NON-PHOTONIC ELECTRON DISTRIBUTIONS AT PSEUDO-RAPIDITIES BETWEEN 1.1 AND 1.5 IN PROTON-PROTON COLLISIONS AT $\sqrt{s} = 200$ GEV AT RELATIVISTIC HEAVY ION COLLIDER

A dissertation submitted to
Kent State University in partial
fulfillment of the requirements for the
degree of Doctor of Philosophy

by
Naresh L. Subba

August, 2010
Dissertation written by

Naresh L. Subba

B.Sc., Sherubtse College, Bhutan, 1992

M.Sc., Tribhuvan University, Nepal, 1996

Ph.D., Kent State University, USA, 2010

Approved by

Dr. Bryon Anderson, Chair, Doctoral Dissertation Committee

Dr. Declan Keane, Members, Doctoral Dissertation Committee

Dr. Spyridon Margetis

Dr. Laura Bartolo

Dr. Robin Selinger

Accepted by

Dr. Bryon Anderson, Chair, Department of Physics

Dr. Timothy Moerland, Dean, College of Arts and Sciences
Table of Contents

List of Figures ...................................................... vii

List of Tables ...................................................... xvi

ACKNOWLEDGMENTS .................................................. xvii

1 INTRODUCTION ..................................................... 1
  1.1 RHIC Goals ...................................................... 1
  1.2 A Short Introduction to QCD ................................. 2
  1.3 QGP at RHIC ..................................................... 6
  1.4 Spin Physics at RHIC .......................................... 9
  1.5 Charm Production ............................................. 13
    1.5.1 Non-Photonic Electron Spectrum ......................... 16
    1.5.2 Charm Cross-Section .................................... 17
  1.6 Physics Motivation for this Dissertation .................. 20
    1.6.1 Limitations .............................................. 20

2 THE EXPERIMENTAL DETAILS ................................. 22
  2.1 The Relativistic Heavy Ion Collider ....................... 22
  2.2 Experimental Detector Systems at RHIC .................... 25
    2.2.1 PHENIX .................................................. 25
    2.2.2 PHOBOS ................................................ 27
    2.2.3 BRAHMS ............................................... 27
## 2.3 The STAR detector
- 2.3.1 Beam Beam Counter ..................................................... 31
- 2.3.2 Central Trigger Barrel .................................................. 31
- 2.3.3 Zero Degree Calorimeter .............................................. 32
- 2.3.4 Silicon Vertex Tracker ................................................... 32
- 2.3.5 Silicon Strip Detector ................................................... 33
- 2.3.6 Time of Flight .............................................................. 33
- 2.3.7 Forward Time Projection Chamber .................................... 34
- 2.3.8 Barrel Electro-Magnetic Calorimeter .................................. 34
- 2.3.9 The STAR Trigger .......................................................... 35
- 2.3.10 The Time Projection Chamber ......................................... 35

## 2.4 The Endcap Electro-Magnetic Calorimeter ............................ 39
- 2.4.1 Mechanical design of the *EEMC* and the tower structure .... 42
- 2.4.2 Pre-shower and post-shower layers ................................... 45
- 2.4.3 Shower maximum detector .............................................. 47

## 2.5 Kent State University (*KSU*) Contribution ......................... 48

## 3 DATA ANALYSIS ................................................................. 53
- 3.1 Run Selection ............................................................... 53
- 3.2 Trigger Selection ........................................................... 53
- 3.3 Event Selection ............................................................. 56
- 3.4 Software Development ..................................................... 57
  - 3.4.1 StRecoEleFinderMaker ............................................... 57
  - 3.4.2 StMcEleAssoMaker .................................................... 59
  - 3.4.3 EleTreeAna .............................................................. 61
3.4.4 EemcEleTree .................................................... 62

3.5 Track Selection .................................................... 62

3.5.1 Range of Interest in $p_t$ and $\eta$ ............................ 62

3.6 Electron Identification ........................................... 64

3.6.1 Energy Deposit and Deposit Shapes of Electrons and Hadrons in the $EEMC$ ........................................... 64

3.6.2 The $EEMC$ Acceptance ........................................ 68

3.6.3 $dE/dx$ and $p/E$ cuts ........................................... 70

3.6.4 Electron Purity .................................................. 71

3.7 Efficiency Corrections ............................................ 75

3.7.1 TPC Efficiency .................................................. 76

3.7.2 $p/E$ Efficiency .................................................. 78

3.7.3 $dE/dx$ Efficiency ................................................ 79

3.7.4 Trigger Efficiency .............................................. 82

3.7.5 Total Efficiency ................................................ 86

3.8 Inclusive Spectrum ............................................... 87

3.9 Reconstruction of Photonic Electrons ($PE$) .................... 88

3.9.1 The Invariant Mass Technique ................................ 90

3.10 Estimation of Non-Photonic Electrons ($NPE$) ............... 94

3.10.1 $PE$ Reconstruction Efficiency ($\varepsilon$) .................. 94

3.10.2 Dependence of $N_{npe}$ on $\varepsilon$ ......................... 96

3.10.3 NPE Spectra .................................................... 97

3.11 Estimation of the Charm Production Cross Section .......... 100

4 SIMULATION STUDIES .............................................. 106
4.1 Photon Conversion Electrons ........................................ 106

4.2 Photonic Electron Reconstruction Efficiency ($\varepsilon$) .......... 108
  4.2.1 Monte Carlo Simulation Studies With Multiple $\gamma$s and
        $\pi^0$s .................................................................. 108
  4.2.2 PYTHIA Simulation ................................................. 111
  4.2.3 Combined Efficiency from $\gamma$ Conversions and $\pi^0$ Dalitz
        Decays .................................................................. 113

4.3 Implications of the Results ............................................. 114

5 RESULTS, DISCUSSION AND CONCLUSIONS ....................... 115

5.1 Results ..................................................................... 115
  5.1.1 Software and Hardware Development For The EEMC ......... 115
  5.1.2 Physics Analysis .................................................... 116

5.2 Discussion ................................................................ 116

5.3 Conclusions ................................................................ 119

A RUN NUMBER LIST ......................................................... 121

B MATERIAL STUDY ........................................................ 123

BIBLIOGRAPHY ................................................................. 125
List of Figures

1.1 Elementary particles according to the Standard Model. 3
1.2 A schematic nuclear phase diagram showing the transition from hadronic matter to a QGP as a function of temperature vs. baryon density. The hatched region indicates the current expectation for the phase boundary based on lattice QCD calculations. 6
1.3 In this figure of a proton-proton collisions, the spin of the particles is shown as arrows circling the spherical particles. The red and green particles represent reaction products from the collision which are “seen” and analyzed by RHIC detectors. 9
1.4 Longitudinal double-spin asymmetry $A_{LL}$ for inclusive jet production at $\sqrt{s} = 200$ GeV as a function of jet $p_t$. This figure is taken from [24]. 13
1.5 A schematic diagram showing the evolution of an electron (positron) through $D^0$ meson from $c\bar{c}$ which is believed to be formed at the very initial stages of heavy ion collisions. 15
1.6 (a) Non-photonic electron spectra from STAR and PHENIX measurements in $p + p$ collisions at $\sqrt{s}=200$ GeV. The bars (boxes) indicate the size of statistical (systematic) errors. The band is the theoretical uncertainty of the FONLL $pQCD$ prediction for the non-photonic electron yield in $p + p$ collisions. (b) Ratio of the measured non-photonic electron yield to the FONLL $pQCD$ calculated yield in $p + p$ collisions. This figure is taken from [44]. 17
1.7 The inclusive total charm cross-section as measured by STAR, PHENIX, and calculated from pQCD. This figure is taken from [41].

2.1 A schematic view of the RHIC accelerator complex at BNL showing only the relevant devices for polarized proton-proton collisions.

2.2 A cutaway drawing of the PHENIX detector with labelled arrows pointing to the major detector subsystems.

2.3 The STAR detector systems showing the location of the detector sub-systems.

2.4 Cross-section of the STAR detectors used in year 2006 showing the location of the detector sub-systems.

2.5 Beam’s eye view of a central event in the STAR TPC.

2.6 The STAR TPC surrounds a beam-beam interaction region at RHIC. The collisions take place near the center of the TPC.

2.7 The energy loss ($dE/dx$) distribution for various particles as measured by the TPC as a function of momentum (p) of the particles.

2.8 The actual view of the EEMC as seen being serviced during one of the regular RHIC shut-downs in summer for repairs/maintenance and upgrades [69].

2.9 Quarter section of the STAR detector with the EEMC shown installed on its west poletip [70].
2.10 Schematic representation of EEMC tower structure: The left-hand view shows one half of the EEMC consisting of 360 towers. The right-hand view represents a cross-section at constant $\phi$, showing the depth($z-$) profile of the calorimeter and the structural tie-rods used at 30° intervals in $\phi$ [68].

2.11 Closeup photographs near the $\eta = 1$ edge of an assembled 6° sub-sector megatile. The upper photo shows the front face of the scintillator with $\sigma$-grooves. The lower photo shows the opposite side of the fiber-routing layer with wavelength-shifting fibers routed through the undulating channels from which they enter the $\sigma$ grooves in each tile.

2.12 Layout of the SMD in a 30° sector. Each SMD layer consists of two orthogonal planes, u- and v-planes, constructed from triangular scintillating strips extruded with an axial hole for the wavelength-shifting fiber.

2.13 The graphic display showing an optimized mapping of SMD strips to LED fibers in one of three MAMPT boxes in a typical LED box. Clearly displayed here are two and only two illuminated pixels in each MAPMT, one corresponding to the SMD strips in the $U$ plane, and the other in the $V$ plane, separated by at least one idle pixel labelled OFF in the figure. This optimized mapping minimizes the cross-talk between the pixels.

2.14 Photograph showing the main components of the device used to measure dark currents in the MAPMTs.
2.15 MAPMT characterization measurements done at Kent State University for a typical MAPMT. Responses are shown for each of the 16 pixels on the phototube. .................................................. 52

3.1 The 2002 layout of EEMC trigger and jet patches with detailed labeling schemes and DSM assignments. ..................... 55

3.2 A typical distribution of the primary vertex \( Z \) for a \( p + p \) run in year 2006. .............................................................. 56

3.3 The flow-chart showing the procedure for the association of \( MC \) and \( RC \) tracks ................................................................. 60

3.4 \( p_t \) and \( \eta \) distribution of primary tracks in the \( EEMC \) ................. 63

3.5 Energy loss, \( dE/dx \), distribution of \( EEMC \) tracks. The red shaded area between \( 3.0 \leq dE/dx \) (keV/cm) \( \leq 5.0 \) represents the selected electron sample. The blue shaded area with \( dE/dx \leq 2.5 \) keV/cm represents the selected hadron sample. .................................................. 65

3.6 “electron” (red) and “hadron” (blue) energy deposits in the \( EEMC \): (a) tower, (b) first pre-shower, (c) second pre-shower, and (d) post-shower. 67

3.7 The logarithm of the energy deposits summed over two \( SMD \) sub-layers vs. \( N_{\text{strips}} \), the total number of fired strips in two \( SMD \) sub-layers. The red and blue symbols represent “electrons” and “hadrons”, respectively. 67

3.8 Energy loss \( dE/dx \) distributions of \( EEMC \) tracks without any \( EEMC \) cut and after each of the four cuts with the first pre-shower, second pre-shower, post-shower, and \( SMD \). ......................... 69
3.9 Energy loss $dE/dx$ distributions of EEMC tracks passing all EEMC cuts in transverse momentum bin between 2.0 and 3.0 GeV/c. The red shaded area represents selected electron candidates. The blue shaded area represents hadrons of high purity used to estimate hadron contamination in selected electron candidates. 70

3.10 $p/E$ distribution of selected EEMC tracks. The red curve is for electron candidates and the blue is for hadrons, after scaling. The final cut is shown with the two vertical dotted lines at $p/E=0.8$ and 1.5. 72

3.11 Electron purity as a function of transverse momentum, $p_t$. The uncertainties shown include both statistical (red) and systematic (black) contributions. 73

3.12 $p_t$ distributions of the matched (left) and generated (right) tracks, respectively. 77

3.13 Electron reconstruction efficiency in the TPC as a function of transverse momentum. 77

3.14 $p/E$ efficiency as a function of transverse momentum. 78

3.15 Gaussian fits to electron (a) and hadron (b) $dE/dx$ distributions. 80

3.16 Gaussian fits to electron and hadron $dE/dx$ distributions compared to the original $dE/dx$ distribution (the black histogram). 81

3.17 $dE/dx$ efficiency as a function of transverse momentum. 81

3.18 Flow chart showing the changes in the number of events after each stage of Data Acquisition (DAQ) and analysis. The meaning of all the symbols used in the flow chart are given in Table 3.4. 84
3.19 Electron $p_t$ distributions of some selected triggers. See Table 3.3 for description of trigger ids labelled in the legend. .......................... 85

3.20 Trigger efficiency of some triggers as a function of transverse momentum. 86

3.21 Total efficiency of some triggers as a function of transverse momentum. 87

3.22 Inclusive electron spectra as a function of transverse momentum. The blue curve shows the inclusive electron spectrum from this analysis and the black curve shows the inclusive electron spectrum measured in the $BEMC[85]$. ................................................................. 88

3.23 Invariant mass distributions of electron-positron pairs before applying any cuts. The red curve represents opposite-sign pairs and the blue curve the same-sign pairs. The shaded area represents the reconstructed photonic electrons. ..................................................... 92

3.24 Invariant mass distributions of electron-positron pairs after applying all the cuts described in the procedure above. The red curve represents opposite-sign pairs and the blue curve the same-sign pairs. The shaded area represents the reconstructed photonic electrons. ......................... 93

3.25 Inclusive to background ratio in blue curve from this study, and in black curve from a published paper [85]. ................................. 96
3.26 Non-photonic electron yield as a function of transverse momentum.

The red curve shows the weighted average denoting the upper limit of 
NPE yield from this work. The black curve shows the BEMC result 
of the NPE measurement from a published paper [85]. This figure also 
shows a series of data points corresponding to NPE yield calculations 
based on several assumed reconstruction efficiencies. See the text for 
other details. .......................................................... 99

3.27 Reconstructed $D^{0}$ (solid squares) $p_{t}$ distributions from $d+Au$ collisions 
at $\sqrt{s_{NN}} = 200$ GeV. Non-photonic electron $p_{t}$ distributions from $p+p$ 
collision (triangles) and $d + Au$ collisions (circle). Solid and dashed 
lines are the fit results from both $D^{0}$ and electron spectra in $d + Au$ 
collisions. The dotted line is scaled down by a factor of $N_{bin}=7.5\pm0.4$ 
from $d+Au$ to $p+p$ collisions. The dot-dashed line depicts a PYTHIA 
calculation [86]. .......................................................... 101

3.28 $d\sigma/dy$ of charm quarks from the STAR and PHENIX measurements 
compared with different theoretical predictions [81]. The two curves 
in red and blue represent the lower and upper bounds corresponding 
to the theoretical predications based on color dipole and PYTHIA 
calculations, respectively. ........................................... 104
3.29 Total $c\bar{c}$ cross section per nucleon-nucleon collision versus the collision energy ($\sqrt{s_{NN}}$). Results from several experiments are shown in the figure. The upper limit from this work is shown in blue star. The dashed line depicts a PYTHIA calculation. The solid and dot-dashed lines depict two NLO PQCD calculations with the Martin-Roberts-Sterling-Thorne highest order set, $m_e = 1.2 \text{ GeV}/c^2$, $\mu_F = 2m_e$, $\mu_R = m_e$, and $2m_e$, respectively [86].

4.1 The 2-D scattering plot for conversion radius $R_v$ vs $Z$. The pattern reflects the material structure of the STAR detectors and their supporting materials. The EEMC (not shown here) is located on the west poletip, i.e. in the $+Z$ direction, $\sim 270$ cm away from the center of the STAR detector at RHIC. It is an annulus with projective geometry with an inner radius $\sim 75$ cm, outer radius $\sim 215$ cm, and a longitudinal depth $\sim 34$ cm. It provides full azimuthal coverage over the pseudo-rapidity range $1 < \eta < 2$.

4.2 Distributions of invariant mass of electron-positrons pairs from $\gamma$ conversions, as a function of transverse momentum.

4.3 Distributions of invariant mass of electron-positrons pairs from $\pi^0$ Dalitz decays, as a function of transverse momentum.

4.4 Photonic electron reconstruction efficiency from $\gamma$ conversions, as a function of transverse momentum.

4.5 Photonic electron reconstruction efficiency from $\pi^0$ Dalitz decays, as a function of transverse momentum.
4.6 Photonic electron reconstruction efficiency from Pythia simulation as a function of transverse momentum. The statistical error is large at high $p_t$ due to the limited number of high $p_t$ electrons. 111

4.7 Left panel: Distributions of photonic electrons from $\gamma$ conversions (blue) and $\pi^0$ Dalitz decays (pink). Right panel: Ratio of the photonic electrons from $\gamma$ conversions and $\pi^0$ Dalitz decays. 112

4.8 Weighted average efficiency of photonic electron reconstruction from simple $MC$ simulations of $\gamma$ conversions and $\pi^0$ Dalitz decays. 113

B.1 Comparison of material in radiation length versus rapidity in $TPC$ and $SVT$ in year 2006 geometry. 124
List of Tables

1.1 D meson decay channels and their branching ratios. ............................................. 15
2.1 Summary of critical EEMC requirements and the physics goals that drive them[68]. ................................................................. 43
3.1 List of QA cuts. These cuts ensure the quality of tracks before generating an electron tree. ............................................................. 59
3.2 List of Electron ID cuts. These cuts help identify electrons. ....................... 75
3.3 Some major EEMC triggers utilized in $p+p$ 200 GeV transverse run in year 2006 [84]. ........................................................... 83
3.4 Meaning of the symbols used in the flow chart in Fig. 3.18 and Eq. 3.4. 85
3.5 Cuts used to reconstruct photonic background by invariant mass technique. ........................................................... 91
3.6 $dN/dy$ of $D^0$ in $d + Au$ collisions and the corresponding $d\sigma/dy$ of $c\bar{c}$ pair per nucleon-nucleon collision at $\sqrt{s_{NN}} = 200$ GeV [86]. .......................... 103
A.1 List of run numbers and their corresponding fill numbers used in this analysis. ................................................................. 121
A.1 Continued. ................................................................................................. 122
ACKNOWLEDGMENTS

First of all, I am extremely thankful to my research advisor, Prof. Bryon Anderson, for his guidance and support throughout the time of my Ph.D. research. His confidence and trust in me, the independence and flexibility he offered me for my research, and the loving care he has had for me and my family, all will be cherished for making me what I am now - a complete man!

My sincere thanks to Dr. Wei-Ming Zhang for his patience, understanding, and expertise in visualizing the next possible step to reach a logical conclusion. The seemingly endless questions and discussions with him provided me new ideas, new thoughts, and alternative approaches to continue to carry out my analysis all through to the final results.

It was Dr. Jan Balewski from IUCF (currently at MIT) from whom I learned real C++ programming technique; one line at a time! My heart-felt thanks to him for getting me started.

My gratitude of thanks to Dr. Steve Vigdor (currently Associate Laboratory Director for Nuclear and Particle Physics at BNL) and Dr. James Sowinski for their hospitality and guidance when I visited and worked at IUCF for a month in 2007.

I gained much insight from enlightening discussions regarding my research with the resident experts, especially, Dr. Aihong Tang, Dr. Zhangbu Xu, Dr. Jerome Lauret, Dr. James Dunlop, Dr. Valeri Fine, Dr. Yuri Fisyak, Dr. Jason Webb, and others at BNL. I would like to thank them for making my stay at BNL a successful one.
I would like to express my thanks to all the faculty members of the Physics Department and especially to Dr. Mark Manley for his counseling as my academic advisor. I would also like to extend my appreciation to all the staff in the Physics Department, including Dr. Alan Baldwin for his help in electronics, Cindy Miller, Loretta Hauser, Chris Kurtz, and Kim Birkner for their quick response and instant solutions for any problems that I encountered.

I am grateful to the members of the dissertation committee, Dr. Declan Keane, Dr. Spyridon Margetis, Dr. Laura Bartolo, Dr. Robin Selinger, and Philip Bos for their comments, suggestions, and questions that helped ensure the quality and standard of my dissertation.

Lunch break in Kent was always a welcome relief because of the wonderful friends like Manoj Shrestha, Naresh Shakya, and Fanindra Bhatta. They will be always fondly remembered for their camaraderie. I also owe many thanks to all the friends at Kent State who have contributed in one way or another towards my personal and/or academic progress.

I am deeply indebted to my parents, brothers, sisters and all my family members for their support, encouragement, and love. I would like to thank my wife, Pavi, from the bottom of my heart for her love and support, which has been a tremendous source of inspiration and strength for me. My sons Mikky and Mingsho deserve my special thanks for their understanding and conviction that their dad had some other important work to finish if he was not available when they needed him the most.

Thanks are also due to the RHIC Operations Group and RCF at BNL for their support, members of the STAR collaboration and in particular the EEMC group who provided so much support and feedback over the years.
Chapter 1

INTRODUCTION

We begin this chapter by reviewing the primary goals of the Relativistic Heavy Ion Collider (RHIC). We include a brief introduction to Quantum Chromo-Dynamics (QCD). We then present a brief review of the investigations of the Quark-Gluon Plasma (QGP) and spin physics at RHIC. We also review some important RHIC results on charm production. Following this review, we provide the physics motivations for our study of non-photonic electron distribution in the Endcap Electro-Magnetic Calorimeter (EEMC).

