in both categories were required to pass tighter calorimeter cuts. By cutting on the difference of the average of the forward calorimeter time and the rear calorimeter time (F-R time) one is able to discriminate against beamgas events which tend to have hits in the rear calorimeter well before the forward calorimeter (see section 6.2). The global time cut was set to 6 ns and the up-down time cut was set to 6 ns which reduces the number of cosmic events (see section 6.2).

Vertex

The good physics events of the total recorded data set have an approximately Gaussian z vertex distribution with a mean of $z=-6.5$ cm and a $\sigma_z = 12$ cm, as measured with the VCTRACK vertex reconstruction package [70]. For the final analysis samples in this analysis vertices from either of two vertex reconstruction routines were used. VCTVTX uses any hits in the vertex chamber and the CTD and fits them to calculate the vertex, RECVTX uses the reconstructed and fitted tracks from the VXD, the CTD and the muon detectors to calculate the vertex. The vertex cut was set conservatively between -50 cm and +40 cm for the NC and CC sample. Only if no VCT vertex was available the REC vertex was used, this is only the case in less than
10% of the preselected events. If neither vertex could be calculated the event was rejected. Since the vertex cut was set at a value greater than three times the sigma of the true vertex distribution, the difference between the 2 vertex reconstruction packages is marginal (mean ≤ 1%, sigma ≤ 1%) with respect to this cut. Figure 7.1.1 shows the vertex distributions (REC and VTX) for preselected data.

Unless otherwise stated all events used in the following analysis have these timing and vertex cuts applied.

Longitudinal energy variable

For the NC sample the value of the longitudinal energy variable ($\delta = \sum E - p_z$ where the sum runs over the entire calorimeter) was used to reject events. When all decay products are detected, except for highly relativistic particles escaping through the forward beam pipe, then $\delta$ is a conserved quantity.

$$-E_e + E_p = p_{lz} + p_{jz} + p_{rz} \quad (7.1)$$

$$E_e + E_p = E_{lz} + E_{jz} + E_{rz} \quad (7.2)$$

$E_e$: electron beam energy

$E_p$: proton beam energy

$E_{lz}, p_{lz}$: energy and z momentum of scattered lepton

$E_{jz}, p_{jz}$: energy and z momentum of the recoiling hadronic parts

$E_{rz}, p_{rz}$: energy and z momentum of the proton remnant
Combining (7.1) and (7.2) and breaking it up into a part which is detected and one which is not:

\[ 2E_e = E_{\text{total}} - p_{z-\text{total}} = E_{\text{vis}} - p_{z-\text{vis}} + E_{\text{nvis}} - p_{z-nvis} \quad (7.3) \]

\( \text{vis (nvis): part of energy and momentum flow that is (not) detected} \)

So assuming \( E_{\text{nvis}} - p_{z-nvis} = 0 \), i.e. the undetected particles coming out of the interaction are highly relativistic or massless and have no transverse component then \( \delta \) is twice the electron-beam energy. Therefore only events with a value of \( \delta \) between 30 and 60 GeV were accepted in the NC fiducial sample. This is a very effective cut against photoproduction events as can be seen from table 7.2. Photoproduction events have \( Q^2 \sim 0 \), therefore the electron is scattered by very small angles only (\( \leq 1^\circ \)) and escapes through the rear beam pipe. Since CC like events stand out through missing transverse momentum due to one or several escaping neutrinos this cut can not be applied to the CC like sample.

**Electron detection**

The best criterion for NC like events is a well identified electron, scattered at a large enough angle so it can be detected in the calorimeter. Almost all the electrons coming from \( e^+ \) decays are very energetic and well isolated, therefore purity against spurious electrons due to \( \pi^0 \)'s or misidentified charged hadrons is paramount in order to minimize the background. It should be pointed out though, that \( e^+ \)'s with masses just above the \( W \) or \( Z \) mass decaying into heavy bosons produce low energy electrons
which have smaller detection efficiencies. This is the single most important loss of
the e* acceptance at low masses.

In order to find electrons the F5STAR electron finder was used. Based on calorimeter
data alone it finds clusters using a cone algorithm. F5STAR does not use tracking
information in its algorithm. It first finds several seeds and calculates a projective
cone from the interaction point centered at those seeds. Then it computes a "probability" for each candidate based on quantities of the cone, such as size, energy
distribution and hadronic to electromagnetic energy ratios. Only seeds with high
"probabilities" are kept.

F5STAR has a high efficiency. In order to test its single electron efficiency the electron
finder was run on NC Monte Carlo events generated with HEARCEL9 and ARIS-ADNE. The following cuts were applied to obtain a meaningful sample to calculate the efficiency of:

(1) $\delta$ between 30 and 60 GeV
(2) VCT vertex between +40 cm and -50 cm
(3) Angle $\theta$ of true electron $\leq 166^\circ$ and energy of true electron $\geq 5$ GeV

Of the events passing the above selection criteria, F5STAR finds in 87% an electron
candidate within a 5° opening angle between the "true" electron and the found
candidate and with less than 5 GeV energy mismatch between the "true" electron
and the candidate, that was found by F5STAR. Figure 7.1.2 shows the variance of
the polar angle and the energy of the "true" electron and reconstructed electron. In
case where there were more than one electron found the maximum variance was plot-
ted. Most importantly though its purity is very high, of the events from the above 
selection only 6% have more than one electron identified by F5STAR. This finder 
was tuned so that it is extremely efficient though at finding second electromagnetic 
clusters in true 2 electron events such as Compton events (see section on Compton 
scattering), where the electrons are well separated. For a sample of Compton Monte 
Carlo events it has a 75% efficiency of correctly identifying a second electromagnetic 
candidate. Its efficiency of finding a second electron candidate as tested on $e^*$ Monte 
Carlo events was above 83% for all masses. The systematic uncertainty of F5STAR 
is discussed in chapter 8. F5STAR is therefore very well designed and tuned for the 
purposes of our search.

7.1.1 The NC fiducial sample

To establish this sample the following set of cuts were applied:

(1) Vertex: $-50 \leq z_{\text{vertex}} \leq 40$ cm
(2) Longitudinal energy variable: $30 \text{ GeV} \leq \delta \leq 60 \text{ GeV}$
(3) Electron: At least one electron found by F5STAR with more than 10 GeV energy 
and scattered by at least $30^\circ$ from its incident direction.

Since in all decay modes the $e^*$ decay products leave significant amount of trans­
verse energy in the detector, one further cut on the value of $E_t$ was introduced.

Applying this cut at the level where the events are generated with the Monte 
Carlo process allows one to produce the simulated events more efficiently. The $E_t$ cut 
was set at 14 GeV at the generator level and at 30 GeV at the analysis level. The $E_t$
distribution of signal Monte Carlo is shown in figure 7.1.3, 7.1.4 and 7.1.5. A cut on $E_t \geq 30$ GeV removes less than 14% of the 50 GeV $e^* \rightarrow e\gamma$ signal, less than 15% of the 125 GeV $eZ$ signal and less than 10% of the 125 GeV $\nu W$ signal Monte Carlo. At higher mass $e^*$ these inefficiencies drop off sharply. A second "generator level" cut was applied to the energy in 25° cone around the rear beam pipe ($E(\text{rear cone}) \leq 5$) GeV. It eliminates most NC DIS events in which the electron is scattered through a small angle from its incident direction. This cut removes an additional 2% from the signal Monte Carlo at the lowest mass. At higher mass points the reduction of the acceptance due to this cut is also less.

(4) $E_t \geq 30$ GeV and $E(\text{rear cone}) \leq 5$ GeV

Applying all the above cuts (1-4) to the preselected data sample leaves 894 events. This is well in agreement with NC Monte Carlo results, the equivalent of 857 events generated with the LEPTO package and 874 events generated with the HERACLES-ARIADNE (HAR) package passed the same set of cuts. The effect of the cuts and the agreement between NC Monte Carlo events and data can be seen in table 7.2 and figures 7.1.6. The cut on the vertex and on $\delta$ reduces the beamgas and photo-production contamination of the data sample. The cut on the polar angle reduces the beamgas background with energy deposits in the RCAL beampipe region. The generator level cuts on $E_t$ and $E(\text{rear cone})$ significantly reduce the events in which the electron has been scattered by a small angle ($\leq 20^\circ$) from the incident direction. The sharp drop in the $\theta$ distribution of NC Monte Carlo which is a result from those cuts can be seen in figure 7.1.6 (bottom). Figure 7.1.7 and 7.1.8 show the $E_t$ and
$E_{\text{(rear cone)}}$ distribution for NC Monte Carlo and data after all NC fiducial cuts (1-3), but without cutting on $E_t$ and $E_{\text{(rear cone)}}$. For these plots another Monte Carlo sample was used that included events over the entire phase space with $Q^2 \geq 4$ GeV without cuts on $E_t$ and $E_{\text{(rear cone)}}$. Figure 7.1.9 demonstrates agreement of the polar angle and transverse energy distributions between the final NC fiducial sample and the DIS Monte Carlo sample. The shift of the distributions of $\delta$ and of the energy of the electron between data and Monte Carlo is due to a lack of dead material in the detector simulation and differences of the shower development between the detector and its simulation. All Monte Carlo statistics are normalized to data luminosity. It also demonstrates that reasonable convergence between Monte Carlo and data events is reached after requiring a 10 GeV electron (see table 7.2). The effect of the fiducial cuts on $e^*$ Monte Carlo events is shown in tables 7.3.

Table 7.2: Cuts used for the fiducial NC sample; the efficiencies of the fiducial NC selection are given in the bottom row.

<table>
<thead>
<tr>
<th></th>
<th>DIS NC MC</th>
<th>$\gamma P$</th>
<th>Compton</th>
<th>Data</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>HERACLES</td>
<td>LEPTO</td>
<td>Direct</td>
<td>Resolved</td>
</tr>
<tr>
<td>Preselection</td>
<td>5990</td>
<td>3440</td>
<td>504</td>
<td>1540</td>
</tr>
<tr>
<td>$E_t \geq 30$</td>
<td>1110</td>
<td>1120</td>
<td>123</td>
<td>482</td>
</tr>
<tr>
<td>$-50 \leq \text{Vertez} \leq 40$ cm</td>
<td>1239</td>
<td>1030</td>
<td>963</td>
<td>104</td>
</tr>
<tr>
<td>$30 \leq \delta \leq 60$ GeV</td>
<td>1020</td>
<td>959</td>
<td>38.9</td>
<td>113</td>
</tr>
<tr>
<td>$e^- \geq 10$ GeV</td>
<td>889</td>
<td>875</td>
<td>0.44</td>
<td>1.65</td>
</tr>
<tr>
<td>$\theta_e \leq 150^\circ$</td>
<td>874</td>
<td>857</td>
<td>0.44</td>
<td>1.65</td>
</tr>
</tbody>
</table>
Table 7.3: Efficiency of $e^* \rightarrow e\gamma, eZ$ signal Monte Carlo through Neutral Current Fiducial cuts.

<table>
<thead>
<tr>
<th>decay</th>
<th>$e\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass</td>
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</tr>
<tr>
<td>efficiency %</td>
<td>78</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>decay</th>
<th>$eZ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass</td>
<td>125</td>
</tr>
<tr>
<td>efficiency %</td>
<td>51</td>
</tr>
</tbody>
</table>

7.1.2 The CC fiducial sample

Transverse momentum imbalance

The most important hallmark of CC events is the imbalance of their momentum in the plane transverse to the beam pipe, due to the escaping neutrino. The transverse momentum distribution of photoproduction events is balanced. None of the events in the $\gamma P$ sample pass the $p_t \geq 13$ GeV cut. A small fraction of NC events have enough $p_t$ to pass this cut and cause a small contamination of the final CC fiducial sample. Therefore the background from Standard Model physics is small. In figure 7.1.10 one sees the $p_t$ distribution of data (top figure) and CC Monte Carlo (bottom figure). The $p_t$ cut at 13 GeV is indicated on the plot.

The final CC cuts

The cross section for CC events ($\sim 64$ pb for $Q^2 \geq 4$ GeV) is much smaller than for NC events ($\sim 280$ nb for $Q^2 \geq 4$ GeV). For establishing this sample neither the electron
requirement nor the cut on the longitudinal energy variable \( \delta \) can be used. The background from beam interactions therefore causes a much larger contamination of the CC fiducial sample. Background events from beam-gas interactions can have large missing transverse momentum, most of it though comes from energy depositions in the calorimeter cells closest to the beampipe. Calculating \( p_t \) coming from calorimeter deposits outside of the first ring of cells around the forward beam hole relative to the \( p_t \) from the entire calorimeter is denoted by \( p_t(\text{no fcone})/p_t \). It measures how much of the net transverse momentum comes from the region close to the forward beampipe. This quantity is an excellent parameter to reduce non-physics contamination of the data sample. Beam gas events can cause contamination with events that deposit their energy in a narrow forward cone which is not balanced in the transverse direction. Therefore a simple and effective way to reduce background is to cut on this quantity. The cut was set at 0.7. Events had to have more than 13 GeV transverse momentum. The distributions justifying the cut on \( p_t(\text{no fcone})/p_t \) for CC Monte Carlo and data are shown in figures 7.1.11. It shows the distribution of \( p_t(\text{no fcone})/p_t \) after the vertex cut and after requiring \( p_t \geq 13 \) GeV and scanning.

Furthermore the Bjorken \( y \) variable \( y_{JB} = \frac{\sum_i E_i - p_z}{2E_e} \), where \( i \) runs over the hadronic contribution of the energy) calculated from the Jaquet-Blondel method was required to be less than 1. This eliminates events that did not come from \( ep \) interactions which can have \( \delta \) values well above twice the electron beam energy.

