Cross Section of Bottom Quark Production in p+p Collisions at $\sqrt{s} = 500$ GeV Using Like-Sign Dimuons at PHENIX

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CROSS SECTION OF $b\bar{b}$ PRODUCTION IN $p + p$ COLLISIONS AT $\sqrt{s} = 500$ GeV

USING LIKE-SIGN DIMUONS AT PHENIX

by

LAURA B. PATEL

Under the direction of Dr. Xiaochun He

ABSTRACT

Lepton pairs resulting from the decay of heavy flavor mesons are an important tool to probe the hot and dense matter created in nucleus-nucleus collisions at the Relativistic Heavy Ion Collider. Due to their large mass, heavy quarks are produced in the earliest stages of the collision and will, therefore, experience the full evolution of the system. The yield of heavy flavor mesons can be measured through their semi-leptonic decay channel by constructing like-sign and unlike-sign lepton pairs. Cross section measurements in $p + p$ collisions provide a test of perturbative quantum chromodynamics (pQCD) theory in addition to a crucial baseline measurement to study the hot and cold nuclear matter effects present in heavy ion collisions.

For the first time, the $b\bar{b}$ cross section in $p + p$ collisions at $\sqrt{s} = 500$ GeV is measured. The results are based on the yield of high mass, like-sign dimuons measured in the PHENIX muon arm acceptance ($1.2 < |y| < 2.2$). The extrapolated total cross section is $25.2 \pm 3.2$ (stat) $^{+11.4}_{-9.5}$ µb (sys). The cross section is comparable to pQCD calculation within uncertainties.

INDEX WORDS: $p + p$, Heavy quark, $b\bar{b}$, Dimuon, 500 GeV, PHENIX, RHIC
CROSS SECTION OF $b\bar{b}$ PRODUCTION IN $p+p$ COLLISIONS AT $\sqrt{s} = 500$ GeV

USING LIKE-SIGN DIMUONS AT PHENIX

by

LAURA B. PATEL

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

in the College of Arts and Sciences

Georgia State University

2013
CROSS SECTION OF $b\bar{b}$ PRODUCTION IN $p + p$ COLLISIONS AT $\sqrt{s} = 500$ GeV

USING LIKE-SIGN DIMUONS AT PHENIX

by

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Office of Graduate Studies
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April 2013
To my grandparents Bernard and Selma Kessler.
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LIST OF ABBREVIATIONS

$A\epsilon$  acceptance $\times$ efficiency
$B$  open bottom meson or baryon
$B^0$  neutral open bottom meson ($B^0_d$ or $B^0_s$)
BG  background
FG  foreground
LO  leading order
NLO  next-to-leading order
$N_{MB}$  number of minimum bias events
PISA  PHENIX Integrated Simulation Application
PHENIX  Pioneering High Energy Nuclear Interaction eXperiment
$p_T$  transverse momentum
QED  quantum electrodynamics
QCD  quantum chromodynamics
QGP  quark gluon plasma
$Q(\bar{Q})$  heavy quark (or antiquark)- bottom or charm
$q(\bar{q})$  light quark (or antiquark)- up, down, or strange
RHIC  Relativistic Heavy Ion Collider
$\sigma$  cross section
$y$  rapidity
$\eta$  psuedorapidity
CHAPTER 1

INTRODUCTION

The goal of heavy ion nuclear physics is to understand matter at extreme temperatures and densities. Heavy ion collisions provide access to conditions thought to be present in the Early Universe approximately 1 µs after the Big Bang. Heavy quarks are particularly good probes to study the medium created because they are produced in the initial parton hard scattering and will, therefore, experience the full evolution of the system. However, before heavy quarks can be used to probe the medium, a baseline for heavy quark production must be established in $p + p$ collisions where no medium is expected to form.

Due to the large mass of the bottom quark, approximately 4.2 GeV/c$^2$, the production cross section should be calculable using perturbative techniques [1]. Comparison of heavy quark-antiquark production in $p + p$ collisions provides a stringent test of perturbative quantum chromodynamics (pQCD) theory. As such, it is essential to understand the production of heavy quarks across a large energy range.

Cross section measurements for bottom production in nucleon-nucleon experiments have been made from fixed-target experiments [2, 3, 4] up to Tevatron and LHC energies [6]. It was found that pQCD predictions seem to match experimental results well at high energy [5], but less so at lower energies. Collisions at RHIC energies occupy an important bridge between the low energy fixed target and high energy (TeV) regimes. PHENIX has previously measured the $b\bar{b}$ cross section in $p + p$ collisions at $\sqrt{s} = 200$ GeV through electron-hadron correlations [7] and dielectrons [8] channels at mid rapidity.
In this dissertation, the total cross section of $b\bar{b}$ production in $p+p$ collisions at center of mass energy of 500 GeV is reported. The results are based on the yield of like-sign dimuons (muon pairs of the same electric charge) at forward/backward rapidity. Like-sign dimuons have previously been used to investigate the phenomenon of neutral $B$ meson oscillations at $e^+e^-$ colliders by the CLEO Collaboration [9], ARGUS Collaboration [10], and ALEPH Collaboration [11] and by the UA1 Collaboration [12] in $p+\bar{p}$ collisions. If $B$ meson oscillation occurs, neutral $B$ mesons can decay through their primary decay channel into a like-sign muon pair. The number of correlated like-sign dimuons due to neutral $B$ meson oscillation is directly related to the total number of open bottom meson pairs and thus can provide a channel to study bottom quark production.

This dissertation is organized as follows. Chapter One outlines the background theory of the Standard Model, a description of neutral $B$ meson oscillation, and a brief overview of the quark gluon plasma. Details of heavy quark production, fragmentation into heavy mesons and subsequent semi-leptonic decay are described in detail in Chapter Two. An overview of the PHENIX experiment, data selection and quality assurance, and detector acceptance and efficiency are provided in Chapter Three, Chapter Four, and Chapter Five, respectively. Data analysis and results are presented in Chapter Six. Finally, conclusions are provided in Chapter Seven.

1.1 The Standard Model

The Standard Model of particle physics is, to date, the most comprehensive theory to describe the interactions of elementary particles through the electromagnetic, weak, and strong forces. The Standard Model is a renormalizable $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory. The
$SU(3)_C$ component represents the coupling of quarks to gluon fields through color charge and the $SU(2)_L \times U(1)_Y$ components represent the unified electroweak interaction.

As shown in Fig. 1.1, there are 12 fermions (6 quarks + 6 leptons) and 4 bosons. Leptons can be divided into three charged leptons ($e, \mu, \tau$) and three neutral leptons ($\nu_e, \nu_\mu, \nu_\tau$). Leptons interact through the electromagnetic and weak forces. The six quark “flavors” are: up ($u$), down ($d$), strange ($s$), charm ($c$), bottom ($b$), and top ($t$). Quarks carry both a fractional electric charge and color charge (red, green, or blue) and will interact through the electromagnetic, weak, and strong force. Each fermion has a corresponding anti-fermion with equal mass but opposite charge. The fermions can be grouped into three generations based on common characteristics. Tables 1.1 and 1.2 list the properties of leptons and quarks, respectively.

Table 1.1: Summary of lepton properties. Masses taken from [13].

<table>
<thead>
<tr>
<th>Particle</th>
<th>Symbol</th>
<th>Charge (e)</th>
<th>Mass (MeV$/c^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron neutrino</td>
<td>$\nu_e$</td>
<td>0</td>
<td>&lt;0.003</td>
</tr>
<tr>
<td>electron</td>
<td>$e$</td>
<td>-1</td>
<td>0.511</td>
</tr>
<tr>
<td>muon neutrino</td>
<td>$\nu_\mu$</td>
<td>0</td>
<td>&lt;0.19</td>
</tr>
<tr>
<td>muon</td>
<td>$\mu$</td>
<td>-1</td>
<td>105.6</td>
</tr>
<tr>
<td>tau neutrino</td>
<td>$\nu_\tau$</td>
<td>0</td>
<td>&lt;18.2</td>
</tr>
<tr>
<td>tau</td>
<td>$\tau$</td>
<td>-1</td>
<td>1776.8</td>
</tr>
</tbody>
</table>

Each interaction is mediated by a gauge boson. The weak force is mediated by two charged, massive $W$ and a neutral, massive $Z$ boson. The photon ($\gamma$) is massless and mediates
the electromagnetic force between particles that carry electric charge. The interactions of photons with matter is well described by the theory of quantum electrodynamics. There are eight spin-1, massless gluons that mediate the strong interaction between particles with color charge. Quantum chromodynamics describes gluons and their interactions with quarks and other gluons.

### 1.1.1 Electroweak Interactions

Sheldon Glashow, Abdus Salam, and Steven Weinberg proposed that the electromagnetic and weak forces were manifestations of one unified electroweak force [14, 15, 16]. They were awarded the Nobel Prize in Physics in 1979 for their work. Electroweak interactions are
Table 1.2: Summary of quark properties. Masses taken from [13].

<table>
<thead>
<tr>
<th>Particle</th>
<th>Symbol</th>
<th>Charge ((e))</th>
<th>Mass (MeV/(c^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>down</td>
<td>(d)</td>
<td>-1/3</td>
<td>3.5-6.0</td>
</tr>
<tr>
<td>up</td>
<td>(u)</td>
<td>+2/3</td>
<td>1.5-3.3</td>
</tr>
<tr>
<td>strange</td>
<td>(s)</td>
<td>-1/3</td>
<td>(104^{+26}_{-34})</td>
</tr>
<tr>
<td>charm</td>
<td>(c)</td>
<td>+2/3</td>
<td>(1,270^{+70}_{-100})</td>
</tr>
<tr>
<td>bottom</td>
<td>(b)</td>
<td>-1/3</td>
<td>(4,200^{+170}_{-70})</td>
</tr>
<tr>
<td>top</td>
<td>(t)</td>
<td>+2/3</td>
<td>171,200±2100</td>
</tr>
</tbody>
</table>

described by the \(SU(2)_L \times U(1)_Y\) symmetry group through the Lagrangian:

\[
\mathcal{L}_{EW} = \mathcal{L}_g + \mathcal{L}_K + \mathcal{L}_H + \mathcal{L}_Y, \tag{1.1}
\]

where \(\mathcal{L}_K\) is the kinetic term describing the interaction of gauge bosons with fermions, \(\mathcal{L}_H\) describes the Higgs field, and \(\mathcal{L}_Y\) describes the Yukawa interaction. The interaction between the electroweak gauge bosons are described by

\[
\mathcal{L}_g = -\frac{1}{4} W^{a\mu\nu} W^a_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu}, \tag{1.2}
\]

where \(W\) and \(B\) are the field strength tensors for the weak isospin and weak hypercharge fields, respectively. The index \(a\) runs from 1 to 3.

There are four massless bosons associated with the electroweak force: \(W^1, W^2,\) and \(W^3\) carry the weak isospin charge \((T)\), and \(B^0\) carries the weak hypercharge \((Y_W)\). The weak hypercharge is related to the electric charge \(Q\) and third component of weak isospin \(T_3\) as \(Y_W = 2(Q - T_3)\). Left-handed fermions have \(T = 1/2\) and can be grouped into doublets with
up-type quarks having $T_3 = +1/2$ and down-type quarks having $T_3 = -1/2$. Right-handed fermions have $T=0$ and form singlets that do not participate in charged weak interactions. All particles, except gluons, have a non-zero weak hypercharge.

Electromagnetic and weak forces decouple by spontaneous symmetry breaking, which occurs through the Higgs mechanism due to the presence of the scalar Higgs field: $SU(2)_L \times U(1)_Y \rightarrow U(1)_{QED}$. After spontaneous symmetry breaking by the vacuum the $B^0$ and $W^3$ transform into the $Z^0$ and $\gamma$ bosons

$$
\begin{pmatrix}
\gamma \\
Z^0
\end{pmatrix}
= 
\begin{pmatrix}
\cos \theta_W & -\sin \theta_W \\
\sin \theta_W & \cos \theta_W
\end{pmatrix}
\begin{pmatrix}
B^0 \\
W^3
\end{pmatrix},
$$

(1.3)

where $\theta_W$ is the weak mixing angle determined by the coupling strength. The $W^\pm$ bosons are linear superpositions of the $W^1$ and $W^2$ particles

$$
W^\pm = \frac{1}{\sqrt{2}}(W^1 \mp W^2).
$$

(1.4)

The Higgs mechanism also gives mass to the $W^\pm$ ($m_W = 80.4$ GeV/$c^2$) and $Z$ bosons ($m_Z = 91.2$ GeV/$c^2$). The masses of fermions and weak force bosons are generated through electroweak spontaneous symmetry breaking through the Higgs mechanism [17].

After spontaneous symmetry breaking, the electroweak Lagrangian transforms into

$$
\mathcal{L}_{EW} = \mathcal{L}_K + \mathcal{L}_N + \mathcal{L}_C + ...$

(1.5)

Again, $\mathcal{L}_K$ is the kinetic term that now contains mass terms. The neutral current ($\mathcal{L}_N$) and charged current ($\mathcal{L}_C$) contains contributions from the now separate electromagnetic and weak interactions. In the next two sections, details and consequences of the electromagnetic and weak interactions are discussed.
Quantum Electrodynamics

Quantum electrodynamics (QED) is an abelian gauge theory with U(1) symmetry that describes the interaction of charged, spin-1/2 particles with the electromagnetic field. The dynamics of this interaction can be expressed by the QED Lagrangian

\[ \mathcal{L}_{\text{QED}} = \bar{\psi} (i \gamma^\mu D_\mu - m) \psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}, \]

where \( \gamma^\mu \) are the Dirac matrices, \( \psi \) are the field of spin-1/2 particles. The electromagnetic field strength tensors are given by

\[ F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \]

and the gauge covariant derivative \( D_\mu \) is

\[ D_\mu = \partial_\mu + ig_e A_\mu, \]

where \( g_e \) is the coupling constant and \( A_\mu \) is the electromagnetic field.

The coupling constant describes the strength of the electromagnetic interaction:

\[ g_e = \sqrt{4\pi \alpha}, \]

where \( \alpha \approx 1/137 \) is the fine structure constant. Higher order processes such as vacuum polarization or electron self energy can change the strength of the electromagnetic interaction. The QED coupling constant “runs” with the energy scale:

\[ \alpha(Q^2) = \left( \frac{1}{\alpha(0)} - \frac{1}{3\pi} \ln \frac{Q^2}{m^2} \right)^{-1}, \]

where \( \alpha(0) \) is the zeroth order value of the structure constant. This results in a decrease in the effective charge and fine structure constant at large distance (smaller momentum
transfer). The charge is screened by virtual charged fermion pairs created from the vacuum and the vacuum behaves as a dielectric medium.

**Weak Interactions & $B^0$ Oscillation**

The neutral mesons $K^0 = d\bar{s}$, $D^0 = c\bar{u}$, $B^0_d = d\bar{b}$, and $B^0_s = s\bar{b}$ are the only mesons capable of mixing with their antiparticles ($\bar{K}^0$, $\bar{D}^0$, $\bar{B}^0_d$, and $\bar{B}^0_s$). This leads to particle-antiparticle oscillation, where the mass eigenstate (observed through decay products) is time-dependent. The focus of this section will be on neutral $B$ meson oscillation as this phenomena can result in like-sign dimuons (see Sect. 2.3.2).