1.1 RHIC Goals

RHIC at Brookhaven National Laboratory (BNL) is a forefront research facility for nuclear physics. It is a unique machine designed to create very high energy nuclear collisions. It is capable of accelerating and colliding heavy ions to create the QGP, which is a deconfined state of quarks and gluons replicating the QGP that is believed to have existed the first few moments after the creation of the Universe following the Big Bang [1]. There are two primary objectives of the RHIC program [2]:

1. To investigate the phase transition to, and study the formation and properties of, the QGP.

2. To study the spin structure of nucleons and other spin studies in a kinematic range with an accuracy never before possible.
1.2 A Short Introduction to \textit{QCD}

There are four basic types of forces in nature acting on a particle, viz., gravity, weak nuclear, electromagnetic and strong nuclear, in order of increasing strength. Each of these forces is mediated by the exchange of vector bosons. \textit{QCD} is an established theory that can describe very well one of these four forces, namely the strong interaction, a fundamental force describing the interactions of the quarks and gluons making up hadrons. \textit{QCD} theory, combined with the electro-weak theory, form the Standard Model (\textit{SM}) which is a successful model that explains all interactions except gravity.

According to the Standard Model, elementary particles are broadly classified into two groups; (i) fermions and (ii) gauge vector bosons. The fermions are defined as elementary particles having spin=1/2 and there are 12 fermions, each with a corresponding anti-particle. The first 6 are called quarks, viz., up (u), down (d), charm (c), strange (s), top (t), and bottom (b) and the other 6 are called leptons, viz., electron (e), muon (\(\mu\)), tau (\(\tau\)), and their corresponding neutrinos. The fermions are grouped into three generations, each comprising two quarks and two leptons as shown in Fig. 1.1, with corresponding particles exhibiting similar physical behavior. Particles in higher generations generally have greater mass and lesser stability, causing them to decay into lower-generation particles by means of the weak interaction. Only first generation quarks occur commonly in nature. Heavier quarks can only be created in high-energy collisions, and they decay quickly; however, they are thought to have been present during the first fractions of a second after the Big Bang, when the universe was in an extremely hot and dense phase.
The defining property of the quarks is that they carry color charge, and hence, they interact via the strong interaction. Quarks also carry electric charge and weak isospin. Hence, they also interact with other fermions both electromagnetically and via the weak nuclear interaction. Leptons, on the other hand, do not carry color charge. The three neutrinos do not carry electric charge either, so their motion is directly influenced only by the weak nuclear force, which makes them very difficult to detect. However, by virtue of carrying an electric charge, the $e$, $\mu$ and $\tau$ all interact electromagnetically.
Gauge vector bosons, shown in the last column of the Fig. 1.1, are the force-mediating particles. Photons, the massless vector bosons, mediate the electromagnetic force between electrically charged particles. This phenomenon is well-described by the theory of quantum electrodynamics (QED). $W^\pm$ and $Z$ gauge bosons mediate the weak interactions between particles of different flavors including all quarks and leptons. These three gauge bosons along with the photons collectively mediate the electroweak interactions. The eight gluons mediate the strong interactions between color charged particles. Gluons are massless. The eightfold multiplicity of gluons is labelled by a combination of color and an anticolor charge. Because the gluon has an effective color charge, gluons can interact among themselves. The gluons and their interactions are described by the theory of QCD.

There are two remarkable features of QCD. First, the force of interaction is large at large distances or small momentum transfer ($Q^2$), causing quarks to be confined in hadrons, either as mesons (a quark-antiquark pair) or baryons (a three quark combination). Free isolated quarks have never been found. This nature of quarks is known as quark confinement. The other remarkable feature is that the force of interaction is small at shorter distances or large momentum transfer ($Q^2$). This is known as the region of “asymptotic freedom” and the quarks are free to move in this region.

For ordinary conditions, the quarks are confined and cannot be isolated. Experiments with ultra-relativistic nuclei are performed to produce and study the QGP – a new state of matter. The QGP is predicted to exist at high temperature and/or high baryon densities. Numerical solutions of QCD using lattice techniques [3, 4] imply that a phase transition from confined hadronic matter, such as protons and neutrons,
to a de-confined state in which hadrons are dissolved into quarks and gluons, will occur at a critical temperature, $T_C \sim 170$ MeV at zero baryon density, corresponding to an energy density $\varepsilon \sim 1.0$ GeV/fm$^3$, nearly an order of magnitude larger than that of normal nuclear matter. Fig. 1.2 shows a schematic nuclear phase diagram of the transition of hadronic matter to a QGP as a function of temperature and baryon density. Regions of temperature and baryon density in which matter exists as a hadron matter, nuclear matter and QGP are shown. The path followed by the early universe as it cooled from the QGP phase to normal matter that we encounter today is also shown. The experimental results from some major analyses are also shown in the figure. The hatched region indicates the current expectation for the phase boundary between hadron matter and the QGP based on lattice QCD calculations [5].
Figure 1.2: A schematic nuclear phase diagram showing the transition from hadronic matter to a $QGP$ as a function of temperature vs. baryon density. The hatched region indicates the current expectation for the phase boundary based on lattice $QCD$ calculations.

1.3 $QGP$ at RHIC

The RHIC accelerator and the STAR detector system were originally conceived and designed for the study of relativistic heavy-ion reactions, and in particular to try to produce the so-called quark-gluon plasma ($QGP$). Because of this historical background, these systems were optimized for this study. We present here a very
brief review of the research that has been performed to date to try to observe and study the QGP. The main thrust of the work of this dissertation has to do with the study of charm quark production in proton-proton ($p + p$) reactions, and we will concentrate on these reactions in the next section and for most of the rest of this work.

Over the last ten years, beginning with the year 2000, RHIC has performed experiments that have provided strong evidence of the formation of the QGP at a temperature $T_C \sim 175$ MeV [6, 7, 8, 9]. Below we briefly mention some of the key observations that underlie theoretical claims [10, 11] that de-confined matter has been produced at RHIC. Some of the key signatures of the QGP are jet quenching, elliptic flow and suppression observed in the nuclear modification factor.

**Jet Quenching:** In relativistic heavy ion collisions, the high $p_t$ particles are believed to be produced from the initial QCD scattering processes followed by parton fragmentation. The initial scattered parton pairs travel in opposite directions, forming showers of quarks and gluons, commonly known as jets. If a pair of jets forms near the boundary of a fireball created in the relativistic heavy ion collision, one jet may quickly travel out of the medium whereas the other traverses through the medium. Perturbative QCD predictions show that a jet traveling through a hot, partonic medium would suffer much more energy loss than a jet traveling through the hadronic gas [12]. This phenomenon is called Jet Quenching and it has been observed by the STAR experiment [13, 14] in a way consistent with the formation of the QGP.

**Elliptic Flow:** Hydrodynamic flow can be used to describe strongly interacting thermalized nuclear matter [15]. Under this assumption, the particle distribution can be described in the azimuthal direction by the following Fourier expansion [16],
\[ E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_t dp_t dy} (1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \psi_r)]). \] (1.1)

where \( p_t \) denotes the transverse momentum, \( y \) the rapidity, \( \phi \) the azimuthal angle and \( \psi_r \) the reaction plane angle of a collision. Elliptic flow, denoted by \( v_2 \), is given by the second coefficient in the Fourier expansion.

The observation of large elliptic flow [17, 18] whose magnitude, mass and \( p_t \) dependence for mid-central collisions are in reasonable agreement with calculations based on ideal hydrodynamic flow [19, 20] are believed to be strong indicators of the creation of de-confined partonic matter (the QGP) in nucleus-nucleus collisions at RHIC.

**Nuclear Modification Factor:** Nuclear effects on hadron production in heavy ion collisions (\( A + B \)) are measured through the comparison with the \( p + p \) spectrum using the ratio

\[ R_{AB}(p_t) = \frac{d^2N/dp_t dy}{T_{AB} d^2\sigma^{pp}/dp_t dy} \] (1.2)

where \( d^2N/dp_t dy \) is the differential yield per event in the nuclear collision \( A + B \), \( T_{AB} = \langle N_{bin} \rangle/\sigma^{pp}_{inel} \) describes the nuclear geometry in which \( \langle N_{bin} \rangle \) denotes the average number of binary (nucleon-nucleon) collisions in the heavy-ion collision system, \( \sigma^{pp}_{inel} \) is the \( p + p \) inelastic scattering cross section, and \( d^2\sigma^{pp}/dp_t dy \) is the yield for \( p + p \) inelastic collisions as determined from the measured \( p + p \) differential cross sections.

It has been observed that \( R_{AB} \) of hadron production in a central \( Au + Au \) collision at \( \sqrt{s_{NN}} = 200 \) GeV, is highly suppressed at high \( p_t \). However, no suppression in \( d + Au \) collisions was observed [14]. This is an indication that the suppression is due to final-state interactions with the dense system generated in the collision, therefore, implying
the creation of the QGP in these heavy ion collisions.

1.4 Spin Physics at RHIC

Another major objective of RHIC experiments is to measure and understand how different factors influence a proton’s spin. The primary goal of the RHIC spin program is to understand the gluon’s spin contribution $\Delta G$ to the proton’s spin structure. RHIC is the world’s only machine capable of colliding high-energy beams of polarized protons, and is a unique tool for exploring the puzzle of the proton’s ‘missing’ spin.

Spin is the intrinsic angular momentum of a particle pictured as spinning around an axis. A proton has a specific spin, which helps give it a characteristic magnetic property. Fig. 1.3 shows the picture of a proton-proton collision in which the spin of the particles are represented by the arrows circling the spherical particles.

\[\text{Figure 1.3: In this figure of a proton-proton collisions, the spin of the particles is shown as arrows circling the spherical particles. The red and green particles represent reaction products from the collision which are “seen” and analyzed by RHIC detectors.}\]

The spin structure of the nucleon is one of the fundamental and unresolved questions in QCD. A simple picture of a proton is that it is composed of three quarks
(uud) and gluons. It was long believed that the spin of a proton was simply the sum of the spins of its component quarks. The quarks each have half-integer spin (in units of $h$) and can couple to give the known spin of the proton, also half-integer. But deep inelastic scattering (DIS) experiments studying polarized leptons scattered off polarized nuclei have found the quark and antiquark spin contributions to the overall spin of the nucleon to be small, at the level of 25% [21, 22], leading to increased interest in the spin contribution from gluons. The rest of the proton spin must hence be carried by the gluons and orbital angular momentum. Unlike quarks, gluons do not couple directly to the virtual photon emitted by the lepton in DIS. Information about $\Delta G$ must be extracted from the next-to-leading-order (NLO) perturbative QCD analysis of the momentum transfer dependence of the same inclusive spin contribution [24].

In a simple model of the nucleon, the proton’s spin structure can be decomposed into four parts: the quark’s contribution, the gluon’s contribution, and the orbital angular momentum of the quarks and gluons, expressed as follows:

$$S_z = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_z^q + L_z^G$$  \hspace{1cm} (1.3)

Here, $\Delta G$ denotes the fraction of the proton’s spin carried by the gluon’s spin, $L_z^q$ and $L_z^G$ denote the orbital angular momentum contributions from the quarks and gluons, respectively. The contribution quarks make to the protons’ spin ($\Delta \Sigma$) is determined from quark helicity asymmetry functions, $\Delta q_i(x)$ (where $x$ is the Bjorken parameter which denotes the momentum fraction carried by the parton in the nucleon) summed over the quark flavors ($n_f$), by:

$$\Delta \Sigma = \sum_{i=1}^{n_f} \Delta q_i$$ where $\Delta q_i = \int_0^1 [q_i^+(x) + \bar{q}_i^+(x) - q_i^-(x) - \bar{q}_i^-(x)] dx$
The components in Eq. 1.3 can be described in a more general way using the quark/anti-quark and gluon helicity parton distribution functions (PDFs) as follows:

\[ \Delta f_i(x, Q^2) \equiv f_i^+(x, Q^2) - f_i^-(x, Q^2) \]  (1.4)

where \( f_i^+(x, Q^2) / f_i^-(x, Q^2) \) denotes a type \( i \) partonic distribution with positive/negative helicity in the proton, and \( Q^2 \) denotes the parton momentum transfer. The spin contribution to the proton spin from type \( i \) parton is given by the integral

\[ \Delta f_i(Q^2) = \int_0^1 \Delta f_i(x, Q^2) \, dx = \int_0^1 (f_i^+(x, Q^2) - f_i^-(x, Q^2)) \, dx \]  (1.5)

However, the orbital angular momentum contributions to the proton spin are unknown so far.

Substituting the gluon role into Eqs. 1.4 and 1.5 we get

\[ \Delta G(Q^2) = \int_0^1 \Delta G(x, Q^2) \, dx = \int_0^1 [G^+(x, Q^2) - G^-(x, Q^2)] \, dx \]  (1.6)

where \( G^+ \) or \( G^- \) denote the gluon polarization in a proton either parallel or anti-parallel to the proton’s longitudinal polarization. The unpolarized gluon distribution in a proton is expressed by

\[ G(x, Q^2) = G^+(x, Q^2) + G^-(x, Q^2) \]  (1.7)

The actual gluon polarization is then defined as \( \frac{\Delta G(x, Q^2)}{G(x, Q^2)} \).

In pertubative QCD, the double spin asymmetry, \( A_{LL} \), is directly sensitive to the polarized gluon distribution function in the proton through gluon-gluon and gluon-quark sub-processess [23]. The double spin asymmetry is defined as

\[ A_{LL} \equiv \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}, \]  (1.8)
where $\sigma^{++}$ and $\sigma^{+-}$ are the cross sections of non-photonic electrons, inclusive $\pi^0$ or jets for equal $(++)$ and opposite $(+-)$ beam helicity configurations; hence, information on $\Delta G$ can be deduced by measuring $A_{LL}$ for the production of inclusive jets and/or inclusive neutral pions.

Both the STAR and PHENIX collaborations have measured double spin asymmetry for inclusive jets and/or neutral pions. Fig. 1.4 shows the result for longitudinal double-spin asymmetry $A_{LL}$ for inclusive jet production at $\sqrt{s} = 200 \text{ GeV}$ as a function of jet $p_t$ [24]. The points show results for jets with statistical error bars, while the curves show NLO pQCD evaluations for inclusive jet $A_{LL}$ based on various sets of polarized gluon distributions [23]. Denoting the spin-averaged gluon distribution function as $g(x, Q^2)$, then the curves correspond to maximally positive [$GRSV$-max: $\Delta g(x, Q_0^2) = +g(x, Q_0^2)$], maximally negative [$GRSV$-min: $\Delta g(x, Q_0^2) = -g(x, Q_0^2)$] and vanishing [$GRSV$-zero: $\Delta g(x, Q_0^2) = 0$] gluon polarizations. The curve labeled $GRSV$-std uses the best fit to inclusive DIS data. The double spin asymmetry $A_{LL}$ is found to lie within the uncertainties of the theoretical prediction from $GRSV$. This small value of $A_{LL}$ of inclusive jets indicates that the gluon contribution to the proton spin is not significant. This result is consistent with results reported by both the STAR [25, 26] and the PHENIX [27] collaborations.
Figure 1.4: Longitudinal double-spin asymmetry $A_{LL}$ for inclusive jet production at $\sqrt{s} = 200$ GeV as a function of jet $p_t$. This figure is taken from [24].

1.5 Charm Production

Currently, charm is the heaviest quark whose hadrons can be directly reconstructed at RHIC energies. Charm quark can be produced in both relativistic $p + p$ and heavy ion collisions. It is believed that the charm quark is produced in initial collisions via gluon fusion. Because of its large mass ($\simeq 1.3GeV/c^2$), the charm production rate is calculated by $pQCD$ [28]. Due to its large mass, new charm quarks are not expected to be produced during the thermalized stage of the QGP fireball. Theories predict that charm is predominantly produced during initial collisions mostly through gluon-gluon scatterings in nuclear collisions at RHIC energies. Therefore, open charm production is a good probe of the initial parton distribution in phase space and the thermalization and equilibration time of the parton plasma [33]. Most
charm is contained within $D^0$, $D^\pm$, $D_s$, and $\Lambda_c$ hadrons at the collision energy of $\sqrt{s_{NN}}=200$ GeV. Charm production, therefore, is considered to be a unique tool for studying the strong interaction described by QCD. Charm quarks are predicted to lose less energy than light quarks by gluon radiation in the medium [29, 36, 37] due to their large mass. However, recent measurements of the $p_t$ distributions and nuclear modification factors of non-photonic electrons from heavy quark decays at high $p_t$ show a suppression level similar to light hadrons [38, 39]. This unexpected observation has renewed the interest in charm production and the interactions of heavy charm quarks with the hot and dense matter produced in nuclear collisions at RHIC.

Systematic studies of charm production in $p + p$, $p + A$ and $A + A$ collisions have been proposed as a sensitive way to measure the parton distribution function (PDF) in nucleons, and nuclear shadowing effects. Heavy quark energy loss, charm quark coalescence, possible $J/\psi$ suppression and charm flow have all been proposed as important tools in studying the properties of matter created in heavy ion collisions at RHIC energies [86].

At present RHIC uses two different methods to study charm hadron production in relativistic heavy ion collisions. The first approach is the direct reconstruction of the charmed D mesons with a hadronic decay $D^0(\bar{D}^0) \rightarrow K^-\pi^+(K^+\pi^-)$. Identification of charmed hadrons is difficult due to their short lifetime [$c\tau(D^0) = 124 \mu m$], low production rates, and large combinatorial background in the complex environment of high energy nuclear collisions [86].

The other approach is the indirect measurement via the semi-leptonic decay of charmed mesons ($D^0$ or $D^\pm$) by measuring single electrons or muons. It is customary in the STAR and PHENIX collaborations to refer to the measurement of electron
<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Branching ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \rightarrow K^- \pi^+$</td>
<td>3.80%</td>
</tr>
<tr>
<td>$D^0 \rightarrow e^+ + X$</td>
<td>6.87%</td>
</tr>
<tr>
<td>$D^\pm \rightarrow e^\pm + X$</td>
<td>17.2%</td>
</tr>
</tbody>
</table>

Table 1.1: D meson decay channels and their branching ratios.

originating from the semi-leptonic decay of charm (or bottom) mesons as non-photonic electron measurement. The branching ratios of the relevant hadronic decay and semi-leptonic decay to electrons are listed in Tab. 1.1. Fig. 1.5 is a schematic diagram showing the evolution of an electron through $D^0$ meson from $c\bar{c}$ which is believed to be formed at the very initial stages of heavy ion collisions. This same process can occur in relativistic $p+p$ collisions. In this work, we study this process to estimate the cross-section of $c\bar{c}$ by measuring the electron (positron) from semi-leptonic D meson decay in $p+p$ collisions at the nucleon-nucleon center of mass energy $\sqrt{s}=200$ GeV.

Figure 1.5: A schematic diagram showing the evolution of an electron (positron) through $D^0$ meson from $c\bar{c}$ which is believed to be formed at the very initial stages of heavy ion collisions.
1.5.1 Non-Photonic Electron Spectrum

Both $STAR$ and $PHENIX$ have measured non-photonic electron yields from semi-leptonic decay of charm mesons. Fig. 1.6(a) shows the non-photonic electron spectra from $STAR$ [86, 85] and $PHENIX$ [34] measurements in $p + p$ collisions at $\sqrt{s}=200$ GeV. Till date, $STAR$ has measured non-photonic electrons in two independent ways; the first one using the Time Projection Chamber ($TPC$) and the Time of Flight ($ToF$) shown as triangles in the figure, and the second one using the $TPC$ and the Barrel Electro-Magnetic Calorimeter ($BEMC$) shown as black solid circles in the figure. Also shown in the figure is the uncertainty band from a fixed-order-plus-next-to-leading-log ($FONLL$ $pQCD$) calculation [35] for non-photonic electron yields in $p + p$ collisions. Fig. 1.6(b) shows the ratio of non-photonic electron yield measured in $STAR$ and $PHENIX$ to the non-photonic electron yield based on $FONLL$ calculation in $p + p$ collisions. The $FONLL$ calculation shows large uncertainties (yellow band) due to parameter choices of quark masses, factorization and renormalization scales, etc. The $FONLL$ calculation can describe the shape of the measured spectra reasonably well. The dashed lines are the ratio of $STAR$ and $PHENIX$ measured total charm cross-section to the $FONLL$ calculation. There is a factor of $\sim 2$ discrepancy between the $STAR$ and $PHENIX$ experimental results. How the total charm cross-section in $STAR$ and $PHENIX$ is extracted, is described in the following section.
Figure 1.6: (a) Non-photonic electron spectra from STAR and PHENIX measurements in $p + p$ collisions at $\sqrt{s}=200$ GeV. The bars (boxes) indicate the size of statistical (systematic) errors. The band is the theoretical uncertainty of the FONLL pQCD prediction for the non-photonic electron yield in $p + p$ collisions. (b) Ratio of the measured non-photonic electron yield to the FONLL pQCD calculated yield in $p + p$ collisions. This figure is taken from [44].