After requiring this 129 events are left in the data sample, all of which were scanned. 99 events were rejected either as cosmic events or beam-gas events occurring
in coincidence with a good $ep$ collision. This leaves 38 CC candidates eight of which have multiple vertices and vertices that do not line up with tracks. Of those 30 CC candidates which are left 8 have an isolated electromagnetic cluster in the event, which yields 22 "good" CC candidates and 8 candidates in the $ev$ or $ev\nu$ modes. The CC fiducial sample consists of these $22+8=30$ candidates, so that it can be used for both $e^+ \rightarrow nW \rightarrow qq$ and for $e^+ \rightarrow eZ \rightarrow e\nu\nu$ decay modes. Those 22 events constitute the CC fiducial sample. This agrees well with the 23 candidates found by the other group analyzing high-$Q^2$ CC events [71]. If one applies the same cuts to CC Monte Carlo one finds the equivalent of 21 events using the LEPTO generator and 24 events using HERACLES in combination with ARIADNE. Because of the larger contamination of the CC sample it is difficult to compare directly the distributions of the critical variables before scanning the preselected events. Figure 7.5.2 shows the $E_t$ distribution of the final 38 CC candidates and the prediction from Monte Carlo simulations. Table 7.4 lists the effects of the cuts described in this section on Monte Carlo and data. The effect of the fiducial cuts on $e^+$ Monte Carlo events is shown in tables 7.5. The efficiencies listed in the $e^+ \rightarrow eZ$ of table 7.5 are higher than one would expect from the $Z \rightarrow \nu\nu$ branching ratio, since this channel also picks up a small fraction of $Z \rightarrow \mu\mu$ and $Z \rightarrow qq$ channels.
Table 7.4: Efficiencies of cuts for fiducial CC sample. *DataQuality: vertex cuts (-50 \leq VTXz \leq 40 \text{ (cm)}) and y_{JB} \leq 1. *: this is an upper limit, results from a different generator (LEPTO) give less than 1 event at this cut level.

<table>
<thead>
<tr>
<th></th>
<th>DIS CC MC</th>
<th>DIS NC MC</th>
<th>( \gamma P )</th>
<th>Data</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>HERACLES</td>
<td>LEPTO</td>
<td>HERACLES</td>
<td>Direct</td>
</tr>
<tr>
<td>Data Quality</td>
<td>28.7</td>
<td>26.0</td>
<td>25726</td>
<td>504</td>
</tr>
<tr>
<td>( p_t \geq 13\text{ GeV} )</td>
<td>24.0</td>
<td>22.6</td>
<td>3.87*</td>
<td>0</td>
</tr>
<tr>
<td>( P_{NFC} / P_z \geq 0.7 )</td>
<td>23.7</td>
<td>22.4</td>
<td>3.87</td>
<td>0</td>
</tr>
<tr>
<td>Scanning</td>
<td>23.7</td>
<td>22.4</td>
<td>3.87</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 7.5: Efficiency of e* \rightarrow \nu W and e* \rightarrow eZ signal Monte Carlo through Charged Current Fiducial cuts. The decay mode e* \rightarrow eZ \rightarrow e\nu\nu falls into the CC category.

<table>
<thead>
<tr>
<th>decay</th>
<th>( \nu W )</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass</td>
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<tr>
<td>efficiency %</td>
<td>90</td>
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</table>

<table>
<thead>
<tr>
<th>decay</th>
<th>eZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass</td>
<td>125</td>
</tr>
<tr>
<td>efficiency %</td>
<td>22</td>
</tr>
</tbody>
</table>

The search for e*’s was based on the NC and CC fiducial sample. Each decay mode is described in detail in the following three sections. Since the most dominant background for the e* \rightarrow e\gamma decay channel are Compton scattering events. The analysis of the Compton events is described in a separate section.
Figure 7.0.1: Feynman diagram of $e^*$ production in $ep$ collisions. The top figure shows the elastic production of an $e^*$ which dominates at high $e^*$ masses and the bottom figure shows the inelastic production. The top figure shows the elastic production of an $e^*$ which dominates at high mass and the bottom figure shows the diagram for the inelastic production.
Figure 7.1.1: Vertex distributions of DIS selected events. VCT (solid line) and REC (dotted line) reconstruction packages. VCT fits VXD (vertex detector) and CTD (Central Tracking Detector) hits globally in order to calculate the vertex, whereas REC matches the locally fitted tracks to extrapolate the vertex. The figure shows that there is no systematic shift or difference between the widths of the two vertex reconstruction packages. The mean of the distributions is at -6.5 (cm) and the width is 12 (cm). This shift from the nominal $z$-vertex is presumed to be where the machine delivered the bunches in 1993.
Figure 7.1.2: Resolution of the *F5STAR* electron finder. Top figure shows the difference between the true and the reconstructed electron for events in which the true electron is scattered by more than 15° degrees from the incident direction and has more than 5 GeV. The true electron is the electron as it is produced by the generator. The figure in the middle shows the difference of the energy of the true electron and the reconstructed electron for the same events as in the top figure. Note the logarithmic scale for the number of events in the top and middle plot. The bottom plot shows the angular versus the energy resolution for those events. Those figures demonstrate that the angular and energy resolution of the *F5STAR* electron finder suffices the needs of our search, i.e. for 87% of the events one finds an electron within 5° and 5 GeV of the true electron.
Figure 7.1.3: $E_t$ distribution of signal Monte Carlo $e^* \rightarrow e\gamma$ without any cuts.
Figure 7.1.4: $E_t$ distribution of signal Monte Carlo $e^* \rightarrow eZ$ without any cuts. The secondary peak at lower $E_t$ comes from neutrino decay modes of the $Z$, where only the decay electron of the $e^*$ contributes to $E_t$. 
Figure 7.1.5: $E_t$ distribution of signal Monte Carlo $e^* \rightarrow \nu W$ without any cuts. The tail of the $E_t$ distribution results from the leptonic decays of the $W$ where some of the $E_t$ is lost due to neutrinos.
Figure 7.1.6: The top figure shows the $\delta (\sum E - p_z)$ distribution of NC Monte Carlo (Heracles and Lepto) on the left side and data on the right side after requiring a $z$ vertex between -50 and plus +40 cm. The figures in the middle show the energy distribution of the electromagnetic cluster after the cut on the vertex and the $\delta$ variable. The bottom figure shows the distribution of the polar angle ($\theta$) of the electron after the cut on the $z$ vertex, on $\delta$ and on the energy of the electromagnetic cluster. Since the NC Monte Carlo events were only generated with $E_t \geq 30$ GeV, the $\theta$ distribution of the electron drops off sharply at 2.6 rad. The cuts on $\delta$ and on the energy and $\theta$ of the electron are indicated on the figures respectively.
Figure 7.1.7: Distribution of $E_t$ for NC Monte Carlo and data after all NC fiducial cuts: $30 \leq \delta \leq 60$ GeV, and at least one electron with $E_e \geq 10$ GeV and $\theta_e \leq 2.6$ (rad). But no generator level cuts on $E_t$ and on the energy in the ring of calorimeter cells closest to the rear beam pipe were applied $E$(rear cone). Due to the missing $E_t$ cut the contamination from low $E_t$ physics and beam gas background introduces a discrepancy between the data and the Monte Carlo distribution.

---

dotted: 1993 Data
hashed: NC Monte Carlo
Figure 7.1.8: Distribution of the energy in the ring of calorimeter cells closest to the rear beam pipe $E(\text{rear cone})$ for NC Monte Carlo and data after all NC fiducial cuts but no generator level cuts on $E_t$ and on $E(\text{rear cone})$ (see figure 7.1.7). The large discrepancy between NC Monte Carlo and Data at high $E(\text{rear cone})$ values is due to other physics processes and non-ep background which have a low $E_t$ distribution and therefore deposit more energy in the rear cone. The energy shift between Monte Carlo and data is pronounced in the calorimeter cells in the rear cone.
Figure 7.1.9: Comparison of NC Monte Carlo (HERACLES) and data. The distributions of $\delta$, the energy and polar angle ($\theta$) of the electron and $E_t$ (clockwise starting at top left) are shown after all cuts for the NC fiducial sample have been applied: $30 \leq \delta \leq 60$ GeV, and at least one electron with $E_e \geq 10$ GeV and $\theta_e \leq 2.6$ (rad). The shift in the energy measurement between the data and the Monte Carlo is on the order of 3% (top figures). It is due to insufficient dead material in the detector simulation and inadequacies in the modelling of the shower development in the detector. It is not fully understood. The cuts on the energy of the electron (10 GeV), on $E_t$ (30 GeV) and on $E$(rear cone) (5 GeV), which eliminates $e^-$'s which are scattered by a small angle.
Figure 7.1.10: $p_t$ distribution of all preselected data (top) and of CC Monte Carlo (bottom) after the trigger simulation. Most CC Monte Carlo has to be accepted in the CC trigger category and has therefore a sharp drop below $p_t=8$ GeV. The CC Monte Carlo has not been normalized to data luminosity. The cut on $p_t$ for establishing the CC fiducial sample is indicated on the plot.
Figure 7.1.11: Distribution of the ratio of $p_t$ calculated without and with the innermost ring in FCAL ($p_t$(no fcone)/$p_t$) (as explained in section 7.1.2). The cut for establishing the CC fiducial sample is indicated on the plot. The data is shown after cutting on the vertex (-50 ≤ vtx ≤ 40 cm), $Y_{JB} < 1$ and $p_t ≥ 13$ GeV. The data distribution after scanning (top figure) shows a slight excess of events below $p_t$(no fcone)/$p_t$=1 compared with Monte Carlo, the peak is more pronounced before scanning.
7.2 Analysis of the e\gamma final state

The most outstanding decay mode is that of e* going into e\gamma, it leaves two very energetic electromagnetic clusters in an otherwise quiet detector. A total of 25 events from the NC sample have a second electromagnetic cluster.

As the e* mass increases, the polar angle of the decay electron as well as the decay photon in the lab frame decrease, i.e. the decay products become more peaked in the forward direction (incoming proton direction). Figure 7.2.1 shows the distribution of the larger of the polar angles of the two electromagnetic clusters for e* Monte Carlo events at three mass points. This shows that the cut on the polar angle (\(\theta = 150^\circ\) or 2.6 rad) which is applied for the NC fiducial sample does not affect the search signal significantly. In contrast, deep-inelastic scattering produces electrons predominantly in the backward direction.

Requiring that the energy of both electromagnetic clusters is greater than 10 GeV is highly efficient for signal events while reducing the background from deep inelastic scatters. Figure 7.2.2 shows the distribution of the energy of one electromagnetic cluster versus the other for e*, Compton and DIS Monte Carlo and the fiducial NC sample. It shows that the search signal is unaffected by requiring that both electromagnetic clusters are greater than 10 Gev. The DIS Monte Carlo is strongly reduced by this cut though. It leaves 5 data events, all of which have masses below 50 GeV. The mass is calculated by

\[ M_{e\gamma} = M_{\text{inv}} = \sqrt{(p_e + p_{\gamma})^2 - (E_e + E_{\gamma})^2} \]

Scanning those 5 events shows all of them to be good physics events and three of those
Table 7.6: Efficiencies for the $e^* \rightarrow e\gamma$ analysis cuts for background and data. In the last line (overall total) the cumulative effects of experimental acceptance and analysis cuts are listed.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$e^*$ Mass (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td>%</td>
<td>91</td>
</tr>
<tr>
<td>2nd em cluster</td>
<td>100</td>
</tr>
<tr>
<td>$E_{1,2} \geq 10$ GeV</td>
<td>70</td>
</tr>
<tr>
<td>Overall total</td>
<td>50</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>DIS MC</th>
<th>$\gamma P$</th>
<th>Compton</th>
<th>Data</th>
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</thead>
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<tr>
<td></td>
<td>HERACLES</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NC Fiducial</td>
<td>874</td>
<td>0.44</td>
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<td>7.63</td>
</tr>
<tr>
<td>2nd em cluster</td>
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<td>$E_{1,2} \geq 10$ GeV</td>
<td>4.62</td>
<td>0</td>
<td>0</td>
<td>4.32</td>
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</tbody>
</table>

5 events could be Compton events (2 inelastic and one elastic) in good agreement with the prediction from Monte Carlo. The invariant mass distributions for signal and background Monte Carlo samples as well as for the data can be found in figure 7.2.3. The effects of the various cuts are listed in table 7.6 and the overall acceptance as a function of the $e^*$ mass is shown in figure 7.2.4. There is no evidence for an $e\gamma$ resonance. Using an average detection efficiency estimate of 80%, we obtained an upper limit on the production cross section for an $e^*$ decaying into two electromagnetic clusters of 5.1 pb at the 90% confidence level for an invariant mass above 50 GeV.
Figure 7.2.1: The $\theta$ distributions for the 50, 100 and 290 GeV $e^+ \rightarrow e\gamma$ after cutting on $\delta$ ($30 \leq \delta \leq 60$ GeV) and requiring that at least one electron with more than 10 GeV is found. This demonstrates that the cut on the polar angle can safely be set at $\theta \leq 2.8$ (rad) in this mode ($e \rightarrow e\gamma$).
Figure 7.2.2: Distribution of one electromagnetic cluster versus the other for events that pass the NC fiducial cuts (δ: 30 ≤ δ ≤ 60 GeV) and requiring at least one electron with $E_e \geq 10$ GeV and $\theta_e \leq 2.6$ (rad) is found) and have two electromagnetic clusters (without any energy or angle requirements). Clockwise starting at the top left: 50 GeV $e^*$, Compton, DIS Monte Carlo and data. The solid lines indicate where the cuts on the energies of the electromagnetic clusters are set. It shows that this cut does not affect the detection efficiency of $e^*$, but removes a large amount of NC DIS background from the search sample. The Monte Carlo statistics are not normalized to data luminosity.
Figure 7.2.3: Distribution of the invariant mass after the NC fiducial cuts and the cut in the $e^* \rightarrow e\gamma$ search mode: $30 \leq \delta \leq 60$ GeV, at least one electron with $\theta_e \leq 2.6$ (rad) and two electrons with $E_{1,2}(\text{electron}) \geq 10$ GeV. The dotted line indicates the background consisting of NC and Compton Monte Carlo events and the solid line indicates the data points. It shows that there is no resonance signal in the $e^* \rightarrow e\gamma$ mode.
Figure 7.2.4: Acceptance of $e^* \rightarrow e\gamma$ as a function of mass. At low $M_{e^*}$ values the acceptance suffers from the energy cut on the electron in NC fiducial sample. For $M_{e^*}$ close to the kinematic limit the efficiency drops due to either the decay electron or $\gamma$ escaping through the forward beam hole. The curve shows the overall combined efficiency due to experimental effects and analysis cuts.
7.3 High Energy Compton Scattering

One of the backgrounds for the $e^*$ search is Compton scattering, which is an interesting subject in its own right. Compton events are produced through purely electromagnetic interactions based on the reaction $ep \rightarrow e'p\gamma$. The cross section is calculated from the same Feynman diagrams as bremsstrahlung events (figure 7.3.1), but in a different region of phase space. Since in Compton scattering the energy transfer is small the energy of the electron and the gamma have to add up approximately to the original electron beam energy. This can be used to estimate shifts in the energy calibration of the calorimeter.