In the strong and electromagnetic interactions flavor eigenstates and mass eigenstates are the same. However, in weak interactions, which can change the quark flavor, these two eigenstates are not the same, but actually a mixture of different generations. The Cabibbo-Kobayashi-Maskawa (CKM) matrix relates the weak eigenstates (left) to the mass eigenstates (right):

$$
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix} =
V_{\text{CKM}}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
$$

(1.11)

where the CKM matrix is defined as:

$$
V_{\text{CKM}} =
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix} =
\begin{pmatrix}
  0.974 & 0.225 & 0.003 \\
  0.225 & 0.973 & 0.041 \\
  0.009 & 0.040 & 0.999
\end{pmatrix}
$$

(1.12)

The magnitude of each CKM matrix element reflects the strength of the coupling between the quark flavors, the values of which are experimentally determined [18]. By convention,
the up-type quarks remain unmixed.

The charged current term in the weak interaction Lagrangian describing the coupling of the $W$ boson to quarks is

$$\mathcal{L}_{CC} = -\frac{g_W}{\sqrt{2}} \sum_{j,k=1,2,3} [\bar{u}_{jL} \gamma_\mu (1 - \gamma_5) V_{jk} d_{kL} W^+_{\mu} + \bar{d}_{kL} \gamma_\mu (1 - \gamma_5) V^*_{jk} u_{jL} W^-_{\mu}]$$  \hspace{1cm} (1.13)

where the indices $j$ and $k$ run over the three quark generations, $g_W$ is the weak coupling constant, $\bar{u}$ is an up-type quark, $d$ is a down-type quark, and $V_{jk}$ is an element of the unitary CKM matrix. The subscript “L” indicates that $W^\pm$ only couple to left handed fermion doublets (and right handed anti-fermion doublets). According to Eqn. 1.13, the mass eigenstates of an up-type quark can interact with a mixture of mass eigenstates from a down-type quark of different generations.

As a result of higher order flavor changing weak interactions, transitions between neutral mesons and antimesons can occur. A schematic of the box diagram for this process in the $B^0$ system is shown in Fig. 1.4. Oscillation in the $B^0_d$ system was first observed by the ARGUS Collaboration in 1987 [10]. That same year, the UA1 Collaboration observed the first hints of $B^0_s$ oscillation [12].

To quantify the effect of oscillation and determine the oscillation parameters the time-evolution of the $B^0$ system must be considered. The “light” $B^0_L$ and “heavy” $B^0_H$ mass eigenstates are a linear combination of the weak ($B^0, \bar{B}^0$) eigenstates:

$$|B^0_L\rangle = p|B^0\rangle + q|\bar{B}^0\rangle, \quad |B^0_H\rangle = p|B^0\rangle - q|\bar{B}^0\rangle$$  \hspace{1cm} (1.14)

which are subject to the the normalization condition $|p|^2 + |q|^2 = 1$. Here, $B^0$ can be either $B^0_d$ or $B^0_s$. The evolution of a $B^0$ mass eigenstate is governed by the time-dependent Schrödinger
Figure 1.2: Box diagram of neutral $B$ meson oscillation through the exchange of a $W$ boson or top-type quark. $B^0$ can be either $B^0_d$ or $B^0_s$.

Equation:

$$i \frac{d}{dt} \begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix} = H \begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix}$$

(1.15)

Where the Hamiltonian $H$ can be written in terms of a mass matrix $M$ and a decay matrix $\Gamma$:

$$H = M - \frac{i}{2} \Gamma.$$  

(1.16)

In the absence of oscillation, only diagonal matrix elements would exist in the Hamiltonian. However, since the mass eigenstates are linear combinations of the weak states, off-diagonal elements exist:

$$H \begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix} = \begin{pmatrix} m_{11} - \frac{i}{2} \Delta \Gamma_{11} & \Delta m_B - \frac{i}{2} \Delta \Gamma_B \\ \Delta m_B - \frac{i}{2} \Delta \Gamma_B & m_{22} - \frac{i}{2} \Delta \Gamma_{22} \end{pmatrix} \begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix}$$

(1.17)
where \( m_{11} = m_{22} = m \) is the mass of the weak eigenstates \( \Gamma_{11} = \Gamma_{22} = \Gamma \) is the decay rate of the weak eigenstates, \( \Delta m = m_H - m_L \) is the mass difference between the heavy and light mass eigenstates, and \( \Delta \Gamma = \Gamma_L - \Gamma_H \) is the decay width difference between the mass eigenstates. In the \( B^0 \) system, \( \Delta m \gg \Delta \Gamma \) indicating that the frequency of oscillation is primarily dependent on the mass difference.

The time-integrated probability that a \( B^0 \) meson will oscillate to a \( \bar{B}^0 \) meson before decay (and vice versa) is described by the mixing parameter

\[
\chi = \frac{\text{Prob}(B^0 \rightarrow \bar{B}^0 \rightarrow l)}{\text{Prob}(B^0 \rightarrow B^0 \rightarrow l)} = \frac{1}{2} \left[ \frac{(\Delta m/\Gamma)^2}{1 + (\Delta m/\Gamma)^2} \right].
\]

(1.18)

If \( \Delta m >> \Gamma \) a large number of oscillations will occur before the meson decays. In the \( B^0_d \) system \( (\Delta m_d = 0.51 \times 10^{12} \text{ s}^{-1} \text{ and } \Gamma_d = 6.6 \times 10^{11} \text{ s}^{-1}) \) \( \chi_d \sim 0.17 \) and for the \( B^0_s \) system \( (\Delta m_s = 17.7 \times 10^{12} \text{ s}^{-1} \text{ and } \Gamma_s = 6.7 \times 10^{11} \text{ s}^{-1}) \) \( \chi_s \sim 0.49 \) [13]. However, if \( \Delta m << \Gamma \), the meson will decay before oscillation occurs. This is the case for \( D^0 \) \( (\Delta m < 7 \times 10^{10} \text{ s}^{-1} \text{ and } \Gamma = 2.4 \times 10^{12} \text{ s}^{-1}) \) where oscillation is minimal. In many experiments the two neutral \( B \) meson states can not be separated. The mixing parameter \( (\bar{\chi}) \) can be calculated as the weighted average of the two neutral \( B \) meson mixing parameters \( \chi_d \) and \( \chi_s \).

\[
\bar{\chi} = f_d \chi_d + f_s \chi_s = 0.12,
\]

(1.19)

where \( f_d = 0.401 \) and \( f_s = 0.113 \) are the branching fractions of the \( b \rightarrow B^0_d \) and \( b \rightarrow B^0_s \) mesons, respectively.

### 1.1.2 Strong Interaction

The behavior of quarks and gluons interacting through the strong force can be described by the non-abelian, Yang-Mills gauge theory with \( SU(3) \) symmetry. The fundamental theory of the strong interaction is described by quantum chromodynamics (QCD). The QCD
The Lagrangian is:

\[ \mathcal{L}_{\text{QCD}} = \bar{\psi}_i \left( i \gamma^\mu D_\mu \right)_{ij} - m \delta_{ij} \psi_j - \frac{1}{4} G_{a\mu\nu}^a G^{a\mu\nu} \]  

(1.20)

where \( \gamma^\mu \) are the Dirac matrices, \( m \) is the mass of the quark, \( \psi \) are the quark color fields,

\[
\psi = \begin{pmatrix} \psi_{\text{red}} \\ \psi_{\text{blue}} \\ \psi_{\text{green}} \end{pmatrix}.
\]  

(1.21)

The gluonic field strength tensor, \( G \) is

\[
G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g_s f^{abc} A_\mu^b A_\nu^c
\]  

(1.22)

where \( A \) are the eight gluon fields (\( a = 1, ..., 8 \)), \( g_s \) is the gauge coupling, and \( f^{abc} \) are the SU(3) structure constants. \( D_\mu \) is the covariant derivative defined as:

\[
D_\mu = \partial_\mu + ig_s \lambda^i_2 A_\mu^i
\]  

(1.23)

where \( \lambda^i \) are the Lie group generators, the Gell-Mann matrices. The last term in Eqn. 1.22 leads to gluon self interaction. QCD interactions will change the color of a quark, but the quark’s flavor must be conserved.

The strong coupling constant is dependent on the energy scale:

\[
\alpha_s(Q^2) \equiv \frac{g_s^2(Q^2)}{4\pi} = \frac{1}{\beta_0 \ln \left( \frac{Q^2}{\Lambda_{\text{QCD}}^2} \right)}
\]  

(1.24)

where \( Q \) is the momentum transfer and \( \beta_0 \) is the first coefficient of the QCD beta function.

At lower momentum, and larger distances, the coupling become stronger. The momentum scale below which the strong force becomes non-perturbative is set by QCD scale \( \Lambda_{\text{QCD}} \) (\( \approx 200 \text{ MeV} \)). In general, “light” quarks are those with masses less than the QCD scale and “heavy” quarks are those with masses much larger than the QCD scale.
This scale dependence results in some unique phenomena such as asymptotic freedom which can be explained by higher order virtual corrections. Similar to vacuum polarization in QED, virtual quark-antiquark pairs can screen the color charge. However, since gluons themselves carry charge, the presence of virtual gluons arising from the vacuum can augment the quark’s color charge and lead to color anti-screening. The contributions from gluon anti-screening is larger than the screening effect from quark-antiquark pairs and results in the effective color charge appearing stronger at larger distances.

1.2 Quark Gluon Plasma

In normal nuclear matter, quarks and gluons are confined inside hadrons. However, at sufficiently high temperatures and densities a transition occurs to a state where quarks and gluons are no longer confined. A state such as this may have existed in the Early Universe shortly after the Big Bang. The only way to produce these conditions in the laboratory is through relativistic heavy ion collisions at facilities such as the Relativistic Heavy Ion Collider at Brookhaven National Laboratory or the Large Hadron Collider at CERN.

One of the primary goals of the PHENIX experiment is to study the quark gluon plasma (QGP). The understanding of heavy quark production is essential as it provides a baseline for heavy ion studies. While heavy ion collisions were not studied in this dissertation work, a short review of the QGP is provided.

Lattice QCD calculations predict that a phase transition from normal matter into a state of matter where quarks and gluons are essentially deconfined should occur at a critical temperature of approximately 170 MeV ($10^{12}$ K) [19]. This corresponds to an energy density of $\sim 1$ GeV/fm$^3$, approximately an order of magnitude more dense than the atomic nucleus.
Because the strong coupling becomes weaker at shorter distances, a transition will occur into a state of deconfined quarks and gluons. The exact nature of this phase transition is not yet known. Figure 1.3 shows a QCD phase diagram. On the $y$-axis is temperature and on the $x$-axis is baryon chemical potential. Collisions at RHIC and the LHC allow access to the high temperature, low baryon potential portion of the phase diagram.

The time development of a relativistic heavy ion collision is analogous to the expansion of the Early Universe and proceeds through the following steps [20]:

1. Thermalization- The interacting partons reach thermal equilibrium on a timescale of 1 fm/c.

2. Hydrodynamic Expansion- The locally thermalized QGP is created and the evolution of the system can be described using relativistic hydrodynamics.
3. Freeze-out - A transition occurs from a strongly interacting to a weakly interacting system. Hadrons will stop interacting and freely stream to the detector.

During a heavy ion collision, the nuclei are accelerated to close to the speed of light. This results in the nuclei becoming Lorentz contracted. In the initial collision, hard scattering takes place producing high-$p_T$ particles. Formation of the QGP occurs on the time scale of $\sim 1$ fm/c. Thermalization takes place through the soft scattering of particles which allows the matter to reach thermal equilibrium. The QGP will expand and can be described in the framework of hydrodynamics. Recent results show that this newly created matter behaves as a nearly perfect fluid [21].

As the QGP continues to expand, the system will transition from a strongly interacting hadronic matter into a weakly interacting system. Quarks and gluons again become confined within hadrons. Once freeze-out occurs the hadrons will stop interacting and freely stream to the detector. There are two phases of freeze-out: chemical freeze out, where inelastic collisions cease, and thermal (or kinetic) freeze-out where elastic collisions cease [20]. Chemical freeze-out temperature $T_{chem}$ can be determined experimentally by measuring hadron multiplicities. The chemical freeze-out will occur at higher temperature than thermal freeze-out.
because inelastic scattering will cease before elastic scattering. After thermal freeze-out, the momentum distributions of the particles are fixed. The temperature of thermal freeze-out $T_{\text{therm}}$ can be determined by studying the transverse momentum of particles.

### 1.2.1 Studying the QGP

Of the six known quarks, heavy flavor quarks (i.e. charm and bottom) are important probes to study the properties of the QGP as heavy quarks carry information from the earliest stages of the collision. The coupling of heavy quarks to the medium can be experimentally investigated by studying the amount of energy loss as it traverses the QGP and their flow properties [22].

As a heavy quark traverses the QGP it will interact strongly with the medium and radiate gluons in a process similar to electromagnetic Bremsstrahlung. This effect is expected to decrease as the quark mass increases. Energy loss can also occur due to collisions with lighter quarks. The parameter $R_{AA}$, which is the yield of heavy quarks in a heavy ion collision relative to the yield in a $p + p$ collision scaled by the number of collisions, can give insight into the modification of heavy quarks in a medium.

The flow of heavy quarks provides information on the strength of coupling to the QGP. During a heavy ion collision, the colliding nuclei do not completely overlap, resulting in a QGP that is non-spherical. The medium will, thus, not expand isotropically and an asymmetry in the final momentum of the particles is observed. This effect can be described by the elliptic flow coefficient, $v_2$. By studying the flow of heavy quarks in heavy ion collisions, the equations of state and evolution of the QGP can be explored. Previous work at PHENIX has studied the energy loss and flow of heavy quarks through its electron decay channel at
mid rapidity [23]. It was found that the amount of suppression and flow are larger than expected, indicating that the quarks are more strongly coupled to the QGP than previously anticipated.
CHAPTER 2

HEAVY FLAVOR THEORY

The original quark model, first proposed by Murray Gell-Mann in 1964, contained only the up, down, and strange quarks [24]. Shortly thereafter, Glashow and Bjorken extended the quark model to include a fourth quark, charm [25]. The discovery of the $J/\psi$ ($c\bar{c}$) meson in 1974 marked the first observations of the charm quark [26, 27]. In 1973, Makoto Kobayashi and Toshihide Maskawa proposed the existence of a third generation of quarks to explain CP violation [28]. Four years later, the bottom quark was observed as part of the $\Upsilon$ ($b\bar{b}$) resonance state [29] and the top quark was observed in 1995 [30, 31].