1.5.2 Charm Cross-Section

STAR has measured the $D^0(\bar{D}^0) \rightarrow K^-\pi^+(K^+\pi^-)$ decay in $d + Au$ [86], $Au + Au$ [40] and more recently $Cu + Cu$ [41] systems at $\sqrt{s_{NN}}=200$ GeV. STAR has also measured the semi-leptonic ($e$ and $\mu$) decays of open charm in $p + p$, $d + Au$ and $Au + Au$ systems all at $\sqrt{s_{NN}}=200$ GeV [40, 85, 86]. The total inclusive charm cross-section per nucleon-nucleon collision obtained for the $d + Au$ system at $\sqrt{s_{NN}}=200$ GeV is $\sigma_{c\bar{c}} = 1.3 \pm 0.2 \pm 0.4$ mb from the $D^0(\bar{D}^0) \rightarrow K^-\pi^+(K^+\pi^-)$ decay channel alone and $\sigma_{c\bar{c}}^{NN} = 1.4 \pm 0.2 \pm 0.4$ mb from the combined fit to $D^0$ and electrons
In $Au + Au$ collisions, a combined fit to the $D^0$ meson reconstructed from kaons and pions, the muons and electrons from heavy flavor decays yielded a total inclusive charm cross-section of $\sigma_{c\bar{c}}^{NN} = 1.29 \pm 0.12 \pm 0.36$ mb [40]. The total charm cross-section measured in $Cu + Cu$ system at $\sqrt{s_{NN}}=200$ GeV is $1.06 \pm 0.26 \pm 0.29$ mb from the $D^0(\bar{D}^0) \to K^-\pi^+(K^+\pi^-)$ [41]. These three results are consistent with each other within errors, implying that open charm cross-section scales with the number of binary collisions. As the charm production does not depend on the collision system, the charm production must be independent of the medium, QGP or otherwise. Consequently, this implies that charm is produced during the initial gluon fusion.

The other major RHIC experiment, PHENIX has also measured the charm cross-section, so far, all via electrons from semi-leptonic decays. Their most current results include $\sigma_{c\bar{c}}^{NN} = 0.567 \pm 0.057 \pm 0.193$ mb for $\sqrt{s}=200$ GeV $p + p$ collisions [42] and $\sigma_{c\bar{c}}^{NN} = 0.622 \pm 0.057 \pm 0.160$ mb for $\sqrt{s_{NN}}=200$ GeV $Au + Au$ collisions [43]. These results are also consistent with binary scaling, however, they are roughly a factor of 2 below the results from STAR measurement. Investigations are ongoing in both collaborations to better understand the source of discrepancy. Fig. 1.7 shows the inclusive total charm cross-section as measured by STAR, PHENIX, and calculated from $pQCD$. 
Figure 1.7: The inclusive total charm cross-section as measured by STAR, PHENIX, and calculated from pQCD. This figure is taken from [41].

It is now established that there is a consistent binary scaling from $d + Au$ to $Cu + Cu$ to $Au + Au$ at a collision energy of $\sqrt{s_{NN}} = 200$ GeV. The logical next step is to see whether this binary scaling is continued down to elementary $p + p$ collisions. Measurement of the open charm $p_t$ spectrum in $p + p$ collisions, ideally using both hadronic and semi-leptonic decay channels will complete the binary scaling picture for relativistic heavy-ion collisions. A $p + p$ measurement will also allow the $R_{AA}$ to be evaluated for STAR data without the cold nuclear matter effects in $d + Au$ collisions [41].
1.6 Physics Motivation for this Dissertation

As mentioned in the previous sections charm production is a sensitive way to measure partonic distribution functions in nucleons and nuclear shadowing effects. Such measurements are of interest in their own right and also will help to resolve the discrepancy in open charm production in relativistic heavy-ion reactions as measured by the STAR and PHENIX detector groups at RHIC. Studies done on charm production, so far, by the STAR group used the Time Projection Chamber (TPC) at $|\eta| < 1.0$ with either the Barrel Electro-Magnetic Calorimeter (BEMC) or the Time of Flight (TOF) system with various beams. There are also independent studies done on charm production by the PHENIX group. Our study uses a different detector, viz., the Endcap Electro-Magnetic Calorimeter (EEMC) on the STAR detector, in an attempt to independently compare with the earlier results obtained by the STAR and the PHENIX measurements. These new measurements were performed by measuring non-photonic electron distributions at pseudo-rapidities, $\eta^1$, between 1.1 and 1.5 in proton-proton collisions at $\sqrt{s}=200$ GeV.

1.6.1 Limitations

Because the RHIC accelerator and the STAR system were originally conceived and designed for the study of heavy-ion reactions, and these systems were optimized for that study, they may not be adequate for some studies of spin physics and/or charm

---

$^1$A particle’s rapidity is defined as $y = \frac{1}{2} \ln \left( \frac{E+p_z}{E-p_z} \right)$ where $E = \sqrt{p^2 + m^2}$ is the particle’s energy. Rapidity is Lorentz invariant. In experiments, where the particle’s identity and its mass is unknown, another variable called pseudo-rapidity ($\eta$) can be quite useful. A particle’s pseudo-rapidity is defined as $\eta = \frac{1}{2} \ln \left( \frac{p+p_z}{p-p_z} \right)$. In high energy experiments, it is common to have $p \gg m$, so pseudo-rapidity $\eta$ is a good approximation for the rapidity $y$. $\eta$ can also be written as $\eta = -\ln \left[ \tan(\theta/2) \right]$, where $\theta$ is the angle between the particle momentum $p$ and the beam axis. $\theta$ can be easily measured experimentally with today’s detector technology.
production in $p+p$ collisions, especially at forward rapidities where the main detector used in this work (the EEMC) is located. In particular, the long radiation length provided by the supporting structure for the Silicon Vertex Tracker (SVT) detector generated a very large amount of photonic background electrons. Although we hoped to be able to remove this background, as we will show in this work, this background is so overwhelmingly large that it cannot be estimated or removed accurately enough and only an upper limit for non-photonic electron yield and total charm production can be obtained from this study.
Chapter 2

THE EXPERIMENTAL DETAILS

This chapter describes the experimental set-up in general. In the first section we briefly discuss the RHIC collider located at Brookhaven National Laboratory, Long Island in New York. In the second section we briefly discuss the experimental detector systems including PHENIX, PHOBOS and BRAHMS, as part of the RHIC facility. In the third section we include detailed descriptions of most of the detector sub-systems at STAR since the data presented in this dissertation were taken using the STAR detector systems. The fourth section is entirely devoted to the detailed description of the EEMC detector as this was the main detector employed, in conjunction with the TPC, for the data used in this dissertation. The last section briefly reviews the Kent State University contribution in the software and hardware development for the EEMC.

2.1 The Relativistic Heavy Ion Collider

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) is a world-class scientific research facility that began operation in 2000, following 10 years of development and construction. Hundreds of physicists from around the world use RHIC to study what the universe may have looked like in the first few moments after its creation. RHIC drives two intersecting beams of heavy ions or polarized protons in head-on subatomic collisions. What physicists learn from these collisions may help us understand more about why the physical world works the way
it does, from the smallest subatomic particles, to the largest stars.

RHIC is built to accelerate and collide heavy ions and polarized protons with high luminosity. It is an intersecting storage ring particle accelerator with two independent rings, called blue and yellow, sharing a common horizontal plane in the tunnel. Each RHIC ring has hexagonal symmetry, with a circumference of 3,834 m. The beam is steered via 1,740 super-conducting magnets. Each point where the beams cross is an interaction point. There are six such locations at RHIC, each described by a clock position as schematically shown in Fig. 2.1. STAR and PHENIX, the only two detectors in operation at the time of writing this dissertation, are located at interaction points corresponding to the 6 o’clock and 8 o’clock positions, respectively. PHOBOS and BRAHMS, located at the 10 o’clock and 2 o’clock positions respectively, are no longer in operation. The last two collisions points are for possible expansion.

Ions are accelerated through several stages of boosters before reaching the RHIC storage ring. Ions other than protons begin in the Tandem Van de Graaff accelerator, while polarized protons are injected from the 200 MeV linear accelerator (Linac). The second stage is the Booster Synchrotron which injects the accelerated particle into the Alternating Gradient Synchrotron (AGS). From there, particles are transferred into the RHIC accelerator and storage ring via the AGS-To-RHIC Beam Transfer Line (ATR), which enters RHIC at the six o’clock position.

Polarized beams are difficult to maintain at high energies due to the increased density and strength of “spin resonances”. Spin resonances occur for certain beam energies and magnetic field strengths that will cause the spin angular momentum of the beam particle to precess excessively. A technique called “Siberian Snakes” has been designed and implemented to provide a full 180° spin flip each time the
Figure 2.1: A schematic view of the RHIC accelerator complex at BNL showing only the relevant devices for polarized proton-proton collisions.
beam passes through the Snakes. The 180° spin precession on each orbit causes the unwanted spin precession in the steering and focussing magnets to “undo” what happened on the previous orbit, preserving the desired beam polarization. Each snake is constructed from four 2 m helical dipole modules. Four such Siberian Snakes have been installed in the collider rings, two in each ring 180° apart, as shown in Fig. 2.1. These Snakes are able to accelerate, store, and collide polarized proton beams at ultra-high center of mass energies [2]. In addition to these Snakes, two Spin Rotators (see Fig. 2.1) also have been installed on each side of the STAR and PHENIX detectors. These helical shaped dipole-magnet spin rotators are used to change the beam spin orientations prior to collisions with either transverse or longitudinally polarized beams.

2.2 Experimental Detector Systems at RHIC

Given below is a brief introduction to the main features of detectors, viz., PHENIX, PHOBOS and BRAHMS at RHIC. The STAR detector is described in detail in next section.

2.2.1 PHENIX

The Pioneering High Energy Nuclear Interaction eXperiment (PHENIX) detector is designed to perform a broad study of $A+A$, $p+A$, and $p+p$ collisions to investigate nuclear matter under extreme conditions. A wide variety of probes, sensitive to all timescales, are used to study systematic variations with species and energy as well as to measure the spin structure of the nucleon. The PHENIX detector measures electron and muon pairs, photons, and hadrons with excellent energy and momentum resolution.
The *PHENIX* detector is comprised of four instrumented spectrometers, or arms, and three global detectors. The detector consists of a number of subsystems as shown in Fig. 2.2 with the major subsystems labelled. The east and west central arms are centered at zero rapidity and instrumented to detect electrons, photons and charged hadrons. The north and south forward arms have full azimuthal coverage and are instrumented to detect muons. Each of the four arms has a geometric acceptance of approximately one steradian. The global detectors measure the start time, vertex and multiplicity of the interactions [45].

![Figure 2.2: A cutaway drawing of the *PHENIX* detector with labelled arrows pointing to the major detector subsystems](image-url)
2.2.2 PHOBOS

The PHOBOS detector was designed to perform comprehensive studies of global parameters of ultra-relativistic heavy ion collisions with almost complete coverage of the solid angle. The multiplicity of emitted charged particles were measured over the pseudo-rapidity interval $-5.4 < \eta < 5.4$ using an array of silicon-pad detectors arranged in an octagonal barrel geometry covering the mid-rapidity region $|\eta| < 3.2$ complemented by six ring detectors that extended the pseudo-rapidity range to $|\eta| < 5.4$.

The PHOBOS collaboration successfully measured several charged particle multiplicites, particle/anti-particle ratios, and collective flow characteristics [46].

2.2.3 BRAHMS

The Broad RAnge Hadron Magnetic Spectrometers (BRAHMS) experiment was designed to measure charged hadrons over a wide range of rapidity and transverse momentum to study reaction mechanisms of relativistic heavy ion reactions at RHIC and the properties of highly excited matter formed in these reactions. The experiment took its first data during the RHIC 2000 year run and completed data-taking in June 2006.

The BRAHMS setup consists of two rotatable spectrometers, the mid-rapidity spectrometer (MRS) and the forward spectrometer (FS), complemented with an event characterization system used to determine the geometry of the collisions. The MRS spectrometer measures the momentum of charged particles with two tracking stations and a single dipole magnet. Particle identification in this spectrometer is done with time-of-flight spectrometer hodoscopes and a threshold Cherenkov detector. The FS
measures the much higher momenta of charged particles produced at small angles with five tracking stations. Particle identification in the FS is done with a complement of two time-of-flight hodoscopes, one threshold Cherenkov counter and the Ring Imaging Cherenkov (RICH) detector. A detailed description of the BRAHMS experimental set up is given in [47].

2.3 The STAR detector

The STAR detector system was constructed to investigate the behavior of strongly interacting matter at high energy density and to search for signatures of quark-gluon plasma formation. Key features of the nuclear environment at RHIC are a large number of produced particles and high momentum particles from hard parton-parton scattering [48].

As we mentioned in the Introduction Chapter, there are two primary main objectives of the STAR program. The first one is to investigate the phase transition to, and study the formation and properties of, the (QGP), a state of matter believed to exist at sufficiently high energy densities. Detecting and understanding the QGP allows us to understand better the universe in the moments after the Big Bang, where the symmetries (or lack of symmetries) of our surroundings were initiated. The other objective is to study the spin structure of nucleons and other spin studies in a kinematic range with an accuracy never before possible.

Unlike other physics experiments where a theoretical idea can be tested directly by a single measurement, STAR must make use of a variety of simultaneous studies in order to draw strong conclusions about the QGP and the proton spin. This is due both to the complexity of the system formed in the high-energy nuclear collision and the unexplored landscape of the physics we study. STAR therefore consists of
several types of detectors, each specializing in detecting certain types of particles or characterizing their motion. These detectors work together in an advanced data acquisition system and subsequent physics analysis that allows final statements to be made about the collision.

In order to accomplish these objectives, STAR was designed primarily for measurements of hadron production over a large angle, featuring detector systems for high precision tracking, momentum analysis, and particle identification at the center of mass (c.m) rapidity.

STAR is a large acceptance apparatus comprising several detector sub-systems within a 0.5 T solenoidal magnetic field. The layout of the STAR detector is shown in Fig. 2.3. In the year 2006 when the dataset used for this analysis was taken, the STAR detector comprised of the following sub-detector systems: Beam-Beam Counters (BBC), Central Trigger Barrel (CTB), Zero Degree Calorimeter (ZDC), Silicon Vertex Tracker (SVT), Silicon Strip Detector (SSD), Time Projection Chamber (TPC), Forward Time Projection Chamber (FTPC), Time of Flight (ToF), Photon Multiplicity Detector (PMD), Forward Pion Detector (FPD), Barrel Electro-Magnetic Calorimeter (BEMC) and Endcap Electro-Magnetic Calorimeter (EEMC). Fig. 2.4 shows the cross-section of the STAR detectors used in year 2006. Since then, some detectors have been removed, and some new detectors have been either already added or are in R&D phase.

The main detectors for this analysis were the TPC and EEMC. The TPC was used primarily to distinguish electrons from hadrons by measuring their ionization energy loss ($dE/dx$) and momentum ($p$). The EEMC was used to further enhance the discrimination of electrons from hadrons based on their strong differences in shower
Figure 2.3: The STAR detector systems showing the location of the detector sub-systems.

Figure 2.4: Cross-section of the STAR detectors used in year 2006 showing the location of the detector sub-systems.
probability and longitudinal shower development, the details of which is described in later sections. What follows is a brief introduction of some major detector sub-systems in STAR including the TPC and EEMC.

2.3.1 Beam Beam Counter

The Beam Beam Counter (BBC) consists of a pair of scintillating detectors for charge-particle solid angle multiplicity. These detectors are mounted on the outside of the east and west poletips of the STAR magnet. Each BBC is made up of an inner and outer ring of scintillating material with the inner ring covering pseudo-rapidity of $3.9 < \eta < 5.0$ and the outer ring covering $3.4 < \eta < 3.9$. The BBC is a very fast detector and hence capable of counting the total number of particles crossing its plane very rapidly and therefore it is basically used to trigger events where the use of ZDCs is impossible or impractical due to the low neutron content of the colliding nuclei, as is the case for $p + p$ collisions. BBCs can also be used as vertexing detectors. The $z$ position of the collision can be determined by comparing the arrival time of collision remnants to each of the BBC faces. In addition to these, the BBCs are also used to monitor the beam quality during the experimental runs [49].

2.3.2 Central Trigger Barrel

The Central Trigger Barrel (CTB) is a collection of scintillating slats surrounding the TPC. The CTB provides full azimuthal coverage i.e. $0 < \phi < 2\pi$ over the pseudo-rapidity range $|\eta| < 1$. The analogous to digital converter (adc) voltages from the slats are proportional to the multiplicity of charged particles hitting the slats. It is a very fast detector (260 ns) capable of measuring the mid-rapidity charged particle multiplicity in real-time, which is useful for further trigger information [50].
2.3.3 **Zero Degree Calorimeter**

The Zero Degree Calorimeter (ZDC) consists of a pair of small hadron calorimeters located downstream (east and west) of the interaction region. The ZDC is placed at \(\approx 18m\) from the center of STAR and subtends a solid angle of approximately 30\(\mu\)sr. Each ZDC consists of 3 modules containing a series of tungsten plates. The ZDCs measure the energy of neutrons associated with the spectator matter, and they are used for beam monitoring, triggering and locating interaction vertices [50].

2.3.4 **Silicon Vertex Tracker**

The Silicon Vertex Tracker (SVT), an inner tracking detector for the STAR experiment, consists of 216 silicon drift detectors, each mounted on three concentric barrels. The wafers are mounted onto beryllium ladder structures holding either 4, 6, or 7 detectors depending on the barrel number. The ladders are arranged in polygon-shaped barrels with 8, 12 and 16 ladders each to surround the colliding beams and their point of interaction at radii of 6.6, 10.6 and 14.5 cm, respectively.

The SVT was designed to improve the primary vertexing, the two-track separation resolution, and the energy-loss measurement for particle identification. The SVT enables the reconstruction of very short-lived particles, primarily strange and multi-strange baryons, and potentially D-mesons, through secondary vertexing close to the interaction zone. It also expands the kinematical acceptance for primary particles to very low momentum by using independent tracking in the SVT alone for charged particles that do not reach the active volume of the TPC due to the applied magnetic field [51].
2.3.5 Silicon Strip Detector

The Silicon Strip Detector (SSD), also an inner tracking detector for the STAR experiment, is installed between the SVT and the TPC. The SSD is placed at a distance of 230 mm from the beam axis, covering a pseudo-rapidity range of $|\eta| < 1.2$ which leads to a total silicon surface close to 1 $m^2$.

The SSD is designed to enhance the tracking capabilities of the STAR experiment by measuring accurately the two-dimensional hit position and energy loss of charged particles. It aims specifically at improving the extrapolation of TPC tracks through SVT hits and increasing the average number of space points measured near the collision, thus increasing the detection efficiency of particles with a certain range of lifetimes [52].

2.3.6 Time of Flight

The Time of Flight (TOF) detector was developed to greatly extend the particle identification (PID) of charged hadrons to high transverse momentum, $p_t$, at STAR in combination with the TPC. The TOF can identify pions, kaons and (anti)protons in the intermediate/high $p_t$ range and electrons at low/intermediate $p_t$. The TOF also extends STAR’s detection power to the heavy flavor region by increasing the signal-to-noise ratios for charm hadron reconstruction for $D^0, D^+, D^+_s$, and $J/\psi$, enabling STAR to make systematic studies of charm thermalization and charm meson flow [53, 54].

A full barrel TOF detector using the multi-gap resistive plate chamber (MRPC) covering $\eta < 1$ pseudo-rapidity and $2\pi$ in azimuth was constructed and operated in the most recent RHIC run in 2009 [53, 55]. One tray of the prototype TOF detector
based on MRPC which was installed in STAR in 2003 covers $1/60$ of $2\pi$ in azimuth and $-1 \leq |\eta| \leq 0$ in pseudo-rapidity at the outer radius of the TPC, 220 cm from the interaction point. Two identical pseudo-vertex position detectors ($pVPD$) were installed to record the start time for the TOFr, each 5.4 m away from the TPC center along the beam line. Each $pVPD$ covers $\sim 19\%$ of the total solid angle in $4.4 \leq |\eta| \leq 4.9$. More information of the TOF design and its features can be found in [56].

2.3.7 Forward Time Projection Chamber

The Forward Time Projection Chamber ($FTP C$) was constructed to extend the acceptance of the STAR experiment, covering the pseudo-rapidity range $2.5 < |\eta| < 4.0$ on both sides of STAR (See Fig. 2.3 and Fig. 2.4) and can measure momenta and production rates of positively and negatively charged particles as well as neutral strange particles [57].

2.3.8 Barrel Electro-Magnetic Calorimeter

The Barrel Electromagnetic Calorimeter ($BEMC$) is located inside the aluminium coil of the STAR solenoid and covers $|\eta| \leq 1.0$ and $2\pi$ in $\phi$, thus matching the acceptance for full TPC tracking. The front face of the calorimeter is at a radius of $\lesssim 220$ cm from and parallel to the beam axis.