Since it involves the same final state particles as the $e^* \rightarrow e\gamma$ process, the Compton events serve as a control sample to demonstrate our understanding of the efficiency and systematics involved in the analysis of the $e\gamma$ final state. The cleanest sort of Compton process is one in which the proton does not fragment and therefore only an electron and a photon are visible in an otherwise quiet detector (elastic Compton). Phenomenologically the difference between $e^* \rightarrow e\gamma$ events and an elastic Compton events is the invariant mass of the electron and the gamma. Compton events have a broadly falling invariant mass distribution up to $\sim 50$ GeV at the current level of data luminosity, whereas $e^*$ events form a peak at the $e^*$ mass. Figure 7.3.10 shows the invariant mass distribution of the electron and the gamma of the events in the final Compton sample, which is explained below.

The elastic Compton cuts

For the analysis of the Compton events the fiducial NC sample is not suitable, since
the Compton events are strongly peaked at low $E_t$. Figure 7.3.2 shows the $E_t$ distribution of Compton Monte Carlo events. Furthermore Compton electrons and gammas are scattered mainly in the rear direction and requiring that the electron be scattered by more than 30° from the incoming beam electron direction would reduce the acceptance for Compton events by almost a factor of three. In figure 7.3.4 the distribution of the polar angle of one electromagnetic cluster versus the other after the $\delta$ cut and the energy cut ($30 \leq \delta \leq 60$ GeV and $E_{1,2} \geq 5$ GeV) can be seen. The angle and energy cuts were therefore loosened. Both electromagnetic clusters have to be detected in the fiducial volume of the calorimeter, each having more than 5 GeV energy. No cut on the polar angles of the electron and the gamma are applied. The same cut on the longitudinal energy variable as in the NC fiducial cut was used. Since a large fraction of the Compton events leave the electron and the gamma close to the rear beam pipe and have therefore a poor tracking efficiency a looser cut on the vertex was implemented. Figure 7.3.3 shows the distributions of the energy of one electromagnetic cluster versus the other for Monte Carlo and data events that passed the cut on the longitudinal energy variable $\delta$.

The cut on the energy of the two clusters clearly reduces the background. The large number of DIS events at a large polar angle dominate the search signal of Compton events nevertheless. In order to reduce the background from DIS events and select the elastic fraction of the Compton events, a cut on the ratio of hadronic to total energy was used. Figure 7.3.5 shows $E_h/E_{total}$ distribution for DIS and Compton Monte Carlo and data after the cut on the longitudinal energy variable and after requiring
two electromagnetic clusters with more than 5 GeV. It shows that one can safely cut on $E_h/E_{total}$ as low as 0.05. The disagreement between data and Monte Carlo at this level of filtering is clearly visible. After the cut on $E_h/E_{total}$ however, the agreement between Monte Carlo and data can be seen from table 7.7. The contamination of the final Compton sample from the NC DIS is estimated to be 8%.

Elastic events have very small $Q^2$ values. At low $Q^2$ the electron is scattered by a small angle only and the wide angle bremsstrahlung of the scattered electron leaves the momentum of the electromagnetic system balanced in the transverse plane ($x - y$ plane). Therefore the electron and the gamma in an elastic Compton event are produced back to back in the transverse ($x - y$) plane. Figure 7.3.6 shows the distribution of $d\phi$ (opening angle between the electron and the gamma in the $x - y$ plane) after the cut on $E_{had}/E_{total}$.

Figure 7.3.7 shows the sum of energies of the two electromagnetic clusters for data, which was scaled up by 2.4% in order to account for the energy shift in the calorimeter. The Compton Monte Carlo events which passed all cuts ($30 \leq \delta \leq 60$ GeV, two electromagnetic clusters both with $E_{1,2} \geq 5$ GeV and $E_h/E_{total} \leq 0.05$) are shown as a solid line in this figure and the data is shown as dots. For Compton events the energy transfer is small (the time component of $q_2$ in figure 7.3.1) and the sum of the energies of the two electromagnetic clusters is approximately equal to the electron beam energy. The peak in the $E_1 + E_2$ (electron and gamma) agrees therefore well with the predicted value of approximately twice the electron beam energy after the overall shift was applied to the data.
Table 7.7: Selection for the elastic Compton scatters. "2 em clusters": 2 electromagnetic clusters with $E_{1,2} \geq 5.0 \text{GeV } AND \delta$ between 30 and 60 GeV.

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<th>DIS MC HERACLES</th>
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<th>Compton</th>
<th>Data</th>
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<td>Preselection</td>
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<td>84078</td>
</tr>
<tr>
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<td>187</td>
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</tbody>
</table>
Figure 7.3.1: Feynman diagrams of the two lowest order contributions to Compton scattering in $ep$ interactions.
Figure 7.3.2: Transverse energy $E_t$ distribution of Compton Monte Carlo. It shows that the Compton cross section is very sensitive to cuts on $E_t$. 
Figure 7.3.3: Distribution of the energy of one electromagnetic cluster versus the other for events that passed the $\delta (30 \leq \delta \leq 60$ GeV) cut and have two electromagnetic clusters (no energy or angle requirement). In the Compton events (top figure) the sum of the energies of two electromagnetic clusters add up to the electron beam energy within the experimental resolution. The Monte Carlo distributions are not normalized to data luminosity.
Figure 7.3.4: Distribution of the polar angle of one electromagnetic cluster versus the other cluster for events that passed the $\delta$ ($30 \leq \delta \leq 60$) cut and have two electromagnetic clusters above 5 GeV. Since the Compton cross section peaks at large angles of the final electron and gamma, a cut on their polar angles cannot be applied in order to discriminate against background from NC DIS events, as can be seen from these distributions.
Figure 7.3.5: $E_{\text{had}}/E_{\text{tot}}$ distribution of NC DIS Monte Carlo (top), Compton Monte Carlo (middle) and data (bottom). Only events that passed the longitudinal energy cut (30 ≤ $\delta$ ≤ 60 GeV) and the cut on the energy of the electromagnetic clusters ($E_1$ and $E_2$ ≥ 5 GeV) are shown. The Monte Carlo statistics are not normalized to the data luminosity. The arrow indicates where the cut on $E_{\text{had}}/E_{\text{tot}}$ is set.
Figure 7.3.6: $d\phi$ distribution of combined NC DIS and Compton Monte Carlo (hashed) and data (dotted) of events that passed the longitudinal energy cut ($30 \leq \delta \leq 60$ GeV) and the cut on the energy of the electromagnetic clusters cut ($E_1$ and $E_2 \geq 5$ GeV) and the $E_{\text{had}}/E_{\text{tot}}$ cut. The contamination of the Compton data sample with NC DIS events is estimated $\sim 8\%$. There was no cut applied to the $d\phi$ variable. The Monte Carlo statistics are normalized to data luminosity. This demonstrates that the events in the Compton sample are balanced in the $x - y$ plane, i.e. the sample consists of inelastic Compton events.
Figure 7.3.7: Distribution of the sum of the energies of the two electromagnetic clusters after all cuts used in the Compton study ($30 \leq \delta \leq 60$ GeV, 2 electromagnetic clusters above 5 GeV and $E_{\text{had}}/E_{\text{tot}} \leq 0.05$). The hashed area is the distribution of the combined Compton (92%) and NC DIS (8%) Monte Carlo and the dots indicate the data events. The data curve is shifted up in energy by 2.4%. The curves show the expected peak at the electron beam energy.
Figure 7.3.8: Distribution of the invariant mass of the two electromagnetic clusters after all cuts used in the Compton study ($30 \leq \delta \leq 60$ GeV, 2 electromagnetic clusters both above 5 GeV and $E_{\text{had}}/E_{\text{tot}} \leq 0.05$). The hashed area is the distribution of Compton (80%) and NC DIS (≤ 8%) and the dots indicate the data events. The curves show that there is no outstanding peak indicating the absence of any new signal. The three events with $M_{\gamma\gamma} \geq 50$ GeV were eliminated by the cut on the polar angle in the $e^+ \rightarrow e\gamma$ search mode.
7.4 Analysis of the eZ final state

Three decay modes are used to search for the exclusive $e^* \rightarrow eZ$ transitions: $Z \rightarrow e^+e^-, \nu\bar{\nu}, q\bar{q}$. A final state with three electromagnetic showers is characteristic of the decay chain $e^* \rightarrow e^-Z \rightarrow e^-e^+e^-$. One event passes the vertex and longitudinal energy cut of the NC fiducial sample and has three electromagnetic showers. The highest energy for any pair of electromagnetic showers in this event is 22 GeV, which is inconsistent with a $Z \rightarrow e^-e^+$ decay. Background MC predicts one event from DIS.

Although there a negligible backgrounds to the $e^-e^+e^-$ final state, increased sensitivity to $eZ$ can be achieved by searching for decays of $Z$ bosons into quark—antiquark pairs, since $B(Z \rightarrow q\bar{q})$ is 69.8% compared to $B(Z \rightarrow e^+e^-)$ which is 3.3%.

The analysis of this channel is based on the fiducial NC sample. In addition it was required that there be exactly one electromagnetic shower (the NC fiducial sample requires at least one electromagnetic shower). This shower had to have a polar angle, that is smaller than 2.0 rad. The polar angle of the decay electron of the $e^*$ becomes smaller as the mass of the $e^*$ increases. Figure 7.4.1 shows the distributions of the polar angle of the decay electron for three different $e^*$ masses. It shows that the cut at $\theta=2.0$ rad can be applied safely, without reducing the $e^* \rightarrow eZ$ detection efficiency significantly.

Starting with the fiducial cuts only an additional 10% of the acceptance is lost for an $e^*$ with 125 GeV mass by requiring that the polar angle of the final electron is smaller than 2.0 rad, for an $e^*$ with a mass of 290 GeV the loss is less than 2%. Figures 7.4.2 shows the $\theta$ distributions of a 125 GeV $e^*$ and background Monte Carlo
and data after the NC fiducial cuts and requiring one electromagnetic cluster. In order to reduce the background in this mode a cut on the transverse hadronic energy ($E_t^{\text{hadronic}}$) is applied, where $E_t^{\text{hadronic}}$ is calculated by subtracting the transverse energy of the electron and the transverse energy deposited in the ring closest to the forward beampipe from the total transverse energy in the calorimeter. The hadronic decay of a Z boson deposits a large amount of transverse hadronic energy in the detector. With increasing $e^*$ mass, $E_t^{\text{hadronic}}$ increases while the hadronic transverse energy for events from deep inelastic scattering is typically about 30 GeV. Figure 7.4.3 shows the distribution of the transverse hadronic energy for 125 GeV $e^*$ and DIS Monte Carlo and the data after the angle and energy cut on the electron ($E_e > 10$ GeV and $\theta_e < 2.0$ rad). An $E_t^{\text{hadronic}} > 60$ GeV cut removes over 99% of the backgrounds and retains 69% of the signal at $M_{e^*} = 100$ GeV and 73% of the signal at $M_{e^*} = 290$ GeV.

In the channel $Z \rightarrow \nu \bar{\nu}$ only the decay electron from the $e^*$ is visible and the $\nu$'s lead to an imbalance of transverse momentum in the detector. Therefore the analysis of this channel is based on the CC fiducial sample. This additional mode can increase the overall acceptance in the $e^* \rightarrow eZ$ channel by $\sim 20\%$. In addition the $p_t$ requirement was raised up to 15 GeV and one electromagnetic cluster with more than 10 GeV and $\theta \leq 2.6$ rad was required. This leaves one candidate in the data sample. With CC and NC Monte Carlo one can estimate that the number of background events in this mode is 1.29 events (normalized to data luminosity).

The $Z$ mass was reconstructed from the energy in the calorimeter after subtracting
the four-momentum of the electron:

$$M_Z = \sqrt{(\sum_i \vec{p}_i^2 - \vec{p}_e^2)^2 + (\sum_i E_i - E_e)^2}$$  \hspace{1cm} (7.4)$$

where $i$ runs over all calorimeter cells except for the cells closest to the forward beampipe and the subscript $i$ indicates the energy and momentum of the electron.