Since their discovery, the production of heavy flavor quarks has been an active area of research. However, quarks cannot be studied in isolation and all information must be inferred from their decay products. The cross section of final state observables, $F$, from a single heavy quark $Q$ can be written schematically as

$$\frac{E d^3\sigma(F)}{dp^3} = \frac{E_Q d^3\sigma(Q)}{dp_Q^3} \otimes D(Q \to H_Q) \otimes f(H_Q \to F)$$  \hspace{1cm} (2.1)$$

where the first term is the production cross section of heavy quarks, $D(Q \to H_Q)$ represents the fragmentation and hadronization of the heavy quark into a hadron, and the branching ratio into the final state observable $F$ is represented by $f(H_Q \to F)$. Due to flavor conservation of the strong force, heavy quarks must always be produced in pairs. In the following subsections, details of the production, fragmentation, and decay of heavy quark pairs will be discussed.
2.1 Heavy Quark Production

Due to their large mass, heavy quarks (\(Q\bar{Q} = c\bar{c}\) or \(b\bar{b}\)) are produced in the initial hard scattering. Because the mass of heavy quarks is well above the QCD scale (\(\Lambda_{QCD} \approx 200\) MeV), perturbative methods can be used to calculate production cross sections. Using pQCD, the double differential cross section to create a pair of heavy quarks from the interaction of partons \(i\) and \(j\) during the collision of nuclei \(A\) and \(B\) is given by

\[
E_Q E_{\bar{Q}} \frac{d\sigma_{AB}}{dp_Q^3 dp_{\bar{Q}}^3} = \sum_{i,j} \int dx_1 dx_2 F^A_i(x_1, \mu_F) F^B_j(x_2, \mu_F) E_Q E_{\bar{Q}} \frac{d\bar{\sigma}_{ij}(p_1, p_2, m_Q, \mu_R)}{d^3 p_Q d^3 p_{\bar{Q}}} \tag{2.2}
\]

where \(p_1\) and \(p_2\) are the 4-momenta of parton 1 and 2, \(F^A_i\) and \(F^B_j\) are the parton distribution functions evaluated at \(x_{1,2}\) (momentum fraction carried by parton 1 or 2) and \(\mu_F\) (factorization scale). Parton distribution functions are non-perturbative in origin and must be extracted from data at some fixed scale. The cross section \(\hat{\sigma}_{ij}\) can be calculated perturbatively by expanding in powers of the strong coupling constant at a set renormalization scale, \(\alpha_s(\mu_R)\). The cross section can be expressed as

\[
\hat{\sigma}_{ij} = \frac{\alpha_s^2(\mu_R)}{m_Q^2} \left[ f_{ij}^0(\rho) + \frac{\alpha_s(\mu_R)}{2\pi} \left[ f_{ij}^1(\rho) + \bar{f}_{ij}^1(\rho) \ln\left(\frac{\mu_R^2}{m_Q^2}\right)\right] + O(\alpha_s^2) + \ldots \right] \tag{2.3}
\]

where \(\rho = 4m_Q^2/s\) and \(s\) is the square of the parton-parton center of mass energy.

The first term in Eqn. 2.3, \(f_{ij}^0\), is the leading order (LO) contribution to the production cross section and the second term, \(f_{ij}^1\), is the next-to-leading order (NLO) contribution to the production cross section. LO and NLO contributions to the total cross sections of charm and bottom as a function of center of mass energy are shown in Fig. 2.1. For charm production there are significant contributions from higher order terms across all energy ranges. Bottom production is less dependent on higher order terms at lower energies. However, as center of mass energies approach the TeV scale, NLO processes become important. Next-to-next-
to-leading order terms and higher are generally not considered. Combinations of possible parton interactions \((i \text{ and } j)\) for the different processes are discussed below.

2.1.1 Leading Order

At leading order, \(O(\alpha_s^2)\), pair production takes place in the hard scattering through the fusion of gluons or light quarks:

\[
g + g \rightarrow Q + \bar{Q} \\
q + \bar{q} \rightarrow Q + \bar{Q}
\]

In both cases, gluon radiation can occur. Figure 2.2 shows the Feynman diagrams for these processes. At RHIC energies, gluon fusion is the dominant mechanism of bottom quark production. This is a result of the large abundance of gluons in \(p + p\) collisions. To conserve momentum, leading order processes produce quarks that are back-to-back in azimuth.

Cross section calculations at LO tend to underestimate the experimental cross sections.
A “K-factor”, defined as \( \sigma_{Q\bar{Q}}^{NLO}/\sigma_{Q\bar{Q}}^{LO} \), can be introduced to artificially scale the production cross section to closely match the NLO prediction.

![Feynman diagrams](image)

Figure 2.2: Leading order production mechanisms for heavy quarks include gluon fusion (left), quark fusion (center), and pair production with gluon emission (right).

### 2.1.2 Next-to-Leading Order

Next-to-leading order, \( O(\alpha_s^3) \), production processes include flavor excitation and gluon splitting. Examples of NLO processes including virtual corrections are:

\[
g + g \rightarrow Q + \bar{Q} + g \\ (2.6)
\]

\[
q + \bar{q} \rightarrow Q + \bar{Q} + g \\ (2.7)
\]

\[
q(\bar{q}) + g \rightarrow Q + \bar{Q} + (\bar{q})q \\ (2.8)
\]

In NLO processes, the heavy quarks are not produced at the hard scattering vertex which is shown in the Feynman diagrams in Fig. 2.3. For example, during flavor excitation the \( Q\bar{Q} \) is generally created through initial state gluon splitting. Only one of the heavy quarks will participate in the hard scattering, where it is put on mass shell by scattering off a parton in the other beam. In final state gluon splitting no heavy quark participates in the hard scattering vertex.
2.1.3 Calculating Heavy Quark Cross Sections

Heavy quark cross sections are generally calculated in one of two frameworks: Next-to-Leading Order (NLO) or Fixed-Order Next-to-Leading Log (FONLL) [33]. Specifics of these frameworks are detailed below.

- NLO calculations rely on cross sections calculated from QCD theory. Heavy quarks are considered massive and treated as inactive flavors. Inputs generally include the quark mass, factorization scale, and renormalization scale. There are various codes that implement the NLO QCD framework for particle production: MNR [1], MC@NLO [34], etc.

- FONLL is a method to calculate double differential, single inclusive heavy quark cross sections. The differential cross section is evaluated using massive fixed-order NLO components. Gluon splitting or gluon emission will generate $\alpha_s \log k(p_T/m)$ terms. These terms are resummed with next-to-leading logarithm accuracy. The full cross section is obtained by integrating over the transverse momentum ($p_T$) and rapidity distributions. Inputs include the quark mass and the strong coupling constant. Factorization and

Figure 2.3: Next-to-leading order production mechanisms for heavy quarks include flavor excitation (left), gluon splitting (center), and flavor excitation with gluon splitting (right).
renormalization scales are used to estimate uncertainty. Heavy quarks are treated as active flavors for $p_T >> m_Q$.

### 2.2 Heavy Quark Fragmentation

A property of the strong force is that quarks must be confined within hadrons. As such, the heavy quarks can not exist independently and must combine with other quarks to form color-neutral hadrons. A heavy quark can hadronize with an anti-quark of the same flavor to form quarkonia, or with a lighter quark to form an open meson. Baryons can also be created if the heavy quark combines with two other quarks. The lifetime of the top quark is not long enough for it to hadronize before decaying into a lighter quark.

The differential cross section for heavy mesons can be calculated by combining perturbative calculations for heavy quark production with a fragmentation function [35], $D(Q \rightarrow H_Q)$, describing the probability of a heavy quark hadronizing into a given hadron:

$$\frac{d\sigma(p_T)}{dp_T} = \int dx \frac{d\sigma_Q}{x \ dq_T} (\frac{p_T}{x}, m) \ D_{Q \rightarrow H}(x).$$  \hspace{1cm} (2.9)

The fragmentation of heavy quarks into heavy mesons can not be calculated using perturbative methods and is generally extracted from fits to experimental data. Fragmentation affects the hadron kinematics, not the heavy quark production cross section.

Due to the large mass of the heavy quarks, the $p_T$ is minimally changed as it picks up a light quark from the vacuum. Bjorken [36] and Suzuki [37] proposed, based on QCD, that the fractional momentum of the heavy quark lost when hadronizing can be described by:

$$<x> \approx 1 - \frac{\Lambda_{QCD}}{m}.$$  \hspace{1cm} (2.10)

Because the mass of the heavy quark is much larger than the QCD scale, the amount of
momentum lost will be small. Figure 2.4 shows the $p_T$ distributions of the $b(c)$ quarks and $B(D)$ mesons as a function of $p_T$ in both the central ($y = 0$) and forward ($y = 1.7$) rapidity regions in 500 GeV $p + p$ collisions. These calculations were done using FONLL framework [38]. The heavier $b$ quark shows less momentum loss when hadronizing than the lighter $c$ quark.

2.3 $Q\bar{Q}$ Decay to Dileptons

Hadrons containing heavy quarks are unstable and will subsequently decay into lighter particles which can be observed experimentally. The probability of a hadron decaying through a specific channel is described by its branching ratio. For a meson containing a
heavy quark, the branching ratio to a lepton $B(H_Q \rightarrow l)$ is $\approx 10\%$, making this decay channel very useful. The branching ratio of the $Q\bar{Q}$ pair into a dilepton is simply that of the single lepton squared.

The dilepton mass spectrum is constructed by calculating the invariant mass of lepton pairs:

$$M_{ll} = \sqrt{2(m_l^2 + E_1 E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2)}$$

(2.11)

where $m_l$ is the mass of the lepton, $E_1$ and $E_2$ are the energies of the two leptons, and $\mathbf{p}_1$ and $\mathbf{p}_2$ are the momentum vectors of the two leptons. Dimuon decays of vector mesons, a $1 \rightarrow 2$ process, can be fully reconstructed and will result in a peak in the unlike-sign dilepton mass spectra. The semileptonic decay of open heavy flavor mesons is a many body process and is only partially reconstructed. This results in a continuum shape in the mass spectra. The invariant mass and charge correlation of the dileptons provide information into the source of the leptons. A summary of the mass region and charge correlation is provided in Table 2.1.

2.3.1 Unlike-Sign Spectrum

The unlike-sign dilepton invariant mass spectrum can be roughly divided into three distinct regions, each providing access to unique physics processes:

- The low mass region ($m_{ll} < 1.1$ GeV) is dominated by the decay of vector mesons with light quark content: $\rho$, $\phi$, and $\omega$ mesons. If a QGP is created, the modification of these low mass vector mesons can be studied. These mesons are sensitive to chiral symmetry restoration that can appear as a mass shift, peak broadening, or excess in yield [39].

- The intermediate mass region ($1.1 < m_{ll} < 3$ GeV) lies between the low mass vector
Table 2.1: Dominant physics processes that can contribute to dimuon signal in specified mass range and charge correlation. There can be hadronic background present in all cases.

<table>
<thead>
<tr>
<th>N^{+-}</th>
<th>N^{±±}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quarkonia ($J/\psi$, $\psi'$)</td>
<td>$c$-decay chain</td>
</tr>
<tr>
<td>$b$-decay chain (same $b$)</td>
<td>$b$-decay chain (diff $b$)</td>
</tr>
<tr>
<td>$m_{\mu\mu} &lt; 4$ GeV</td>
<td>$b\bar{b} \rightarrow \mu\mu$</td>
</tr>
<tr>
<td></td>
<td>$c\bar{c} \rightarrow \mu\mu$</td>
</tr>
<tr>
<td></td>
<td>Drell-Yan</td>
</tr>
<tr>
<td>Quarkonia (Y family)</td>
<td>$b\bar{b} \rightarrow \mu\mu$ (prompt with osc)</td>
</tr>
<tr>
<td>$b$-decay chain (diff $b$)</td>
<td>$b$-decay chain (diff $b$)</td>
</tr>
<tr>
<td>$m_{\mu\mu} &gt; 4$ GeV</td>
<td>$b\bar{b} \rightarrow \mu\mu$</td>
</tr>
<tr>
<td></td>
<td>$c\bar{c} \rightarrow \mu\mu$</td>
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<td></td>
<td>Drell-Yan</td>
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</tbody>
</table>
mesons and the charmonia states. This region is dominated by the semileptonic decay of open charm mesons. In heavy ion collisions this region can be used to study the modification of charm production in addition to QGP thermal radiation [40].

- The high mass region ($m_{ll} > 3$ GeV) is dominated by the decay of quarkonia ($J/\psi$ and $\Upsilon$), the Drell-Yan process ($q\bar{q} \rightarrow \gamma^* \rightarrow l^+l^-$), and the semileptonic decay of open bottom mesons. One of the signatures of deconfinement in a QGP is the temperature-dependent suppression of quarkonia due to color screening [41]. The high mass region also allows for the study of open bottom modification.

An example plot for the unlike-sign dielectron spectrum in 200 GeV $p+p$ collisions is shown in Fig. 2.5. Similar contributions are expected in 500 GeV dimuon invariant mass spectra. Not shown is the low mass region. Open bottom decays dominate the spectra between the $J/\psi$ and $\Upsilon$ resonance peaks.

### 2.3.2 Like-Sign Spectrum

The like-sign dilepton invariant mass spectrum is dominated by the semi-leptonic decay of open bottom mesons. In the low mass region there can be a contribution from $D$ decay chain or possibly $D^0$ oscillation, though the effects of the latter are expected to be small. These sources are not present in the high mass region and will not be discussed here. In this section, the focus will be on muon pairs, however, the same holds true for electrons.

Open bottom meson decays can produce correlated like-sign pairs in two way:

1. Correlated primary-secondary leptons from decay chain (see Fig. 2.6).

2. Correlated primary leptons from neutral $B$ meson particle/anti-particle oscillation (see Fig. 2.7).
Figure 2.5: Dielectron invariant mass spectrum for p+p collisions at 200 GeV. A similar distribution is expected for dimuons at 500 GeV.

The like-sign dilepton distribution is more naturally broken into two regions based on the ancestor quark. Simulation is used to demonstrate the source and charge correlation of open bottom mesons that decay to muon pairs using $b\bar{b}$ events generated with Pythia 6.421, a Monte Carlo event generator. A detailed discussion of the simulation is provided in Section 6.2. Figure 2.8 shows the invariant mass distributions of dimuons from the same $b$ quark ancestor, different $b$ quark ancestor, and the sum of both quark ancestors. Muons from the same $b$ quark ancestor will predominately result in unlike-sign pairs. Due to the small opening angle, these pairs will appear at lower mass. Like-sign pairs resulting from decay chain or oscillation must be from different $b$ quark ancestors. They will generally have a larger opening angle, and thus, a larger invariant mass. In this study, like-sign dimuons in the high mass region ($m_{\mu\mu} > 5$ GeV) are used to calculate the cross section of $b\bar{b}$.
Figure 2.6: Correlated muon pairs from the primary/secondary $B$ decays. Here, $B$ and $\bar{B}$ are generic open bottom hadrons; $X$, $Y$, and $X'$ are arbitrary decay products.

Figure 2.7: Correlated primary muon pairs from neutral $B$ decays due to oscillations. Here, $B$ is a generic open bottom hadron and $B^0$ can be either $B^0_d$ or $B^0_s$; $X$ and $X'$ are arbitrary decay products.
Figure 2.8: Simulated invariant mass spectra of unlike-sign dimuons (left) and like-sign dimuons (right) from the same $b$ quark ancestor (red), different $b$ quark ancestor (blue), and sum of all unlike-sign (black).
CHAPTER 3

THE PHENIX EXPERIMENT

3.1 The Relativistic Heavy Ion Collider

The Relativistic Heavy Ion Collider (RHIC) is a 3.8 km in circumference particle accelerator at Brookhaven National Laboratory on Long Island, New York. A layout of the RHIC complex is shown in Fig. 3.1. For $p + p$ collisions the beam starts in the LINAC, then is injected into the BOOSTER, AGS, and finally the main RHIC tunnel. For heavy ions collisions, the beams start in the TANDEM where the ions are stripped of their electrons and then accelerated through the BOOSTER and AGS before injection into the RHIC tunnel. RHIC is capable of accelerating heavy ions up to 100 GeV/c$^2$ and protons up to 250 GeV/c$^2$. Table 3.1 lists the beam species and energies that have been collided to date.

RHIC has six intersection points where the two independent rings (denoted yellow and blue) intersect. There are currently two experiments in operation: PHENIX (Pioneering High Energy Nuclear Interaction eXperiment), located at the 8 o’clock position, and STAR (Solenoidal Tracker At RHIC) at the 6 o’clock position.
Figure 3.1: Photograph of the Relativistic Heavy Ion Collider. PHENIX is located at the 8 o’clock position.