The $BEMC$ is a very fast detector and it is utilized to trigger on and study rare, high $p_t$ processes (jets, leading hadrons, direct photons, heavy quarks) and provide large acceptance for photons, electrons, $\pi^0$ and $\eta$ mesons in systems spanning polarized $p+p$ through $Au+Au$ collisions. It is also used for general event characterization in heavy ion collisions including ultra-peripheral collisions [58].
2.3.9 The STAR Trigger

The STAR Trigger is designed to facilitate the search for new states of matter such as the quark-gluon plasma and the quest to understand the interior of hadrons. It is a pipelined system in which digitized signals from the fast trigger detectors are examined at the RHIC crossing rate ($\sim 10$ MHz) [59]. This information is used to determine whether to begin the amplification-digitization-acquisition cycle for slower, more finely grained detectors. The slow detectors like the TPC, SVT, FTPC, etc. provide momentum and particle identification on which our physics conclusions are based, but in 2006, they could only operate at rates of $\sim 100$ Hz. Interactions rates at RHIC can be very high, so the fast detectors must provide means to reduce the rate by up to 5 orders of magnitude. Interactions are, therefore, selected based on the distributions of particles and energy obtained from the fast trigger detectors viz., the CTB, the BBC, the ZDC, BEMC, EEMC, etc. [50].

The trigger system is divided into 4 different levels. The first three levels, 0, 1, and 2, are based on fast detector information. The final trigger decision is made in level 3 based on tracking in the slow detectors. This trigger also provides an online visual display of the events almost in real time as shown in Fig. 2.5.

2.3.10 The Time Projection Chamber

The TPC is the primary tracking device of the STAR detector [60, 61]. It records the tracks of particles, measures their momenta, and identifies the particles by measuring their ionization energy loss ($dE/dx$). Its acceptance covers $\pm 1.8$ units of pseudo-rapidity through the full azimuthal angle and over the full range of multiplicities.

The STAR TPC is shown schematically in Fig. 2.6. It sits in a large solenoidal
Figure 2.5: Beam’s eye view of a central event in the STAR TPC

magnet that operates at 0.5 T [64]. It is 4.2 m long and 4.0 m in diameter. The cylinder is concentric with the beam pipe, and the inner and outer radii of the active volume are 0.5 m and 2.0 m, respectively.

The TPC is divided into two parts by the central membrane, which is typically held constant at 28 kV high voltage. A chain of resistors and equipotential rings along the inner and outer field cage create a uniform drift field $\sim 135 \text{ V/cm}$ from the central membrane to the ground planes where anode wires and pad planes are organized into 12 sectors for each sub-volume of the TPC. The volume of the TPC is filled with P10 gas (10% methane, 90% argon) regulated at 2 mbar above atmospheric pressure to minimize any leakage of gasses like $O_2$. The electron drift velocity in P10 is relatively fast, $5.5 \text{ cm/µs}$ at $130 \text{ V/cm}$ drift field.

The charged particles traversing the TPC liberate electrons from the TPC gas due to ionization energy loss ($dE/dx$). These electrons drift through the gas towards the
end-cap planes of the TPC. There, the signal induced on a readout pad is amplified and integrated by a circuit containing a pre-amplifier and a shaper. It is digitized and then transmitted through a set of optical fibers to the STAR DAQ.

Given the time of the collision, the read-out time and 2D location ($\phi, R$), it is possible to reconstruct the 3D location of any ionization event in the TPC. This allows the full 3D reconstruction of tracks in the TPC. The Time Projection chamber Tracker (TPT) algorithm [65] is then used to reconstruct tracks by helical trajectory fit. The resulting track collection from the TPC is combined with any other available tracking detector reconstruction results and then refit by application of a Kalman filter routine - a complete and robust statistical treatment [66]. The primary collision vertex is then reconstructed from these global tracks and a refit on these tracks with the distance of closest approach ($dca$) less than 3 cm is performed by a constrained...
Kalman fit that forces the track to originate from the primary vertex. The primary
vertex resolution is \( \sim 350 \, \mu \text{m} \) with more than 1000 tracks. The refit results are stored
as primary tracks collection. The reconstruction efficiency, including the detector
acceptance for primary tracks, depends on the particle type, track quality cuts, \( p_t \),
track multiplicity, etc.

**Ionization in the TPC**

The mean range of energy loss for a particle with charge \( Z \) and speed \( \beta = v/c \)
passing through the TPC gas is given by the well-known Bethe-Bloch formula [67]:

\[
-\frac{dE}{dx} = K z^2 Z \frac{1}{A \beta^2} \left[ \frac{1}{ln} \frac{2m_e c^2 \beta^2 \eta^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]
\]

where \( T_{max} \) is the maximum kinetic energy which can be imparted to a free electron
in a single collision; the other variables are defined in [67].

The mean energy deposited depends on the speed of the particle, the charge it
carries, its mass and the target material. This means that in some kinematic ranges
it is possible to determine the type of particle based on the mean energy deposited
in the hits that make up the track. Fig. 2.7 represents a standard plot from STAR
where \( dE/dx \) is plotted as a function of reconstructed momentum for all tracks in a
large number of events. The points cluster around the characteristic bands for the
various particles whose ideal \( dE/dx \) curves have been superimposed.
2.4 The Endcap Electro-Magnetic Calorimeter

An Endcap Electro-Magnetic Calorimeter (EEMC), shown in Fig. 2.8, was constructed and installed 2.7 m away from the center of the STAR detector at RHIC. It is located on the west poletip of the STAR detector, as shown in Fig. 2.9. The EEMC is an annulus with projective geometry with an inner radius $\approx 75$ cm, outer radius $\approx 215$ cm and a longitudinal depth $\approx 34$ cm. The inner and outer radii grow with depth. The EEMC provides full azimuthal coverage for high-$p_t$ photons, electrons and electromagnetically decaying mesons ($\pi^0$, $\eta$) over the pseudorapidity range $1.086 \leq \eta \leq 2.00$. It consists of a scintillating-strip shower-maximum detector to provide $\pi^0/\gamma$ discrimination and preshower and postshower layers to aid in distinguishing between electrons and charged hadrons. The triggering capabilities and coverage it offers...
are crucial for the studies of the spin physics program using polarized proton-proton collisions [68].

Figure 2.8: The actual view of the EEMC as seen being serviced during one of the regular RHIC shut-downs in summer for repairs/maintenance and upgrades [69].

The increased acceptance of the EEMC provides access to critical phase space regions for colliding beams of polarized protons or heavy nuclei, allowing STAR to provide:

- the measurement of the gluon contribution to the spin of a proton;
- an effective separation of antiquark vs. quark contributions to the proton spin in $W^\pm$ production;

- enhanced sensitivity to hyperon spin structure in measurements of the polarization transfer from beam protons to hyperon fragments of jets;

- meaningful Standard Model tests via measurement of parity-violating helicity asymmetries in hard jet production; and

- access to the most interesting kinematic regime in nuclear gluon distributions, probed in $p + A$ collisions.

The EEMC enables STAR to meet some of the most important goals of the RHIC
spin program, as well as to measure nuclear properties crucial to the RHIC heavy-ion collision programs [71]. In particular, with the detection of direct photons, the longitudinal helicity preference for gluons $\Delta G(x_g)$ inside a polarized proton, as a function of $x_g$ of the fraction of the proton’s momentum carried by the gluon can be probed. This helicity preference can strongly constrain the net gluon contribution to the proton’s spin, which is of great interest [72, 73]. The most important spin physics at STAR involving electrons and positrons is the measurement of flavor-dependence of sea anti-quark polarization via the production of $W^\pm$ tagged by a decayed energetic electron or positron with its transverse momentum $p_t$ of tens of GeV/$c$ [71, 74]. The above physics opportunities set the requirements for the EEMC. Some of the characteristics mentioned above are summarized in Table 2.1, together with the physics goals that drive them.

2.4.1 Mechanical design of the EEMC and the tower structure

The EEMC is a lead-plastic scintillator sampling calorimeter with a total depth of 21.4 radiation lengths at normal incidence and a shower energy sampling fraction of 5.0%. The full annulus is split into two halves along a line 15° from the horizontal, to allow for the easier handling and staging in construction, with one half shown in Fig. 2.10. The top and the bottom halves take advantage of different features on the STAR poletip to provide primary support of the weight. The total mass of the radiator sheets and active elements, for the two EEMC halves combined, is $\approx 25,000$ kg. The EEMC is mechanically divided into 12 modules of 30°, also known as sectors, each fixed to the magnet poletip. The segmentation of each module is 5 intervals in $\phi$ (6°), also known as sub-sectors, and 12 intervals in $\eta$. Each single elementary volume of the EEMC that covers $\Delta \eta \Delta \phi$ is called a tower. The EEMC is
<table>
<thead>
<tr>
<th>Feature</th>
<th>Requirement</th>
<th>Driving physics goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geom. acceptance</td>
<td>$1 \lesssim \eta \leq 2; \text{ full } \phi$</td>
<td>$\gamma + \text{jet sensitivity to } 0.01 \lesssim x_g \lesssim 0.3$</td>
</tr>
<tr>
<td>$E_{min}$ in one tower</td>
<td>$\approx 0.2$</td>
<td>MIPs for calibration; $\gamma$'s from asymmetric $\pi^0$ decay; $\approx 2%$ shower leakage from $p_T = 10 \text{ GeV/c } \gamma$'s</td>
</tr>
<tr>
<td>$E_{max}$ in one tower</td>
<td>$150 \text{ GeV}$</td>
<td>$e^\pm$ from $W^\pm$ decay at $\eta = 2$</td>
</tr>
<tr>
<td>Linearity</td>
<td>$&lt; 10%$ integral non-linearity, $\sim 1$-$150 \text{ GeV}$</td>
<td>Correct to give $W^\pm$ daughter $p_T$ to $\pm 1 \text{ GeV/c}$ from lower-$E$ calibration</td>
</tr>
<tr>
<td>Depth</td>
<td>$\geq 20X_0, \leq 30X_0$</td>
<td>$&lt; 10%$ shower leakage for $150 \text{ GeV } e^\pm$; minimize hadron sensitivity to fit within existing space</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>$(\frac{\sigma_E}{E}) \leq \left( \frac{16%}{\sqrt{E}} \right) + (2%)$</td>
<td>$x_q$ uncertainty $\lesssim \pm 0.01$ for $W^\pm$ reconstruction at $p_{T,e} \leq 30 \text{ GeV/c}$</td>
</tr>
<tr>
<td>$\gamma/\pi^0$ discrimination</td>
<td>$\pi^0/\gamma$ suppresss factor $&gt; 3$ for $p_T \approx 10$-$20$ $\text{ GeV/c } \Rightarrow \text{ SMD}$</td>
<td>Keep background subtraction from enlarging $\Delta G(x)$ errors by more than a factor of 2</td>
</tr>
<tr>
<td>$e^\pm/h^\pm$ discrimination</td>
<td>$h^\pm/e^\pm$ by $&gt; 10$ for $p_T \geq 5$ $\text{ GeV/c } \Rightarrow$ pre/post-shower</td>
<td>Reach $&gt; 3:1$ $W$ signal/hadronic bkgrd. ratio for $p_T &gt; 20 \text{ GeV/c }$; enhance Drell-Yan signal/bkgrd.</td>
</tr>
<tr>
<td>Jet reconstruction</td>
<td>$\sigma \approx 0.1$ for $\eta_{jet}, \phi_{jet}$</td>
<td>Reconstruct $x_{1,2}$ values for colliding partons in $\gamma + \text{jet coin.}$ to $\approx \pm 0.01$</td>
</tr>
<tr>
<td>Segmentation/rate capability</td>
<td>$&lt; 10%$ $L_{pp} = 2 \times 10^{32}$; tower size $\geq 2x$ shower diam.</td>
<td>Trigger on isolated $\gamma$ or $e^\pm$ vs. jet; minimize tower hadron occupancy; obey WLS fiber min. bend radius</td>
</tr>
<tr>
<td>Tower calibration</td>
<td>Absolute $E$ calibration to $\pm 2%$($\pm 10%$ online)</td>
<td>Minimize systematic errors in extracted $x_g, \int \Delta G(x)dx$ ($p_T$, hence $x$, threshold at acceptable trigger rates)</td>
</tr>
<tr>
<td>Coverage gaps</td>
<td>$&lt; 2%$ systematic shower $E$ loss in cracks</td>
<td>Minimize systematic errors in extracted $x_g, \int \Delta G(x)dx$</td>
</tr>
<tr>
<td>SMD calibration</td>
<td>Relative gains of adjacent strips known to $\lesssim \pm 10%$</td>
<td>Maintain sufficient $\gamma$ vs. $\pi^0$ shower shape discrimination</td>
</tr>
<tr>
<td>Timing response</td>
<td>$&lt; 1 \text{ RHIC beam crossing period (110 ns)}$</td>
<td>Aid in TPC pileup rejection; no occupancy from neighboring beam crossings</td>
</tr>
</tbody>
</table>

Table 2.1: Summary of critical $EEMC$ requirements and the physics goals that drive them[68].
composed of 720 towers, each of which spans 6°, which is equivalent to $\Delta \phi=0.1$ in azimuthal angle and increasing range in pseudorapidity, starting from $\Delta \eta=0.057$ to 0.099 as one moves from the outer radius near $\eta=1$ to the inner radius at $\eta=2$. Each tower contains 23 layers of lead and stainless steel absorber interleaved with 24 layers of plastic scintillator. A standard layer of the calorimeter consists of Pb/stainless steel laminate followed by a 4 mm thick plastic scintillator. Each radiator sheet comprises 4.57 mm thick calcium-loaded Pb sheets laminated on each face with 0.5 mm stainless steel, for a total of $\approx0.85$ radiation lengths. There are four specially configured layers providing pre-shower, post-shower and shower maximum detectors which are described in later sections.

The optical system is organized according to the tower segmentation and plays a very important role in energy collection for the EEMC. The tower segmentation is produced using megatile construction. One 30° sector of a calorimeter layer contains two 12° megatiles and a 6° smaller megatile. Wavelength-shifting (WLS) optical fibers, inserted into $\sigma$-shaped grooves machined in the face of each tile, run through channels in a white plastic fiber-routing layer (FRL) out to the $\eta\approx1$ edge of each megatile. A photograph of one megatile and its accompanying FRL is shown in Fig. 2.11. Optical connectors are used to couple the WLS fibers from the 12 tiles within a given sub-sector megatile to clear fibers. The clear fiber bundles from each of the 24 scintillator layers within a given sub-sector are connected to a photo-multiplier tube (PMT) box containing 12 PMT’s corresponding to each tower in the given sub-sector. Light from the 24 layers within each tower is combined via an optical mixer in a single PMT, to produce a signal proportional to the total energy deposited in that tower.
2.4.2 Pre-shower and post-shower layers

The first two layers of scintillator tiles immediately after the EEMC front plate and the last layer are specially configured scintillator layers, known as pre-shower and post-shower respectively. Pre-shower and post-shower are indicated in Fig. 2.10. Each layer of the pre-shower and post-shower consists of two independent WLS fibers inserted in the $\sigma$-grooves for light transportation. For each layer, the light transported by one of these fibers is added to that from other scintillator layers and is routed to
Figure 2.11: Closeup photographs near the $\eta = 1$ edge of an assembled $6^\circ$ sub-sector megatile. The upper photo shows the front face of the scintillator with $\sigma$-grooves. The lower photo shows the opposite side of the fiber-routing layer with wavelength-shifting fibers routed through the undulating channels from which they enter the $\sigma$ grooves in each tile.

the $PMT$ that measures the total light produced by the tower. The second fiber is used to transport light from each tile separately to a channel of a multi-anode $PMT$, to form a pre-shower or post-shower detector. The pre-shower and post-shower megatiles are made from thicker and brighter scintillator than the normal megatiles to compensate for the light loss caused by the parallel readout, thus enabling proper gain matching of these layers to the rest of the tower.

The main purpose for the construction of pre-shower and post-shower detectors is to aid in distinguishing electrons from hadrons by exploiting their strong differences in shower probability and longitudinal shower development. They also improve the $\pi^0/\gamma$ discrimination at high energies since it is roughly twice as likely for a $\gamma$ as for a similar energy $\pi^0$ to deposit no energy in these layers. This $e/h$ discrimination provided by the $EEMC$ is very important in the endcap region where the $TPC$ tracking resolution
is very poor [68].

2.4.3 Shower maximum detector

The shower maximum detector \((SMD)\) is one of the four specially configured layers in the \(EEMC\) as mentioned in the previous section. The \(SMD\) is located after the fifth radiator plate which is about five radiation lengths deep within the \(EEMC\). It is designed to provide the fine granularity crucial to distinguishing the transverse shower profiles characteristic of single photons vs. the close-lying photon pairs from \(\pi^0\) and \(\eta^0\) decay. It is also useful in electron-hadron discrimination by comparing their shower patterns, as well as in tracking charged particles by matching of \(TPC\) tracks with hits on the \(EEMC\).

The \(SMD\) is made up of scintillator strips of triangular cross-section organized into orthogonal planes known as u-planes and v-planes which overlap at the sector edges as shown schematically in Fig. 2.12. The triangular cross-section enhances the position resolution and the stability of the measured shower profile shape due to the sharing of the energy deposition among the adjacent strips. The \(SMD\) scintillators are segmented into \(30^\circ\) modules, so that there are 12 sectors of \(SMD\) covering the entire \(EEMC\) azimuthally with a u- and v-plane in each sector. Each \(SMD\) layer consists of three sub-layers in depth, containing one active u-plane and one active v-plane module, and a third sub-layer filled with a passive plastic spacer module. There are 288 scintillator strips with varying lengths in each \(SMD\) plane.

Light from the \(SMD\) is transported by \(WLS\) fibers that run along the length of each strip in each plane to the clear fibers via 12-fiber outer optical connectors at the outer circumference of the \(SMD\). These optical connectors, then, transport the light to 16-anode \(PMTs\) housed in steel boxes on the rear of the \(STAR\) poletip. Three
such boxes, each containing 12 multi-anode photo-multiplier tubes (MAPMT) collect the light transported from a total of 576 strips from both the planes in the SMD. Information on energy deposition from the individual strips or a combination of them can then be obtained from these MAPMT signals.

Figure 2.12: Layout of the SMD in a 30° sector. Each SMD layer consists of two orthogonal planes, u- and v-planes, constructed from triangular scintillating strips extruded with an axial hole for the wavelength-shifting fiber.

2.5 Kent State University (KSU) Contribution

KSU-EEMC group, headed by Prof. Bryon Anderson, has been a collaborating member of the EEMC project ever since its inception[71]. KSU has made major contributions in both software and hardware development for the EEMC. In particular, KSU was responsible for the design of the optimized configuration of mapping from EEMC SMD strips to LED boards, burn-in and measurement of the characteristics
of multi-anode photo multiplier tube (MAPMTs) and, for the design and fabrication of the LED monitoring system.

It was mentioned in Section 2.4.3 that the SMD plays a crucial role in distinguishing particle types based on their shower patterns, so getting the SMD strips properly mapped to LED fibers is of paramount importance. The KSU Senior Research Fellow, Dr. Wei-Ming Zhang, wrote a program in order to achieve this goal. There are a total of 576 SMD strips, 192 for each of the three MAPMT boxes. The total number of SMD connectors is 62, 20 (eight 12-strip and twelve 8-strip) for MAPMT box I, and 21 (six 12-strip and fifteen 8-strip) for each of the other two MAPMT boxes II and III. There are 36 MAPMTs, 12 in each box. An MAPMT has 16 pixels, making a total of 192 pixels in each box. There are eight LED boxes, each driving eight fibers, making a total of 64 fibers. An LED box illuminates 72 strips, 24 for each MAPMT box. Each set of 24 strips is connected to either two 12-strip or three 8-strip connectors. The basic idea for optimization is that every LED box illuminate two and only two pixels in one MAPMT, and there is at least one idle pixel to separate any two excited pixels in a MAPMT, thereby minimizing the cross-talk between the pixels. A typical optimized mapping of SMD strips to LED boxes is shown in Fig. 2.13. See Ref. [75] for further details.

Dark current is a relatively small electric current that flows through the MAPMTs even in the absence of radiation. Physically, dark current is due to the random generation of electrons and holes within the depletion region of the tubes that are then swept by the high electric field. This response adds to the signal produced when the tube is used to measure light and so must be dealt with to determine how much of the detector response is actually due to radiation. Before measuring the dark
Figure 2.13: The graphic display showing an optimized mapping of SMD strips to LED fibers in one of three MAMPT boxes in a typical LED box. Clearly displayed here are two and only two illuminated pixels in each MAPMT, one corresponding to the SMD strips in the U plane, and the other in the V plane, separated by at least one idle pixel labelled OFF in the figure. This optimized mapping minimizes the cross-talk between the pixels.

 currents each MAPMT was burned-in by placing it in a specially designed apparatus and leaving it overnight with the high voltage ON. The MAPMT was then carefully placed in an electronic device, one of several electronic devices that was designed by the KSU Research Engineer, Dr. Alan Baldwin, as shown in Fig. 2.14, making sure that all the sixteen pixels were correctly and securely connected. First, the current flowing through each of the 16 pixels of the MAPMT was measured in complete darkness. Then, the current in each pixel was also measured without the MAPMT to determine the leakage current. The difference in these two currents is the net dark current flowing in each pixel of the MAPMT.
Once the dark currents were measured, a specially designed electronic device and acquisition software, was used to determine single photon response, gain response, and cross-talk response of the MAPMT. Fig. 2.15 shows the characterization measurements for each of the 16 pixels on a typical MAPMT [76, 77]. An MAPMT with one or more pixels measuring unusually high dark currents and/or very low gain response was considered defective and hence rejected. These individual pixel characterizations were then used for calibration of the EEMC scintillators for experimental runs at RHIC. These measurements and testing were part of this dissertation project.
Figure 2.15: MAPMT characterization measurements done at Kent State University for a typical MAPMT. Responses are shown for each of the 16 pixels on the phototube.
Chapter 3

DATA ANALYSIS

In this chapter we describe the analysis methods and procedures used for the measurement of non-photonic electrons at $\eta$ between 1.1 and 1.5 in proton-proton collisions at $\sqrt{s} = 200$ GeV. We start by describing the data sets used for this analysis, including the criteria used for event and track selections. We provide a detailed description of the method used for the identification of electrons. This is followed by the description on how various electron reconstruction efficiencies were corrected. We provide a detailed description of the technique called invariant mass technique used to determine photonic background electrons. Finally, we present the invariant yields of inclusive and non-photonic electrons, and the total charm cross section from this analysis.