No further cut on $M_{\text{had}}$ was made. Figure 7.4.4 shows that the ZEUS detector is capable of reconstructing $Z$ bosons decaying into hadronic final states. The reconstructed mean of the $Z$ mass lies within two standard deviations of the $Z$ mass. The measured peak is shifted down by 13% from the true mass peak of the $Z$. This energy loss in the overall summation of (7.4) is due to dead material in front of the calorimeter and due to partial losses of the hadronic decay products through the forward beam hole. By including the cells around the forward beam hole in the mass calculation one increases the peak of the distribution, but widens the mass resolution by more than a factor of two.

The effect of the various cuts are listed in table 7.8 and the overall acceptance as a function of the $e^*$ mass is shown in figure 7.4.5. In the Monte Carlo studies for the $eZ$ final state, the $Z$ boson decay was not limited to hadronic channels. The overall acceptance listed is therefore our best estimate of our ability to detect $e^*$ decaying via $e^-Z$.

Using the energy and angle of the electron, as well a $Z$ mass constraint, the mass of the $e^*$ candidates is calculated by the formula

$$M_{\text{inv}}^2 = M_{e^*}^2 = \frac{4E_eE_{e^*}\cos^2\theta_e - M_Z^2}{1 - \frac{E_e^2}{E_{e^*}\sin^2\theta_e}}$$  \hspace{1cm} (7.5)$$
where $E_e$ is the electron beam energy and $E_e^*$ and $\theta_e$ are the energy and the polar angle of the scattered electron. This formula assumes that the transverse momentum of the $Z$ and of the final state electron balance, i.e. that $e^*$ production occurs predominantly at low $Q^2$ and that $E_{\text{remnant}} = p_{Z\text{remnant}}^*$ holds approximately true for the proton remnant. Invariant mass distributions for simulated $e^*$'s, background and for data after all cuts are given in figures 7.4.6. The derivation of equation 7.5 is detailed in the appendix.

There is no evidence for an $eZ$ resonance. Only three events passed the above cuts, DIS MC predicts 5 events using the HERACLES+ARIADNE generator, whereas according to LEPTO the equivalent of 6 events should survive the cuts. 0 events in the Compton and $\gamma P$ Monte Carlo sample pass those cuts. The hadronic masses of the three surviving events is spread between 100 and 150 Gev. The three observed events correspond to an upper limit (90%) of 12 pb for the cross section of $eZ$ production above 100 Gev using an average estimate of 70% for the overall acceptance. This value for the acceptance includes the $Z \rightarrow q\bar{q}$ and $\rightarrow \nu\bar{\nu}$ branching fraction.
Table 7.8: Efficiencies for the $e^* \rightarrow eZ$ analysis cuts for background and data. In the last line (overall combined) the cumulative effects of experimental acceptance and analysis cuts are listed.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$e^*$ Mass (GeV)</th>
</tr>
</thead>
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<td></td>
<td>125</td>
</tr>
<tr>
<td>$NC$ Fiducial</td>
<td></td>
</tr>
<tr>
<td>$\theta_e \leq 115^o$</td>
<td>84</td>
</tr>
<tr>
<td>$E_t^{hadronic}$</td>
<td>69</td>
</tr>
<tr>
<td>$CC$ Fiducial</td>
<td></td>
</tr>
<tr>
<td>$p_t \geq 14$ GeV</td>
<td>95</td>
</tr>
<tr>
<td>one em cluster</td>
<td>95</td>
</tr>
<tr>
<td>overall combined</td>
<td>53</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>DIS MC</th>
<th>$\gamma P$</th>
<th>Compton</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>nbr of evt's</td>
<td>NC</td>
<td>CC</td>
<td>Dir</td>
<td>Res</td>
</tr>
<tr>
<td>$NC$ Fiducial</td>
<td>874</td>
<td>30</td>
<td>0.44</td>
<td>1.65</td>
</tr>
<tr>
<td>$\theta_e \leq 115^o$</td>
<td>144</td>
<td>0</td>
<td>0.22</td>
<td>0</td>
</tr>
<tr>
<td>$E_t^{hadronic}$</td>
<td>4.17</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$CC$ Fiducial</td>
<td>3.87</td>
<td>23.7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$p_t \geq 15$ GeV</td>
<td>2.58</td>
<td>22.3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>one em cluster</td>
<td>1.29</td>
<td>0.23</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>combined</td>
<td>5.00</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 7.4.1: The distribution of the polar angle ($\theta$) of the decay electron of the 125, 200 and 290 GeV $e^*$'s $\rightarrow eZ$ after the $\delta$ ($30 \leq \delta \leq 60$ GeV) cut and requiring that there be exactly one electromagnetic cluster with $E_e \geq 10$ GeV. This demonstrates that the cut on the polar angle of the electromagnetic cluster can safely be set at $\theta \leq 2.8$ rad in this mode ($e^* \rightarrow eZ$).
Figure 7.4.2: The distributions of the polar angle ($\theta$) of the decay electron of 125 GeV $e^+s \rightarrow eZ$ (top figure) and of combined NC DIS and Compton Monte Carlo (solid) overlayed with data (dots) after the $\delta$ (30 $\leq$ $\delta$ $\leq$ 60 GeV) cut and requiring that there be exactly one electromagnetic cluster with $E_e \geq$ 10 GeV. The cut on $\theta$ is indicated on the figure at 2.0 rad. This demonstrates that the cut on $\theta$ only eliminates a small fraction of the signal.
Figure 7.4.3: The top figure shows the $E_t$ distributions of the $125$ GeV $e^* \rightarrow eZ$. The bottom figure shows the distribution of the same variable for NC DIS and Compton Monte Carlo (solid) events overlayed with data (dots) events. Only events which pass the NC fiducial cuts and the more restrictive cuts (in the $eZ$ channel) on the electron variables are shown: $30 \leq \delta \leq 60$ GeV, only one electron with $E_e \geq 10$ and $\theta_e \leq 2.0$ rad. The cut on $E_t$ is indicated on the figure at 60 GeV. $E_t$ is calculated without including the energy from the cells closest to the forward beampipe and by subtracting the energy of the electron. It is the equivalent of the transverse component of the hadronic energy.
Figure 7.4.4: Distribution of $M_{\text{had}}$ (equation 7.4) in the $e^* \rightarrow eZ$ channel of a 125 GeV $e^*$ Monte Carlo signal. Only events which pass the NC fiducial cuts and $\theta_e \leq 2.0$ rad and $E_t \geq 60$ GeV are shown. $M_{\text{had}}$ is calculated by taking the invariant mass of the calorimeter without the electron and without the cells around the forward beam hole. It shows the capability of the detector to reconstruct a $Z$ boson (top figure). The peak of the reconstructed $Z$ mass is shifted down from the true $Z$ mass by 13%. This shift is due to dead material in front of the calorimeter and due to partial losses of hadronic decay products through the forward beam hole. The bottom figure shows the data overlayed on NC DIS Monte Carlo.
Figure 7.4.5: Acceptance of $e^* \rightarrow eZ$ as a function of mass. The $e^*$ mass formula is given in equation 7.5. The curve shows the overall combined efficiency due to experimental effects and analysis cuts.
Figure 7.4.6: Distribution of the invariant mass (equation 7.5) after all cuts in the $e^* \rightarrow eZ$ channel (vertex, $\delta$, electron energy and angle and $E_t^{\text{hadronic}}$. This plot combines the two candidates found in the hadronic decay mode of the $Z$ and one event found in the $Z \rightarrow \nu \nu$ mode. No mass peak is visible.
7.5 Analysis of the $\nu W$ final state

A third decay channel of $e^*$'s exists via $\nu W$. Since it involves a neutrino in the final state the CC fiducial sample was used for the analysis in this decay mode. The hadronic decay modes of the $W$ were used here, from direct hadronic decays of the $W$ or via the $\tau$, setting the maximally detectable fraction of $W$ decays at 76%. For this decay the only signal visible in the detector is the $W$, motivating a cut on the total invariant mass of the energy in the detector. In order to separate out the beam remnant from the rest of the visible event, the energy deposited in the first ring around the forward beampipe was removed from the total mass calculation for this cut. So only one additional criterion was needed to be imposed on the charged current sample defined in section 7.1.2. Candidate events were required to have an invariant mass ($M_{\text{had}}$) greater than 50 GeV. $M_{\text{had}}$ is the invariant mass of the total 4momentum of the calorimeter,

$$M_{\text{had}} \sim M_W = \sqrt{-(\sum_{\text{cells}} p_i)^2 + (\sum_{\text{cells}} E_i)^2}$$

(7.6)

where the sum runs over all cells except those around the forward beampipe.

The $M_{\text{had}}$ distributions to justify this cut are shown in figure 7.5.1. The top figure shows the distribution of $M_{\text{had}}$ of 125 GeV $e^* \rightarrow \nu W$ after the CC fiducial sample selection. It demonstrates the capability of the ZEUS detector to reconstruct $W$ bosons decaying into hadrons. In the bottom figure one sees the data events after the CC fiducial cuts overlayed on the Monte Carlo prediction. Figure 7.5.2 shows the $E_t$ distribution of the CC fiducial data set and the Monte Carlo prediction, indicating a good understanding of the background in this analysis. The acceptance as a function
Table 7.9: Efficiencies for the $e^* \rightarrow \nu W$ analysis cuts for background and data. In the last line (overall total) the cumulative effects of experimental acceptance and analysis cuts are listed.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$e^* \text{ Mass (GeV)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>100 125 150 200 250 290</td>
</tr>
<tr>
<td>CC Fiducial</td>
<td>68  81  75  74  73  76</td>
</tr>
<tr>
<td>overall total</td>
<td>32  62  60  57  52  48</td>
</tr>
</tbody>
</table>

-of the $e^*$ mass can be found in figure 7.5.4, while 7.5.3 contains the invariant mass distributions ($M_{e^*}$). Table 7.9 lists the efficiencies and background rates for this decay mode.

In this mode there is no information available from the electron to reconstruct the invariant mass of the $e^*$ candidates. Therefore the information from the hadronic decay of the $W$ and the missing momentum due to the escaping neutrino are used to calculate the invariant mass.

\[
M_{\text{inv}}^2 = M_{e^*}^2 = \frac{4p_t^2 E_e^2 + 2E_e M_W^2 (2E_e - \delta)}{\delta (2E_e - \delta)}
\]  

(7.7)

where $E_e$ is the electron beam energy, $p_t$ the transverse momentum of the hadronic system, and $\delta$ is the longitudinal energy variable defined in 4.6. This mass formula is based on the same assumption as in the $eZ$ channel, i.e. that the transverse
momentum of the $W$ balances the transverse momentum of the neutrino and that $E_{\text{remnant}} = p_{\text{remnant}}^x$ holds approximately true for the proton remnant. The derivation of equation 7.7 is detailed in the appendix.

Of the 30 CC events, four passed this last cut. Only one has an invariant mass as calculated from the total calorimeter energy of more than 60 GeV. Those three events left are therefore inconsistent with the decay signature of a $W$. There is no evidence for a $\nu W$ resonance. Normalized to data luminosity, one event from the Heracles MC sample and two events from the Lepto MC sample survive the above cuts. If interpreted as a $e^* \rightarrow \nu W$ decay, the four observed events correspond to an upper limit of 14 pb for the cross section of $\nu W$ production above a mass of 100 GeV at the 90% confidence level. This limit is calculated using an average value of 50% for the detector acceptance and a background of 1 event.
Figure 7.5.1: Distribution of the invariant mass $M_{\text{had}}$ (as defined in equation 7.6) of the energy in the detector after subtracting the energy in the cells around the forward beam hole ($M_{\text{had}}$). The top figure shows the $M_{\text{had}}$ distribution of 125 GeV $e^\ast$'s $\rightarrow \nu W$. The bottom figure shows the distribution of the same variable for CC Monte Carlo and for data events. Only events which pass the CC fiducial cuts are shown: $Y_{JB} \leq 1$, $p_t(\text{no fcone})/p_t(\text{total}) \geq 0.7$ and $p_t \geq 13$ GeV. It is indicated on the figure that the cut on this variable $M_{\text{had}}$ is set at 50 GeV. This eliminates all but four data events.
Figure 7.5.2: Distribution of $E_t$. The hashed area indicates the CC Monte Carlo distribution, the dots indicate the data. Only events which passed the CC fiducial cuts and the cut on $M_{had}$ are shown. It shows good agreement between the prediction from Monte Carlo and data. No cut was applied on this variable in the $e^* \rightarrow \nu W$ mode.
Figure 7.5.3: The distribution of the invariant mass $M_{\text{inv}}$ (as defined in equation 7.7) after all cuts in the $e^* \rightarrow \nu W$ channel: $Y_{JB} < 1$, $p_t(\text{no fcone})/p_t(\text{total}) \geq 0.7$, $p_t \geq 13$ GeV, and $M_{\text{had}} \geq 50$ GeV.
Figure 7.5.4: Acceptance of $e^* \rightarrow \nu W$ as a function of mass. The $e^*$ mass formula is given in equation 7.7. The curve shows the total efficiency due to experimental effects and analysis cuts.
CHAPTER VIII

Systematic Uncertainties

Any experimental measurement has systematic errors that distort the result of the measurement. Since systematic uncertainties are intrinsic to manifold aspects of the experimental apparatus, a reliable estimate of the systematic error requires a good understanding of the experiment. The estimates of the various sources for the systematic errors are gained from varying measured quantities and analysis procedures (particle identification methods, cuts, reconstruction methods) in a controlled way and looking at what effect this has on the final result, i.e. number of final events, efficiencies, estimates of background and luminosity.

