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Sarah Lapointe
Wayne State University

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D MESON MEASUREMENTS IN STAR USING THE SILICON INNER TRACKER

by

SARAH LAPOINTE

DISSERTATION

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Chapter 1

Introduction

1.1 Motivation - The Quark Gluon Plasma

A framework, called the Standard Model, is currently the most detailed description of the building blocks of our universe. The model describes our universe in terms of matter (fermions) and forces (bosons). The fermion group contains six quarks, six leptons, and their anti-particles. The bosons are considered to be the mediators of four fundamental forces: gravity, electromagnetism, the weak, and the strong force. An atomic nucleus is composed of protons and neutrons and they are each composed of three quarks. The strong force is responsible for binding the quarks inside of these baryons, and it is mediated by gluons. In addition to quark triplet bound states, there exist particles, called mesons, that essentially contain two quarks. As of yet, no isolated quark has been observed in nature. Quarks carry a property called color, analogous to charge, which requires that they be combined, yielding a object that is colorless. For example, a meson composed of a green and anti-green quark, or a baryon composed of a red, blue, and green quark are considered colorless objects. A quantum field theory that was developed to describe the strong interaction of these colored objects is called Quantum Chromodynamics (QCD). In addition to describing how the quarks are held together, QCD calculations predict that hadronic matter can undergo a phase transition toward a matter composed of deconfined quarks and gluons (collectively called partons). For this to occur the proper conditions of temperature
and density must be met, such that distances between quarks get small, and the strong force becomes negligible. In the new phase, the quarks and gluons are the relevant degrees of freedom, not the baryons. The term Quark-Gluon Plasma (QGP) is used to describe such a state.

1.2 Quantum Chromodynamics

In Quantum Electrodynamics (QED) the electromagnetic force is mediated by photons, which carry no charge. Similarly, in Quantum Chromodynamics (QCD) the gluons are the carriers of the strong force, but unlike the photon they carry color charge, meaning that they can interact with one another. In QED, the electrodynamic coupling constant $\alpha = 1/137$, whereas the QCD strong coupling constant, $\alpha_s$, can be 1 or larger. In quantum field theory when a coupling constant is much smaller that 1 the theory is said to be weakly coupled. When the coupling nears 1 the theory is strongly coupled, hence the name ”strong” force.

In QCD the strong interaction between two quarks can be described using the following potential

$$V(r) = -\frac{4\alpha_s}{3r} + kr$$  (1.1)

here $r$ is the separation distance between the two quarks, $\alpha_s$ is the strong coupling constant, and $k$ is also a constant that is approximately 1 GeV/fm. Due to the gluon self-interactions, the renormalized QCD coupling shows renormalization scale ($\mu$) dependence [11]. The running coupling constant $\alpha_s(\mu)$ can be written as

$$\alpha_s(\mu) \equiv \frac{g_s^2(\mu)}{4\pi} \approx \frac{4\pi}{\beta_0 \ln(\mu^2/\Lambda_{QCD}^2)}$$  (1.2)

where $g_s$, the strong charge in the gauge group, and is the only parameter in the QCD Lagrangian besides the quark masses. $\beta_0$ is the first coefficient of the beta-
Three very important properties of QCD arises from such a potential and running coupling constant. They are confinement, asymptotic freedom, and (hidden) chiral symmetry. For large distance scales the second term in the potential equation dominates. This means that the coupling between the two quarks is large, making it so that no free quarks are observed in nature, i.e. a quark never exists on its own for longer than $1/\Lambda_{QCD}$, where $\Lambda_{QCD} = 217$ MeV. The up, down, strange, charm, and bottom quarks all hadronize on the timescale $1/\Lambda_{QCD}$, the top quark decays before it has time to hadronize. Therefore, all but the top quark will be confined inside hadrons. Experimentally, no single quark in a color-triplet state has been observed. In nature, we only find color-octet bound states over large distances. The only stable
Figure 1.2: Demonstration of the quark masses of all six flavors. The masses from electroweak symmetry breaking (current quark masses) are shown as blue bars, labeled Higgs mass. A large fraction of the light quark mass is from chiral symmetry breaking in the QCD vacuum (constituent quark masses), shown as yellow bars.