3.1 Run Selection

We used the transversely polarized proton-proton beam data from year 2006 to measure production of non-photonic electrons in the EEMC. Based on trigger and luminosity information, a total of 300 transverse runs from 31 fills were selected for the final analysis. The complete list of the runs and fills used for this analysis is provided in Appendix A.

3.2 Trigger Selection

In $p+p$ run in 2006, the full capability of the trigger system was extended and utilized leading to a rather complicated mix of triggers utilizing level 2. For the first
time, the Trigger Patch (TP) and Total Energy Threshold were added in the EEMC trigger system besides the High Tower (HT) and the Jet Patch (JP) triggers that already existed in the previous runs.

A trigger is a system that uses some simple criteria to rapidly decide which events in a particle detector to keep when only a small fraction of the total can be recorded due to rate and data storage limitations. Triggers are designed so that only “interesting events”, such as decays of rare particles that occur at a relatively low rate, are detected and recorded subsequently (See Sub-Section 2.3.9 for details).

For the $p + p$ run in 2006, several EEMC triggers were utilized including eemc-ht2-mb-emul, eemc-jp1-mb, eemc-jp0-mb, eemc-http, eemc-http-mb-l2gamma, eemc-jp0-etot-mb-L2jet (See Table 3.3 for details). Efficiencies of all of these triggers were estimated in our analysis as a consistency check. However, in the end, we used only three good triggers, namely, eemc-jp1-mb, eemc-http-mb-l2gamma and eemc-jp0-etot-mb-L2jet corresponding to trigger id 127271, 127641 and 127652, respectively, for the final analysis (See Section 3.7.4 for further details). HT is defined as an event seen in a single tower with energy deposition above a certain threshold while TP is defined as an event seen in a cluster of adjacent towers whose sum of energy deposition exceeds a certain energy threshold. Similary, JP is defined as an event seen in a cluster of trigger patches whose sum of transverse energy deposition observed by the STAR BEMC or EEMC over a $\Delta \eta \times \Delta \phi \sim 1 \times 1$ region surpasses a certain threshold. Fig. 3.1 shows the layout of trigger and jet patches in the EEMC with detailed labeling schemes and Data Storage and Manipulation (DSM) assignments.
### EEMC Trigger Patches

*looking west from STAR center*

<table>
<thead>
<tr>
<th>TP#</th>
<th>Brd. #</th>
<th>Chn. #</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>3-7, 11-15</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>80-87</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0-2, 8-10</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>19-23, 27-31</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>88-95</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>16-18, 24-26</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>35-39, 43-47</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>96-103</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>32-34, 40-42</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>51-55, 59-63</td>
</tr>
<tr>
<td>11</td>
<td>4</td>
<td>104-111</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>48-50, 56-58</td>
</tr>
<tr>
<td>13</td>
<td>3</td>
<td>67-71, 75-79</td>
</tr>
<tr>
<td>14</td>
<td>4</td>
<td>112-119</td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>64-66, 72-74</td>
</tr>
</tbody>
</table>

**Individual towers span** $\Delta \phi = 0.1 \otimes \Delta \eta = 0.057-0.099$

**Small trig. patches--6, 8 or 10 towers--span** $\Delta \phi = 0.2 \otimes \Delta \eta \approx 0.3$

**15 small patches form jet patch of** $\Delta \phi = 1.0 \otimes \Delta \eta = 1.0$

**In one jet patch, same color small patches go to same FEE card**

**Jet patches chosen to give near left-right & up-down symmetry**

**Jet patches span physical EEMC sector and half boundaries!**

**Jet patches match in $\phi$ (within 3°) to BEMC jet patches**

Figure 3.1: The 2002 layout of EEMC trigger and jet patches with detailed labeling schemes and DSM assignments.
3.3 Event Selection

As was mentioned in Section 2.4, the EEMC is located at a distance of \(\sim 2.7\) m west of the center of the STAR detector. It has been observed that the TPC tracking resolution deteriorates with increasing pseudo-rapidity in the EEMC region [61]; thus, in order to maximize the statistics and to achieve a reasonable acceptance in the EEMC, the collision vertex was required to lie within \(\pm 120\) cm along the beam line. Unfortunately, it was observed that due to this large \(Z\) cut requirement, photon conversion electron background swamped the non-photonic electrons in the EEMC. Especially, the events originating from the negative \(Z\)-direction contributed predominantly large photonic background as these events had to traverse through a lot of material to reach the EEMC (See Fig. 4.1). Fig. 3.2 shows the position of the primary vertex \(Z\) distribution of all events.

![Figure 3.2](image)

Figure 3.2: A typical distribution of the primary vertex \(Z\) for a \(p + p\) run in year 2006.
3.4 **Software Development**

We will now describe the software developed using ROOT [62] by our group to achieve our analysis goals. Basically, we developed two main programs; the first one generates “electron tree” with QA and some loose cuts and the second one uses the information from the tree to identify electrons based on several electron identification cuts that will be discussed in detail in Sub-Section 3.6.

What follows below is a brief description of each program.

3.4.1 **StRecoEleFinderMaker**

*StRecoFinderMaker*, as the name implies, is a program that is basically responsible for reconstruction of events and generation of electron tree of the reconstructed (RC) tracks. The electron tree contains all the relevant information that we need for electron analysis in the later stage.

The following procedure is adopted to generate the electron tree of the RC tracks.

1. Provide *MuDst* root file as INPUT to the *StRecoFinderMaker* class.

2. Accept an event with *primary vertex* \(^1\) satisfying \(|Z_{vertex}| < 120\) cm.

3. Accept an event satisfying the *EEMC* triggers.

4. Now search for a *primary track* \(^2\) from the event and accept the track that satisfies the following conditions:

   (a) A valid track that is reconstructed in the *TPC*.

---

\(^1\)primary vertex a collision point of an event from which the tracks are supposed to have originated.

\(^2\)primary track is a track that has its origin in the primary vertex with the distant of closest approach \((dca) < 3\) cm.
(b) Ratio of number of hits used in the fit and the number of possible hits on the track > 0.52 to eliminate duplicate tracks.

(c) Position of the last measured point along the Z direction > 170 cm in order to pick up tracks heading towards the EEMC.

(d) Track that actually makes an entry into the EEMC detector.

(e) Track with SMD energy integrated over ± 10 strips around the hit strip.

5. When all of the above conditions are met, create and save an electron tree of the RC tracks containing all possible information relating to the event selected and the corresponding accepted track(s). For instance, information for an event may include \( Z_{\text{vertex}} \) position, event id, run id, trigger id, etc. Similarly, information for a track may include parameters like track id, pseudo-rapidity \( \eta \), transverse momentum \( p_t \), total momentum \( p \), azimuthal angle \( \phi \), ionization energy loss \( dE/dx \), charge \( q \), distance of closest approach \( dca \), momentum of helix, the origin of helix, etc.

Cuts mentioned above in steps 2 through 4 basically ensure the quality of tracks and hence the tracks that pass these cuts are said to have satisfied the Quality Assurance (QA) cuts in this analysis. Table A.1 lists all the QA cuts.

\textit{StRecoEleFinderMaker} is also used to generate electron tree corresponding to \textit{global tracks}\(^3\). The only criterion required for the track selection is that it is a valid TPC reconstructed track. Information from the global tracks is required during the

\(^3\)global track is any track which doesn’t necessarily originate from a primary vertex. However, a global track may have a corresponding primary track. In general, for every primary track there is one corresponding global track but every global track does not necessarily have a corresponding primary track.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary vertex along z direction</td>
<td>[-120.0, +120.0] cm</td>
</tr>
<tr>
<td>EEMC triggers required</td>
<td>Yes</td>
</tr>
<tr>
<td>Primary track reconstructed in TPC</td>
<td>Yes</td>
</tr>
<tr>
<td>(no. hits used in fit)/(no. of possible hits on track)</td>
<td>≥ 0.52</td>
</tr>
<tr>
<td>Last measured point of track along z direction</td>
<td>≥ 170 cm</td>
</tr>
<tr>
<td>Track required to enter the EEMC</td>
<td>Yes</td>
</tr>
<tr>
<td>Track with SMD energy integrated over</td>
<td>± 10 strips around the hit strip</td>
</tr>
</tbody>
</table>

Table 3.1: List of QA cuts. These cuts ensure the quality of tracks before generating an electron tree.

reconstruction of invariant mass of electron/positron pairs to determine the photonic background in the electron sample.

3.4.2 StMcEleAssoMaker

*StMcEleAssoMaker*, as the name implies, is a program that makes an association between Monte Carlo (MC) and reconstructed (RC) tracks. This program extracts MC information contained in the event sample and matches it with the corresponding RC track. Thus, this provides the information on the final number of tracks matched versus the total number of initial tracks. This will, therefore, enable us to calculate the electron reconstruction efficiency in the TPC. Fig. 3.3 is a flow-chart depicting the procedure for the association of MC tracks and RC tracks.
Figure 3.3: The flow-chart showing the procedure for the association of MC and RC tracks

In other words, the following procedure is employed for the association of MC and RC tracks which ultimately form an “electron tree” of the associated tracks.

1. The StMcEleAssoMaker takes StEvent and StMcEvent as INPUT.

2. Accept MC event with primary vertex satisfying $|Z_{\text{vertex}}| < 120$ cm.

3. Accept MC event satisfying a conversion point $R_v = \sqrt{X_v^2 + Y_v^2} < 60$ cm.
4. Accept $MC$ track satisfying Geant ID = 3 or 2 corresponding to a \textit{positron} or \textit{electron}, respectively.

5. Accept $MC$ track that actually makes an entry into the $EEMC$ detector.

6. Pass the track to the standard $STAR$ library class $StAssociationMaker$\footnote{Basically a spatial proximity matching is done between the $MC$ and $RC$ tracks for association. In particular, the requirements are as follows:
(a) The separation between $X$, $Y$, and $Z$ position of $MC$ and $RC$ tracks is less than 0.5 cm, i.e., $\Delta X = \Delta Y = \Delta Z < 0.5$ cm.
(b) number of common $TPC$ hits $> 5$.}

7. Accept the associated track satisfying the number of hits used in the fit to the number of possible hits ratio $> 0.52$.

8. Save the unique track id (also known as track key) for further analysis in the later stage.

9. Finally, create and save the electron tree of the associated tracks for further analysis in the later stage.

Based on this information the electron reconstruction efficiency of the $TPC$ was calculated. See Sub-Section 3.7.1 for further details.

3.4.3 \textbf{EleTreeAna}

This is the program which actually performs the analysis part of this research work. Electron identification cuts including $p$, $p_t$, $dE/dx$, $\eta$, and the EEMC energy cuts are applied at this stage. This is described in detail in Sub-Section 3.6. This is also the stage where the reconstruction of invariant mass of \textit{electron-positron} pairs is
done in order to determine the photonic background in the electron sample. Detailed description is given later in Section 3.9.

3.4.4 EemcEleTree

EemcEleTree is a special program where all the information in RC electron tree of primary tracks, RC electron tree of global tracks, and also that of MC electron tree, are stored for easy access during the analysis.

3.5 Track Selection

In this section we will describe the track-specific analysis which is the most important part of this research work. A major portion of my research time was spent writing the appropriate codes and in the optimization of electron identification cuts. Also, a substantial amount of effort was invested on the reconstruction of invariant mass of electron-positron pairs for the determination of the photonic background in the electrons sample which will be described in detail in a later section.

3.5.1 Range of Interest in $p_t$ and $\eta$

Fig. 3.4 (a) shows the $p_t$ distribution of primary tracks in the EEMC. Primary tracks that survive after undergoing a series of cuts are identified as electrons in our study. These electrons tend to have lower $p_t$ distributions. Similarly, Fig. 3.4 (b) shows the $\eta$ distribution of primary tracks in the EEMC. Track reconstruction efficiency decreases with increasing pseudo-rapidity due to the limited number of TPC pads in this region [61]. Therefore, in order to have some $p_t$ bins with reasonable statistics and track reconstruction efficiency, our analysis was performed for $p_t$ between 1.5 and 6.0 GeV/c, and for $\eta$ between 1.1 and 1.5.
Figure 3.4: $p_t$ and $\eta$ distribution of primary tracks in the EEMC
3.6 Electronic Identification

Ionization energy loss, $dE/dx$, in the TPC and the associated momentum of a charged particle are two important observables that help identify particles, say, electrons from hadrons, mainly in mid-rapidity region. In the forward rapidity region, where only a few TPC pads are involved, the TPC information alone is not good enough, so the EEMC information will be used to provide an additional power in distinguishing electrons from hadrons.

3.6.1 Energy Deposit and Deposit Shapes of Electrons and Hadrons in the EEMC

In this section, we will compare energy deposits and deposit shapes of electrons and hadrons in the EEMC. To select electron and hadron samples, tracks in $p+p$ collision events were first required to pass the QA cuts described in Sub-Section 3.4.1 above. Tracks that survived these QA cuts at forward pseudo-rapidities between 1.1 and 1.5 were extrapolated from the TPC to EEMC. The tracks that possessed total momentum $\geq 1.5 \text{GeV/c}$ were, then, required to pass the following fiducial cuts:

1. The entry point to the EEMC and the exit point from the EEMC must be in the same tower.

2. The entry and exit points must both lie at least 0.5 cm away from the tower edges.

Tracks that survived the QA cuts and fiducial cuts and an extra transverse momentum cut of $1.5 \text{GeV/c} \leq p_t \leq 6.0 \text{GeV/c}$ are called EEMC tracks in this study.
Energy loss, \(dE/dx\), in the TPC is a valuable tool for identifying particle species [61]. Fig. 3.5 shows the energy loss distribution of EEMC tracks. At the momentum range of interest, the energy loss of electrons is larger than that of hadrons [63]. EEMC tracks with \(dE/dx\) between 3.0 \(keV/cm\) and 5.0 \(keV/cm\) were selected as the electron sample and those with \(dE/dx\) below 2.5 \(keV/cm\) as the hadron sample, as shown by the red and blue shaded areas, respectively, in Fig. 3.5. The selected hadron sample has a high purity because hadrons dominate in this \(dE/dx\) range and the contamination from electrons is negligible.

Figure 3.5: Energy loss, \(dE/dx\), distribution of EEMC tracks. The red shaded area between \(3.0 \leq dE/dx\ (keV/cm) \leq 5.0\) represents the selected electron sample. The blue shaded area with \(dE/dx \leq 2.5\ keV/cm\) represents the selected hadron sample.
Most of the electrons in the selected electron sample arise from photonic electrons predominantly produced by photon conversions from $\pi^0 \to \gamma\gamma$ decays and $\pi^0$ Dalitz decays. Relatively pure photonic electrons were extracted with the “invariant mass technique” from the electron sample for the purity and acceptance study. This invariant mass technique will be described in Sub-Section 3.9.1.

The likelihood that multiple EEMC tracks traversing the same tower is negligible in proton-proton collisions at $\sqrt{s} = 200$ GeV. The energy deposit in the tower from an EEMC track was taken to be the energy of the track observed in the EEMC. Energy sharing with neighbor towers was neglected. Energy deposits in a whole tower, two pre-showers, and the post-shower from the “hadron” tracks in the selected hadron sample shown in Fig. 3.5 and that from the extracted photonic electrons are plotted with the blue and red curves, respectively, in different panels of Fig. 3.6. From Fig. 3.6, we see that electrons tend to deposit more energy in tower and in pre-showers, and less in post-shower than hadrons, as expected. Fig. 3.7 displays $\log(E_{SMD})$, the logarithm of the summed energy in the two orthogonal SMD sub-layers vs. $N_{\text{strips}}$, the total number of fired SMD strips in its two sub-layers, for “electrons” and “hadrons” with the red and blue symbols, respectively. It is clear from this figure that electrons tend to fire more strips and to deposit more energy in the SMD than hadrons. Cuts applied to select electrons are indicated with vertical lines in Fig. 3.6 and with the box at the top right in Fig. 3.7.
Figure 3.6: “electron” (red) and “hadron” (blue) energy deposits in the EEMC: (a) tower, (b) first pre-shower, (c) second pre-shower, and (d) post-shower.

Figure 3.7: The logarithm of the energy deposits summed over two SMD sub-layers vs. $N_{\text{strips}}$, the total number of fired strips in two SMD sub-layers. The red and blue symbols represent “electrons” and “hadrons”, respectively.
3.6.2 The EEMC Acceptance

We applied cuts with the EEMC first to all EEMC tracks defined in Sub-Section 3.6.1 to identify electrons. Further identification with the energy loss $dE/dx$ of EEMC tracks in the TPC and with a comparison between track momentum measured in the TPC and track energy measured in the EEMC are discussed in the next sub-section.

The applied EEMC cuts, each of which uses one of the four special layers, are listed as follows:

1. The energy in the first pre-shower $\geq 2.1\text{ MeV}$.

2. The energy in the second pre-shower $\geq 4.2\text{ MeV}$.

3. The energy in the post-shower $\leq 0.2\text{ MeV}$.

4. The logarithm of the summed energy in the two sub-layers of SMD $\geq 1.6$, i.e. $\log(E_{SMD}) \geq 1.6$ (equivalently, $E_{SMD} \geq 39.8\text{ MeV}$) and the total number of fired SMD strips in its two sub-layers $\geq 30$, i.e $N_{\text{strips}} \geq 30$.

The acceptance of each cut was calculated as the ratio of the number of combinatorial background subtracted photonic electrons after the cut to the one before the cut (See Sub-Section 3.9.1 for details). The acceptances were $(73 \pm 1)\%$, $(91 \pm 2)\%$, $(82 \pm 1)\%$, and $(88 \pm 2)\%$ for the first to fourth cuts listed above. The overall acceptance of all EEMC cuts was $(52 \pm 2)\%$. Pre-shower, post-shower and SMD cuts were found to be not strongly correlated with one another, and hence the overall acceptance was only slightly higher than the product of the individual acceptances. The uncertainties in the acceptances include both statistical and systematic contributions. The systematic uncertainty is dominated by the uncertainties in selection of photonic electron
samples with the energy loss $dE/dx$ and invariant mass. The hadron acceptance was calculated to be about 2.0% from the assumed hadron distribution shown. It is only about $1/25^{th}$ of the electron acceptance of 52%.

The four cuts listed above were sequentially applied to EEMC tracks to reject hadrons. Energy loss $dE/dx$ distributions of EEMC tracks without any cut and after each of the four cuts are plotted in Fig. 3.8. From this figure, we see that hadron candidates at $dE/dx$ below 2.5 keV/cm are suppressed by a factor of $\sim50$ with the four EEMC cuts, as expected.

![Energy loss $dE/dx$ distributions of EEMC tracks without any EEMC cut and after each of the four cuts with the first pre-shower, second pre-shower, post-shower, and SMD.](image)

Figure 3.8: Energy loss $dE/dx$ distributions of EEMC tracks without any EEMC cut and after each of the four cuts with the first pre-shower, second pre-shower, post-shower, and SMD.
3.6.3 $dE/dx$ and $p/E$ cuts

Starting with this sub-section, we split *EEMC tracks* into several bins according to their transverse momentum for a more detailed study. Figure 3.9 shows the energy loss $dE/dx$ distribution of *EEMC tracks* passing all the *EEMC* cuts described in Sub-Section 3.6.2 for a typical transverse momentum bin $2.0 \leq p_t \leq 3.0 \text{ GeV/c}$.

![Energy loss $dE/dx$ distributions of EEMC tracks passing all EEMC cuts in transverse momentum bin between 2.0 and 3.0 GeV/c. The red shaded area represents selected electron candidates. The blue shaded area represents hadrons of high purity used to estimate hadron contamination in selected electron candidates.](image)

Tracks with $dE/dx$ between 3.0 and 5.0 keV/cm were selected as electron candidates, as shown by the red shaded area in Fig. 3.9. To determine the number of electrons in the selected area, as well as the hadron contamination, we applied a fit of two Gaussians, one for electrons and the other for hadrons, to the whole $dE/dx$ range in Fig. 3.9. However, even with a narrow transverse momentum bin, the fit
still did not give reliable results for particle populations due to poor resolution of the $dE/dx$ measurement at forward pseudo-rapidities [61]. Therefore, we applied a different approach to determine the number of electrons and hadrons in this study.

Figure 3.10 shows the $p/E$ ratio distribution of the selected electron candidates by a red curve, where $p$ is the track momentum measured with the TPC and $E$ is the energy deposit of the track in the EEMC. The $p/E$ ratio of electrons is expected to be around 1.0 (see footnote\textsuperscript{5}) because electrons tend to deposit all of their energy in the EEMC with a total radiation length of 21 [68]. The tail at high $p/E$ in Fig. 3.10 is believed to be from hadron contamination. To confirm this, $p/E$ ratios of hadrons of high purity with $dE/dx$ below 2.5 $keV/cm$ were calculated to compare with the $p/E$ ratios of the selected electron candidates. The blue curve in Fig. 3.10 is a scaled $p/E$ distribution of those hadrons. The scaling makes the number of hadrons and electrons at the $p/E$ ratio above 2.0 equal for a close comparison. From Fig. 3.10, we see that the blue curve of hadrons matches well with the red curve of electrons at $p/E$ ratios above 2.0. This matching implies that entries in the tail of high $p/E$ are almost all from hadron contamination and that the contamination of hadrons in the selected electron candidates in the whole range of the $p/E$ ratio can be represented by the scaled hadron curve.