In addition to systematic errors there are theoretical uncertainties that affect how well one understands and models the underlying physical process that should be measured and checked against prediction.

The estimate of the systematic errors is difficult and not as clear cut as the treatment of the statistical errors. There are three main sources for systematic errors in this study.

- Luminosity measurement
- Systematic error in the acceptance calculation
- Theoretically uncertainty in calculating the cross section
Systematic error of luminosity measurement

The error on the luminosity measurement depends among other things mainly on how well the acceptance of the luminosity detector is understood and how much background from electron-gas interaction reaches the luminosity detectors. Furthermore the existence of the proton satellite bunch leads to an overestimate of the luminosity. The number of particles in the satellite bunch fluctuated during the 1993 runs and presently the uncertainty from this contribution is estimated to be 3.5%. In 1993 the combined error of the luminosity measurement was improved appreciably from over 10% in 1992 to 6.5% for last year's runs.

Theoretical uncertainty

The theoretical uncertainty in calculating the $e^*$ production cross section is in principle undetermined, since different models will yield quite different results. Given the chosen model though the main contributions to the error are due to radiative effects and the modelling of the hadronic system. When the proton radiates a $\gamma$ before the production of an $e^*$ the center of mass energy is lowered, leading to a systematic uncertainty in the production mechanism of the $e^*$. This was checked by implementing radiative corrections in the generator. The contribution due to the error of the modelling of the hadronic system was checked by using different structure functions in the $e^*$ generator and was found to be less than 1%. The uncertainty of the $e^*$ width
due to hadronic radiation is much smaller than the uncertainty from the leptonic side and therefore not included in the overall uncertainty separately. The theoretical uncertainties were found $\sim 7\%$.

**Uncertainty of the acceptance of the detector**

The calculation of the systematic error on the acceptance implies understanding by how much the detector efficiency and the data acquisition can downgrade and distort the search signal.

The energy resolution for electromagnetic showers is $18\%/\sqrt{E}$. The detector resolution widens the signal and shifts the mean of the mass peak. Figure 10.2 shows the width and the shift of the search signal as a function of mass. The width and shift can be explicitly folded into the calculation of the limit (see section 9.).

The uncertainty of the acceptances can be broken up into the following groups:

**Uncertainty in establishing the NC and CC fiducial samples:**

- error on the vertex reconstruction
- error on the energy scale and the angular resolution
- particle identification

**Uncertainty in the final analysis cuts:**

- $E_c$ and $\theta_c$ cut
- $E_t$ cut
- $p_t$ cut
- $M_{\text{had}}$ cut
Since a vertex is required in all search channels, the uncertainty in the efficiency of reconstructing the vertex accurately is important. The error on the vertex calculation was estimated by redoing the analyses with two different vertex reconstruction routines. This yielded an upper limit on this uncertainty of 6%.

The effect of the overall energy shift, relevant to the $E - p_z$ cuts and the cuts on energy are ≤ 3%. The overall shift of the energy can be seen from the figures of the electron energy and $\delta$ (figure 7.1.6 and 7.1.9).

The angular resolution of the detector is excellent which can be seen from the comparison of the distributions of data and Monte Carlo predictions of the scattered electron in DIS events (see figure 7.1.6 and 7.1.9). Compared to the error on the energy shift, the error of the angular measurement is negligible.

The error on the particle identification is rather difficult. An estimate can be reached by varying the energy and cone thresholds of the finder used in this analysis. This gives an upper limit of the systematic error for particle identification of 3.7%. Equivalently, a comparison with another electron finder can give an estimate of the systematic uncertainty of particle ID.

Varying the cuts in the three channels gives an estimate on what systematic effect is introduced by their settings. The uncertainty in the variable that is distributed translates into an uncertainty in the cut of this variable and can be used to estimate its associated error. A cut that is located at a steeply rising or falling slope of a distribution has a larger systematic effect than at a flat region of the distribution. Table 8.1 shows the effects of varying the most important cuts in this analysis on
Table 8.1: Contributions to the systematic error from the uncertainty of the acceptance (n.a.: not applicable).

<table>
<thead>
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<th>uncertainty (%)</th>
<th>$\varepsilon\gamma$</th>
<th>$\varepsilon Z$</th>
<th>$\nu W$</th>
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</thead>
<tbody>
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<td>vertex</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$E - p_z$</td>
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<tr>
<td>particle id</td>
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<td>overall</td>
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<td></td>
</tr>
<tr>
<td>$E_t$</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>$E_e$</td>
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<td>n.a.</td>
</tr>
<tr>
<td>$\theta_e$</td>
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<td>1</td>
<td>n.a.</td>
</tr>
<tr>
<td>$p_t$</td>
<td>n.a.</td>
<td>n.a.</td>
<td>1</td>
</tr>
<tr>
<td>$M_{had}$</td>
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<td>n.a.</td>
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</tr>
<tr>
<td>overall</td>
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<td>4.3</td>
<td>4.2</td>
</tr>
<tr>
<td>Total</td>
<td>8.3</td>
<td>8.8</td>
<td>8.8</td>
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</table>

The uncertainty of estimating the background in the NC and CC DIS channel were done by using a second DIS sample in the analysis. At the level of the fiducial samples (NC and CC, see section 7.1.1 and 7.1.2) the effect was less than 1% (checking HERACLES against LEPTO).

The calculation of the limit curves requires one to parametrize the cross section and acceptance as functions of the mass of the $e^*$. This parametrization introduces an additional error of 5%.

Under the assumption that the various systematic errors are uncorrelated, the
errors are added in quadrature. Table 8.2 lists the errors and the total systematic error.

Table 8.2: Contributions to the overall systematic error.

<table>
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</tr>
<tr>
<td>Acceptance</td>
<td>8.3-8.8</td>
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<tr>
<td>Fitting procedure</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>13</td>
</tr>
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CHAPTER IX

Limit setting procedures

In the absence of an $e^*$ signal the numbers of observed events and background events are used in a statistically consistent way [72] [73] to set upper limits on the inclusive production cross section of $e^*$'s and on their couplings to Standard Model leptons and gauge bosons. This procedure is described here in detail.

9.1 Upper limits in Poisson processes

If $n_0$ events are observed from a process that is assumed to obey a Poisson distribution $P(n, N)$ or a product of Poisson distributions with an unknown mean $N$, it is possible to set an upper limit $N_+$ to this unknown $N$, by solving

$$
\sum_{r=0}^{r=n_0} P(r, N_+) = \alpha \sum_{r=0}^{r=\infty} P(r, N_+) \quad (9.1)
$$

for $N_+$, where $1 - \alpha$ is the confidence level. $N_+$ is then called the upper limit at a given confidence level. Equivalently one can solve

$$
\int_0^{N_+} P(n_0, N)dN = (1 - \alpha) \int_0^{\infty} P(n_0, N)dN \quad (9.2)
$$

for $N_+$. It can be shown that (9.1) and (9.2) are mathematically equivalent.

This means, that if the true value of $N$ of the unknown distribution is really $N_+$, the probability of getting a result $n$ which is this small or smaller is only $\alpha\%$, and for
$N$ larger than $N_+$ it is even smaller. Thus one says one is "90% confident" that $N$ is not greater than $N_+$, and averaging over many such statements one will be right 9 out of 10 times.

If there is no background from Monte Carlo prediction, $P(n, N)$ is given by

$$P(n, N) = \frac{N^n e^{-N}}{n!} \quad (9.3)$$

In the case where there are background events the probability distribution has to be such as to include this information and "subtract" out those background events, accounting for all combinations of signal and background events that yield a certain number $n_o$ of observed events.

$$P(n, N) = \sum_{m=0}^{n} \frac{N^m e^{-N_S} N^m e^{-N_B}}{m! (n-m)!} \quad (9.4)$$

with the constraint $N_S + N_B = N$ where $N_S$ is the number of signal and $N_B$ the number of background events. Solving (9.1) with either (9.3) or (9.4) yields the upper limits of the mean of the signal distributions ($N_+$) with and without background counts respectively. The relation between the total cross section for the production of $e^*$'s and $N_+$ is given by

$$\sigma_+^{\text{inclusive}} = \frac{N_+}{\mathcal{L} \epsilon B} \quad (9.5)$$

where $\mathcal{L}$ is the integrated luminosity, $\epsilon$ is total acceptance for the search signal and $B$ is the branching fraction of the $e^*$ decaying into the final state under consideration. $\sigma_+^{\text{inclusive}}$ is then the upper limit on the production cross section. The last column in table 9.1 give the upper limits on $\sigma_+^{\text{inclusive}}$ at the 90% confidence level.
9.2 Setting a limit on the coupling constant

The signal cross section is easily separable into a multiplicative coupling constant
\[ \lambda = \sqrt{|c|^2 + |d|^2}/\Lambda^2 \] and a "raw" cross section \( \sigma_0 \), which depends on the mass of the \( e^* \) (mass hypothesis \( m_0 \)).

The search was conducted in all three decay modes. The Hagiwara model that was chosen to set a limit on the production of \( e^* \)'s does not determine the branching ratios into these decay modes apriori. Thus they depend on couplings \( c_{VF} \) and \( d_{VF} \) (\( V \): decay boson, \( F \): excited electron and \( f \) standard electron). Therefore the limits which are set in the individual channels include the product of coupling \( (|c_{\gamma e\pi}|^2 + |d_{\gamma e\pi}|^2)/\Lambda^2 \) and branching ratio \( B \). In order to achieve the best limit on this product it is necessary to account for the variation of acceptance and crosssection over the signal mass range and to assign probabilities to the events according to how far they are from the signal mass point \( m_0 \) under consideration. For this the signal mass distribution has to be fitted to include detector resolution effects. In this analysis it was fitted to a Gaussian distribution.

The maximum likelihood function is used to derive this probability.

\[
\Psi(n_\sigma) = \prod_{i=1}^{n_\sigma} \frac{N_i^n e^{-N_i}}{n!} \tag{9.6}
\]

where \( n_\sigma \) is the number of observed events and the information in the probability function is maximized by partitioning the phase space such that there is only one event per mass bin, therefore each event is included in the product (9.6) separately. This can be done rigorously by shrinking the mass bin size down so that every observed event will wind up in a separate bin. So setting \( n = 0 \) for all empty mass bins and
$n = 1$ otherwise, (9.6) yields

$$\Psi(n_o) = \prod_{i=1}^{\text{all bins}} e^{-N_i} N_i^{n_o} = e^{\sum_{i=1}^{\text{all bins}} N_i \prod_{i=1}^{n_o} N_i} \quad (9.7)$$

where $n_o$ is the number of observed events and $N_i$ is the number of events expected at the mass of the $i$th event from signal and background. It is important to note that the first product runs over all bins, whereas the second product only over the bins with an observed event. $N_i$ is defined by

$$N_{\text{total}} = \sum_{i=0}^{\text{all bins}} N_i = \sum_{i=0}^{\text{all bins}} L \alpha_i \sigma_i \delta_i = L \alpha \sigma \quad (9.8)$$

where $\mathcal{L}$ is the integrated luminosity, $\alpha_i$ is the acceptance and $\sigma_i$ is the cross section expected at the mass of the $i$th event in the $i$th bin. $\delta_i$ is the width of the $i$th bin and can be absorbed in an overall constant which cancels out in the final integration of the likelihood functions. $N_i$ is therefore the number of expected events in the $i$th bin.

In the case where the observed event can be either signal or background, it can easily be shown that for $n = 0, 1$ relation (9.7) holds true with

$$N_i = N_i^B + N_i^S = \mathcal{L} \delta_i (a_i^S \sigma_i^S + a_i^B \sigma_i^B) \quad (9.9)$$

with $a_i^S B \sigma_i^S B = \sum_{i}^{\text{all bins}} a_i^S B \sigma_i^S B$. It is important to note that only $\sigma_i^S$ depends on the coupling parameter $\lambda$. Then (9.7) can be rewritten

$$\Psi(n_o) = e^{-\sum_{i=1}^{(N_i^S + N_i^B)} n_o} \prod_{i=1}^{N_i^S + N_i^B} \mathcal{L} \delta_i (a_i^S \sigma_i^S + a_i^B \sigma_i^B) \quad (9.10)$$

and
\[ \Psi(n_0) = Ke^{-N_{\text{total}}^S} \prod_{i=1}^{n_0} (a_i^S\sigma_i^S + a_i^B\sigma_i^B) \] (9.11)

where all terms independent of \( \lambda \) are absorbed into \( K \) and

\[ N_{\text{total}}^S = \mathcal{L} \sum_{i}^\text{all bins} a_i^S\sigma_i^S = \mathcal{L}a\sigma_o^S \lambda \] (9.12)

where \( a \) is the acceptance and \( \sigma_o^S \) is the cross section at the mass hypothesis. Only the signal term depends on the mass hypothesis \( m_o \) and is weighted with a gaussian distribution. The final likelihood function is then

\[ \Psi(n_0) = Ke^{-N_{\text{total}}^S} \prod_{i=0}^{n_0} a_i^B\sigma_i^B + a_i^S(m_o)\sigma_o(m_o)\lambda \frac{e^{-\left(m_i-m_o\right)^2/2\sigma_o^2(m_o)}}{\sqrt{2\pi}\sigma_o(m_o)} \] (9.13)

where \( N_{\text{total}}^S = \mathcal{L}a\sigma_o^S \lambda \), \( m_o \) is the mass hypothesis, \( m_i \) is the mass of the ith event, \( \lambda \) is the coupling constant and \( \sigma_o \) is the resolution of the signal at \( m_o \). If there is an accumulation of events within some mass range, then \( \Psi(n_o, N) \) grows quickly near this mass and leads to a spike in the likelihood function, which can be interpreted as a signal.