color-singlets with size on the order of 1 fm are quark-antiquark pairs, mesons, and three quark states, baryons. Asymptotic freedom arises when the quarks are at a small distance from one another or with a large enough momentum transfer ($\alpha_s \to 0$ as $\mu \to \infty$). The potential will go like $1/r$ and the effective coupling between the quarks decreases, allowing for a quasi-free quark. The final property is called chiral symmetry, also not observed in nature. It is a symmetry in QCD in the limit of vanishing quark mass. In this limit quarks are either left of right handed, such that the QCD Lagrangian is symmetric. However, when quarks are confined to hadrons they have large dynamical masses, called constituent or QCD mass. Here the chiral symmetry is said to be "broken" (or hidden). In the small $\alpha_s$ limit some quarks will have small mass, called current mass. In this limit, chiral symmetry is said to be (partially) restored. Figure 1.2 demonstrates the magnitude of these masses in units of MeV.
In our world, quarks and gluons are confined in QCD matter or inside hadrons. By significantly increasing the temperature and energy density the strong force holding the quarks and gluons together may be reduced, unbinding them from the hadrons. This phenomenon is known as "deconfinement". Deconfinement implies that there exists a phase transition from a gas of hadrons to a new form of matter of free quarks and gluons, called the Quark-Gluon Plasma (QGP).

One way to gain a better understanding of the QGP and the conditions that must be met for its formation is to estimate critical parameters. The thermodynamics of the transition of quarks and gluons from the hadronic phase to the quark gluon plasma phase have been analyzed through numerical calculations in the framework of lattice regularized QCD. Here quarks and gluons are studied on a discrete space-time lattice. Working on the lattice solves the problem of divergences in pQCD. Such divergences arise from loop diagrams. The lattice also provides a natural momentum cut-off. Over the years calculations on the lattice have been greatly improved. This is partially from stronger computing resources and improvements of the standard Wilson and staggered fermion actions [2]. Figure 1.3 shows these recent results. Here the energy density ($\epsilon$) divided by $T^4$ and its dependence on $T/T_c$ is presented. Because of the energy density dependence on the number of degrees of freedom a sharp rise can be seen at the critical temperature, $T_c$. This corresponds to a clear phase transition to a system of deconfined quarks and gluons.

1.3 Nuclear Phase Diagram

Critical parameters can also be estimated by mapping out the nuclear phase diagram, shown in Figure 1.4. The diagram demonstrates the transition from a gas of hadrons to a QGP as a function of temperature (T) and baryo-chemical potential ($\mu_B$). The hatched region represents the expected phase boundary between partonic and hadronic matter form lattice QCD calculations. The estimates for LHC and
Figure 1.3: The ratio of energy density and $T^4$ as a function of $T/T_c$ in lattice QCD calculations. Figure taken from [2]

Figure 1.4: Phase diagram of hadronic and partonic matter. The chemical freeze out points are determined from thermal models fit to heavy ion data at SIS, AGS, and SPS energies. Figure taken from [3]
A peripheral collision occurs when the impact parameter is large the number of participants is small. For a central collision the impact parameter is small and mostly all nucleons collide.

Results from thermal analysis of [12, 13, 14] show that the chemical potentials $\mu_B$ and temperatures $T$ place the chemical freeze-out of the system (when inelastic collisions cease) quite close to the currently accepted phase boundary between a plasma of quarks and gluons and a hadron gas. The solid curve, which goes through the low energy data points, is the freeze out trajectory. This curve closely follows the hatched region, where one expects deconfinement to occur.

1.4 The Creation of a QGP

Ultra-relativistic heavy ion collisions are thought to allow for the creation of the quark gluon matter that existed right after the Big Bang [15]. The crucial requirements are that the system have maximum energy density and sufficient collective temperature. The Relativistic Heavy Ion Collider (RHIC) was built to create and search for this state of matter by colliding various ions at energies up to $\sqrt{s_{NN}} = 200$ GeV.

A cartoon of a heavy ion collision can be seen in Figure 1.5. The ions are traveling
at 99.995% the speed of light, causing them to Lorentz contract, so they appear as thin disks. In each collision a fraction of nucleons participating in the collision, while some will simply be spectators. The impact parameter, $b$, allows us to categorize the type of collision. A large impact parameter means few participants, called peripheral collisions. For a more central collision, where $b$ is small, therefore many nucleons participate. These central collisions are thought to be the type where the hottest and densest environment is achieved.

A QGP, post production, will eventually expand out because of internal pressures. As the system expands it also cools. The space-time evolution of the expansion can be seen in Figure 1.6 (right side). A and B represent the two incoming ion beams. After a pre-equilibrium phase a QGP is formed. As it expands, the system will eventually reach what is known as the critical temperature ($T_c$). At this point partons begin to hadronize and this will continue until chemical freeze out ($T_{ch}$), when inelastic collisions cease. At this stage the distribution of hadrons is frozen. As cooling and
expansion continues the hadrons reach what is called thermal freeze out ($T_{fo}$). Here the elastic collisions stop and the hadrons carry fixed momenta.