### 3.6.4 Electron Purity

In order to reject more hadrons and to increase electron purity, a final cut of $p/E$ ratio between 0.8 and 1.5 was applied to the selected electron candidates, as shown by the two vertical lines in Fig. 3.10. The red curve within the cut represents electron

\textsuperscript{5}p is in GeV/c and E is in GeV. Therefore, the ratio is not dimensionless. Throughout this dissertation, the factor of $1/c$ is understood when quoting numerical values of the $p/E$ ratio.
Figure 3.10: $p/E$ distribution of selected EEMC tracks. The red curve is for electron candidates and the blue is for hadrons, after scaling. The final cut is shown with the two vertical dotted lines at $p/E=0.8$ and 1.5.

candidates after the final selection and the blue the hadron contamination as stated in Sub-Section 3.6.3.

Purity was calculated as the difference in the integrals over the red and the blue curves within $x = p/E$ ratio cuts between 0.8 and 1.5 divided by the integrals over the red curve in the same $p/E$ range as follows

$$\text{Purity} = \frac{\int_{x_1}^{x_2} f_e \, dx - \int_{x_1}^{x_2} f_h \, dx}{\int_{x_1}^{x_2} f_e \, dx}$$

(3.1)

where $f_e$ and $f_h$ represent the red and blue curves as a function of $x = p/E$, respectively, in Fig. 3.10, and $x_1=0.8$ and $x_2=1.5$.

The purities of final selected electrons with transverse momenta $p_t$ between 1.5 and 6.0 GeV/c were found to vary slightly between $\sim 92\%$ to $\sim 96\%$. Figure 3.11 shows
purity plotted as a function of $p_t$ between 1.5 and 6.0 GeV/c. Both statistical and systematic uncertainties are shown in Fig. 3.11. In general, the statistical uncertainty increases with the increase in transverse momentum because only few electrons make it to higher $p_t$ range. On the other-hand, the statistical uncertainties is larger both at lower and high transverse momentum. This is because of relatively larger impurity at lower $p_t$ and limited statistics at higher $p_t$.

![Figure 3.11: Electron purity as a function of transverse momentum, $p_t$. The uncertainties shown include both statistical (red) and systematic (black) contributions.](image)

The systematic uncertainties arise mainly due to the following three sources, viz., (i) selection of $EEMC$ cuts, (ii) selection of hadron sample, and (iii) scaling factor discussed previously. The uncertainties from systematic contributions from all the three cases were calculated separately by varying the cuts in the corresponding case, one with tighter and the other with looser cuts compared to the optimized cuts. The consistency of the determined particle populations with $EEMC$ cuts was checked
as an effort to study the validity and quality of the approach which determined them. Several sets of EEMC cuts, some of which were looser and some tighter than the optimized, were applied to the same collection of EEMC tracks. The number of electrons in the collection of EEMC tracks was calculated for each set. The calculated numbers with different sets of EEMC cuts differed less than 10% from each other for the high transverse momentum bin. However, the difference was \( \sim 20\% \) at the lowest transverse momentum bin. Also, we found that it was more consistent for cuts going tighter than looser. This finding implies that the less hadron contamination, the better the approach works. The uncertainty reflecting this difference dominates the systematic uncertainty of the purity which includes minor contributions from the uncertainties in the selection of the hadron sample and in scaling.

In conclusion of this section on electron identification we list all the the cuts used for the identification of electrons in this study as shown in Table 3.2. This set of cuts is called Electron ID cuts in this analysis, for convenience.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse momentum ( (p_t) ) of a track</td>
<td>([1.5, 6.0]) GeV/c</td>
</tr>
<tr>
<td>Pseudo-rapidity ( (\eta) ) of a track</td>
<td>([1.1, 1.5])</td>
</tr>
<tr>
<td>Total momentum ( (p) ) of a track</td>
<td>(\geq 1.5) GeV/c</td>
</tr>
<tr>
<td>Entry and exit points in the EEMC in the same tower</td>
<td>Yes</td>
</tr>
<tr>
<td>Entry and exit points in the EEMC from edge of the tower</td>
<td>(\geq 0.5) cm</td>
</tr>
<tr>
<td>Energy in the first pre-shower</td>
<td>(\geq 2.1) MeV</td>
</tr>
<tr>
<td>Energy in the second pre-shower</td>
<td>(\geq 4.2) MeV</td>
</tr>
<tr>
<td>Energy in the post-shower</td>
<td>(\leq 0.2) MeV</td>
</tr>
<tr>
<td>Logarithm of summed energy in ( U ) and ( V ) SMD layers</td>
<td>(\geq 1.6)</td>
</tr>
<tr>
<td>No. of fired SMD strips in ( U ) and ( V ) layers</td>
<td>(\geq 30)</td>
</tr>
<tr>
<td>Ratio of TPC momentum to EEMC tower energy, ( p/E )</td>
<td>([0.8, 1.5])</td>
</tr>
<tr>
<td>Energy loss in the TPC, ( dE/dx )</td>
<td>([3.0, 5.0]) keV/cm</td>
</tr>
</tbody>
</table>

Table 3.2: List of Electron ID cuts. These cuts help identify electrons.

3.7 Efficiency Corrections

After extracting electrons by subtracting hadron background we have to make a correction for various kinds of reconstruction efficiencies, viz. TPC efficiency, EEMC efficiency/acceptance, \( p/E \) efficiency, \( dE/dx \) efficiency and trigger efficiency. The sub-sections below will explain how each of these efficiencies was determined in this analysis.
3.7.1 TPC Efficiency

The electron reconstruction efficiency of the TPC was studied using MC electron simulation. The TPC efficiency, $\varepsilon_{tpc}$, is defined as the ratio of the number of electrons reconstructed by the TPC which are matched with MC electron tracks, $n_1$, over the number of incident MC electrons in the same events, $n_0$, i.e.

$$\varepsilon_{tpc} = \frac{n_1}{n_0}$$  \hspace{1cm} (3.2)

The matching or association procedure is described in detail in Sub-Section 3.4.2.

Fig. 3.12 shows the $p_t$ distributions of matched electron tracks (left) and generated incident $MC$ electron tracks (right). Hence, the TPC efficiency can be obtained by dividing the histogram on the left by the histogram on the right of Fig. 3.12. The reconstruction efficiency, as shown in Fig. 3.13, is found to be almost uniform throughout the transverse momentum of interest from 1.5 to 6.0 $GeV/c$. The uncertainty for each channel shown in the Fig. 3.13 was calculated as

$$\delta\varepsilon_{tpc} = \sqrt{\frac{n_1 \times (n_0 + n_1)}{n_0^3}}$$  \hspace{1cm} (3.3)
Figure 3.12: $p_t$ distributions of the matched (left) and generated (right) tracks, respectively.

Figure 3.13: Electron reconstruction efficiency in the TPC as a function of transverse momentum.
3.7.2 \( p/E \) Efficiency

\( p/E \) efficiency, \( \varepsilon_{p/E} \), is defined as the ratio of number of electrons that survive the \( p/E \) cuts between 0.8 and 1.5, to the number of electrons before the cuts. In other words, it is obtained by taking the difference in the integrals over the red and blue curves in \( p/E \) between 0.8 and 1.5 divided by the difference in the integrals over the red and blue curves through the entire \( p/E \) range, in Fig. 3.10.

\( p/E \) efficiency as a function of transverse momentum is shown in Fig. 3.14. In general, the efficiency increases slowly with the increase in transverse momentum.

![p/E efficiency](image)

Figure 3.14: \( p/E \) efficiency as a function of transverse momentum.
3.7.3 dE/dx Efficiency

As mentioned earlier, since dE/dx resolution is poor at forward pseudo-rapidities, we cannot use Fig. 3.9 for the dE/dx efficiency calculation. Therefore, a different approach was applied to determine the dE/dx efficiency in this study.

The basic idea is to obtain as pure an electron sample as possible. Considerably pure electrons were obtained by applying a cut on p/E between 0.8 and 1.5 in Fig. 3.10. Fig. 3.15(a) shows the dE/dx histogram with a Gaussian fit to the selected electrons. dE/dx efficiency, \( \varepsilon_{dE/dx} \), is simply the ratio of electrons that survive the dE/dx cuts between 3.0 and 5.0 keV/cm (denoted by two vertical lines in Fig. 3.15(a)) to the number of electrons before the cut. The dE/dx efficiency as a function of transverse momentum is shown in Fig. 3.17.

Similarly, considerably pure hadrons were obtained by applying a cut on p/E > 2.0 in Fig. 3.10. Fig. 3.15(b) shows the dE/dx histogram with a Gaussian fit to the selected hadrons. The values of mean and width corresponding to the electron and hadron dE/dx distributions were then used to fit two Gaussians, one for the electron distributions and the other for the hadron distributions, to the original dE/dx distribution shown in Fig. 3.9. The resultant dE/dx distribution shown in Fig. 3.16 exhibits a reasonable fit to the original dE/dx distribution, consistent with the assumption that this approach works.
(a) Gaussian fit to electron $dE/dx$ distribution. The two dashed vertical lines corresponding to $dE/dx = 3.0$ and $5.0$ keV/cm are the cuts used for the final selection of electrons.

(b) Gaussian fit to hadron $dE/dx$ distributions.

Figure 3.15: Gaussian fits to electron (a) and hadron (b) $dE/dx$ distributions.
Figure 3.16: Gaussian fits to electron and hadron $dE/dx$ distributions compared to the original $dE/dx$ distribution (the black histogram).

Figure 3.17: $dE/dx$ efficiency as a function of transverse momentum.
3.7.4 Trigger Efficiency

Some major EEMC triggers utilized in the p+p 200 GeV transverse run in year 2006 are summarized in Table 3.3 below. Different triggers have different prescale factors. The prescale factor for a given trigger may be different from run to run. Prescale factor is a parameter used to adjust the number of events accepted for different triggers so that the detector system may process and record events periodically after a certain interval of event counts. For instance, if a trigger has a prescale factor of 2,000, the detector system will process and record 1 event after every 2,000 events. Similarly, if a trigger has a prescale factor of 1, the detector system will process and record every single event produced.

The flow chart shown in Fig. 3.18 outlines the changes in the number of events after each stage of Data Acquisition (DAQ) and analysis. The meaning of all the symbols used in the flow chart are given in Table 3.4.

The total number of events involving non-photonic electrons (NPE), \( N_e \), is the same independent of whether it is obtained from the minimum biased trigger or any other trigger after due correction for their respective prescale factors and trigger efficiencies. Following the sequence of changes in the number of events from one stage to another as shown in the flow chart in Fig. 3.18, it can be shown that

\[
N_e = \frac{N_{det}^{mb} \times S_{mb}}{\varepsilon_{mb} \times \varepsilon_{det}^{mb}} = \frac{N_{det}^{trg} \times S_{trg}}{\varepsilon_{trg} \times \varepsilon_{det}^{trg}}
\]

Therefore, \( \varepsilon_{trg} = \frac{N_{det}^{trg} \times S_{trg}}{N_{det}^{mb} \times S_{mb}} \),

since \( \varepsilon_{mb} = 100\% \) and \( \varepsilon_{mb}^{det} = \varepsilon_{trg}^{det} \).

Fig. 3.19 shows the prescale factor corrected electron event distributions of some major triggers including the minimum bias trigger. As is evident from the figure,
minimum bias events are statistics limited and they are mostly low \( p_T \) electrons. That makes it almost impossible to calculate trigger efficiency at higher \( p_T \) region. Therefore, this analysis is limited to transverse momentum between 1.5 and 6.0 GeV; however, it is reassuring to note that \( p_T \) distributions, with different triggers, all agree within statistics, as expected since events with high \( p_T \) \( NPE \) would easily pass any of the trigger thresholds.

The uncertainty in trigger efficiency is dominated by statistical contributions.
There are not many NPEs produced at high $p_t$ from 3-6 GeV/c from minimum bias data. We combine $p_t$ bins to get enough NPEs for a rough estimation of trigger efficiencies at this height $p_t$ region as shown in Fig. 3.19. Besides the limited statistics, the binning procedure makes a substantial contribution to the systematic uncertainties, in particular, at high $p_t$. The relative uncertainty $d\varepsilon_{trg}/\varepsilon_{trg}$ is about 20% in low $p_t$ bins and 40% in high $p_t$ bins.
Symbol | Meaning
--- | ---
$N$ | Number of collision events
$N_e$ | Number of events involving $NPE$
$N_{trg}$ | Number of triggered events
$N_{ps}$ | Number of prescaled events
$N_{det}$ | Number of events that pass the detectors ($TPC+EEMC$)
$\varepsilon_{trg}$ | Efficiency of a trigger
$\varepsilon_{mb}$ | Efficiency of minbias ($mb$) trigger
$\varepsilon_{det}$ | Detector efficiency with a trigger
$\varepsilon_{det}^{mb}$ | Detector efficiency with the $mb$ trigger
$S_{trg}$ | Prescale factor of a trigger
$S_{mb}$ | Prescale factor of the $mb$ trigger
$bkg/BKG$ | Background particles; mostly hadrons

Table 3.4: Meaning of the symbols used in the flow chart in Fig. 3.18 and Eq. 3.4.

![Figure 3.19: Electron $p_t$ distributions of some selected triggers. See Table 3.3 for description of trigger ids labelled in the legend.](image-url)
Fig. 3.20 shows the trigger efficiencies of some triggers whose $p_t$ distributions are shown in Fig. 3.19.

![Trigger efficiency graph](image)

Figure 3.20: Trigger efficiency of some triggers as a function of transverse momentum.

3.7.5 Total Efficiency

At this point we have all the efficiencies estimated, so, we can calculate the total efficiency of electron reconstruction, $\varepsilon_{tot}$. The total efficiency is simply the product of all the efficiencies mentioned in the preceding sub-sections, i.e,

$$\varepsilon_{tot} = \varepsilon_{tpc} \times \varepsilon_{eemc} \times \varepsilon_{p/E} \times \varepsilon_{dE/dx} \times \varepsilon_{trg}$$  \hspace{1cm} (3.5)

The total efficiency for some triggers as a function of transverse momentum are...
shown in Fig. 3.21.

Figure 3.21: Total efficiency of some triggers as a function of transverse momentum.

3.8 Inclusive Spectrum

Having gathered all the required information we can now calculate the number of inclusive electrons for \( p + p \) collisions at 200 GeV/c. Fig. 3.22 shows the hadron subtracted and efficiency corrected inclusive electron spectra from our analysis together with the one from BEMC[85] measurement. It is seen that our result is more than one order higher than that of the BEMC. This indicates that there are many more photonic electrons in our inclusive spectrum than in the BEMC. This makes it very difficult to estimate non-photonic electron production in EEMC.
3.9 Reconstruction of Photonic Electrons (PE)

The inclusive electrons, in the STAR environment, consist of various types of electrons originating from different sources. The major sources are discussed here.

1. Photon conversions in the detector material between the interaction point and the TPC. There are several sources for the creation of conversion photons, viz., direct photons, photons from $\pi^0$, $\eta$ decays, etc. Photon conversion is represented
by

$$\gamma \longrightarrow e^+ + e^-$$  

(3.6)

2. Scalar meson Dalitz decays from $\pi^0$, $\eta$, etc.

$$\pi^0 \longrightarrow e^+ + e^- + \gamma \ (1.198 \pm 0.032)\% \quad (3.7)$$

$$\eta \longrightarrow e^+ + e^- + \gamma \ (0.60 \pm 0.08)\% \quad (3.8)$$

3. $\rho, \omega, \phi$ vector meson di-electron decays and/or Dalitz decays.

4. $K^\pm \rightarrow Ke3$ decays

5. Heavy flavor (charm and bottom) meson semi-leptonic decays

6. Other sources such as Drell-Yan, heavy quarkonium decays, thermal electrons, etc.

In this analysis, we consider semi-leptonic decay of heavy flavor mesons as the only significant source of electron signal which is commonly referred to as non-photonic electrons (NPEs) in the STAR Collaboration. It is believed that other possible sources such as Drell-Yan, heavy quarkonium decay, thermal electrons, etc. have negligible contributions as shown in theoretical predictions[78, 79].

The first four sources are considered to contribute towards photonic background. It was reported [80] that electrons from photon conversions and $\pi^0$ Dalitz decays dominate the total yield. Contributions from all other sources of photonic background combined is only a few percent of the total background and hence can be ignored when compared to systematic uncertainties. Subsequently, what follows below is the
reconstruction of the dominant sources of photonic electron background using the invariant mass technique.

3.9.1 The Invariant Mass Technique

A detailed study on kinematics of photon conversion and $\pi^o$ Dalitz decay processes investigated using PYTHIA for the $p+p$ system with full detector description showed that most of the electron-positron pairs from these conversion photons or $\pi^o$ Dalitz decays have a small invariant mass and/or small opening angles in $\phi$ and $\theta$, while there is no such correlation for non-photonic electrons [81]. Thus the photonic background can be identified by pairing electrons or positrons with their corresponding partners and calculating their invariant mass and opening angles.

The procedure to reconstruct the photonic electrons may be stated as follows:

1. Identify an electron candidate from the primary track pool reconstructed in the $EEMC$ by applying the $QA$ cuts and the $Electron ID$ cuts described in the previous sections.

2. Loop over the global track pool to form pairs with either the opposite-sign or same-sign charge to the electron candidate, in the same event. The only requirement for the partner candidate is a very loose cut on $dE/dx$ around an electron band and within the $TPC$ acceptance in order to maximize the efficiency of finding partners.

3. Calculate and apply the distance of closest approach ($dca$) of the primary track and its partner global track.

4. Apply some geometric cuts, viz., opening angle in $\phi$ and $\theta$, on these two tracks.
5. Trace the momenta of these two tracks back to the point where the \( dca \) of the pair is measured, and calculate the invariant mass of the pair using the momenta found.

6. Select one pair for each primary track with the smallest invariant mass.

Table 3.5 lists the parameters and their corresponding cut values used in the above procedure to identify photonic electrons.

Note that this invariant mass technique was also used to select photonic electrons for acceptance and purity study described in Sub-Sections 3.6.2 and 3.6.4

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track to Track ( DCA )</td>
<td>( \leq 1.0 ) cm</td>
</tr>
<tr>
<td>Opening angle in ( \phi )</td>
<td>( \leq 0.10 ) radian</td>
</tr>
<tr>
<td>Opening angle in ( \theta )</td>
<td>( \leq 0.02 ) radian</td>
</tr>
<tr>
<td>Invariant mass</td>
<td>( \leq 0.14) GeV/( c^2 )</td>
</tr>
</tbody>
</table>

Table 3.5: Cuts used to reconstruct photonic background by invariant mass technique

Figs. 3.23 and 3.24 show the invariant mass distributions of all \( e^+e^- \) pairs before and after applying cuts, respectively. The \( dca \) and the geometric cuts reject the fake pairs as is evident from Fig. 3.24. The red curve represents the opposite-sign electron pairs which exhibit a sharp peak near zero. The secondary broad peak on the right side is caused by the limited \( TPC \) tracking resolution [82]. Considerably pure photonic electrons are obtained by applying a cut on invariant mass \( \leq 0.14 \) GeV/\( c^2 \) (shown by a vertical line) in addition to the \( dca \) and geometric cuts. However, some non-photonic electrons may be randomly identified as photonic electrons.
This combinatorial background can be estimated by calculating the invariant mass of same-sign electron pairs as shown in Fig. 3.24 by the blue curve. The combinatorial background is found to be small in proton-proton collisions. The shaded area represents the reconstructed photonic electrons. The number of reconstructed PEs, $N_{rc}$, is obtained by subtracting the number of combinatorial background electrons, $N_{ss}$, from the number of opposite-sign electron-positron pairs, $N_{OS}$, i.e.,

$$N_{rc} = N_{OS} - N_{ss}$$  \hspace{1cm} (3.9)

Number of photonic electrons, $N_{pe}$, can be calculated using the following relation

Figure 3.23: Invariant mass distributions of electron-positron pairs before applying any cuts. The red curve represents opposite-sign pairs and the blue curve the same-sign pairs. The shaded area represents the reconstructed photonic electrons.
Figure 3.24: Invariant mass distributions of electron-positron pairs after applying all the cuts described in the procedure above. The red curve represents opposite-sign pairs and the blue curve the same-sign pairs. The shaded area represents the reconstructed photonic electrons.

\[ N_{pe} = \frac{N_{rc}}{\varepsilon} \]  

(3.10)

where \( \varepsilon \) is the reconstruction efficiency of photonic electrons.

If \( N_{inc} \) is the number of inclusive electrons, the number of non-photonic electrons, \( N_{npe} \), can be calculated as
\[ N_{npe} = N_{inc} - N_{pe} = N_{inc} - \frac{N_{os} - N_{ss}}{\varepsilon} \] (3.11)

The reconstruction efficiency of photonic electrons, \( \varepsilon \), is determined using Monte Carlo simulations. It plays a crucial role in the determination of non-photonic electrons, especially when the inclusive electrons are dominated by the photonic electron background, as is the case in our study. Therefore, the determination of this efficiency deserves a separate chapter. See Chapter 4 for further details and discussion.