Table 3.1: Beam species and center of mass energy provided by RHIC. Data used in this analysis was recorded in 2009 from $p + p$ collisions at 500 GeV.

<table>
<thead>
<tr>
<th>Beam Species</th>
<th>√s (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p + p$</td>
<td>62.4, 200, 500, 510</td>
</tr>
<tr>
<td>$d + Au$</td>
<td>200</td>
</tr>
<tr>
<td>$Au + Au$</td>
<td>7.7, 19.6, 27, 39, 62.4, 130, 200</td>
</tr>
<tr>
<td>$Cu + Cu$</td>
<td>22.4, 62.4, 200</td>
</tr>
<tr>
<td>$Cu + Au$</td>
<td>200</td>
</tr>
<tr>
<td>$U + U$</td>
<td>192</td>
</tr>
</tbody>
</table>
3.2 The PHENIX Detector

The PHENIX detector was designed to study the properties of the hot, dense matter created in heavy ion collisions in addition to understanding the structure of proton spin. It is designed to detect electrons, hadrons, and photons in the central arm and muons in the muon arms. A schematic of the detector system is shown in Fig. 3.2. The central arm detectors cover the rapidity region $|y| < 0.35$ and have an azimuthal coverage of $\pi/2$; the muon arms cover the rapidity range $1.2 < |y| < 2.2$ with $2\pi$ azimuthal coverage.

Data used in this analysis was collected by the muon arms. There are two independent muon spectrometers each consisting of two subsystems: the muon tracker and muon identifier [42]. The north arm covers the rapidity range $1.1 < y < 2.4$ and the south arm covers $-2.2 < y < -1.2$ in rapidity. PHENIX detectors relevant to this study are briefly described in the following subsections.

3.2.1 Beam-Beam Counter

Beam-Beam Counters (BBC) are global detectors used to characterize an event. There are two BBC detectors positioned 144 cm on either side of the interaction point. Each detector consists of 64 Cherenkov counters. The BBCs are used to determine the vertex position, initial collision time, and trigger minimum bias events. The two BBC detectors cover a rapidity range $3.0 < |y| < 3.9$ and azimuthal angle of $2\pi$.

During heavy ion runs, the BBC is used to determine the centrality of an event, defined as:

$$\%\text{Centrality} = 88.5\%(1 - frac(Q_{BBC}))$$  \hspace{1cm} (3.1)

where $frac(Q_{BBC})$ is the fraction of the total BBC charge distribution integrated from zero.
Figure 3.2: The PHENIX detector in 2009 showing the central arm detectors (top) and muon arm detectors (bottom).
to $Q_{BBC}$ and 88.5% is the efficiency of the minimum bias trigger. Using a Glauber Model, the centrality of an event can be related to the mean number of nucleon-nucleon collisions $<N_{\text{coll}}>$ and the mean number of participant nucleons $<N_{\text{part}}>$.

### 3.2.2 Muon Tracker

The Muon Tracker (MuTr) was designed to provide precision tracking of charged particles even in a high-multiplicity environment. It has a mass resolution of $\sigma(M)/M \approx 6%/\sqrt{M}$, corresponding to a spatial resolution of 100 $\mu$m. This degree of resolution should allow the separation of the two charmonia peaks, $\rho/\omega$ from $\phi$, and $\Upsilon_1$ from $\Upsilon_{2s+3s}$.

The MuTr consists of 3 stations of cathode strip chambers positioned within the conical Muon Magnets. Figure 3.3 shows the positions of each station. Station 1 (closest to the interaction region) is divided into quadrants, whereas Stations 2 and 3 are divided into octants. Each station contains three gaps, except Station 3 which only has 2. An optical alignment system is used to keep the chambers within ±25 $\mu$m of their intended position.

Within each station are gaps containing an anode plane, gas gap, and cathode plane. The arrangement of the gaps is shown in Fig. 3.4. Half the cathode plane strips run parallel to the anode wires, while the other half are rotated at stereo angles between 0 and ±11.25° relative to the anode wires. A schematic showing the layout of the gaps for one octant in the south arm is provided in Fig. 3.5. The anode planes are made of alternating 20 mm Au-plated W wires and 75 mm Au-plated CuBe wires spaced 10 mm apart. The gas gaps contain a recirculating mixture of 50% Ar, 30% CO$_2$, and 20% CF$_4$. The detector operates at a voltage of 1850 V and has a gain of $\sim 2 \times 10^4$.

In each station, the position of a muon hit is recorded. Based on the particles’ bend
in the radial magnetic field the momentum of the particle can be determined. Figure 3.6 shows a schematic of the muon magnet polarities. During the 500 GeV $p + p$ run in 2009, the magnet polarity was +++. 

Figure 3.3: South MuTr showing the location of the three stations [42].
Figure 3.4: Structure of the gaps within a station. Each gap consist of two cathode strip planes (blue) and an anode wire plane (red).

Figure 3.5: One octant from south MuTr Station 1 showing the three gaps and orientation of the strips.
Figure 3.6: Schematic of the muon arm magnet polarity. For Run-9 500 GeV $p+p$ collisions the polarity was ++.
3.2.3 Muon Identifier

The Muon Identifier (MuID) is used to identify muons even amidst the large hadronic background. The detector consists of five layers of alternating steel absorbers and Iarocci tubes. Each gap has four large panels and two smaller panels of Iarocci tubes running horizontally and vertically. The orientation of the MuID panels are shown in Fig. 3.7.

Iarocci tubes are planar drift tubes operated in proportionality mode. The tubes consist of 100 µm CuBe anode wires positioned in a plastic cathode which is coated with graphite. Figure 3.8 shows a schematic of an Iarocci tube. The tubes are filled with a gas mixture of CO₂ and up to 25% isobutane.

Due to the large flux of pions and kaons, multiple layers of steel absorbers are used to obtain a $\pi/\mu$ rejection ratio of $\sim 10^{-4}$. The first absorber is the muon magnet backplate which is 30 cm thick in the north arm and 20 cm thick in the south arm. The first two steel plates are 10 cm in thickness and the last two are 20 cm thick. The combined absorber material provides $\sim 5.4$ hadronic interaction lengths. A muon generated at the vertex must have a minimum mean energy of 1.9 GeV to reach the MuID and 2.7 GeV to traverse to the last gap of the MuID.
muons, which increases the acceptance for the $\phi$ meson.

Each MuID gap consists of six panels as shown in Fig. 3.9. They are labeled from 0 to 5 arranged around the square hole where the beam pipe passes through. Panels 0, 2, and 4 lie on the same surface which is 10 cm closer to the vertex than the other panels. The acceptance reaches down to 10$^\circ$ except at the four corners of the square beam hole. The overlap of each panel on the edge minimizes the dead area due to the panel frames.

Figure 3.9: MuID layout

The panels consist of Iarocci type streamer tubes inside aluminum boxes. The tubes are installed in horizontal and vertical orientations as shown in Fig. 3.10. For each orientation there are two layers of tubes which are staggered by one half-cell (5 mm). The two layer tubes are read out as a single-channel and called a two-pack. Compared to a single tube, this two-pack configuration allows a significant increase in efficiency due to the

Figure 3.7: Layout of a single panel in the MuID. There are 5 layers of alternating detector panels and steel absorber.

Figure 3.8: Schematic of the Iarocci tubes used in the MuID.
3.2.4 Muon Event Reconstruction

A fully reconstructed muon event combines the MuID road and the MuTr track. Tracks in the north and south arms are reconstructed independently. Track reconstruction begins in the MuID, in part because the occupancy is lower than in the MuTr due to the absorber layers. First, adjacently hit Iarocci tubes are combined into clusters. At each MuID gap a 2D track is formed using the horizontally and vertically oriented panels. MuID roads (3D tracks) are constructed by matching the $x, y$ hit positions in each of the panels. Since no magnetic field is present in the MuID, the road should be a straight line.

The MuID roads are used as seeds to reconstruct tracks in the MuTr. Adjacently hit strips in the MuTr will be combined into clusters. The distribution of charge within the cluster is fit with a Mathieson distribution to extract the cluster’s center. Cluster centroids from the different planes (rotated at stereo angles to one another) are combined into gap coordinates in the $x, y$ plane. A tracklet or stub is formed using a linear fit to the gap coordinates within a single station. A stub in the last station of the MuTr is matched to potential roads at the first gap in the MuID. The stubs from the other two stations in the MuTr are then combined using a bending plane fit. A linear fit will not work because the MuTr is within a magnet. As will be discussed in the next chapter, various cuts can be placed on the track to ensure its quality.
CHAPTER 4

DATA SELECTION

Data is collected in smaller portions called runs that are usually of no more than one hour in duration. Before any physics analysis can be performed, the quality of the data must be checked. First, an extensive quality assurance analysis is performed on all recorded runs to ensure that the detectors were operating properly. Once good runs are determined, quality cuts are placed on the individual events, tracks, and muon pairs.

The final number of processed runs used in this analysis, minimum bias events, and integrated luminosities for each arm are listed in Table 4.1. The integrated luminosity is related to the number of minimum bias events as:

\[ L = \frac{N_{MB}}{\sigma_{pp}} \quad (4.1) \]

where \( \sigma_{pp} = 59.3 \text{ mb} \) is the inelastic cross section of \( p + p \) collisions at 500 GeV.

Table 4.1: Total number of minimum bias events and luminosity used for this analysis.

<table>
<thead>
<tr>
<th>Arm</th>
<th>Runs Analyzed</th>
<th>( N_{MB} )</th>
<th>Integrated Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>209</td>
<td>( 2.040 \times 10^{11} )</td>
<td>6.63 ( pb^{-1} )</td>
</tr>
<tr>
<td>South</td>
<td>198</td>
<td>( 1.906 \times 10^{11} )</td>
<td>6.19 ( pb^{-1} )</td>
</tr>
</tbody>
</table>
4.1 Quality Assurance & Run Conditions

In this section, a summary of the muon arm quality assurance (QA) for the $\sqrt{s}=500$ GeV $p+p$ data collected in 2009 is provided. There were 306 runs recorded at 500 GeV with run numbers ranging from 275899 to 280242. The following criteria were used to determine the quality of each run:

- Relevant shift leader comments - discard runs that did not end cleanly or where muon arm detectors were not operating properly.

- Number of disabled high voltage channels in the MuTr - run must have less than 25 disabled channels in the north arm and 65 channels in the south arm.

- Cluster size and muon hits- look at the number of muon hits and strips in a cluster and reject any outliers.

- Cluster charge distribution - look at the most probable value and sigma from a Landau fit to the cluster charge distribution. Any outliers were rejected.

- Hot packets are defined as hits more than $2\sigma$ away from the mean and dead packets are defined as packets with no hits. A maximum threshold was set at 5.

- Hot planes are defined as planes with hits more than $1\sigma$ away from the mean and dead planes are defined as planes with no hits. A maximum threshold was set at 5.

Only runs lasting longer than 5 minutes were considered. Run numbers 276324, 276327, 276333, 276332, 276732, 277564, 277837, 278636, 278774, 278804, 279105, 279207, 279208, and 280075 were removed based on relevant shift leader comments.
To ensure that a significant portion of the detector is not disabled, the number of disabled high voltage channels in the MuTr are considered. The number of disabled high voltage channels in the MuTr for both the south and north arms are plotted in Fig. 4.1. A threshold on the maximum number of disabled channels was set at 25 for the north arm and 65 for the south arm. One run in the south arm (276327) did not meet the criteria for maximum number of disabled high voltage channels and was discarded.

The number of clusters and muon hits in each station provide an estimate of how well the channels in the MuTr were operating. Figure 4.2 shows the average number of clusters and muon hits in each MuTr station as a function of run number. Also plotted are the
mean number of clusters and muon hits per station. Table 4.2 lists the mean and standard deviation of the number of clusters in each station of the north and south arms. Runs with significantly larger number of clusters or hits indicates that the detector had significant background noise, while too few clusters or hits indicates that the detector may not be operating properly. Three runs were removed from the north arm data (276528, 276997, 277564) and 13 runs from the south arm data (275941, 276528, 276997, 277019-277022, 277564, 278384, 278399, 278400-278402) due to low cluster numbers and muon hits.

Table 4.2: Average number of clusters in each station in the MuTr.

<table>
<thead>
<tr>
<th>Station</th>
<th>South</th>
<th>North</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.096 ± 0.156</td>
<td>1.189 ± 0.137</td>
</tr>
<tr>
<td>2</td>
<td>1.090 ± 0.122</td>
<td>1.275 ± 0.145</td>
</tr>
<tr>
<td>3</td>
<td>3.119 ± 0.925</td>
<td>6.872 ± 2.114</td>
</tr>
</tbody>
</table>

The distribution of charge within the clusters is fit with a Landau function. The resulting Landau most probable value (MPV) and sigma are extracted for each run. The values from each station are averaged and shown in Fig. 4.3. Runs with a significant deviation in the MPV and sigma were removed. Two runs were removed (276528 and 277564) in the north arm and 5 runs were removed (276464, 276465, 276528, 276619, 276736) in the south arm for significant deviation in the Landau peak sigma.

Figure 4.4 shows the hot and dead packets for both the north and south muon arms. The plots of the hot and dead planes are shown in Fig. 4.5. All runs had less than 4 hot/dead packets and planes. No runs were removed due to hot/dead packets or planes.
Figure 4.2: Number of clusters and muon hits per station for the south (top) and north (bottom) muon arms. 13 runs in the south arm and 3 runs in the north arm were removed.
Figure 4.3: Most probable value and sigma from a Landau fit to the cluster charge distribution for the south (top) and north (bottom) muon arms. 5 runs from the south arm and 2 runs from the north arm were discarded.
Figure 4.4: Hot and dead packets for the south (top) and north (bottom) muon arms. No runs were discarded.
Figure 4.5: Hot and dead planes for the south (top) and north (bottom) muon arms. There are no hot planes or packets. No runs were discarded.
After QA analysis there are 285 good runs in the north arm and 271 good runs in the south arm. A list of these run numbers can be found in the appendix. Unfortunately, not all these runs have files available for data analysis.

4.2 Data Quality Cuts

After data is reconstructed by the PHENIX software, quality cuts are applied to increase the quality of the tracks and reduce unwanted contributions from fake and background tracks. Cuts can be applied at the event, track, or dimuon level. The purpose of these cuts is to increase the probability of selecting a dimuon from heavy flavor decay. The following cut variables are applied to this analysis (values are given in Table 4.3):

- Event BBCz: BBC $z$-vertex cut.
- Track DG0: distance between the reconstructed track projection in the MuTr station 3 to the gap 0 of the MuID and the position of its associated road in this gap.
- Track DDG0: angular difference between the tangent of the MuTr track and the MuID road angle with respect to the beam direction.
- Track $\chi^2$: quality of the track fit.
- Track $p_Z$: muon track longitudinal momentum.
- Track $p_T$: muon track transverse momentum.
- Event $\chi^2_{vtx}$: muon pair vertex fit $\chi^2$.
- MuTr octant cut: requires that the two muons have hits in different octants.
- MuID isolation cut: pair roads do not share the same MuID panel or must be separated by at least 100 cm in the $x, y$-plane.

- MuID hit number cut: roads must have a minimum number of gaps hit.

Some data cuts such as rapidity, MuTr octant cuts, MuID isolation cuts, and BBC $z$-vertex cuts are standard PHENIX muon cuts for heavy flavor analysis. The rapidity ranges of the north and south muon arms are defined using standard values of $1.2 < y < 2.2$ and $-2.2 < y < -1.2$, respectively. The opening angle of muons from heavy flavor decays is large enough that the two muons should not hit the same octant in the MuTr and should be more than 100 cm apart in the MuID. Applying the MuTr octant cut and MuID isolation cut will reduce false tracks and help prevent pairing of muons with hadrons.