The systematic errors are also folded into \( \Psi(n_0) \) with Gaussian distributions. For example the luminosity is distributed as

\[ \frac{1}{\sqrt{2\pi}\sigma_L} e^{-\left(\overline{L} - \sigma_L^2\right)/2\sigma_L^2} \]

where \( \sigma_L \) is the uncertainty of the luminosity measurement and \( \overline{L} \) is the mean value of the integrated luminosity. Then (9.11) becomes with \( \mathcal{L} \rightarrow L_{\text{err}} \)

\[ \Psi(n_0) = \int Ke^{-(L_{\text{err}}a\sigma_o^S)}\frac{e^{-\left(L_{\text{err}} - \sigma_L^2\right)/2\sigma_L^2}}{\sqrt{2\pi}\sigma_L} \prod_{i=1}^{n_0} (a_i^S\sigma_i^S + a_i^B\sigma_i^B) dL_{\text{err}} \] (9.14)
Similar treatment of the systematic uncertainty of the acceptance turn (9.14) into a 2-dimensional integral over $d\mathcal{L}$ and $da_{\text{err}}$. Integrating over those two uncertainties leaves $\Psi_o$ independent of the unknown quantities $\mathcal{L}$ and $a_{\text{err}}$.

Integrating $\Psi(n_o)$ (equation 9.13) over the coupling $\lambda$ the $K$ cancel when solving

$$\int_0^{N_+} \Psi(n_o)d\lambda = (1 - \alpha) \int_0^{\infty} \Psi(n_o)d\lambda \quad (9.15)$$

for $N_+$. This has to be done for each mass hypothesis, yielding a mass dependent upper limit $N^+$ at the $\alpha$ confidence level.

In this analysis the coupling $\lambda$ is given by $\sqrt{|d^2 + |d| }B$ and this procedure gives an upper limit on it.
CHAPTER X

Conclusions

I have searched in a model-independent manner for resonances in the $e\gamma, \nu W$ or $eZ$ channel in an $ep$ experiment with the ZEUS detector. The previous sections showed that there is no evidence for such a resonance in the 1993 data of 554 nb$^{-1}$. It was shown that the ZEUS detector has an excellent efficiency for discovering excited electrons and is capable of reconstructing the mass of the $e^*$ accurately in all three decay modes. Figure 7.2.4, 7.4.5 and 7.5.4 show the acceptances and figure 10.1 shows the mass resolution and mass shift in the three modes as a function of mass. For all the decay modes we have studied, the number of signal events remaining after our analysis cuts is consistent with the estimated background. We have also observed high energy elastic Compton scattering in an $ep$ experiment in agreement with theory. Table 10.1 summarizes the results from this search and lists an upper limit on the inclusive production cross section in each channel.
Table 10.1: Number of events and expected backgrounds for the channels studied in this analysis. $\sigma_+$ is the upper limit on the cross section at the 90% C.L. The acceptance is for an $e^*$ decay into the corresponding channel; the acceptance varies as a function of the $e^*$ mass.

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Mass range (GeV)</th>
<th>Number of events</th>
<th>Expected background</th>
<th>Acceptance</th>
<th>$\sigma_+$ pb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\gamma$</td>
<td>45-296</td>
<td>5</td>
<td>9</td>
<td>80%</td>
<td>5.1</td>
</tr>
<tr>
<td>$eZ$</td>
<td>120-230</td>
<td>3</td>
<td>5</td>
<td>50%</td>
<td>12</td>
</tr>
<tr>
<td>$\nu W$</td>
<td>120-230</td>
<td>4</td>
<td>1</td>
<td>50%</td>
<td>14</td>
</tr>
</tbody>
</table>

The upper limit on the inclusive production cross section as a function of mass is shown in figure 10.3.

The upper limits on the $e^*$ coupling constant as a function of mass were calculated up to $M_{e^*} = 230$ GeV. The statistical method of this calculation was shown in the previous section. For higher masses the width of the states increases such that they cannot be resolved experimentally any more. Also the limit on the coupling would become too weak, since any signal would be exponentially damped out as was shown in the previous section.

Figure 10.4 shows the 95% confidence limit on the products of the coupling constant and the square root of the branching fraction for each of the three possible $e^*$ decay channels as a function of $m_{e^*}$. The advantage of showing the results as limit on the gauge parameters $c$, $d$ and the branching ratio $B$ is that it avoids any assumption about the relative size of $f$ and $f'$, i.e. about the preferred decay modes of $e^{*'}$s. The figure also indicates where the most recent LEP limits are set. It is clear that due to
our high center of mass energy and our excellent acceptance at masses above the $Z$ mass we are able to set the best limits worldwide on the production of $e^+e^-$.

**Future outlook**

In case no signal is discovered in the future ZEUS data the upper limit on the production cross section as well as the coupling constants will scale down with increasing luminosity. In the absence of any background the upper limit on the cross section scales with $1/\sqrt{\mathcal{L}}$. It is to be expected though that with increasing beam intensity and high $Q^2$ deep inelastic scattering events the amount of physics and non-physics background will also increase. As the background increases the scaling of the limit will be better described by a smaller power of $\mathcal{L}$. When LEP200 turns on with a center of mass energy of at least 170 GeV the limit from LEP experiments will be moved out to become an almost vertical line at half of the center of its center of mass energy. This still leaves HERA as the only place to have access to the window of discovering high mass $e^+e^-$. 
Figure 10.1: The top figure shows the mass resolution of the search signal in the three decay modes. The smearing of the mass is due to detector effects (for all generated mass points the theoretical width is negligible). The $\epsilon\gamma$ and $\nu W$ resolution improves with increasing mass due to the $1/\sqrt{E}$ dependence of the calorimeter. In the case of the $\epsilon Z$ the same trend is visible initially, but at higher masses the lepton starts escaping through the forward beampipe and this quickly offsets the increased energy resolution of the calorimeter. The bottom figure shows the mass shift, the difference between the mean of the reconstructed signal and the 'true' signal.
Figure 10.2: Upper limit on the inclusive production cross section for $e^*$ in the three search channels as a function of the $e^*$ mass at the 95% confidence level. The individual candidates are easily recognizable as bumps in the limit curves.
Figure 10.3: Upper limit on the product of the coupling constant and the square root of the branching fraction $(|c_{\gamma e}e|^2 + |d_{\gamma e}e|^2)^{\frac{1}{2}}/\Lambda B^\frac{1}{2}$ for $e\gamma$, $eZ$ and $\nu W$ final states at the 95% confidence level. The excluded areas in each channel are above the limit curves. The dotted line indicates where the most recent limit from the LEP experiments are set relative to the ZEUS limits. The excluded area is to the right of the vertical LEP line.
Appendix A

The Mass Reconstruction

The mass of the $e^*$ in the $eZ$ decay mode can be calculated from its decay products $e$ and $Z$.

$$M_{ee}^2 = (p'_e + p_Z)^2 \quad (A.1)$$

where $p'_e = (p'_{ex}, p'_{ey}, p'_{ez}, E'_e)$ is the 4-momentum of the decay electron and $p_Z = (p_{zx}, p_{zy}, p_{zz}, E_Z)$ the 4-momentum of the decay $Z$. From an experimental point of view it is most practical to manipulate A.1 such that it is a function of the $Z$ mass and the electron variables only.

$$M_{ee}^2 = -(p'_{ex} + p_{zx})^2 - (p'_{ey} + p_{zy})^2 - (p'_{ez} + p_{zz})^2 + (E'_e + E_Z)^2 \quad (A.2)$$

Under the assumption that

$$p_t = \sqrt{+(p_{ex} + p_{zx})^2 + (p_{ey} + p_{zy})^2} \sim 0$$

equation A.2 becomes

$$M_{ee} = ((E'_e + E_Z) - (p'_{ez} + p_{zz}))((E'_e + E_Z) + (p'_{ez} + p_{zz})) \quad (A.3)$$
Using energy and momentum conservation

\[-E_e + E_p = p'_{ez} + p_z + p'_{pz}\]

\[p_z \text{ conservation} \quad (A.4)\]

\[+E_e + E_p = E'_e + E_Z + E'_p\]

\[E \text{ conservation} \quad (A.5)\]

where \(E'_p\) and \(p'_{pz}\) are the energy and momentum of the proton remnant and the approximation that the remnant disappears in the forward beam hole, i.e. \(E'_p = p'_{pz}\), then \(\delta\) is defined as

\[\delta = 2E_e = ((E'_e + E_Z) - (p'_{ez} + p_z))\]

Then equation A.3 becomes:

\[M^2_{e*} = 2E_e (E'_e + p'_{ez} + E_Z + p_z) \quad (A.6)\]

Equations (A.4) and (A.5) and the Z mass constraint \(M^2_Z = -p^2_{2x} - p^2_{2y} - p^2_{2z} + E^2_Z\), the approximation \(p_t \sim 0\), i.e. \(\sqrt{p^2_{2x} + p^2_{2y}} = \sqrt{p^2_{ez} + p^2_{cy}}\), and \(E'_p = p'_p\) yield

\[E_z + p_{Zz} = \frac{p^2_{e\text{ perp}} + M^2_z}{2E_e - (E'_e - p'_{ez})} \quad (A.7)\]

where \(p^2_{e\text{ perp}} = \sqrt{p^2_{ez} + p^2_{cy}}\). Inserting A.7 into A.6 gives

\[M^2_{e*} = 2E_e \frac{2E_e (E'_e + p'_{ez}) + M^2_z}{2E_e - (E'_e - p'_{ez})} \quad (A.8)\]

which is equivalent to equation 7.5.
In the decay channel \(e^* \rightarrow \nu W\) the mass is reconstructed similarly. Equation A.6 becomes

\[
M_{e^*}^2 = 2E_e(E'_\nu + p'_{\nu z} + E_W + p_W) \quad (A.9)
\]

where \(p_\nu = (p_{\nu x}, p_{\nu y}, p_{\nu z}, E_\nu)\) is the 4-momentum of the decay neutrino and \(p_W = (p_{W x}, p_{W y}, p_{W z}, E_W)\) the 4-momentum of the decay \(W\). Analogously A.7 becomes

\[
E_\nu + p_{\nu z} = \frac{p_{\nu \perp}^2}{2E_e - (E_W - p_{W z})} \quad (A.10)
\]

The \(e^*\) mass is then given by

\[
M_{e^*}^2 = 2E_e \frac{2E_e(E_W + p_{W z}) - M_W^2}{2E_e - (E_W - p_{W z})} \quad (A.11)
\]

Since only the \(W\) is visible, \(\delta\) is given by \(E_W - p_{W z}\).

\[
M_{e^*}^2 = \frac{4E_e^2(M_W^2 - p_{W \perp}^2) - 2E_eM_W^2\delta}{\delta(2E_e - \delta)}
\]

which is equivalent to equation 7.7.
Appendix B

The Fast Clear

The Fast Clear (FC) was designed to further reject first level triggers from beam-gas background to ensure that the effective First Level Trigger (FLT) processing rate is less than 1 kHz. In the overall scheme, the FC sits between the first and the second level triggers. It is a fast, special purpose digital processor which examines and processes digitized calorimeter data for each trigger issued by the Global First Level Trigger (GFLT).

After an event has been FLT accepted the full width digitization of the data can take up to 50 μsec thereby creating significant dead time. This gives FC a window for a more detailed study of every GFLT accepted event. Monte Carlo studies have shown that FC processing time per event stays on the average below 20 μsec.

FC [36] is a cluster finding processor using Calorimeter First Level Trigger (CALFLT) data [69] only. A cluster is defined as a group of neighboring calorimeter towers which have energy depositions exceeding a pre-programmed threshold. The FC study is based on the properties of those clusters, it calculates the following quantities for each cluster: number of towers (cells), electromagnetic energy, hadronic energy, energy distribution and position of cluster.
B.1 FC Strategy and abort logic

It is important to note that FC does not actively veto an event, but only sends an "abort" recommendation to the GFLT. The abort decision is ultimately made by the GFLT based on the FC recommendation together with other information available to the GFLT.

The FC decision is based on 3 criteria:

(1) is there an isolated electron in the event (ISOE)

(2) does the event have significant missing transverse momentum (MTM)

(3) is the event a beam gas interaction (RCAL)

I. Isolated Electrons

The selection criteria of the isolated electron are (also see section B.3.1 for more details):

* Bit 0 Electromagnetic showers are focused in narrow cones, therefore only very few towers should be hit (≤ four towers).

* Bit 1 The energy in a electromagnetic shower is very narrowly peaked. MC studies show that the energy deposited in the periphery of an electron candidate should be less than 15% of the total energy

* Bit 2 In an electromagnetic shower most of the energy is deposited in the EMC part of the calorimeter. MC studies show that the ratio of HAC to EMC energy should be less than 0.2
* Bit 3 Faked electrons from BG have a different $\theta - E$ distribution than NC events. An energy dependent angle cut can therefore differentiate between them.

II. Missing transverse momentum

A significant amount of missing transverse energy indicates a charged current event and reduces the probability that the event resulted from a beam gas interaction [fig.1 and fig.2], where missing transverse energy is defined as

$$\sqrt{(\sum E_i \sin \theta_i \cos \phi_i)^2 + (\sum E_i \sin \theta_i \sin \phi_i)^2}$$

$N_t$: Number of trigger towers with energy deposits above threshold

$\theta_i$: polar angle of a trigger tower

$\phi_i$: azimuthal angle of a trigger tower

$E_i$: energy of a trigger tower

Then Bit 4 is set if $MTM$ is larger than some programmable threshold (see section B.3.2 for more details).