### 3.10 Estimation of Non-Photonic Electrons (NPE)

#### 3.10.1 PE Reconstruction Efficiency (\( \varepsilon \))

With the inclusive electrons extracted and the reconstructed photonic electrons determined, we can now estimate how much PE contamination is in the inclusive spectrum. An accurate measurement of PE, which is crucial to the calculation of NPE production, depends upon the estimation of its reconstruction efficiency. The well-known embedding technique is widely used in estimation of efficiencies in high energy and heavy-ion physics. However, we have trouble applying the embedding technique for the EEMC because of the issue of two vertices. Unlike the case of BEMC embedding where the vertex of a MC event and the vertex of a real selected event are both around \( Z = 0 \), the two vertices in EEMC embedding can be more than 100 cm apart. How to match them is still an unresolved issue in the STAR simulations. Thus, our estimations rely on simple simulations. Details of the simulations are described in Chap. 4. Here, a brief description is presented.

We estimated the efficiency with two different types of MC samples. The first type
of sample was comprised of a set of events of multiple $\gamma$s or $\pi^\circ$s whose reconstruction efficiencies were estimated separately as described in Sub-Section 4.2.1. We calculated the average of these reconstruction efficiencies using Eq. 4.2. Another sample was from a *PYTHIA* simulation of $p+p$ collisions at 200 GeV as described in Sub-Section 4.2.2. There was only a small difference between these two efficiencies with the simple *MC* and the Pythia samples, as expected. We used the average of these two efficiencies as our final *PE* reconstruction efficiency. Using this final *PE* reconstruction efficiency, we calculated the number of $N_{\text{pe}}$ in real $p+p$ data from the year 2006 run according to Eq. 3.10. Also, we calculated the inclusive to background ratio, $R = N_{\text{inc}}/N_{\text{bkg}}$. Fig. 3.25 shows this ratio together with the ratio from the *BEMC* measurement as a comparison. There is more material for tracks to traverse to reach the *EEMC* than to the *BEMC*. It is shown in Apppendix B that there are 4-5 more radiation lengths of material for tracks to reach the *EEMC* than to reach the *BEMC*. Therefore, we would expect to see at least ten times more *PE* in the *EEMC* than in the *BEMC*. The ratio $R_E$ for *EEMC* should be less than 1.05 since the ratio $R_B$ for *BEMC* is around 1.5. (Note that the weak dependence of $N\text{PE}$s on $\eta$ from 0 to 1.5 allows this rough comparison). However, we see that the ratio $R_E$ is between 1.1 to 1.3 in Fig. 3.25. This tells us that our *PEs* are underestimated and that the efficiency is overestimated and that *PE* still dominates the electron sample which we claim to be $N\text{PE}$ after the correction for *PE* reconstruction efficiency. At this moment, we can neither find an effective way to eliminate *PE* which contaminates the extracted $N\text{PE}$ sample nor find an accurate way to estimate how much the contamination is. With the dominated *PE*, we can not claim we have a measurement of $N\text{PE}$ production, as well as the deduced charm cross section. The best we can do is to obtain an upper
limit of the cross section. In the following sections, for the quoted measured $NPE$ and cross sections of ours, we really mean the upper limit.

![Inclusive to background ratio graph](image)

Figure 3.25: Inclusive to background ratio in blue curve from this study, and in black curve from a published paper [85].

### 3.10.2 Dependence of $N_{npe}$ on $\varepsilon$

From Eq. 3.11 we can obtain the following relations

$$
\frac{dN_{npe}}{dN_{inc}} = 1 \quad (3.12)
$$

$$
\frac{dN_{npe}}{dN_{rc}} = -\frac{1}{\varepsilon} \quad (3.13)
$$

$$
\frac{dN_{npe}}{d\varepsilon} = \frac{N_{rc}}{\varepsilon^2} \quad (3.14)
$$
From these three relations, we see that $N_{npe}$ is more sensitive to $\varepsilon$ than to $N_{inc}$ or $N_{rc}$, especially when $N_{inc}$ and $N_{rc}$ are both $\gg N_{npe}$ and $\varepsilon$ is not close to 100%, as in our study. A slight over-estimation would make the measurement of non-photonic electron production unreasonably high; while a slight under-estimation may have an unrealistic negative non-photonic electron production.

With the current MC simulations for the efficiency, we are not able to make a sound measurement of non-photonic electron production. However, we can still make a prediction of the correct efficiency that would give a realistic estimation of non-photonic electron production. Our calculation shows that the correct efficiency lies somewhere between 51% and 53%. Note that for efficiency below 51% the non-photonic electron production becomes negative and hence unphysical.

3.10.3 NPE Spectra

Once the photonic electrons were estimated, the raw number of NPEs was calculated using Eq. 3.11. This number was corrected for total electron reconstruction efficiency obtained from Eq. 3.5 to obtain the real NPEs. The NPE yields were calculated for the three triggers, namely with trigger ids 127271, 127641 and 127652 using the average PE reconstruction efficiency. The weighted average of the NPE yield was calculated from these three measurements. Fig. 3.26 shows the resultant NPE spectrum (red curve) for $p+p$ collisions at 200 GeV. As a matter of fact, it is only an upper limit as explained in the previous sub-section. This figure also shows a series of data points corresponding to NPE yield calculations based on several assumed reconstruction efficiencies. The objective here is to find the sensitivity to the reconstruction efficiency for extracting the production of NPEs. The blue solid circle points correspond to an $\varepsilon \sim 54.0\%$ which is approximately 10% lower than the efficiency used
to obtain the red curve. At $\varepsilon=53.3\%$ we still have all the five data points denoted by the pink stars. The moment we decrease the efficiency to 53.1% we obtain only the first four data points denoted by the green squares and the data point in the last $p_t$ bin becomes negative. Note that these four data points are uniformly distributed above and below the $BEMC$ curve corresponding to the $NPE$ measurement at the mid-rapidity region from a published paper [85] –our reference curve for this study. At $\varepsilon=51.0\%$ we obtain only two non-zero data points denoted by the grey triangles, and finally at $\varepsilon=50.94\%$ we have just one data point denoted by a blue open star. All these observations lead us to conclude that the correct reconstruction efficiency must lie somewhere between 51% and 53%, assuming the $BEMC$ result is correct and that we need an estimation of $PE$ reconstruction efficiency within uncertainties less than 2% to make a reliable measurement of $NPE$s.

The $NPE$ spectra at forward rapidities are predicted to be a little lower than that at mid-rapidities [81]. But our $NPE$ spectrum is about an order of magnitude larger than that of the $BEMC$ result as shown in Fig. 3.26. The difference, unfortunately, diverges further at higher transverse momentum. This result indicates that we have a serious over-estimation of the efficiency and that our non-photonic electron production is still dominated by photonic electrons. Statistical uncertainties shown in the red curve increase with the increase in $p_t$ due to the reduced number of electrons in high $p_t$. The uncertainties are mainly due to the large uncertainty in $PE$ reconstruction efficiency, which, in turn, contributes to a large uncertainty in the determination of photonic electrons, the result of which directly affects the obtained yield for $NPE$ production.
Figure 3.26: Non-photonic electron yield as a function of transverse momentum. The red curve shows the weighted average denoting the upper limit of NPE yield from this work. The black curve shows the BEMC result of the NPE measurement from a published paper [85]. This figure also shows a series of data points corresponding to NPE yield calculations based on several assumed reconstruction efficiencies. See the text for other details.
3.11 Estimation of the Charm Production Cross Section

The total charm production cross-section per nucleon-nucleon interaction at RHIC energy can be calculated from Eq. 3.15 [86].

$$\sigma_{c\bar{c}}^{NN} = \frac{d\sigma_{c\bar{c}}^{NN}}{dy} \bigg|_{y=y_0} \times f = \frac{dN_{D^0}}{dy} \bigg|_{y=y_0} \times R \times \frac{\sigma_{pp}^{inel}}{\langle N_{bin} \rangle} \times f$$  \hspace{1cm} (3.15)

In this equation, f is a factor used to convert the $d\sigma_{c\bar{c}}^{NN}/dy$ at rapidity $y = y_0$ to the total cross-section, R is a factor used to convert the $D^0$ yield to a total $c\bar{c}$ yield, $\sigma_{pp}^{inel}$ is the $p + p$ inelastic scattering cross-section, and $\langle N_{bin} \rangle$ is the scale factor for conversion from $A + A$ to $p + p$ collisions.

In the case of $p + p$ collisions with $\langle N_{bin} \rangle = 1$, Eq. 3.15 becomes

$$\sigma_{c\bar{c}}^{NN} = \frac{d\sigma_{c\bar{c}}^{NN}}{dy} \bigg|_{y=y_0} \times f = \frac{dN_{D^0}}{dy} \bigg|_{y=y_0} \times R \times \frac{\sigma_{pp}^{inel}}{\langle N_{bin} \rangle} \times f$$  \hspace{1cm} (3.16)

For our measurement at $\langle y \rangle = 1.3$, we have

$$\sigma_{c\bar{c}}^{NN} = \frac{d\sigma_{c\bar{c}}^{NN}}{dy} \bigg|_{y=1.3} \times f = \frac{dN_{D^0}}{dy} \bigg|_{y=1.3} \times R \times \frac{\sigma_{pp}^{inel}}{\langle N_{bin} \rangle} \times f$$  \hspace{1cm} (3.17)

$STAR$ has measured $\frac{dN_{D^0}}{dy} \bigg|_{y=0}$ with the reconstructed $D^0$ $p_t$ distribution from $d + Au$ collisions and the non-photonic electron $p_t$ distributions from $d + Au$ collisions shown in Fig. 3.27 [86]. We call this measurement $M_0$ in the following text.
Figure 3.27: Reconstructed $D^0$ (solid squares) $p_t$ distributions from $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Non-photonic electron $p_t$ distributions from $p + p$ collision (triangles) and $d + Au$ collisions (circle). Solid and dashed lines are the fit results from both $D^0$ and electron spectra in $d + Au$ collisions. The dotted line is scaled down by a factor of $N_{bin}=7.5\pm0.4$ from $d + Au$ to $p + p$ collisions. The dot-dashed line depicts a PYTHIA calculation [86].

We have only a measurement of non-photonic electron $p_t$ distributions at $y = 1.3$ from $p + p$ collisions and we are not able to perform the same analysis as that for $M_0$. 
We do not extract $dN_{D^0}/dy$ directly with fitting as for $M_0$. Instead, we try to estimate it by comparing the distributions with the non-photonic electron $p_t$ distributions at $y = 0$ from $p + p$ collisions in $M_0$. To make the comparison easy and possible in the estimation, we make the following three assumptions.

1. Our measurement of non-photonic electron $p_t$ distributions at $y = 1.3$ are several times higher than that at $y = 0$ in $M_0$. $R_{dN}$ represents the average ratio of ours to that in $M_0$. We do not have the distributions at very low $p_t$ and assume that these distributions at very low $p_t$ are also higher than that at $y = 0$ in $M_0$ with a ratio equal to $R_{dN}$.

2. For $M_0$ analysis, the results for $dN_{D^0}/dy$ with $d + Au$ collisions are obtained which are listed in Table 3.6. One result is extracted with a fit to the reconstructed $D^0$ $p_t$ distribution. The other result is obtained with a combined fit which fits simultaneously the reconstructed $D^0$ $p_t$ and the non-photonic electron $p_t$ distributions shown in Fig. 3.27. The two results agree with each other within uncertainties. Based on this agreement, we assume that a fit to the non-photonic electron distributions from $d + Au$ collisions would give a result of $dN_{D^0}/dy$ in agreement with that shown in Table 3.6.

3. We assume that we can use NPE distributions from $p + p$ collisions in determining $dN_{D^0}/dy$ since NPE distributions from $p + p$ collisions agree with that from the $d + Au$ collisions scaled down by a factor of $\langle N_{\text{bin}} \rangle = 7.5 \pm 0.4$ as shown in Fig. 3.27. The NPE distributions shown in Fig. 3.27 are measured with the $TPC+TOF$, and they agree well with the NPE results measured using $TPC+BEMC$ which was used to compare our result as shown in Fig. 3.26.
With these three assumptions, we have

\[
\begin{align*}
\left. \frac{dN_{D^0}}{dy} \right|_{y=1.3} &= R_{dN} \times \left. \frac{dN_{D^0}}{dy} \right|_{M_0} \\
\left. \frac{d\sigma_{c\bar{c}}^{NN}}{dy} \right|_{y=1.3} &= R_{dN} \times \left. \frac{d\sigma_{c\bar{c}}^{NN}}{dy} \right|_{M_0} \\
\text{and } &\quad \sigma_{c\bar{c}}^{NN} = R_{dN} \times \left. \sigma_{c\bar{c}}^{NN} \right|_{M_0} \times R_f
\end{align*}
\]  

(3.18)  

(3.19)  

(3.20)

where the subscript $M_0$ indicates the measurement results at $y = 0$ for $M_0$ and $R_f = f_{y=1.3}/f_{y=0} = 1.2$. The value of $R_f$ is estimated with an averaging over various theoretical predictions [81].

| $dN(D^0)/dy |_{y=0} \times 10^{-2}$ | $d\sigma_{c\bar{c}}^{NN}/dy |_{y=0} (mb)$ |
|-----------------|-----------------|
| $D^0$           | $2.8 \pm 0.4 \pm 0.8$ | $0.29 \pm 0.04 \pm 0.08$ |
| $D^0 + e^\pm$   | $2.9 \pm 0.4 \pm 0.8$ | $0.30 \pm 0.04 \pm 0.09$ |

Table 3.6: $dN/dy$ of $D^0$ in $d + Au$ collisions and the corresponding $d\sigma/dy$ of $c\bar{c}$ pair per nucleon-nucleon collision at $\sqrt{s_{NN}} = 200 \ GeV$ [86].

Fig. 3.28 shows the $d\sigma/dy$ of charm quarks from the $STAR$ and $PHENIX$ measurements compared with different theoretical predictions [81]. The solid star represents the $STAR$ result at mid-rapidity. The solid circle represents the $PHENIX$ results at mid-rapidity and forward rapidity. There is a factor of $\sim 2$ between the $STAR$ and $PHENIX$ results at mid-rapidity. The open star represents the $d\sigma/dy$ result from this analysis measured with the $EEMC$ detector at forward rapidity. This result is a little more than an order of magnitude larger than the $STAR$ result at mid-rapidity.
Figure 3.28: $d\sigma/dy$ of charm quarks from the STAR and PHENIX measurements compared with different theoretical predictions [81]. The two curves in red and blue represent the lower and upper bounds corresponding to the theoretical predictions based on color dipole and PYTHIA calculations, respectively.

Fig. 3.29 shows the total charm cross-section per nucleon-nucleon collision converted from \( \left( \frac{d\sigma_{NN}}{dy} \right) \big|_{y=1.3} \) versus the collision energy \( \sqrt{s_{NN}} \). The conversion factor \( f_{y=1.3} \sim 5.6 \) is calculated with \( f_{y=1.3} = R_f \times f_{y=0} \), where \( f_{y=0} = 4.7 \pm 0.7 \) is estimated from simulation[86]. The solid black star shows the STAR result measured from decays of \( d + Au \rightarrow D^0 + X \) and \( d + Au \rightarrow e + X \) at \( \sqrt{s_{NN}} = 200 \) GeV at mid-rapidity. The solid blue star shows the corresponding result from this analysis for
\[ p + p \rightarrow (e^- + e^+)/2 \] at \( \sqrt{s} = 200 \) GeV measured by the EEMC at forward rapidity.

![Graph showing total \( \bar{c}c \) cross section per nucleon-nucleon collision versus the collision energy (\( \sqrt{s_{NN}} \)). Results from several experiments are shown in the figure. The upper limit from this work is shown in blue star. The dashed line depicts a PYTHIA calculation. The solid and dot-dashed lines depict two NLO PQCD calculations with the Martin-Roberts-Sterling-Thorne highest order set, \( m_c = 1.2 \) GeV/\( c^2 \), \( \mu_F = 2m_c \), \( \mu_R = m_c \), and \( 2m_c \), respectively [86].

Figure 3.29: Total \( \bar{c}c \) cross section per nucleon-nucleon collision versus the collision energy (\( \sqrt{s_{NN}} \)). Results from several experiments are shown in the figure. The upper limit from this work is shown in blue star. The dashed line depicts a PYTHIA calculation. The solid and dot-dashed lines depict two NLO PQCD calculations with the Martin-Roberts-Sterling-Thorne highest order set, \( m_c = 1.2 \) GeV/\( c^2 \), \( \mu_F = 2m_c \), \( \mu_R = m_c \), and \( 2m_c \), respectively [86].
Photonic electron reconstruction efficiency is a key parameter for the determination of photonic electron yield in real data. Simulation studies were done using a simple MC simulation of events of multiple $\gamma$s and $\pi^0$s as well as using PYTHIA to determine the photonic electron reconstruction efficiency. In this chapter, we will describe the procedure for the determination of photonic electron reconstruction efficiency, and the implications of the results thus obtained.

4.1 Photon Conversion Electrons

There are many sources of photonic electrons of which two major sources are photon conversions and $\pi^0$ Dalitz decays. They contribute $\sim95\%$ of the photonic background while the rest come from direct photons, $\rho$, $\omega$, and $\phi$ meson di-electron decays (See Section 3.9 for details). Most of the photonic electron background comes from conversions due to the materials in the STAR detector. Fig. 4.1 shows the radius, $R_v = \sqrt{X_v^2 + Y_v^2}$, of a vertex where a conversion happens, versus the $Z$ vertex in the beam direction. This plot was generated from the simulation data with the PYTHIA generator and GEANT $^1$ [87] incorporated into STAR detector configurations in 200 GeV $p + p$ collisions. It is obvious from this figure that most of the conversions take place in the SVT detector and its supporting cone, and the TPC wheel, covering the

---

$^1$GEANT is the acronym for GEometry ANd Tracking. GEANT is a program that describes the passage of elementary particles through the matter. The principal applications of GEANT in High Energy Physics are: (1) the tracking of particles through an experimental setup for simulation of detector response, and (2) the graphical representation of the setup and of the particle trajectories.
forward rapidity region where, incidentally, the EEMC is located. It is worthwhile to recall that the EEMC is located on the west poletip, i.e. in the $+Z$ direction, $\sim 270$ cm away from the center of the STAR detector at RHIC as shown in Fig. 2.9.

Figure 4.1: The 2-D scattering plot for conversion radius $R_v$ vs $Z$. The pattern reflects the material structure of the STAR detectors and their supporting materials. The EEMC (not shown here) is located on the west poletip, i.e. in the $+Z$ direction, $\sim 270$ cm away from the center of the STAR detector at RHIC. It is an annulus with projective geometry with an inner radius $\sim 75$ cm, outer radius $\sim 215$ cm, and a longitudinal depth $\sim 34$ cm. It provides full azimuthal coverage over the pseudo-rapidity range $1 < \eta < 2$. 
4.2 Photonic Electron Reconstruction Efficiency ($\varepsilon$)

4.2.1 Monte Carlo Simulation Studies With Multiple $\gamma$s and $\pi^0$s

In order to estimate the photonic electron reconstruction efficiency for photon ($\gamma$) conversion electrons, $MC$ multiple $\gamma$s were generated in flat $p_t$ and $\eta$ distributions. These photon events were input to the $STAR$ $GEANT$ program to simulate the interaction of these particles with the real detector materials resulting in the generation of conversion electrons. These conversion electrons were analyzed using the same method and the same cuts that were applied in the real data analysis. The electron identification routine described in Sub-Section 3.6 accepts a fraction of the total photon conversion electrons. Similarly, the low invariant mass technique described in Sub-Section 3.9.1 reconstructs a fraction of the accepted photon conversion electrons. The ratio of the latter divided by the former gives an estimate of the efficiency of reconstruction of photonic electron background as function of $p_t$.

Photonic electron reconstruction efficiency for $\pi^0$ Dalitz decay electrons was also estimated following the same procedure described above for photon conversion electrons.

Figs. 4.2 and 4.3 show the distributions of invariant mass of electron-positron pairs for multiple $\gamma$s and $\pi^0$ Dalitz decays, respectively. Black histograms denote the opposite sign electron-positron pairs, blue histograms denote the same sign electron-electron or positron-positron pairs (random combinatorial background), and the shaded red histograms denote the photonic electron pairs which is equal to the difference in opposite and same sign electron/positron pairs. Even though almost of all of the photonic electrons from photon conversions lie below $\sim 40$ $MeV/c^2$, a cut on invariant mass $<140$ $MeV/c^2$ was applied to identify reconstructed photonic electrons to
account for some photonic electron contributions from $\pi^0$ decays as well.

Figure 4.2: Distributions of invariant mass of electron-positrons pairs from $\gamma$ conversions, as a function of transverse momentum.

Figure 4.3: Distributions of invariant mass of electron-positrons pairs from $\pi^0$ Dalitz decays, as a function of transverse momentum.
Figs. 4.4 and 4.5 show the photonic electron reconstruction efficiencies from multiple $\gamma$s, and $\pi^0$s, respectively.

Figure 4.4: Photonic electron reconstruction efficiency from $\gamma$ conversions, as a function of transverse momentum.