Other cuts are dependent on the year the data was collected due to changes in detector material. The optimal values of DG0, DDG0, MuTr $\chi^2$, $|p_z|$, and event $\chi^2$ were determined using simulation. Unfortunately, dimuons from $B\bar{B}$ cannot be used to determine quality cuts because the events are so rare. Instead, cuts are determined by comparing simulated $J/\psi$ events to those from data. Dimuons from $J/\psi$ were chosen due to the relatively high yield and the ability to isolate the signal in data. One million $J/\psi$ events were generated using the Pythia event generator using a realistic BBC $z$-vertex distribution from data and run through the PHENIX detector simulation chain using the PHENIX setup from 2009. Figures 4.7 through 4.11 show a comparison between the simulation and data. Both the simulation and data have been normalized to one.

The quality of track matching between the MuID and MuTr can be controlled by placing cuts on DG0, DDG0, and track $\chi^2$. A schematic of the cuts is shown in Fig. 4.6. Figures 4.7 through 4.9 show the normalized counts for simulation and data. The values for each
4.3 Definition of cuts

Two track-based residual cut sets are used in this analysis as a cross-check. The first sample loose or default are the set of cuts defined where the muon residual distribution drops to zero, thereby encompassing all muons. The second sample tight are a $p_T$-dependent set of cuts which retains 95% of muons for each cut. By definition, this latter set reduces the background substantially, however the trade-off with statistics needs to be considered.

Parameter are chosen in such a way that $\sim 99\%$ of the simulated $J/\psi$ events survive. The values of the parameters used in this analysis are given in Table 4.3.

Cuts are also placed on track $p_T$ and $|p_Z|$. Requiring a minimum $p_T$ for each muon can help reduce the contribution from hadronic background (pions and kaons). A muon must have a minimum $|p_Z|$ in order to make it to the last gap of the MuID and be reconstructed. As shown in Fig. 4.10, there are no reconstructed tracks with $|p_Z| < 1.75$ GeV. Any track with $|p_Z|$ less than this minimum most likely did not originate at the vertex and is not included in this analysis.

Finally, the quality of the pair’s vertex is considered. Figure 4.9 shows the $\chi^2/\text{ndf}$ of the fit to the dimuon vertex. Muons from heavy flavor decay should have vertex positions very close to the event vertex. If one muon in the pair is not from heavy flavor decay or is a hadron, the quality of the dimuon vertex fit will be poor. A $\chi^2/\text{ndf} < 6$ is required for data analysis.

Figure 4.6: Schematic of DG0, DDG0, and track $\chi^2$ definitions.
Figure 4.7: Comparison between data and simulation of the DG0 distribution. Track cut of DG0 < 12 and DG0 < 20 are applied to the north and south arms, respectively.

Figure 4.8: Comparison between data and simulation of the DDG0 distribution. Track cuts of DDG0 < 9 are applied to both the north and south arms.
Figure 4.9: Comparison between data and simulation of the MuTr $\chi^2$ distribution. A track cut of MuTr $\chi^2 < 18$ and MuTr $\chi^2 < 15$ are applied to the north and south arms, respectively.

Figure 4.10: Comparison between data and simulation of the track longitudinal momentum distribution. Track cut of $|p_z| > 1.75$ is used for both the north and south arms.
Figure 4.11: Comparison between data and simulation of the vertex $\chi^2$ distribution. Track cuts of $\chi^2 < 6$ will be applied to both the north and south arms.
<table>
<thead>
<tr>
<th>Cut Type</th>
<th>Cut Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event</td>
<td></td>
<td>BBC z-vertex range</td>
</tr>
<tr>
<td></td>
<td>DG0 North/South</td>
<td>12/20</td>
</tr>
<tr>
<td></td>
<td>DDG0 North/South</td>
<td>9/9</td>
</tr>
<tr>
<td>Track</td>
<td>MuTr $\chi^2$ North/South</td>
<td>18/15</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>p_Z</td>
</tr>
<tr>
<td></td>
<td>single muon $p_T$</td>
<td>$&gt; 1 \text{ GeV}$</td>
</tr>
<tr>
<td></td>
<td>MUID HIT NUMBER CUT</td>
<td>8</td>
</tr>
<tr>
<td>Pair</td>
<td>MUID ISOLATION CUT</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>$\chi^2_{vtx}$</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>rapidity</td>
<td>$1.2 &lt;</td>
</tr>
</tbody>
</table>

Table 4.3: Summary of quality cuts used in this analysis.
CHAPTER 5

ACCEPTANCE AND EFFICIENCY

No detector is 100% efficient nor can it have full geometrical acceptance. Because of this, the detector will only record a fraction of the actual events. To properly correct the observed data it is essential to understand the acceptance and efficiency ($A\epsilon$) of the detector including the efficiency that the charge of the muon is correctly assigned. In the following sections, the $A\epsilon$ correction and charge reconstruction efficiency will be discussed.

5.1 $A\epsilon$ Correction

The $A\epsilon$ is determined using a full GEANT simulation. Twenty million like-sign dimuon events were generated with flat invariant mass between 0.5-15 GeV/c$^2$, flat $p_T$ between 0-12 GeV/c, flat rapidity ($1.0 < |y| < 2.5$), and a realistic z-vertex distribution from data. The input distributions are shown in Fig. 5.1. Because their interaction with the detector material could differ, $\mu^+\mu^+$ and $\mu^-\mu^-$ events were analyzed separately.

The simulated events were then run through PISA and the standard PHENIX offline reconstruction software. A reference run number is used to mimic relevant detector conditions such as MuID tube efficiencies, disabled high voltage channels, and dead areas of the detector. The reference run 278077 was chosen because it occurred approximately halfway through the run period and in the middle of a beam fill. The run dependence of the $A\epsilon$ was accounted for by rerunning the simulation using two different reference run numbers. Run number 275936 occurred early in the run period and was the first run of the fill; run number
280079 was taken at the end of the run period and at the end of the fill. The uncertainty due to run-by-run fluctuations is $\pm 2\%$.

The dimuon invariant mass spectra were constructed for $\mu^+\mu^+$ and $\mu^-\mu^-$ using the same data quality cuts (see section 4.2) as data. The $A\epsilon$ was calculated by dividing the number of reconstructed events by the number of generated events in a given kinematic bin:

$$A\epsilon = \frac{\text{pairs reconstructed}}{\text{pairs generated}}. \quad (5.1)$$

The $A\epsilon$ versus invariant mass for $\mu^+\mu^+$ and $\mu^-\mu^-$ in the north and south arms are shown in Fig. 5.2. In the lower mass region, the $A\epsilon$ is strongly mass dependent. In the higher mass region ($m_{\mu\mu} > 5 \text{ GeV/c}^2$) the $A\epsilon$ becomes flat and approaches $\sim 10\%$ in the south arm and $\sim 11\%$ in the north arm.

During data analysis the total like-sign signal ($\mu^+\mu^+ + \mu^-\mu^-$) is used. Therefore, the
Figure 5.2: $A_\epsilon$ for like-sign dimuons. $\mu^+\mu^+$ are shown in the top panel and $\mu^-\mu^-$ in the bottom panel.

The charge dependence of the $A_\epsilon$, if any, needs to be considered. To accomplish this, the ratio of $A_\epsilon$ for $\mu^+\mu^+$ to $\mu^-\mu^-$, shown in Fig. 5.3, was examined. It was found that the ratio is approximately 1, indicating no significant charge-dependence in the kinematic regions of interest. When correcting the like-sign data, the average of the $A_\epsilon$ for $\mu^+\mu^+$ and $\mu^-\mu^-$ is used and a $\pm2.8\%$ uncertainty is assigned.
5.2 Charge Reconstruction Efficiency

The possibility exists that the detector could incorrectly assign the charge of the muon. High $p_T$ single muon analysis observed that the efficiency of charge reconstruction is dependent on $p_T$. The charge reconstruction efficiency was studied using the 20 M simulated $\mu^+\mu^+$ or $\mu^-\mu^-$ events. To determine the charge reconstruction efficiency, the number of reconstructed $\mu^+\mu^+$ (or $\mu^-\mu^-$) are compared to the total dimuon output ($\mu^+\mu^+ + \mu^-\mu^- + \mu^+\mu^-$) in each $p_T$ bin. For example, the charge reconstruction efficiency for $\mu^+\mu^+$ is calculated as:

$$\text{charge reconstruction efficiency} = \frac{\# \text{ of } \mu^+\mu^+}{\# \text{ of } (\mu^+\mu^+ + \mu^-\mu^- + \mu^+\mu^-)}.$$ (5.2)

Figure 5.4 shows the charge reconstruction efficiency for the south and north muons arms as a function of dimuon $p_T$ for dimuons within the mass range 4-12 GeV/$c^2$ and single muon $p_T > 1$ GeV/$c$. The histograms shown have been rebinned to compare the average charge efficiency over the entire $p_T$ range. The average charge efficiency for the north arm is 0.999

Figure 5.3: Ratio of $A\epsilon$ for $\mu^+\mu^+$ to $\mu^-\mu^-$. The points are consistent with 1.
for both $\mu^+\mu^-$ and $\mu^+\mu^-$. For the south arm the value for $\mu^-\mu^-$ and $\mu^+\mu^-$ is 0.999 and 0.998, respectively.

Figure 5.4: Charge efficiency for $\mu^+\mu^+$ and $\mu^-\mu^-$ in the north (right) and south (left) arms.

Next, the propagation of possible charge misassignment to the data set was examined. To estimate the fraction of unlike-sign muon pairs falsely reconstructed as a like-sign pair, the percent of misassigned charge ($1 - \text{charge reconstruction efficiency}$) for the north (0.001) and south (0.002) arms are multiplied by the ratio of unlike-sign pairs to like-sign pairs from data. Figure 5.5 shows the fraction of fake like-sign pairs versus invariant mass of the dimuon. The average fraction of fake like-sign is 0.4% in the south arm and 0.2% in the north arm. However, this contribution to the uncertainty in not included in the final systematic errors because it is minuscule compared to other uncertainties.
Figure 5.5: Fraction of fake like-sign pairs averaged over both positive and negative charges.
6.1 Analysis Overview

This analysis is the first to use like-sign dileptons to calculate a cross section for bottom quark production. The like-sign signal is a relatively cleaner signal than the unlike-sign signal as it does not contain contributions from quarkonia, open charm, or Drell-Yan. In the high mass region, contributions to correlated like-sign dimuons should mainly come from $B\bar{B}$ decays with a small fraction of hadronic background (dijets or punch through hadrons). Simulation is used to separate the two contributions.

A new analysis method was developed to calculate the $b\bar{b}$ cross section in $p + p$ collisions by utilizing the properties of correlated like-sign dimuons from $B$ meson decays. Using both like-sign and event mixing techniques, the like-sign correlated dimuon signal can be extracted [43]. The properties of like-sign and event mixing techniques in PHENIX are described in detail in PHENIX analysis note #116 [44]. Here, the same notations found in other PHENIX analyses are used.

- Like-sign technique: In a high multiplicity environment where more than two muons are created in one event multiple muon pairs can be made. Some of the pairs are correlated and some are combinatorial (random pairs). These are designated foreground (FG) pairs.

- Event mixing technique: In this technique, muons from one event are paired with
muons from previous events. These are purely combinatorial pairs as correlations can not exist between different events. These are designated background (BG) pairs.

By subtracting the BG pairs from the FG pairs it is possible to isolate the correlated like-sign pairs. The number of correlated like-sign dimuons due to neutral $B^0$ meson oscillation is directly related to the total number of open bottom meson pairs.

The following sections describe the simulations used to separate the signal from $B$ decay and hadronic background, data analysis, and summary of systematic uncertainties.

6.2 Signal Extraction from Simulation

The like-sign signal from bottom decay results from decay chain and $B^0$ oscillation. However, in this analysis the yield of muons from primary $B^0$ decay is needed. Simulation must be used to convert from all like-sign dimuons to primary dimuons from $B$ decay. Pythia 6.421 [45], a Monte Carlo event generator, was used to extract three parameters necessary for this analysis:

1. The ratio of correlated like-sign dimuons from $B^0$ oscillation to the total number of correlated like-sign dimuons. This value is mass dependent.

$$\alpha(m) = \frac{\bar{b}b \to B B^0_{osc} \to \mu^+ \mu^-}{\bar{b}b \to B B \to \mu^+ \mu^-}$$ (6.1)

2. A factor to convert the number of like-sign dimuons resulting from a neutral $B$ meson that has oscillated to the total number of $B$ meson pairs that decay into a dimuon (independent of muon charge) through the primary decay channel.

$$\beta = \frac{\bar{b}b \to B B^0_{osc} \to \mu^+ \mu^-}{\bar{b}b \to B B \to \mu \mu}$$ (6.2)
3. To calculate the total $b\bar{b}$ cross section, the number of dimuons within the visible kinematic range must be converted to the total number of $BB \to \mu\mu$ in all phase space. This is accomplished through a scale factor defined as:

$$scale = \frac{B\bar{B} \to \mu\mu(1.2 < y < 2.2; 5 < m_{\mu\mu} < 10)}{BB \to \mu\mu(all)} \quad (6.3)$$

Results from a NLO simulation were used during data analysis. For comparison, a leading order (LO) Pythia simulation was also run. The differences between the two simulations are included in the systematic uncertainties. The LO simulation is also used to extract the line shape of the like-sign dimuons from open bottom decay.

6.2.1 Next-to-Leading Order Simulation

Approximately 200 billion minimum bias events were generated using Pythia. Parameters used to simulate $b\bar{b}$ production at next-to-leading order from $p+p$ collisions at $\sqrt{s} = 500$ GeV are listed in Table 6.1. By default Pythia includes particle-antiparticle oscillation in the neutral $B$ meson system. Based on the Pythia output, the signal from $B$ mesons that decay into like-sign dimuons due to oscillation can be isolated.

Invariant mass spectra for unlike-sign dimuons, all correlated like-sign dimuons from $B$ decay, like-sign dimuons due to oscillation, and like-sign dimuons due to $b$-decay chain are shown in Fig. 6.1. The peak in the unlike-sign spectrum is from $B \to J/\psi \to \mu^+\mu^-$ decay. In the low mass region the like-sign signal is dominated by dimuons from decay chain. At higher mass the contributions from decay chain and oscillation become comparable. The ratio of like-sign from oscillation to the total like-sign signal in the high mass region is plotted in Fig. 6.2. To determine $\alpha(m)$, the ratio shown in Fig. 6.2 was fit with a 2nd order polynomial.
Based on this simulation study, $\alpha(m) = -0.139 + 0.136m - 0.007m^2$ is used to convert the total like-sign dimuon counts into those due to oscillation.

Muons from decay chain generally have lower $p_T$ than those from primary decay. By applying a minimum $p_T$ cut on each muon the like-sign pairs from decay chain are reduced, thus increasing the percentage of the correlated like-sign dimuons due to $B$ oscillation. Figure 6.2 shows the ratio of correlated like-sign dimuons due to oscillation with no $p_T$ cut and with a 1 GeV $p_T$ cut. While the single muon $p_T$ cut does not drastically affect the high mass signal, the 1 GeV $p_T$ cut was used for data analysis in order to reduce the hadronic background. The percent of like-sign dimuons due to oscillation is larger in the muon arm acceptance than in $4\pi$ acceptance. This is because the rapidity cut acts as a cut on the opening angle of the muons.