II. Beam Gas Identification

The rear calorimeter (RCAL) is sensitive to the incoming beam gas particles generated from $-35m \leq z \leq -2.5m$. The energy deposition in the RCAL from the physics events will be different from the beam-gas events. In the neutral current (NC) events there are some scattered electrons hitting the RCAL, but very few hadron jets
from charged current (CC) events are back scattered into the RCAL. In contrast about 80% of the beam gas particles are hadronic. Therefore the RCAL EMC energy will be dominant from physics events and HAC energy will be dominant from beam gas events. Therefore the following parameter

\[ R_f = \frac{EMC - HAC}{EMC + HAC} \]

is calculated for each cluster in RCAL. Looking at \( R_f \) of the most energetic cluster versus the radial distance \( \rho \) of it from the \( z \) axis is a useful criterion for distinguishing beam gas from physics events. Bit 6 is set if \( R_f \) is larger than some threshold which depends on \( \rho \) of the most energetic cluster (see section B.3.3 for more details).

If the electron bit (\( ISOE \)) is set, the event is always kept regardless of the other bits. If the (\( MTM \)) bit is not set, as expected for beam gas, then events are aborted. Beam gas events with missing transverse momentum above the MTM threshold (\( METH \)) are further tagged by the (\( RCAL \)) bit. The complete logic for an FC abort/keep decision is given in table B.1.

B.2 Organisation of FC

The hardware design and test are described here.

B.2.1 Rawdata-Interface with CALFLT

The Calorimeter First Level Trigger CALFLT reads in the photomultiplier signals of the 3 calorimeter sections: rear calorimeter, forward calorimeter and barrel calorime-
Table B.1: Trigger table for FC

<table>
<thead>
<tr>
<th></th>
<th>RCAL</th>
<th>MTM</th>
<th>ISOE</th>
<th>fc-decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>abort</td>
</tr>
<tr>
<td>FC1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>keep</td>
</tr>
<tr>
<td>FC2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>keep</td>
</tr>
<tr>
<td>FC3</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>keep</td>
</tr>
<tr>
<td>FC4</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>abort</td>
</tr>
<tr>
<td>FC5</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>keep</td>
</tr>
<tr>
<td>FC6</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>abort</td>
</tr>
<tr>
<td>FC7</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>keep</td>
</tr>
</tbody>
</table>

ter (RCAL, FCAL and BCAL) and combines them into analog EMC and HAC supertower sums. One supertower typically (depending on the position in the calorimeter) includes 4 HAC (2 left - 2 right) and 8 EMC (4 left - 4 right) photomultipliers. There is a total of 224 supertowers in FCAL and RCAL each and 448 supertowers in BCAL.

So CALFLT issues one HAC and one EMC signal for each supertower. CALFLT then digitizes (this is not the full digitization) those signals into 8 bit words plus one scale bit. For FCAL data, if the scale bit is not set, the maximally dynamic range is 0-12.5 GeV and if the scale bit is set, the range is 0-400 GeV. For RCAL and BCAL the numbers are 0-12.5 GeV and 0-100 GeV respectively. CALFLT transfers the digitized data to FC in parallel on a 24 ns clock cycle. The readout of the EMC and HAC data is upstream of CALFLT's own processing and analysis effort.

There are two protocol lines for communications between FC and CALFLT: Hold and Valid. Hold indicates that FC is working on an event and Valid that CALFLT
is transmitting valid data to FC.

Figure B.1 shows how FC interfaces with the CFLT as well as the other trigger components.

### B.2.2 Architecture

The data from each detector subsystem (RCAL, BCAL and FCAL) is processed in parallel and independently in its individual input cage. An input cage consists of 8(16) FCAL/RCAL (BCAL) input cards, one buffer card, one control card and one cluster card. The FCAL and RCAL cards are combined in one Fastbus cage and BCAL is contained in another. After the input cage, the data are then sent in parallel to a VME cage. The information from each of the three detector subsystems is combined there to form a calorimeter trigger decision and is formatted and stored for transfer to the second level trigger and the event builder.

The CALFLT data from a 7x4 supertower region of the detector is read into one input card. There are 8 such regions for FCAL and RCAL each and 16 for BCAL requiring a total of 32 input cards.

In figure B.2 the crate organization of FC can be seen.

One input card receives the EMC and HAC signals of 28 supertowers and expands them from 8 bits plus a scale bit to 12 bits with a common scale. The sum of EMC and HAC is calculated and stored in on-board memories. It also generates two hitmaps where the geometric patterns of bits are set according to whether the energy in a tower exceeds one of two thresholds (Member and Seed).

On a customized backplane those hitmaps are then sent to the Cluster Card
and stored in the hit memories. At this time all the information needed for the cluster finding algorithm exists on the cluster card. Looking through both memories simultaneously the seed search generates a bit mask which consists of a single bit corresponding to the first bit exceeding the seed threshold and not belonging to a previous cluster. Starting with the output of the seed search, the cluster search identifies nearest neighbour groups of cells as clusters. Those bit masks of clusters are sent to the Control Card where the address finder locates the physical address of a given cluster member (input card number and memory location). Given the address of the member of a cluster, the energy stored there is looked up and then sent through the Buffer Card to the VME cage. In the VME cage there is one Processor Card (PC) for each of the 3 subsystems (RCAL, FCAL and BCAL). Each PC receives the EMC, HAC and Total Energy (EC) of the clusters in the respective calorimeter section. The PC then processes the data further. It sums up the transverse energy components of the cluster (Ex, Ey), it finds the supertower with with the highest energy in a cluster and stores its geometric address (AMAX), it sums up the energy deposited in the periphery of a cluster (Ep), it counts the number of towers in a cluster (NT), it separately sums up the EMC, the HAC and the EC energy in an event. The HAC, EMC and EC energies of each supertower are also stored in memories on the processor card, from where they can be read out to the equipment computer. For this purpose the starting address (SA) as well as the size of an event (Word Count, WC) stored in the onboard memories are also recorded and transferred downstream to the Trigger Card.
B.2.3 Trigger Card

The Trigger Card (TC) was designed, built and tested by myself. The Trigger Card combines the data from all three PC's to issue an FC-Abort recommendation, i.e. based on whether the event was identified as a NC, CC, or BG. It also issues an event summary which is stored in a FIFO and it keeps the summary of each cluster in a DPM (Dual Port Memory), again keeping track of the starting addresses and the number of clusters in an event. As soon as data is available in one of the PC Fifos a “Data Available” (DAV) signal is sent to TC, which then starts reading out the respective PC Fifos. The format of the cluster data is shown in table B.2. This cluster information is then processed in parallel and from it various comparisons are calculated based on which the FC decisions are made (also see table B.2).

The results of the comparisons are kept in input controlled flip flops and the following flags are set

* if bits 0,1,2 and 3 are all true then a isolated electron is flagged (ISOE)
* if bit 4 is true a charged current event is flagged (MTM)
* if bit 5 is true a beam gas event is flagged (RCAL)

and the FCResult word (4 bits wide) is issued according to table B.1

FCResult0: isolated electron (NC)
FCResult1: missing transverse energy (CC)
FCResult2: beam gas (BG)
FCResult3: FC-Abort

All thresholds are programmable parameters (HETH, PETH, NTTH, METH, ELTH, EFTH) and ELTH and EFTH are dependent on the position of the clusters
Table B.2: Cluster variables and their algorithms on the trigger card

<table>
<thead>
<tr>
<th>AMAX:</th>
<th>location of tower with max energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC:</td>
<td>total energy</td>
</tr>
<tr>
<td>HAC:</td>
<td>hadronic energy</td>
</tr>
<tr>
<td>EMC:</td>
<td>electromagnetic energy</td>
</tr>
<tr>
<td>PE:</td>
<td>energy in the periphery</td>
</tr>
<tr>
<td>NT:</td>
<td>number of towers</td>
</tr>
<tr>
<td>AMAX:</td>
<td>location of tower with max energy</td>
</tr>
<tr>
<td>EC:</td>
<td>total energy</td>
</tr>
<tr>
<td>EX:</td>
<td>energy in the x direction</td>
</tr>
<tr>
<td>EY:</td>
<td>energy in the y direction</td>
</tr>
</tbody>
</table>

1. \( \frac{HAC}{EMC} \leq 0.2 \)
2. \( NT \leq 4 \)
3. \( EC \geq \) threshold(\( \theta \))
4. \( \frac{PE}{EC} \leq .15 \)
5. \( \frac{EMC-HAC}{EMC+HAC} \geq \) threshold(\( \rho \))
6. \( EC \geq E_{\text{max}} \)
7. \( \sum EC = \) total energy of event
8. \( EMC \geq 5 \cdot HAC = \) \( HETH \cdot HAC \)
   \( NTTH > NT \)
   \( EC > \) \( ELTH \)
   \( EC \geq 6.7 \cdot PE = \) \( PETH \cdot PE \)
   \( MTE^2 > \) \( METH^2 \)
   \( EMC-HAC < \) \( EFTH \cdot EC \)

\( E_{\text{max}} \): largest previous energy in an event
\( \sum EC \): this is part of the data summary of each event but is not compared to a threshold
\( HETH, METH, NTTH, PETH \): global thresholds which are independent of the location of the cluster
and therefore have to be stored in a look up table. METH has a 20 bit resolution, EFTH has 12 bit-two’s complement format and all other thresholds have positive 12 bit format. HETH-HAC and PETH-EC are calculated on single port multipliers (ADSP1010B), which allow the thresholds HETH and PETH to be loaded into the devices at startup and stored there throughout the processing. EFTH-EC is calculated on a dual port multiplier (ADSP1110). Because EFTH is dependent on the cluster location, it is stored in a RAM which directly feeds into one of the multiplier ports and EC is fed into the other one. The difference between EMC and HAC (EMC-HAC) is calculated in a Logic Cell Array (LCA) and fed directly into the comparator. The missing transverse energy calculation is the most difficult, since for each cluster $\sum EX$ and $\sum EY$ has to be calculated, then the sums have to be squared and added after all clusters are processed. All this is accomplished in 3 dualport Mac’s (Multiplier-Accumulator).

The LCA’s are large programmable logic devices which allow the user to integrate many clocked logic functions into a single device (i.e. comparators, registers etc.). With 145 input/output pins they are ideally suited to be used in a heavily parallel environment such as ours.

The design of the Trigger Card relies heavily on LCA’s. At the algorithm stage (multiplications and summations) of the board (most upstream), the total energy of the event and the difference between EMC and HAC plus several holding registers are implemented in the first LCA (LCA00). All the comparisons, multiplexing between various data lines and pipelining are done in the other two LCA’s. The logic for issuing
the FCResult's and the comparison are implemented in the second LCA (LCA01).
The comparator is relatively slow, it takes four clock cycles to get the result out.
Because of its pipeline structure though, the compared values can be clocked through
the comparator one right after the other. So all seven comparisons could be made in
as few as 7+4=11 clock cycles.

The third LCA (LCA02) contains little logic and mainly acts as a register bank
and pipeline of the data before it is written to the memory and Fifo, both of which
are 32 bits wide. The DPM is built out of four 8x2048 memories (IDT7132 and
IDT7142), where two are combined in a low bank for data bits 0-15 and two in a high
bank for bits 16-31 (over 512 clusters can be stored). The two banks can be written
to independently of each other, but all 0-31 data bits have to be read out at once.
Similarly four Fifo devices (IDT7204, 9 bits wide and 4096 words deep) make two
banks, where the two banks can be filled independently of each other, but the output
of all four devices is enabled at once for readout (585 events can be stored).

The event summary and the cluster information are written to an onboard (TC)
Fifo and DPM regardless of whether the event is accepted or not. The storage loca-
tions are listed in table B.3. The starting address (WA) of the clusters on the other
hand is only updated if GFLT accepts the event containing those clusters. Given the
address pointers stored in the TC fifos, the cluster information of all accepted events
and the EMC, HAC and EC of all supertowers in the identified clusters of an event
can be read out of the PC and TC DPM.

It takes TC 23 clock cycles to digest each cluster and to write the cluster infor-
Table B.3: FIFO and DPM memory locations

<table>
<thead>
<tr>
<th>bit</th>
<th>16-31</th>
<th>0-15</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>WC (BCAL)</td>
<td>SA (BCAL)</td>
</tr>
<tr>
<td>1</td>
<td>WC (RCAL)</td>
<td>SA (RCAL)</td>
</tr>
<tr>
<td>2</td>
<td>WC (FCAL)</td>
<td>SA (FCAL)</td>
</tr>
<tr>
<td>3</td>
<td>WCNT (DPM)</td>
<td>WA (DPM)</td>
</tr>
<tr>
<td>4</td>
<td>FCRResult</td>
<td>Total Energy</td>
</tr>
<tr>
<td>5</td>
<td>Processing time</td>
<td>MTE (Low)</td>
</tr>
<tr>
<td>6</td>
<td>Error Flags</td>
<td>MTE (High)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>bit</th>
<th>16-31</th>
<th>0-15</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>EMC</td>
<td>HAC</td>
</tr>
<tr>
<td>1</td>
<td>NT</td>
<td>PE</td>
</tr>
<tr>
<td>2</td>
<td>EC</td>
<td>AMAX</td>
</tr>
<tr>
<td>3</td>
<td>EY</td>
<td>EX</td>
</tr>
</tbody>
</table>

**WC:** number of words in an event in the PC memory  
**SA:** starting address points to the beginning of an event in the PC memory  
**WCNT:** number of words  
**WA:** (ie. number of clusters, 4 words make one cluster)  
**WA:** starting address points to the beginning of an event in the TC DPM
mation to DPM. At the end of an event it takes another 22 clock cycles to write the event summary to the Fifo and to set the card up for the next event. Therefore the total time TC takes to process one event is given by the following formula:

\[ n_{cycles} = 23 \cdot n_{cluster} + 22 \]

then \( T_{processing} \geq 2.25 \mu s \) if one cycle is 50 ns

- \( n_{cycles} \): number of clock cycles
- \( n_{cluster} \): number of clusters

Since many of the algorithms run in parallel it becomes necessary to have a powerful control system. This is implemented in the form of micro programmable controllers (AM29CPL154). Four such controllers are required on the TC, since a total 49 control lines are needed to steer TC.