Figure 4.5: Photonic electron reconstruction efficiency from $\pi^0$ Dalitz decays, as a function of transverse momentum.
4.2.2 PYTHIA Simulation

Reconstruction efficiency was also calculated using a Pythia simulation. The data-sets consist of Pythia samples used by the STAR Jet Group for their di-jet studies. These data-sets were generated using CDF tune A with a wide range of partonic $p_t$ and pseudo-rapidity for $p+p$ collisions at $\sqrt{s} = 200$ GeV. NPE production is turned off in Pythia and all electrons except a very few are photonic electrons.

The Pythia simulation is a more realistic simulation of the real data compared to a simple MC simulation of $\gamma$s or $\pi^0$s. Fig. 4.6 shows the reconstruction efficiency as a function of transverse momentum from the Pythia simulation. The statistical error is large at high $p_t$ due to the limited number of high $p_t$ electrons.

Figure 4.6: Photonic electron reconstruction efficiency from Pythia simulation as a function of transverse momentum. The statistical error is large at high $p_t$ due to the limited number of high $p_t$ electrons.
The Pythia simulation was used also to estimate the production of $\gamma$ conversion and $\pi^0$ Dalitz decay electrons by checking their corresponding parents in the GEANT record as shown in Fig. 4.7 (left panel). The blue curve shows the distribution of photonic electrons from $\gamma$ conversions and the pink curve from $\pi^0$ Dalitz decays. The plot in the right panel shows the ratio of these photonic electrons from $\gamma$s to that from $\pi^0$ Dalitz decays. A straight line fit on this ratio plot in $p_t$ between 1.5 and 6.0 GeV/c yields the value of

$$R = \frac{N_1(p_t)}{N_2(p_t)} \sim 11$$

and this $R$ provides the ratio of photonic electrons from $\gamma$ conversions and $\pi^0$ Dalitz decays while $N_1(p_t)$ and $N_2(p_t)$ denote the number of photonic electrons as a function of $p_t$ in the $\gamma$ and $\pi^0$ samples in Pythia, respectively.

Figure 4.7: Left panel: Distributions of photonic electrons from $\gamma$ conversions (blue) and $\pi^0$ Dalitz decays (pink). Right panel: Ratio of the photonic electrons from $\gamma$ conversions and $\pi^0$ Dalitz decays.
4.2.3 Combined Efficiency from $\gamma$ Conversions and $\pi^0$ Dalitz Decays

The reconstruction efficiencies from $\gamma$ conversions and $\pi^0$ Dalitz decays were found to be slightly different from each other. So, we calculated the combined efficiency by taking the weighted average of the two efficiencies as follows:

$$
\varepsilon = \frac{N_1(p_t)\varepsilon_1(p_t) + N_2(p_t)\varepsilon_2(p_t)}{N_1(p_t) + N_2(p_t)} = \frac{R}{R+1}\varepsilon_1(p_t) + \frac{1}{R+1}\varepsilon_2(p_t) \quad (4.2)
$$

where $\varepsilon_1(p_t)$ and $\varepsilon_2(p_t)$ denote the photonic electron reconstruction efficiencies from $\gamma$ conversions and $\pi^0$ Dalitz decays, respectively, as a function of transverse momentum, and $R$ as given by Eq. 4.1.

Fig. 4.8 shows the weighted average efficiency of photonic electron reconstruction from simple MC simulations of $\gamma$ conversions and $\pi^0$ Dalitz decays.

Figure 4.8: Weighted average efficiency of photonic electron reconstruction from simple MC simulations of $\gamma$ conversions and $\pi^0$ Dalitz decays.
4.3 Implications of the Results

The weighted average efficiency of photonic electron reconstruction estimated from the simple MC $\gamma$s and $\pi^0$s, and the reconstruction efficiency from Pythia simulations were used to calculate photonic background electrons in the real data (See Section 3.9 for details). These efficiencies play a very crucial role in the determination of photonic electrons as they directly affect the outcome of non-photonic electrons. We know from Eq. 3.14 that non-photonic electron determination is very sensitive to reconstruction efficiency, especially when $N_{inc}$ and $N_{re}$ are both $\gg N_{npe}$ and the reconstruction efficiency is not close to 100%, which is the case in our study. Even a slight under-estimation or over-estimation of $\varepsilon$ has a profound effect on the determination of non-phonic electrons. For instance, in our study, MC simulation of multiple $\gamma$s and $\pi^0$s generate much simpler events than does a $p + p$ collision. This makes reconstruction of conversion pairs much easier and may result in an over-estimation of the reconstruction efficiency. On the other hand, the Pythia simulation is much more like a real $p + p$ collision and subsequently the photonic reconstruction efficiency in Pythia is slightly lower than that of the simple MC simulations. The two estimated efficiencies are not too far away from each other. We used the average of the two efficiencies for the estimation of $PE$ in the inclusive electrons.
Chapter 5

RESULTS, DISCUSSION AND CONCLUSIONS

In this chapter we review and summarize the results of this work. In particular, we review the major contributions we made in both software and hardware development for the EEMC. We present our physics results followed by a brief discussion regarding the outcome of these results. Finally, we make concluding remarks on the entire work as a whole.

5.1 Results

5.1.1 Software and Hardware Development For The EEMC

Our group from Kent State University made major contributions in both software and hardware development for the EEMC. In particular, we designed and optimized configuration of mapping from EEMC SMD strips to LED boards. We designed and fabricated the monitoring LED monitoring system. We burned in several MAPMTs in our lab and measured the dark current flowing through all the sixteen pixels of each MAPMT. Characterization measurements were done for each of the sixteen pixels in an MAPMT. These individual pixel characterizations were used for calibration of the EEMC scintillators for experimental run at RHIC. These contributions were necessary for the development and continued use of the EEMC for physics measurements with the STAR detector.
5.1.2 Physics Analysis

We measured an upper limit of non-photonic electron production at pseudo-rapidities between 1.1 and 1.5 in $p+p$ collisions at $\sqrt{s}=200$ GeV using the EEMC as the main detector in conjunction with the TPC in the STAR detector system. Based on our inclusive electron yield we estimated the upper limit of the $d\sigma/dy$ of charm quarks. Finally, we obtained an upper limit for the total charm cross section per nucleon-nucleon collision at the collision energy $\sqrt{s} = 200 GeV$. The upper limit is an order of magnitude larger than the previously reported STAR measurements [85, 86].

This study was intended to measure the total charm cross section per nucleon-nucleon collision. However, in the process of extraction of NPE, we found that our signal to PE background ratio was considerably higher than expected due to the presence of much more material in front of the EEMC. This ratio indicates that our signal is not clean and is still dominated by NPE. A very high accuracy of PE reconstruction efficiency is required to measure NPE production. For now, we do not have an effective and accurate way to accurately determine this efficiency. Therefore, we can give only a measurement of the upper limit of the total charm cross section from this work.

5.2 Discussion

In this study, we used the EEMC as the main detector in addition to the TPC to identify electrons. The EEMC is, certainly, a very powerful detector to identify electrons from hadrons but, unfortunately, these electrons are swamped by photonic background electrons. It is worthwhile, again, to recall that the EEMC is located $\sim$270 cm away from the center of the STAR detector at RHIC. By virtue of being located at this position, TPC tracking resolution is bound to be poor in the EEMC
region \((1 < \eta < 2)\) \cite{61}. In order to maximize the statistics and to achieve a reasonable acceptance in the \(EEMC\), the collision vertex was required to lie within \(\pm 120\text{ cm}\) along the beam axis. This (necessary) very loose vertex cut requirement was responsible for the presence of much of the photonic background electrons in the inclusive electron spectrum. At the same time, the \(SVT\) detector and its supporting material, the inner cage field of the \(TPC\) and the \(TPC\) wheel, and the beam pipe all contributed also to the production of photonic background electrons. This is due to the fact that most of the particles traversing through these materials would undergo bremsstrahlung and/or photon conversion process resulting in the production of a lot of photonic background electrons. For the \(EEMC\), all electrons appear the same irrespective of their origin, whether they come from semi-leptonic decay of charmed hadrons or from photon conversions or \(\pi^0\) decays.

We used the invariant mass technique to reconstruct photonic background electrons taking advantage of the fact that electron-positron pairs from conversion photons or \(\pi^0\) Dalitz decays have a small invariant mass and small opening angles in \(\phi\) and \(\theta\), while there is no such correlation for non-photonic electrons \cite{81}. After we calculated the photonic electron reconstruction efficiency \((\varepsilon)\) using \(MC\) simulations, we estimated the number of photonic electrons in the inclusive electron spectrum in the real data. The difference between the number of inclusive electrons and photonic electrons is the number of the non-photonic electrons, the invariant yield of which is shown in Fig. 3.26 as a function of transverse momentum. The upper limit to the \(NPE\) yield was found to be an order of magnitude larger than the the previously reported \(STAR\) measurements. This is mainly because of the presence of the predominant photonic background electrons in the inclusive spectrum. In fact, our
calculation indicates that the inclusive to background ratio in the $EEMC$ $\leq 1.05$, implying that even in the perfect scenario, the photonic background to signal ratio is $\geq 95$! Our measurement of the inclusive to background ratio ranges between 1.1 and 1.3, that is, it under-predicts the photonic background electrons in the inclusive spectrum by a large amount, as much as 6 times. In this situation, the only way to get the correct $NPE$ yield is to precisely determine the exact $PE$ reconstruction efficiency, which was clearly not possible in this case, using our $MC$ simulations.

From Fig. 3.26 we see how sensitive the $NPE$ yield is to the $PE$ reconstruction efficiency. We need an estimation of the $PE$ reconstruction efficiency with an error less than $\sim 2\%$ to extract meaningful $NPE$ yield. In the kind of environment where our signal is so completely dominated by the photonic background electrons, simple simulations alone do not provide a reliable reconstruction efficiency. The embedding technique may be able to reach such an accuracy in efficiency estimation. To make a reliable measurement of $NPE$ in the $EEMC$, we should be able to extract inclusive electrons with $NPE$ to $PE$ ratio comparable to that of the $BEMC$. In that case, the uncertainty in the estimation of $PE$ will be much more tolerable. Then, we may be able to estimate the efficiency with the necessary accuracy.

Based on the three assumptions mentioned in Sub-Section 3.11 we estimated the upper limit of the $d\sigma/dy$ of charm quarks and the total charm cross section per nucleon-nucleon collision. The resultant upper limits were found to be a little more than an order of magnitude large compared to the previous results from the $STAR$ measurement [86]. Given the precision of our measurement of the $NPE$ yield in the $EEMC$ this is the best result we could obtain for the total charm production cross section.
5.3 Conclusions

We made a substantial contribution in the development and construction of the EEMC. The optimized configuration of mapping from EEMC SMD to LED boards was a success with no problems reported so far. The blue LED monitoring system, which is used to test fire the MAPMTs to check whether they are all working fine as expected, is functioning properly to this day. The characterization measurements that we did for the MAPMTs formed a basis for the calibration of the EEMC scintillators for experimental runs.

It was a challenging task to try to measure the non-photonic electrons in the EEMC in the STAR detector system at RHIC. The upper limit of the NPE yield and the total charm cross section were found to be larger, by at least an order of magnitude, than the previous results from both STAR and PHENIX measurements; consequently, it is hard to derive any meaningful physics from these results. It is also not possible to conclude that our result supports either the STAR or PHENIX measurements. Therefore, the discrepancy of a factor \( \sim 2 \) in the open charm production in relativistic heavy-ion reactions as measured by the STAR and PHENIX detector groups at RHIC remains unresolved\(^1\) The measurement of NPE production could be improved if better data sets were used for the analysis. Data taken in the absence of the SVT are expected to contain considerably fewer photonic background electrons and they should be better data sets for this kind of analysis. The SVT was, indeed, removed from the STAR detector system in 2007 run. Unfortunately, the EEMC was not tuned to take any physics runs that year. There was no \( p + p \) run the following year in 2008. The

\(^1\)A new measurement by the STAR collaboration is in better agreement with the PHENIX results so that this discrepancy may be resolved. A draft reporting the results of the new STAR measurement has been submitted to the STAR collaboration for review at this time.
2009 run is expected to have a lot of $p+p$ data sets, but they are not yet available for user analysis.

The other major improvement in the measurement of $NPE$ production could come from measuring the $PE$ reconstruction efficiency more precisely using the embedding technique. However, there still remains an unresolved issue in the $STAR$ simulations on how to match the vertex of $MC$ event and the vertex of the real selected event in the $EEMC$. As of now, it looks very unlikely that this issue of two vertices will be resolved anytime soon.

Although this work was unable to extract a meaningful measurement of charm production in $p+p$ collisions at $\sqrt{s}=200$ GeV, the data analysis technique developed here can clearly be used in the analysis of similar data with a smaller background of photonic electrons. Such smaller backgrounds should be available in more recent and future runs with the $STAR$ detector at $RHIC$. 
Appendix A

**RUN NUMBER LIST**

<table>
<thead>
<tr>
<th>Sl. #</th>
<th>Run #</th>
<th>Fill #</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>7097009, 7097010, 7097014, 7097017, 7097018, 7097019, 7097020, 7097024, 7097026, 7097027, 7097032, 7097050, 7097051, 7097053, 7097056</td>
<td>7718</td>
</tr>
<tr>
<td>2.</td>
<td>7097093, 7097095, 7097096, 7097097, 7097099, 7097102, 7097103, 7097104, 7097105, 7098001, 7098002, 7098004, 7098006, 7098007, 7098008</td>
<td>7722</td>
</tr>
<tr>
<td>3.</td>
<td>7098014, 7098015, 7098018, 7098024, 7098025, 7098027, 7098028, 7098029, 7098031, 7098032, 7098033, 7098036, 7098038, 7098039, 7098040, 7098041</td>
<td>7724</td>
</tr>
<tr>
<td>4.</td>
<td>7098053, 7098055, 7098061, 7098062, 7098064, 7098065, 7098066, 7098067, 7098072, 7098073, 7098075, 7098079, 7098080, 7098081, 7098082, 7098083, 7099003, 7099006</td>
<td>7725</td>
</tr>
<tr>
<td>5.</td>
<td>7099014, 7099015, 7099021, 7099022, 7099024, 7099025, 7098026, 7099027, 7099030, 7099033, 7099034, 7099035, 7099045, 7099046, 7099047</td>
<td>7729</td>
</tr>
<tr>
<td>6.</td>
<td>7100052, 7100058, 7100062, 7100064, 7100068, 7100070, 7100071, 7100072, 7100075, 7100077, 7100078</td>
<td>7740</td>
</tr>
<tr>
<td>7.</td>
<td>7101013, 7101015, 710019, 7101023, 7101041, 7101042, 7101046, 7101050, 7101052, 7101054</td>
<td>7744</td>
</tr>
<tr>
<td>8.</td>
<td>7101075, 7101078, 7101082, 7101086</td>
<td>7745</td>
</tr>
<tr>
<td>9.</td>
<td>7103007, 7103008, 7103013, 7103014, 7103016, 7103017, 7103018, 7103024, 7103026, 7103027, 7103040</td>
<td>7753</td>
</tr>
<tr>
<td>10.</td>
<td>7103072, 7103075, 7103082, 7103086, 7103088, 7103089, 7103090, 7103093, 7103095, 7103099</td>
<td>7756</td>
</tr>
<tr>
<td>11.</td>
<td>7116050, 7116057, 7117002, 7117011, 7117017</td>
<td>7785</td>
</tr>
<tr>
<td>12.</td>
<td>7117050, 7117057, 7117058, 7117060, 7117063, 7117064, 7118004, 7118010, 7118014</td>
<td>7788</td>
</tr>
</tbody>
</table>

Table A.1: List of run numbers and their corresponding fill numbers used in this analysis.
<table>
<thead>
<tr>
<th></th>
<th>7118024, 7118033, 7118035, 7118039, 7118041, 7118042, 7118044, 7118045, 7118048, 7118049, 7118050, 7118053, 7118073, 7118075, 7118077, 7118083, 7118084, 7118088, 7118092, 7119001, 7119002, 7119003, 7119004, 7119006, 7119008, 7119019, 7119020, 7119021, 7119023, 7119025, 7119028, 7119032, 7119035, 7119038, 7119065, 7119068, 7119069, 7119079, 7119080, 7119082, 7119084, 7119085, 7119088, 7119090, 7119091, 7120082, 71200100, 7120101, 7120112, 7120113, 7120116, 7120121, 71200128, 7120129, 7120131, 7120132, 7120133, 7120100, 7120118, 7120119, 7120120, 7120122, 7120002, 7120003, 712035, 712037, 712044, 712045, 712047, 712049, 712053, 712056, 712057, 7122069, 7122070, 7123014, 7123015, 7123019, 7123020, 7123022, 7123024, 7123028, 7123030, 7123031, 7123032, 7124009, 7124016, 7124018, 7124012, 7124024, 7124026, 7124029, 7124034, 7125005, 7125013, 7125014, 7125015, 7125016, 7125017, 712521, 7125022, 7125023, 7125044, 7125046, 7125055, 7125056, 7125057, 7125058, 7125059, 7125066, 7125067, 7125070, 7126009, 7126010, 7126012, 7126016, 7126019, 7126022, 7126023, 7126036, 7126056, 7126057, 7126058, 7126059, 7126062, 7126063, 7126064, 7127001, 7127005, 7127006, 7127010, 7127011, 7127024, 7127038, 7127039, 7127041, 7127042, 7127046, 7127049, 7127067, 7127072, 7127077, 7127080, 7128032, 7128045, 7128046, 7128048, 7128050, 7128051, 7128057, 7128061, 7128063, 7129001, 7129002, 7129003, 7129009, 7129018, 7129020, 7129023, 7129027, 7129031, 7129032, 7129035</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7789</td>
<td>7790</td>
</tr>
<tr>
<td></td>
<td>7791</td>
<td>7792</td>
</tr>
<tr>
<td></td>
<td>7795</td>
<td>7796</td>
</tr>
<tr>
<td></td>
<td>7800</td>
<td>7803</td>
</tr>
<tr>
<td></td>
<td>7804</td>
<td>7805</td>
</tr>
<tr>
<td></td>
<td>7810</td>
<td>7815</td>
</tr>
<tr>
<td></td>
<td>7817</td>
<td>7820</td>
</tr>
<tr>
<td></td>
<td>7823</td>
<td>7824</td>
</tr>
<tr>
<td></td>
<td>7825</td>
<td>7827</td>
</tr>
<tr>
<td></td>
<td>7830</td>
<td>7831</td>
</tr>
</tbody>
</table>

Table A.1: Continued.
Appendix B

MATERIAL STUDY

High-energy electrons predominantly lose energy in matter by bremsstrahlung, and high-energy photons by $e^+e^-$ pair production. The characteristic amount of matter traversed for these related interactions is called the radiation length $X_0$, usually measured in $g.cm^{-2}$. It is both (a) the mean distance over which a high-energy electron loses all but $1/e$ of its energy by bremsstrahlung, and (b) 7/9 of the mean free path for pair production by a high-energy photon. It is also the appropriate scale length for describing high-energy electromagnetic cascades. The radiation length is given, to a good approximation, by the expression

$$X_0 = \frac{716.4 \cdot A}{Z(Z+1) \ln(287/\sqrt{Z})} \ g.cm^{-2}$$

where $Z$ is the atomic number and $A$ is the mass number.

A study of the material in radiation length vs. rapidity ($\eta$) was done to understand the difficulty in measuring NPEs in the EEMC. Geantino, a virtual particle, was used as a geometric probe. Geantino is transported through a detector but does not interact with it. Fig. B.1 shows the material in radiation length vs. rapidity. The black curve represents the result in the TPC, the red curve the SVT, and the blue curve the TPC+SVT, all with $Z = 0$ cm and year 2006 geometry. Material in radiation length is about 4-5 times more in the EEMC ($\eta$ between +1 and +2) than in the BEMC ($\eta$ between -1 and +1). This is due to the fact that the EEMC is located behind the west end of the SVT and its supporting conic structure that extends up to the TPC wheel about 2 m from the center point of STAR. It is evident
from the figure that the SVT and its supporting conic structure contribute a lot of photonic conversion electrons in the EEMC than in the BEMC. The material in radiation length in the TPC material alone is much greater in the EEMC than the TPC+SVT in year 2006 in the BEMC. This is one of the reasons why it was possible to extract NPEs in the BEMC [85] whereas it is very difficult in the EEMC. The signal electrons are simply swamped by photonic electrons mainly due to gamma conversions occurring in the materials (TPC and SVT) in front of the EEMC.

**Material in radiation length vs rapidity**

![Material in radiation length vs rapidity](image)

Figure B.1: Comparison of material in radiation length versus rapidity in TPC and SVT in year 2006 geometry.


[26] W. He, Ph.D. Thesis, Indiana University of Bloomington, IN.
[40] B.I. Abelev et al., arXiv:0805.0364v2 [nucl-ex]
[41] Stephen Baumgart, Ph.D. Thesis,
Yale University, USA
[44] X. Lin, Ph.D. Thesis, University of Central China Normal University, China


[76] Ludlum Review 2003, EEMC Progress Update for Winter 2002-3

[77] A. Baldwin, Kent State MAPMT Characterization http://www.iucf.indiana.edu/U/STAR/eemc_proj/


[83] Weihong. He, Ph.D. Thesis, Indiana University Cyclotron Facility, USA

[84] 2006 $p+p$ run (run 6) Trigger FAQ