The value of $\beta$ is extracted by finding the ratio of like-sign dimuons from a $B$ pair where one of the mesons has oscillated to the total number of $B$ pairs that decay into a dimuon, regardless of charge, through the primary decay channel. From this NLO simulation, the value of $\beta$ was found to be 0.212. This value is based solely on the neutral $B$ meson mixing parameters, branching fractions, and semi-muonic branching ratios.

When analyzing data, dimuons from $B$ decays are only observed in a limited kinematic region ($1.2 < |y| < 2.2; 5 < m_{\mu\mu} < 10$ GeV). A scale factor is needed to convert from the observed cross section in the limited visible kinematic region to the full kinematic phase space. To determine the scale factor it is first necessary to understand how the rapidity distribution of the parent $B$ changes when cuts on the muon rapidity and dimuon mass are applied. Figure 6.3 shows the rapidity distribution of the $B$ parent particle when there are no kinematic cuts, when both muons are in the muon arm acceptance, and when both
muons are in the muon arm acceptance and the dimuon mass is between 5 and 10 GeV. As the kinematic range becomes more limited the percent of events that can be detected is reduced. The scale factor of 0.0021 is determined by integrating the histogram with both muon rapidity and dimuon mass cuts and then dividing by the total number of $B \bar{B} \rightarrow \mu \mu$. It should be noted that the muons from parents outside the muon arm rapidity acceptance can decay into the muon arm acceptance. This is contrary to quarkonia (a $1 \rightarrow 2$ process) where both the parent particle and dimuon must have a rapidity within the muon arm acceptance.

Uncertainties in the open bottom simulation can be divided into correlated (Type B) and global (Type C). One source of uncertainty originates from model-dependent simulation inputs. A conservative value of ±35% is assigned as a Type B uncertainty. Additional uncertainties arise from the mixing parameter (±1.3%), $b$ quark fragmentation (±2%), and branching ratios (±3.6%). To get the uncertainty from the branching ratios, the three most significant decay channels were chosen: $B \rightarrow \mu$, $B \rightarrow D^0 \rightarrow \mu$, and $B \rightarrow D^+ \rightarrow \mu$. This results in a total Type C uncertainty of ±4.3% from simulation inputs.
Table 6.1: Parameters used in Pythia simulation for NLO $b\bar{b}$ production.

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Figure 6.1: Invariant mass plots from NLO Pythia simulation showing the unlike-sign (black), all like-sign (green), like-sign from oscillation (red), and like-sign from $B$-decay chain (blue) dimuons from open bottom decay. The plots on the left side are for $4\pi$ acceptance. On the right side are within the PHENIX muon arm acceptance.
Figure 6.2: Ratio of correlated like-sign dimuons from $B$ meson oscillation from a NLO Pythia simulation. The top panel has no $p_T$ cut applied. In the bottom panel a minimum $p_T$ cut of 1 GeV is applied.
Figure 6.3: Rapidity distribution of the muon’s parent from NLO simulation for all kinematic range (black), both muon in the muon arm acceptance (blue), and both muon in the muon arm acceptance and dimuon mass 5-10 GeV (red).
6.2.2 Leading Order Simulation

At LO there are less mechanisms available to produce $b\bar{b}$. Additionally, the $b\bar{b}$ should be produced back-to-back. Another Pythia simulation was run at LO in order to account for any differences from the NLO simulation that may exist. 200 million $b\bar{b}$ events were generated and allowed to decay freely. The parameters used in the $\sqrt{s} = 500$ GeV LO simulation are listed in Table 6.2.

![Table 6.2: Parameters used in the LO Pythia simulation for $b\bar{b}$ production.](image)

<table>
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Similar to the NLO simulation, the invariant mass spectra of unlike-sign dimuons, all correlated like-sign dimuons, like-sign dimuons due to oscillation, and like-sign dimuons due to decay chain are constructed. The invariant mass plots are shown in Fig. 6.4.

Figure 6.5 shows the ratio of correlated like-sign dimuons due to oscillation with no $p_T$
cut and with a 1 GeV $p_T$ cut on the single muons. Similar to the NLO simulation, the ratio is mass dependent. From the LO simulation, a fit to the ratio of like-sign dimuons from $B$ oscillation yields $\alpha(m) = -0.132 + 0.143m - 0.007m^2$. Using the LO simulation the values for $\beta$ and the scale factor were calculated to be 0.216 and 0.0017, respectively.

Differences between results extracted using LO versus NLO simulation contribute to the global Type C systematic uncertainty. Comparing the values of $\alpha(m)$ and $\beta$ between LO Pythia simulation and NLO Pythia simulation results in an uncertainty of +8.8%. The LO and NLO scale factors contribute an additional +25% uncertainty, which will only affect the total cross section.
Figure 6.4: Invariant mass plots from LO Pythia simulation showing the unlike-sign (black), all like-sign (green), like-sign from oscillation (red), and like-sign from $B$-decay chain (blue) dimuons from open bottom decay.
Figure 6.5: Ratio of correlated like-sign dimuons from $B$ meson oscillation from a LO Pythia simulation. The top panel has no $p_T$ cut applied. In the bottom panel a minimum $p_T$ cut of 1 GeV is applied.
Figure 6.6: Rapidity distribution of the muon’s parent from LO simulation for all kinematic range (black), both muon in the muon arm acceptance (blue), and both muon in the muon arm acceptance and dimuon mass 5-10 GeV (red).
6.2.3 Open Bottom Line Shape

To extract the component of like-sign dimuons from open bottom decay in data, the line shape of the invariant mass distribution must be determined using simulation. The LO open bottom simulation was used rather than the minimum bias NLO simulation in order to achieve higher statistics. Muons from open bottom decay were sent through PISA and then analyzed with the PHENIX reconstruction software.

The invariant mass spectra of like-sign dimuons are shown in Fig. 6.7. In the high mass region the shape of the invariant mass spectrum can be approximated by an exponential function. To find the line shape a single exponential function is fit between 5 to 10 GeV. The slopes were found to be $-0.879 \pm 0.043$ for the south arm and $-0.875 \pm 0.038$ for the north arm.
Figure 6.7: Like-sign dimuons from open bottom simulation. An exponential fit (red) was used to get the line shape.
6.2.4 *Open Charm Simulation*

To ensure the correlated like-sign pairs in the high mass region are purely from $b$-decays, a similar Pythia simulation was run for $c\bar{c}$ production. 100 million events were generated at LO and allowed to decay freely. Parameters used to tune the simulation are listed in Table 6.3. The effect of $D^0 (c\bar{u})$ meson oscillation is expected to be extremely small [46]. Therefore, no contribution to the correlated like-sign dimuon signal from the primary decay of open charm mesons is expected. Correlated like-sign pairs can be produced through its decay chain ($D \rightarrow K \rightarrow \mu$). These pairs will appear at lower invariant mass.

The invariant mass distributions for both like-sign and unlike-sign dimuons are shown in Fig. 6.8. Placing a $p_T$ cut of 1 GeV on the single muon removes the majority of like-sign signal. The few counts that are remaining in the high mass region are due to underlying events and are not correlated. Based on the lack of correlate like-sign pairs in the high mass region, it was concluded that there is no significant contribution to the correlated like-sign signal from open charm decay.
Table 6.3: Parameters used in Pythia simulation for $c\bar{c}$ production.

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Figure 6.8: Invariant mass plots of the unlike-sign (black) and all like-sign (green) dimuons from open charm generated in Pythia. The small number of counts in the high mass region are due to underlying events and are not correlated.
6.3 Jet Background Estimates

In nucleus-nucleus collisions many hadrons are produced, especially pions and kaons. These can create a background to the open bottom signal. Some hadron pairs that originate from dijets can be misreconstructed as heavy flavor muons. In other cases the hadrons may punch through the absorbers in the MuID and be recorded as a muon. Simulation is used to estimate the contribution to the correlated like-sign signal from dijets and punch through hadrons. This analysis is broken into three parts:

1. Demonstration of the differences between like-sign and event mixing.

2. Determining the $p_T$-dependent survival probability that a hadron will traverse the muon arm detectors.

3. Calculate the contribution of hadrons to the final correlated like-sign signal.

6.3.1 Like-sign vs Event Mixing

If particle distributions are not Poisson, the like-sign and event mixing methods do not give identical results. To study this effect, 10 million events were generated in Pythia using Tune A parameters and a realistic $z$-vertex distribution from data. Tune A parameters, listed in Table 6.4, were originally proposed by the CDF collaboration in order to account for the multiparticle interactions in underlying event. The same set of parameters has been used in the study of double helicity in jets [47] and $W \rightarrow \mu$ analysis [48] at PHENIX.

First, a foreground (FG) histogram is filled with like-sign pairs from the same event within the same muon arm. A background (BG) histogram is then constructed by pairing a particle in the current event with like-sign particle in the 10 previous events. When making the FG
Table 6.4: Parameters used in Pythia Tune A simulation for jet production.

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Figure 6.9: FG and BG like-sign invariant mass spectra showing the deviation at higher mass.

and BG histograms, only events with similar z-vertex are combined. Just as in data analysis, there are 10 z-vertex bins covering the vertex range from $-30$ cm to $+30$ cm. Figure 6.9 shows the FG and BG histograms for events. In the lower mass region (below 2 GeV) the two histograms appear to overlap. However, as mass increases the number of like-sign pairs from the same event (FG) and from event mixing (BG) begin to deviate. When the BG pairs are subtracted from the total FG signal (as is done to extract the correlated like-sign signal in data), this will result in an excess of like-sign pairs due to hadronic background which can not be removed via the event mixing scheme.
6.3.2 Single Hadron Survival Probability

To find the survival probability for a hadron in the muon arms, pions and kaons from 20 million events generated with Pythia 6.421 were run through the PISA simulation chain. A minimum parton $p_T$ cut of 2.5 GeV was applied to increase the statistics in the high mass region. PISA was run using both FLUKA and GHEISHA hadron interaction packages. Based on single muon analysis [49], it was found that the GHEISHA package propagates fewer hadrons than FLUKA through the absorber layers. However, it was also noted that GHEISHA allows more low $p_T$ hadrons than FLUKA. This last difference between packages shouldn’t significantly affect the single hadron survival probability because a minimum $p_T$ cut at 1 GeV is placed on reconstructed tracks.

Figure 6.10 shows the $p_T$ dependent single hadron survival probability. For each arm, the total output counts in a specific $p_T$ bin are divided by the original number of counts in that $p_T$ bin. Each histogram is then fit with both an exponential and a third degree polynomial function. The line shapes are what are used to determine the survival probability of a single hadron. Differences between the two packages and the two fit functions are included in the systematic uncertainties.

6.3.3 Jet Contribution to Data

Now that the single hadron survival probability has been determined, the contribution from dijets and punch through hadrons to the correlated like-sign signal from data can be estimated. This is done using 40 million minimum bias events generated in Pythia. The FG and BG histograms are constructed with each entry weighted by the probability that the given pair makes it through the detectors. The excess counts that might be present in the
Figure 6.10: $p_T$ dependent hadron survival probability using the FLUKA (top two images) and GHEISHA (bottom two images) hadron interaction packages. A minimum parton $p_T$ of 2.5 GeV was used.
correlated like-sign data due to jets are estimated by subtracting the BG histogram from the FG histogram.

Figure 6.11 show the invariant mass distributions from pions and kaons that are expected in the correlated like-sign spectra for the north and south muon arms in the full data sample. The four different combinations are shown separately in Fig. 6.11: (1) FLUKA package with exponential fit to single hadron survival probability, (2) FLUKA package with 3rd degree polynomial fit to single hadron survival probability, (3) GHEISHA package with exponential fit to single hadron survival probability, and (4) GHEISHA package with 3rd degree polynomial fit to single hadron survival probability. The invariant mass distributions for the four cases are averaged and fit with an exponential function between 5 to 10 GeV. The slopes are found to be $-0.457\pm0.025$ for the south arm and $-0.476\pm0.029$ for the north arm. This line shape, shown in Fig. 6.12, will be used later to extract the irreducible hadronic background from data.
Figure 6.11: Correlated like-sign signal that can be present from jet background in the south arm (top) and north arm (bottom). Four different cases are considered as described in the text.
Figure 6.12: Averaged like-sign jet background in the south arm (top) and north arm (bottom). The simulation was fit with an exponential function (red) in order to extract the line shape.
6.4 Results

The purpose of this analysis is to calculate the cross section of bottom quark production. This is accomplished by developing a new method to use the correlated like-sign signal due to $B^0$ oscillation. The following sections discuss how to extract the correlated like-sign dimuon signal due to $B^0$ oscillation, convert to total number of $B$ meson pairs, and calculate the invariant yield and differential cross section of dimuons from $b\bar{b}$ decays. Finally, the differential cross section of dimuons from bottom decay is extrapolated to a total $b\bar{b}$ cross section and compared with pQCD calculations.

6.4.1 Isolating the Correlated Like-Sign Signal

Using both like-sign and event mixing techniques, the like-sign correlated dimuon signal can be extracted [43]. The like-sign technique is used to create a foreground (FG) signal, constructed by pairing like-sign muons in the same event. This will consist of both correlated and combinatorial like-sign pairs (i.e. $N_{FG}^{\pm\pm} = N_{corr}^{\pm\pm} + N_{comb}^{\pm\pm}$). Using the event mixing technique a background (BG) is constructed by pairing like-sign muons from different events. The BG will contain only combinatorial like-sign pairs (i.e. $N_{BG}^{\pm\pm} = N_{comb}^{\pm\pm}$). By subtracting the signal from event mixing from the like-sign signal the correlated like-sign pairs can be isolated:

$$N_{corr}^{\pm\pm} = N_{FG}^{\pm\pm} - N_{BG}^{\pm\pm} \quad (6.4)$$

The BG will have significantly more statistics since each muon is paired with other muons in the 10 previous events and must be scaled back to the FG. To accomplish this, a mass window is chosen where the integrated number of BG pairs will be scaled to equal the
integrated number of FG pairs. The normalization factor is calculated as:

$$\text{normalization} = \frac{\sqrt{N_{FG}^{++}N_{FG}^{--}}}{\sqrt{N_{BG}^{++}N_{BG}^{--}}}.$$  \hspace{1cm} (6.5)

where $N_{FG}^{++}$ and $N_{FG}^{--}$ are the number of $\mu^+\mu^+$ and $\mu^-\mu^-$ in the FG and $N_{BG}^{++}$ and $N_{BG}^{--}$ are the number of $\mu^+\mu^+$ and $\mu^-\mu^-$ in the BG. The normalization range was chosen so that the contribution of correlated like-sign pairs are negligible. Four different normalization windows of 2.6-3.6 GeV, 1.6-4.2 GeV, 0.5-2.6 GeV and 0.5-3.6 GeV were chosen. The normalization window is never allowed to extend into the high mass region where the correlated like-sign signal becomes significant. The differences in yields between these four normalization windows is included in the systematic uncertainties.