**B.2.4 Hardware Testing**

1. LCA testing: since the LCA’s on TC have fairly complex configurations, it is useful to be able to simulate those configurations in software to aid in the debugging process. The simulation system is called Silos and allows you to clock any input test pattern through the LCA and observe the state of all latched flipflops on the device. Silos helped the design and shakedown of the LCA’s considerably.

2. Section testing: for most of the devices on TC there exists software, which allows one to test each section individually. For this purpose there are diagnostic configurations for the two LCA’s, which are further downstream. These diagnostic configurations are basically large shift registers, so that many data lines can be read
out at once. This way most sections of the board can be tested independent of failures in other sections.

3. Standalone testing: all data coming in from PC is latched through octal registers with serial channels (SPC registers) which allows one to switch from parallel to serial mode and load the register with a desired test word serially from VME. Since the serial shift is slow, standalone tests can not be done with a fast clock.

4. Interfacing with PC: in this test mode the Fifo's on PC containing the cluster data (several events) are filled with test words serially, again with the help of SPC's located at the data input of these Fifos. Then a fast clock is turned on and the TC controller initiates the data read in. It then processes the data and issues a FCResult, which is compared with the expected result through software. In this mode the controller can not run through its whole program though, since whenever the PC Fifo is loaded serially with a new event the controller has to be in a idle state, so as not to throw the microprogram out of sync.

5. Full testing: in this mode the whole dataflow is checked out. At the most upstream entry point the input card registers are loaded with test events. Then the system receives a global reset and the event is run through the whole system. The content of the Fifo (event summary) and the contents of the TC DPM as well as the PC DPM are read out and the results are compared to the expected results from simulation.

All the test routines were developed and used throughout the design and building phase of the board. They are not only important as diagnostic tools, but were vital in
being able to recognize problems and modify the design while building up the boards.

**B.2.5 Results**

With the most recent generation of LCA's it is possible to run TC at clockspeeds well below 50 ns. The full tests were run with Monte Carlo data as input (300 events). The mean time taken by the full processor for one event is slightly lower than what was expected from the design simulations (∼15μs). Figure B.3 shows the timing distribution of event processing.

**B.3 The Fast Clear simulation and the Tuning of Fast Clear Thresholds**

Simulation of the Fast Clear hardware was done with the FLSFC package, which is now integrated in ZGANA (1) and is being called in the current version. In order that the software resembles the hardware as close as possible, FLSFC simulates the processing and algorithms implemented in the FC hardware on a card by card level.

After read-in of the trigger tower data (TRGTWR from CALFLT) in the FC input card simulator (FCINPUT), the data is searched for clusters in the FC cluster card simulator (FCCLUST). The location and energy of the towers in an identified cluster is then read out with the address card simulator (FCADDRS) and the corresponding EMC and HAC energies of each tower are sent to the FC processor card simulator (FCPROCS). There the total and peripheral energy of a cluster is calculated as well as its directional x and y components and the number of towers in each cluster. The processed data is then passed on to the FC trigger card simulator (FCTRIGR)
where the final trigger-veto decision is made. All Monte Carlo data and beam-proton data were processed with FLSFC and only events that were GFLT triggered were considered for this study.

B.3.1 Isolated electrons

A cluster is identified as an isolated electron based on three criteria:

* (1) ratio of HAC to EMC energy of the cluster
* (2) maximum number of calorimeter towers in the cluster
* (3) ratio of peripheral to total energy of the cluster

These three cuts were tuned on single isolated electrons sprayed uniformly over the detector in an energy range between 0-30 GeV. An efficiency of at least 97% was achieved with those three criteria. Since beam-gas events can have clusters that satisfy these three criteria (≥17%) and therefore fake electrons, an additional cut (4) on the energy of a cluster as a function of its polar angle is used to separate out beam-gas events. Clusters that satisfy the other three subbits, but do not pass cut(4) are not tagged as isolated electrons. Electron efficiency versus beam-gas rejection was optimized on NC Monte Carlo and the dedicated proton-beam run data. Only a small part of phase space in the DIS NC cross section is cut out by this additional cut(4), which amounts to a small reduction of the DIS NC efficiency, on the other hand it enhances the FC beam-gas rejection by 11%.

The efficiencies of cut(4) were studied with the following data set. For 6170 GFLT triggered DIS NC events and the 8243 GFLT triggered beam-gas events that were
processed with the current standard cuts:

\[ \text{HAC/EMC} \leq 0.2 \quad \text{Eperipheral/EC} \leq 0.15 \]

\[ \text{Number-of-towers} \leq 5 \quad \text{Missing-transverse-momentum} \leq 4 \text{ GeV} \]

The efficiencies of cut(4) for those events are listed in table B.4. The settings of this cut are shown in table B.5.

Table B.4: Efficiencies of the cut in the energy-angle cut for DIS NC. The binary combinations of the three FC triggers (FC0 — 1) are listed in table B.1

<table>
<thead>
<tr>
<th>Setting</th>
<th>FC 0</th>
<th>FC 1</th>
<th>FC 2</th>
<th>FC 3</th>
<th>FC 4</th>
<th>FC 5</th>
<th>FC 6</th>
<th>FC 7</th>
<th>Keep</th>
<th>eff</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIS NC</td>
<td>81</td>
<td>4019</td>
<td>15</td>
<td>320</td>
<td>251</td>
<td>1431</td>
<td>10</td>
<td>43</td>
<td>5828</td>
<td>94%</td>
</tr>
<tr>
<td>Beam Gas</td>
<td>3445</td>
<td>479</td>
<td>449</td>
<td>1140</td>
<td>2149</td>
<td>218</td>
<td>342</td>
<td>21</td>
<td>5936</td>
<td>72%</td>
</tr>
</tbody>
</table>

Table B.5: Setting of the energy-angle cut

<table>
<thead>
<tr>
<th>$\theta(\degree)$</th>
<th>0-10</th>
<th>10-20</th>
<th>20-50</th>
<th>50-100</th>
<th>100-120</th>
<th>120-180</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

B.3.2 Missing transverse momentum

If no isolated electron is identified, the situation is more complicated, information on the missing transverse momentum (MTM) as well as on the pattern of energy deposition in RCAL, as described below in section B.3.3 are used to discriminate against beam gas interactions. Simulations with CC Monte Carlo show that FC
does very well in calculating the missing transverse momentum and the energy of the event (figure B.4). CC events are characterized by their missing transverse momentum distribution peaking at about 20 GeV. Since beam-gas events peak at very low MTM, a large fraction of beam-gas events can be aborted by setting a minimum MTM threshold without cutting significantly into the CC events as can be seen in table B.6.

To optimize the threshold for the missing transverse momentum cut (METH), the efficiency of this cut was studied with events, which passed the GFLT trigger and had no FC isolated electron bit set, since events with this bit set are not vetoed regardless of their missing transverse momentum. This left 1294 Charged Current events and 6385 beam-gas events. The efficiencies are shown in table B.6. METH is now set at \( \geq 4 \text{ GeV} \) to preserve as many of the Charged Current events as possible.

### Table B.6: Efficiencies at various settings of the missing energy cut (METH)

<table>
<thead>
<tr>
<th>METH (GeV)</th>
<th>Charged Current</th>
<th>accept</th>
<th>Beam Gas</th>
<th>accept</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \geq 2 )</td>
<td>1285</td>
<td>99%</td>
<td>2368</td>
<td>37%</td>
</tr>
<tr>
<td>( \geq 4 )</td>
<td>1265</td>
<td>98%</td>
<td>791</td>
<td>12%</td>
</tr>
<tr>
<td>( \geq 6 )</td>
<td>1226</td>
<td>95%</td>
<td>393</td>
<td>6%</td>
</tr>
<tr>
<td>( \geq 8 )</td>
<td>1174</td>
<td>91%</td>
<td>294</td>
<td>5%</td>
</tr>
<tr>
<td>( \geq 10 )</td>
<td>1135</td>
<td>88%</td>
<td>257</td>
<td>4%</td>
</tr>
</tbody>
</table>

**B.3.3 RCAL as a beam-gas veto wall (RCAL bit)**

To get a handle on the beam-gas events that have MTM above threshold, their energy deposition in RCAL (30% of beam-gas events with MTM \( \geq 4 \) have a least one cluster
in RCAL) is looked at more closely for setting the RCAL bit.

Beam-gas interactions upstream of the RCAL leave a distinct energy distribution in RCAL since the spray from the beam-gas interaction enters the RCAL from the rear side (i.e., the HAC part of RCAL) and is concentrated mainly in a close cone around the beam pipe hole. On the other hand only 15% of the CC events leave any clusters in the RCAL at all.

This allows to use a cut on $E_f$ versus $\rho$ as an additional tag for beam-gas events as explained in section 1.

To optimize the acceptance of Charged Current events and the rejection of beam-gas events the $E_f$ versus $\rho$ cut was studied and accordingly tuned to equation B.1 (described below).

The Monte Carlo data as well as the beam-gas data were processed using the fiducial cuts:

\[
\frac{\text{HAC/EMC}}{\text{Eperipheral/EC}} \leq .2 \quad \frac{\text{Eperipheral}}{\text{EC}} \leq .15
\]
\[
\text{Number-of-towers} \leq 4 \quad \text{Missing-transverse-momentum} \leq 4 \text{ GeV}
\]

To obtain a meaningful sample of events for the study of this particular cut, it was required that the events had a cluster in RCAL as well as missing transverse energy above 4 GeV. This left 451 beam-gas and 193 Charged Current events.

This cut was tuned to correspond to a straight line through the $E_f$-$\rho$ plane

\[E_f = -10 \cdot \rho + 35. \quad (B.1)\]
It is implemented in the FC simulation code approximating the hardware algorithm which is a step function. It leaves 95% of the CC Monte Carlo and 31% of the beam gas events.

B.3.4 Final results and conclusion

Processing the Monte Carlo data and the beam-gas data with the fiducial cuts for the electron bit

\[ \text{HAC/EMC} \leq .2 \]

\[ \text{Eperipheral/EC} \leq .15 \]

\[ \text{Number-of-towers} \leq 4 \]

Energy versus polar angle cut: see table B.5

for the MTM bit

\[ \text{Missing-transverse-momentum} \leq 4. \]

for the RCAL bit

\[ E - f \text{ versus } \rho \text{ cut: } \sim E_f = -10 \cdot \rho + 35 \]

produced the efficiencies which are listed in table B.7.

In order to also preserve a large fraction of photoproduction events, an additional cut is planned for FC that allows one to discriminate the beam gas from the \( \gamma P \) events by considering \( E - p_z \).

As the luminosity increases the need to reduce the GFLT rate will become more pressing so as not to loose large amounts of physics triggers due to time outs. In order to handle increased luminosity one will have to increase trigger thresholds and/or
Table B.7: Efficiencies for NC and CC DIS and beam gas events through FC processing with current settings ($FC_0 - 7$ are defined in table B.1)

<table>
<thead>
<tr>
<th></th>
<th>GFLT</th>
<th>FC 0</th>
<th>FC 1</th>
<th>FC 2</th>
<th>FC 3</th>
<th>FC 4</th>
<th>FC 5</th>
<th>FC 6</th>
<th>FC 7</th>
<th>Keep</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIS NC</td>
<td>6170</td>
<td>81</td>
<td>4019</td>
<td>15</td>
<td>320</td>
<td>251</td>
<td>1431</td>
<td>10</td>
<td>43</td>
<td>5828 (94%)</td>
</tr>
<tr>
<td>DIS CC</td>
<td>1607</td>
<td>16</td>
<td>20</td>
<td>1259</td>
<td>283</td>
<td>13</td>
<td>5</td>
<td>6</td>
<td>5</td>
<td>1572 (98%)</td>
</tr>
<tr>
<td>BG</td>
<td>8243</td>
<td>3445</td>
<td>479</td>
<td>449</td>
<td>1140</td>
<td>2149</td>
<td>218</td>
<td>342</td>
<td>21</td>
<td>2307 (28%)</td>
</tr>
</tbody>
</table>

prescale a larger fraction of the events. FC will be exceedingly useful in avoiding exactly such a situation where good physics will be lost due to prescaling and high thresholds. It has been demonstrated that FC can significantly reduce the GFLT trigger rate due to beam-gas by a factor of 3-4 without cutting into the physics rates by more than 2% for Charged Current events and 6% for Neutral Current events.
Figure B.1: The Fast-Clear and its integration with the ZEUS trigger system.
Figure B.2: Crate organisation of the FC system. There are 48 circuit boards total and 7 different types of cards distributed over 3 crates.
Figure B.3: Distribution of event processing time in $\mu$s. This result was reached by processing Monte Carlo events with FC. The Monte Carlo used for this study was a mix of beam gas, NC and CC events.

Figure B.4: Plots of the missing transverse momentum (left) and the energy (right) calculated by FC (horizontal) versus the full calorimeter 14 bit digitization reconstruction (vertical CALTRU).
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