Figure 6.13 shows the invariant mass spectra using a normalization range of 2.6-3.6 GeV for like-sign pairs from the same event ($N_{FG}^{++} = N_{FG}^{--}$), event mixing ($N_{BG}^{++} = N_{comb}^{--}$), and the difference between the two ($N_{corr}^{++}$). The latter is the correlated like-sign signal used to calculate the bottom yield. This signal, however, contains both the like-sign from $B$ decay along with the hadronic background.
Figure 6.13: Raw invariant mass spectra for like-sign pairs from the same event $N_{\pm\pm}$, event mixing ($N_{\pm\pm}^{comb}$), and the difference between the two ($N_{\pm\pm}^{corr}$) for the south muon arm (top) and north muon arm (bottom). Counts have been scaled by $1/N_{MB}$.
6.4.2 Signal Extraction

The correlated like-sign signal extracted in the previous section contains contributions from both $B$ decay and hadronic background. The two components can be separated using simulation. Similar to previous dimuon analysis, the data is fit with a cocktail of known sources. In this analysis the only contribution to the like-sign signal will be from open bottom decay and some hadronic background. A double exponential function is fit to data, where each exponential represents one of the contributions:

$$Fit(m) = \exp(p_0 + m \cdot p_1) + \exp(p_2 + m \cdot p_3).$$  \hfill (6.6)

A description of each parameter and its value are listed in Table 6.5. When fitting the function to data, the slopes were fixed from simulation (see Sections 6.2.3 and 6.3.3) and the yield allowed to float.

Table 6.5: Parameters used in the double exponential fit. Slopes were fixed to the values listed below and the amplitude was allowed to vary.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_0$</td>
<td>hadronic background yield</td>
<td>free</td>
</tr>
<tr>
<td>$p_1$</td>
<td>slope of hadronic background</td>
<td>-0.457 (S) / -0.476 (N)</td>
</tr>
<tr>
<td>$p_4$</td>
<td>open bottom yield</td>
<td>free</td>
</tr>
<tr>
<td>$p_3$</td>
<td>slope of open bottom</td>
<td>-0.879 (S) / -0.875 (N)</td>
</tr>
</tbody>
</table>

Figure 6.14 shows the raw data from one normalization range (2.6-3.6 GeV) with the double exponential fit (black). Also shown are the individual contributions from open bottom (blue) and from the hadronic background (red). There appears to be more hadronic
background in the south arm as seen in the plots. The contribution from open bottom is almost identical between the two arms. Because the shapes of the two components are not precisely known, the fits are recalculated after varying the slopes by ±10% of the simulated values. These differences are shown by the bands in Fig. 6.14. Uncertainty in the line shapes contribute a combined uncertainty to the Type B systematics of +7.7% in the north arm and +8.9% in the south arm.

To determine the raw yield of like-sign dimuons due to open bottom decay the open bottom component from the fit is integrated between 5 and 10 GeV. Table 6.6 lists the raw yield (i.e. not corrected for $A\epsilon$) of like-sign dimuons from bottom decay from the four normalization ranges and the corresponding RMS value. To extract any physical results, the data cannot be biased by the detector performance. The data is divided bin-by-bin by the mass-dependent $A\epsilon$. The $A\epsilon$ corrected yields from four normalization windows are listed in Table 6.7. When calculating the yield, the average $A\epsilon$ correction for like-sign ($++$ and $--$) is used. This introduces a small systematic uncertainty of ±2%.

The RMS value of the yield from the four normalization windows are used in subsequent calculations. Variations between the normalization windows are included in systematic uncertainty. This results in a Type A uncertainty of ±12.3% in the south arm and ±7.6% in the north arm.
Table 6.7: $A\epsilon$ corrected correlated like-sign dimuon yields from open bottom decay including statistical error for four normalization ranges. The RMS values are used in subsequent cross section calculations.

<table>
<thead>
<tr>
<th>Rapidity</th>
<th>[2.6, 3.6]</th>
<th>[1.6, 4.2]</th>
<th>[0.5, 2.6]</th>
<th>[0.5, 3.6]</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-2.2 &lt; y &lt; -1.2$</td>
<td>1445.6±118.5</td>
<td>1731.6±142.0</td>
<td>2051.3±168.2</td>
<td>1869.7±153.3</td>
<td>1788.3±146.6</td>
</tr>
<tr>
<td>$1.2 &lt; y &lt; 2.2$</td>
<td>1517.0±133.5</td>
<td>1679.8±147.8</td>
<td>1873.1±164.8</td>
<td>1770.3±155.8</td>
<td>1715.0±150.9</td>
</tr>
</tbody>
</table>

A slight excess of correlated like-sign dimuons from open bottom decay is observed in the south muon arm even after $A\epsilon$ correction. A similar trend has been seen in the acceptance corrected $J/\psi$ yields in the same data set [50]. Because this is a symmetric collision system, the arm averaged values are used when calculating the total cross section and a systematic uncertainty assigned.
Figure 6.14: Invariant mass plot of the correlated like-sign dimuons in the south arm (top) and north arm (bottom). The open bottom and hadronic background components are shown along with the double exponential fit. Normalization window is 2.6-3.6 GeV.
6.4.3 Calculating the Number of $B$ Meson Pairs

To get the number of $B \to \mu$ pairs from the yield of like-sign dimuons first the number of $B \to \mu$ pairs due to particle-antiparticle oscillation must be determined. As described in Section 6.2, the number of correlated like-sign pairs in the high mass region due to particle-antiparticle oscillations of $B^0_d$ and $B^0_s$ can be extracted using simulation. The number of like-sign dimuons from oscillation is equal to:

$$N_{\pm \pm}^{\text{osc}} = \alpha(m) \times \frac{N_{\pm \pm}^{\text{corr}, BB}}{A\epsilon}$$

(6.7)

where $\alpha(m)$ is the fraction of like-sign dimuons from $B^0$ oscillation determined from NLO Pythia simulation and $N_{\pm \pm}^{\text{corr}, BB}/A\epsilon$ is the number of $A\epsilon$ corrected like-sign dimuons from $B$ decay.

Next, the total number of $B$ meson pairs that decay into a primary dimuon (regardless of charge) can be extrapolated:

$$N_{BB} = \alpha(m) \times \frac{N_{\pm \pm}^{\text{corr}, BB}}{A\epsilon} \times \frac{1}{\beta},$$

(6.8)

where $\beta$ is the percent of all $B$ meson pairs that decay into primary dimuon as determined from Pythia simulation:

$$\beta = \frac{b\bar{b} \to BB_{\text{osc}} \to \mu^\pm \mu^\pm}{b\bar{b} \to BB \to \mu\mu} = 0.212$$

(6.9)

Table 6.8 lists the $A\epsilon$ correlated like-sign pairs due to oscillation and the total number of $B$ meson pairs that decay into primary muons.
Table 6.8: $A \epsilon$ corrected yields of correlated like-sign pairs due to neutral $B$ meson oscillation and total $B$ meson pairs including statistical error.

<table>
<thead>
<tr>
<th>Rapidity</th>
<th>$N_{osc}^{\pm \pm}$</th>
<th>$N_{B\bar{B}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-2.2 &lt; y &lt; -1.2$</td>
<td>759.8±62.3</td>
<td>3584.0±293.9</td>
</tr>
<tr>
<td>$1.2 &lt; y &lt; 2.2$</td>
<td>728.8±64.1</td>
<td>3437.7±302.5</td>
</tr>
</tbody>
</table>

6.4.4 Invariant Yield Calculations

The invariant yield gives the number of particles per minimum bias event in a given kinematic window. In this analysis only invariant yield with respect to rapidity is considered.

The invariant yield of dimuons from $B\bar{B}$ primary decay is calculated as:

$$
\frac{dN_{B\bar{B}\rightarrow \mu\mu}}{dy} = \frac{1}{\Delta y} \frac{N_{B\bar{B}\rightarrow \mu\mu} \epsilon_{MB}^{BBC} \epsilon_{HS}^{BBC}}{N_{MB}}
$$

(6.10)

where $\epsilon_{MB}^{BBC} = 0.548$ is the BBC efficiency for minimum bias events, $\epsilon_{HS}^{BBC} = 0.91$ is the efficiency of the BBC for hard scattering events, and $N_{MB}$ is the number of minimum bias events. $N_{MB}$ is $2.040 \times 10^{11}$ for the north arm and $1.906 \times 10^{11}$ for the south arm. Values for $N_{B\bar{B}}$ are taken from Table 6.8. Note the number of dimuons from primary decay of $B\bar{B}$ ($N_{B\bar{B}\rightarrow \mu\mu}$) have already been $A \epsilon$ corrected. The resulting invariant yields, including statistical and systematic errors, are listed in Table 6.9.

Table 6.9: Invariant yield of dimuons from $B$ meson pairs in the muon arms.

<table>
<thead>
<tr>
<th>Rapidity</th>
<th>$dN_{B\bar{B}\rightarrow \mu\mu}/dy$ ($\times 10^{-8}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-2.2 &lt; y &lt; -1.2$</td>
<td>$1.13 \pm 0.16$ (stat + Type A) $\pm 0.41$ (Type B)</td>
</tr>
<tr>
<td>$1.2 &lt; y &lt; 2.2$</td>
<td>$1.01 \pm 0.11$ (stat + Type A) $\pm 0.37$ (Type B)</td>
</tr>
</tbody>
</table>
Figure 6.15 shows the invariant yield of dimuons from $B\bar{B}$ decay at forward and backward rapidity. The points are plotted at ±1.7 in rapidity, which is the average rapidity of muons in the muon arm acceptance. Note that for semileptonic decays, muons in the muon arm acceptance can probe $B$ parents outside the acceptance. The average rapidity of muons in the muon arm acceptance and $B$ parents with decay muons in the muon arm acceptance are the same.

Figure 6.15: Invariant yield of muons from $B\bar{B}$ decay. The bars show statistical and uncorrelated errors and the box shows correlated (Type B) errors. There is also a global uncertainty of $+14.0\%$ $-10.9\%$. 

2009 p+p, $\sqrt{s}=500$ GeV
$5$ GeV $< m_{\mu\mu} < 10$ GeV

PHENIX preliminary
6.4.5 Cross Section Calculations

The cross section is a useful measure of particle production and is related to the probability that a specific process or scattering occur. The differential cross section of dimuons from $b\bar{b}$ is calculated from the invariant yield of $B \rightarrow \mu$ pairs:

$$\frac{d\sigma_{b\bar{b}\rightarrow\mu\mu}}{dy} = \frac{dN_{B\bar{B}\rightarrow\mu\mu}}{dy} \sigma_{pp}. \quad (6.11)$$

The cross section of $p + p$ collisions $\sigma_{pp}$ at 500 GeV can be calculated using the BBC cross section and BBC efficiency:

$$\sigma_{pp} = \frac{\sigma_{BBC}}{\epsilon_{BBC}} MB = 59.3 \text{ mb} \quad (6.12)$$

where the $p + p$ cross section at 500 GeV seen by the BBCs is $\sigma_{BBC} = 32.5 \pm 3.2 \text{ mb}$ [51]. This value was determined using Van der Meer scan techniques [52].

The differential cross section for the north and south muon arms in addition to the arm average are listed in Table 6.10. Figure 6.16 shows the differential cross section at forward and backward rapidity. Again, the points are plotted at $\pm 1.7$ in rapidity since this is the average rapidity range covered by muons in the muon arm acceptance. For comparison, the differential cross section from LO Pythia is also plotted. The Pythia points are offset in the $x$-axis for clarity. The uncertainty in the Pythia value is obtained by varying the $b$ quark mass between 4 and 5 GeV. As noted in Section 6.4.2, there is a discrepancy between the north and south arms. Because this is a symmetric system, the arm averaged differential cross section is used to calculate the total cross section and a $\pm 5\%$ uncertainty is assigned.

To extrapolate the differential cross section of dimuons from $b\bar{b}$ decay to a total $b\bar{b}$ cross section the arm-averaged differential cross section is scaled by the ratio of $B$ pairs that decay to muons through the primary decay channel within the visible region to those over the entire
Table 6.10: Differential cross section of muons from $b\bar{b}$ decay. The arm averaged value includes systematic uncertainty due to north/south discrepancy.

<table>
<thead>
<tr>
<th>Rapidity</th>
<th>$d\sigma_{b\bar{b} \rightarrow \mu\mu}/dy$ (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-2.2 &lt; y &lt; -1.2$</td>
<td>$0.67 \pm 0.10 \text{ (stat + Type A)} \pm 0.24 \text{ (Type B)}$</td>
</tr>
<tr>
<td>$1.2 &lt; y &lt; 2.2$</td>
<td>$0.60 \pm 0.07 \text{ (stat + Type A)} \pm 0.22 \text{ (Type B)}$</td>
</tr>
<tr>
<td>arm average</td>
<td>$0.64 \pm 0.08 \text{ (stat + Type A)} \pm 0.23 \text{ (Type B)}$</td>
</tr>
</tbody>
</table>

Figure 6.16: Invariant cross section of muons from $b\bar{b}$ decays. The bars show statistical and uncorrelated errors and the box shows correlated (Type B) errors. A comparison with LO Pythia is provided.
kinematic range. This method is similar to that used by the ZEUS Collaboration [53]. The total cross section is calculated in the following way:

$$\sigma_{b\bar{b}} = \frac{d\sigma_{b\bar{b} \rightarrow \mu\mu}}{dy} \times \frac{1}{\text{scale}} \times \frac{1}{BR_{B \rightarrow \mu}^2}$$  \hspace{1cm} (6.13)$$

where $d\sigma_{b\bar{b} \rightarrow \mu\mu}/dy$ is the arm averaged value from Table 6.10, $BR_{B \rightarrow \mu}$ is the branching ratio of $B$ to muon through the primary decay channel (=10.95%), and $\text{scale}$, defined in Eqn. 6.3, is the factor used to convert from the visible kinematic region to full phase space. The scale factor of 0.0021 was calculated using the Pythia simulation (see Section 6.2). This results in an experimental cross section of $25.2 \pm 3.2$ (stat) $^{+11.4}_{-9.5} \mu b$ (sys).

The $\sigma_{b\bar{b}}$ measured at 500 GeV is shown in Fig. 6.17 and compared to those from other experiments [2, 3, 4, 6, 8, 54] and NLO pQCD theory [55]. The solid line is the cross section from NLO pQCD calculations and the dashed lines are error bands on the NLO pQCD calculations. At $\sqrt{s} = 500$ GeV, NLO pQCD predicts $\sigma_{b\bar{b}} = 11.2^{+6.4}_{-3.3} \mu b$. The bottom panel of Fig. 6.17 shows the ratio of data to theory. The cross section measured using the current dimuon analysis is approximately twice the pQCD theory central value, but consistent within uncertainties. In this analysis, neutral $D$ meson oscillation was not included. The contribution to the like-sign signal is expected to be very small since the oscillation probability is very small. It is possible, however, that this effect could contribute to some of the excess correlated like-sign dimuons.
Figure 6.17: Comparison of $\sigma_{bb}$ at different center of mass energies with NLO pQCD theory. The data point labeled “dimuon” is from this analysis. The bottom panel shows the ratio of data to NLO theory.
6.5 Error Summary

Here, the systematic uncertainties in this analysis are outlined. The following types of uncertainties are considered.

1. point-to-point uncorrelated systematic errors (Type A). Points can vary independently from others within error limits.

2. point-to-point correlated errors (Type B). Points vary together within error limits.

3. global systematic errors (Type C). All points move by a fixed fraction of their values.

The following subsections detail the types of uncertainties and contributions to the final results. A summary of the uncertainties is provided in Tables 6.5 and 6.6. Table 6.5 lists uncertainties contributing to the invariant yield and differential cross section. Table 6.6 lists uncertainties in the total cross section.

6.5.1 Signal Extraction

To find the uncertainty associated with the normalization factor in event mixing, four different normalization windows [2.6,3.6], [1.6,4.2], [0.5,2.6], and [0.5,3.6] were considered. The systematic uncertainty due to normalization range was determined using the RMS between the yields. This results in an uncertainty of ±12.3% in the south arm and ±7.6% in the north arm. These are point-to-point uncorrelated errors (Type A) and added in quadrature to the statistical uncertainty.
6.5.2 North/South Discrepancy and Arm Average

A discrepancy was noticed in the acceptance corrected yields between the north and south arms. Because this is a symmetric system the arm averaged differential cross section was used to calculate the total cross section. This introduces a ±5% Type B uncertainty in the total cross section.

6.5.3 Acceptance and Efficiency

The run dependence of $A\epsilon$ was accounted for by rerunning the simulation using two different reference run numbers. Run number 275936 occurred early in the run period and was the first run of the fill; run number 280079 was taken at the end of the run period and at the end of the fill. The uncertainty due to run-by-run fluctuations is ±2%. These errors are point-to-point correlated (Type B). There is an additional ±2% Type B uncertainty introduced by averaging the $++$ and $--$ $A\epsilon$ histograms. This results in a total Type B uncertainty of ±2.8%.

6.5.4 Detector Efficiency

Based on previous Muon Arm analysis [56], a ±4% uncertainty from MuID tube efficiency and ±2% from MuTr overall efficiency were assigned. These errors are point-to-point correlated (Type B). A global (Type C) uncertainty of ±10% is assigned to account for the BBC efficiency.
6.5.5 Model Dependent Simulation

A global Type C uncertainty results from the mixing parameters, fragmentation ratios, and branching ratios. A ±1.3% uncertainty in the mixing parameter and a ±2% uncertainty due to $b$ quark fragmentation was assigned. To get the uncertainty from the branching ratios, the three most significant decay channels were chosen: $B \rightarrow \mu$, $B \rightarrow D^0 \rightarrow \mu$, and $B \rightarrow D^+ \rightarrow \mu$. This results in a ±3.6% uncertainty from the branching ratio. This total Type C uncertainty from simulation inputs is ±4.3%. The largest unknown is the ratio of like-sign pairs due to oscillation. An additional ±35% uncertainty is added due to uncertainty in the $\alpha(m)$ function, $\beta$, and the scale factor.

6.5.6 Leading Order vs. Next-to-Leading Order

Values for $\alpha(m)$, $\beta$, and the scale factor were extracted from the LO and NLO simulations. The NLO values were used in all calculation, and were compared with LO values to determine uncertainty. The difference between LO and NLO results for the invariant yield and differential cross sections results in a +8.8% uncertainty. An additional uncertainty is introduced when calculating the total cross section due to the scale factor. The uncertainty when calculating the total cross section is +25%. The difference between LO and NLO is a Type C uncertainty.

6.5.7 Jet Contributions

There is a contribution to the total correlated like-sign signal from irreducible jet background. Uncertainties are estimated using two different hadron interaction packages (FLUKA and GHEISHA) and using two different fit functions for the single hadron survival probabil-
ity. An uncertainty of $\pm 4.2\%$ in the south muon arm and $\pm 1.6\% + 1.6\% - 2.2\%$ in the north muon arm is assigned. This is a Type B systematic error.

6.5.8 Open Bottom Line Shape

The line shape of the like-sign dimuons from open bottom decay is not precisely known. To determine the uncertainty the slope is varied by $\pm 10\%$. This results in a Type B uncertainty of $\pm 7.9\% + 7.9\% - 5.8\%$ in the south arm and $\pm 7.5\% + 7.5\% - 6.5\%$ in the north arm.
Table 6.11: Systematic errors included in the invariant yield and differential cross section.

<table>
<thead>
<tr>
<th>Type</th>
<th>Origin</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Signal Extraction</td>
<td>±12.3% (S) / ±7.6% (N)</td>
</tr>
<tr>
<td>B</td>
<td>MuID Efficiency</td>
<td>±4%</td>
</tr>
<tr>
<td>B</td>
<td>MuTr Efficiency</td>
<td>±2%</td>
</tr>
<tr>
<td>B</td>
<td>Acc*Eff</td>
<td>±2.8%</td>
</tr>
<tr>
<td>B</td>
<td>Jet Contributions</td>
<td>±4.2%(S) / +1.6%(N)</td>
</tr>
<tr>
<td>B</td>
<td>Open Bottom Line Shape</td>
<td>±7.9%(S) / +7.5%(N)</td>
</tr>
<tr>
<td>B</td>
<td>Simulation</td>
<td>±35%</td>
</tr>
<tr>
<td>B</td>
<td>Total</td>
<td>±36.3%(S) / ±36.1% (N)</td>
</tr>
<tr>
<td>C</td>
<td>BBC Efficiency</td>
<td>±10%</td>
</tr>
<tr>
<td>C</td>
<td>LO vs. NLO</td>
<td>+8.8%</td>
</tr>
<tr>
<td>C</td>
<td>Simulation Inputs</td>
<td>±4.3%</td>
</tr>
<tr>
<td>C</td>
<td>Total</td>
<td>+14.0% / -10.9%</td>
</tr>
</tbody>
</table>
Table 6.12: Systematic errors included in the total cross section.

<table>
<thead>
<tr>
<th>Type</th>
<th>Origin</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Signal Extraction</td>
<td>$\pm 12.3%$ (S) / $\pm 7.6%$ (N)</td>
</tr>
<tr>
<td>B</td>
<td>MuID Efficiency</td>
<td>$\pm 4%$</td>
</tr>
<tr>
<td>B</td>
<td>MuTr Efficiency</td>
<td>$\pm 2%$</td>
</tr>
<tr>
<td>B</td>
<td>Acc*Eff</td>
<td>$\pm 2.8%$</td>
</tr>
<tr>
<td>B</td>
<td>Jet Contributions</td>
<td>$\pm 4.2%$ (S) / $^{+1.6%}_{-2.2%}$ (N)</td>
</tr>
<tr>
<td>B</td>
<td>Open Bottom Line Shape</td>
<td>$^{+7.9%}<em>{-5.8%}$ (S) / $^{+7.5%}</em>{-6.5%}$ (N)</td>
</tr>
<tr>
<td>B</td>
<td>Simulation</td>
<td>$\pm 35%$</td>
</tr>
<tr>
<td>B</td>
<td>Arm Averaging</td>
<td>$\pm 5%$</td>
</tr>
<tr>
<td>B</td>
<td>Total</td>
<td>$^{+36.3%}_{-36.1%}$ (S) / $\pm 36.1%$ (N)</td>
</tr>
<tr>
<td>C</td>
<td>BBC Efficiency</td>
<td>$\pm 10%$</td>
</tr>
<tr>
<td>C</td>
<td>LO vs. NLO</td>
<td>$+25%$</td>
</tr>
<tr>
<td>C</td>
<td>Simulation Inputs</td>
<td>$\pm 4.3%$</td>
</tr>
<tr>
<td>C</td>
<td>Total</td>
<td>$^{+27.3%}_{-10.9%}$</td>
</tr>
</tbody>
</table>
CHAPTER 7

CONCLUSION

The first measurement of bottom quark production in $p + p$ collisions at $\sqrt{s} = 500$ GeV was carried out based on the yield of correlated like-sign dimuons in the PHENIX muon arm acceptance. The like-sign dilepton signal provides a relatively clean signal to study bottom quark production as many of the physics signal present in the unlike-sign dilepton signal are absent. Using $\sim 6.4 \text{ pb}^{-1}$ of data from $\sqrt{s} = 500$ GeV $p + p$ collisions collected in 2009, the total $b\bar{b}$ cross section was calculated to be $25.2 \pm 3.2$ (stat) $^{+11.4}_{-9.5}$ (sys). This experimental cross section is approximately twice the pQCD value, a trend seen in many other experiments.

Once heavy quark production is understood in $p + p$ collisions, one can use heavy flavor quarks to probe the QGP by study the modification or flow of heavy quarks in the deconfined medium. This is generally done by studying single leptons from heavy flavor decay. Recent upgrades to PHENIX include the installation of two silicon vertex detectors. These detectors are designed to separate single leptons from charm and bottom based on the displaced vertex of leptons from open bottom decay in addition to providing increased background rejection.

Future data taking and detector upgrades will provide important contributions to help understand the properties of the QGP and expanding our knowledge of the Standard Model of particle physics and conditions in the Early Universe.
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48 PHENIX AnalysisNote: 899, “Run 9 evaluation of absorber effects on Hadrons, Muons, and $J/\psi$ in the PHENIX Muon Arms and its implications on the $W \rightarrow \mu$ analysis.

49 PHENIX AnalysisNote: 606, “Measuring heavy flavor single muons at forward rapidity in run 5 $p + p$ at $\sqrt{s} = 200$ GeV/c”.

50 PHENIX Analysis Note: 914, “$J/\psi \rightarrow \mu^+ \mu^-$ spin-alignment from Run-9 $p + p$ collisions at $\sqrt{s} = 500$ GeV”.

51 PHENIX Analysis Note: 888, “$\sigma_{BBC}$ using Vernier Scans for 500 GeV pp Data in Run09”.


PHENIX Analysis Note: 890, “$\Upsilon$ cross section and nuclear modification factors from Run-6 pp and Run-8 dAu in the Muon Arms”.
APPENDICES

Appendix A: Kinematic Variables

A.1 Transverse Momentum $p_T$

Transverse momentum is defined as the component of momentum perpendicular to the beam axis ($z$):

$$p_T = \sqrt{p_x^2 + p_y^2} \quad (A.1)$$

This is a Lorentz invariant quantity.

A.2 Invariant Mass

The invariant mass of two massive particles is defined as:

$$M = \sqrt{(m_1^2 + m_2^2 + 2(E_1E_2 - p_1 \cdot p_2))} \quad (A.2)$$

If the two particles have equal mass, such as in the case of dimuon analysis, the equation simplifies to

$$M_{\mu\mu} = \sqrt{2(m_{\mu}^2 + E_1E_2 - p_1 \cdot p_2)} \quad (A.3)$$

where $m_{\mu}$ is the mass of the muon (=0.106 MeV).

A.3 Rapidity

Rapidity is related to velocity. It describes the rate of motion of a particle with respect to a given point along the beam axis and can be defined mathematically as:

$$y = \tanh^{-1} \beta = \frac{1}{2} \ln \frac{1 + \beta}{1 - \beta} \quad (A.4)$$
where $\beta = v/c$. Because energy and momentum are experimentally accessible quantities, it is useful to define rapidity in terms of these quantities:

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$  \hspace{1cm} (A.5)$$

where $E$ and $p_Z$ are the particle’s energy and longitudinal momentum, respectively. Rapidity can be either positive or negative depending on direction. In a relativistic system it is beneficial to use rapidity rather than velocity because, unlike velocity, it is additive. Additionally, the difference in rapidity between two particles is invariant of the reference frame.
Appendix B: $B$-admixture Properties

Table B.1: Properties of $B$ hadrons [13].

<table>
<thead>
<tr>
<th>Particle</th>
<th>Composition</th>
<th>Mass (GeV/c$^2$)</th>
<th>Lifetime (ps)</th>
<th>Branching Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+(B^-)$</td>
<td>$\bar{u}b$ ($\bar{b}$)</td>
<td>5.279</td>
<td>1.641</td>
<td>0.401</td>
</tr>
<tr>
<td>$B^0(\bar{B}^0)$</td>
<td>$d\bar{b}$ ($\bar{d}b$)</td>
<td>5.280</td>
<td>1.519</td>
<td>0.401</td>
</tr>
<tr>
<td>$B^0_s(\bar{B}^0_s)$</td>
<td>$s\bar{b}$ ($\bar{s}b$)</td>
<td>5.367</td>
<td>1.497</td>
<td>0.103</td>
</tr>
<tr>
<td>$B^+_c(\bar{B}^-_c)$</td>
<td>$c\bar{b}$ ($\bar{c}b$)</td>
<td>6.277</td>
<td>0.453</td>
<td>-</td>
</tr>
<tr>
<td>$b(\bar{b})$- baryon</td>
<td>$qgb$, $qbb$, $\bar{qg}\bar{b}$, etc.</td>
<td>5.619-6.071</td>
<td>1.382</td>
<td>0.093</td>
</tr>
</tbody>
</table>
Appendix C: Good Run Lists

C.1 500 GeV Good Run List: South Muon Arm

After QA analysis the following 283 run numbers are considered good:

275899 275902 275936 275937 275940 276325 276326 276329 276331 276334 276343
276344 276345 276346 276347 276349 276351 276353 276354 276355 276357 276385 276386
276391 276393 276396 276531 276533 276534 276536 276537 276595 276596 276597
276598 276599 276600 276601 276602 276714 276717 276718 276719 276721 276723 276724
276725 276733 276735 276737 276738 276739 276870 276871 276872 276873 276874 276875
276879 277194 277195 277197 277198 277199 277200 277201 277205 277382 277383 277384
277386 277387 277390 277391 277392 277393 277394 277395 277396 277558 277560 277561
277562 277566 277567 277568 277569 277570 277626 277640 277641 277642 277643 277644
277645 277647 277700 277701 277702 277705 277707 277709 277712 277713 277714
277776 277778 277780 277781 277836 277838 277839 277840 277841 277843 277979 277980
277981 277982 277984 277986 278066 278074 278075 278077 278082 278083 278357 278358
278404 278409 278481 278482 278484 278486 278489 278490 278491 278493 278494 278528
278531 278533 278634 278635 278637 278639 278640 278645 278646 278647 278773 278776
278777 278778 278780 278781 278782 278784 278785 278790 278791 278792 278793 278796
278797 278798 278799 278800 278919 278920 278921 278936 278937 278938 278940 278942
278943 279106 279108 279109 279110 279113 279114 279115 279116 279120 279212 279213
279214 279215 279216 279217 279235 279236 279237 279238 279239 279395 279396 279397
279398 279399 279400 279401 279402 279403 279404 279567 279569 279570 279571 279574
279575 279576 279577 279619 279620 279622 279623 279625 279626 279711 279712 279713
279716 279717 279718 279719 279721 279722 279724 279725 279726 279728 279773 279774
279780 279942 279943 279944 279945 279946 279947 279948 279949 279950 280043 280044 280074 280076 280077 280078 280079 280177 280179 280180 280181 280182 280183 280184 280185 280186 280187 280238 280240 280241 280242

C.2 500 GeV Good Run List: North Muon Arm

After QA analysis the following 298 run numbers are considered good:

275899 275902 275936 275937 275940 275941 276325 276326 276329 276331 276334 276343 276344 276345 276346 276347 276349 276351 276353 276354 276355 276357 276385 276386 276391 276393 276396 276464 276465 276531 276532 276533 276534 276535 276536 276595 276596 276597 276598 276600 276601 276602 276619 276714 276717 276718 276719 276721 276723 276725 276733 276735 276736 276737 276738 276739 276870 276871 276872 276873 276874 276875 276879 277019 277020 277021 277022 277194 277195 277197 277198 277200 277201 277205 277382 277383 277384 277386 277387 277390 277391 277392 277394 277395 277396 277558 277560 277561 277562 277566 277567 277568 277569 277570 277626 277640 277641 277642 277643 277644 277645 277647 277700 277701 277702 277705 277707 277708 277710 277712 277713 277714 277776 277778 277780 277781 277836 277838 277839 277840 277841 277843 277979 277980 277981 277982 277984 277986 278066 278074 278075 278077 278082 278083 278357 278358 278384 278399 278400 278402 278403 278404 278409 278481 278482 278484 278486 278489 278490 278491 278493 278494 278528 278531 278533 278634 278635 278637 278639 278640 278645 278646 278647 278773 278776 278777 278778 278780 278781 278782 278784 278785 278790 278791 278792 278793 278796 278797 278798 278800 278919 278920 278921 278936 278937 278938 278940 278942 278943 279106 279108 279109 279110 279113 279114 279115 279116 279120