The QGP state can not be directly observed, because of its short lifetime. Instead, through experiment we measure the final state hadrons, which have a fixed momentum after $T_{fo}$. The observables of interest should tell us about the deconfinement and the thermodynamic properties of the matter. Experimental measurements include yields and $p_T$ spectra of various particle species, azimuthal studies of high $p_T$ particles, phase space distributions, and particle correlations.

1.5 QGP Signatures

For an experiment to claim formation of QGP in relativistic heavy ion collisions certain signatures must be observed. There are two types of measurements to investigate. One being properties of the bulk matter and the other is utilizing high momentum particles, called hard probes. The bulk of the matter, which is produced through multiple, soft interactions between partons, is composed of low momentum, soft particles, where transverse momentum ($p_T$) is below 1.5 GeV/c. Bulk measurements of interest are particle multiplicities, yields, momentum spectra, and correlations. The high momentum particles are produced through hard scatterings. These energetic particles will experience the medium differently from the bulk, making them unique probes.

The questions asked in this analysis concern charm quarks. It is thought that charm quarks do not interact with the medium in the same manner as the lighter partons, primarily because of their large current mass, which is approximately 1300 MeV/c. In order to outline how the charm can be used as a probe it is important to discuss what measurements have been made that are characteristic to QGP formation.
Jets are produced by the hard scattering of energetic parton pairs. The high $p_T$ parton will fragment into additional partons while traveling along a single axis. Since confinement requires that each parton hadronizes, the result is a cone of hadrons, which can be referred to as a jet. In p+p collisions, where no medium is present, di-jets form. The di-jet comes from the initial scattering pairs that travel back-to-back, shown in Figure 1.7 (left). However, if the jet is formed on the boundary of a medium, also shown in the figure (right), one jet would move away from the boundary while the other would move through the QCD medium. It was predicted using pQCD [16] that as a quark traverses the partonic medium it interacts strongly, through gluonic bremsstrahlung, resulting in the suppression of high $p_T$ particles. In a sense, the jet partner moving through the medium would be lost, but conservation of momentum requires the lost energy be dispersed through the medium. This phenomenon is referred to as ”jet quenching”.

One signature of partonic energy loss in a deconfined system is through the measurement of the nuclear modification factor, $R_{AA}$. It is the ratio of particle yields
as a function of $p_T$ in heavy ion collisions compared to p+p collisions, scaled by the number of binary collisions, defined in [13] 

$$R_{AA} = \frac{1}{\langle N_{bin} \rangle} \frac{d^2N_{AA}(p_T)/dp_Tdy}{d^2N_{pp}(p_T)/dp_Tdy}$$ (1.3)

here $\langle N_{bin} \rangle$ is the average number of binary (nucleon on nucleon) collisions in the heavy ion collision system.

STAR has reported on $R_{AA}$ in Au+Au collisions for various centralities [17]. Figure 1.8 shows $R_{AA}(p_T)$ of inclusive charged hadrons for various centrality collisions in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The distribution monotonically increases at $p_T < 2$ GeV for all centralities and saturates near unity for the most peripheral collisions. If no suppression occurs in central collisions the expected shape of the ratio would still include an increase at low $p_T$, where thermal production is dominant, and would saturate near unity in the high $p_T$ region, where the hard cross section in p+p collisions scales with the number of binary collisions. However, $R_{AA}(p_T)$ for the most central collisions reaches a maximum and decreases above $p_T = 2$ GeV, showing a suppression of charged hadron yield relative to the $p + p$ reference. The observed suppression of high $p_T$ hadrons in central Au+Au collisions can be interpreted as energy loss of the energetic partons while traversing medium.

1.5.2 Collective Motion

Properties of the matter after kinetic freeze out (when elastic collisions have ceased) can be found by measuring the particles spectrum. Final state hadrons can be used to extract information about the previous partonic phase. Not all of the hadrons that come streaming into the detectors have the same interaction probability after hadronization and this allows various species to be used to probe different stages of the collision. This is done by analyzing different particles $p_T$ distributions. 

One model that can be fit to the $p_T$ distribution is the Blast Wave thermal model
Figure 1.8: $R_{AA}(p_T)$ in $|\eta| < 0.5$ for various centralities of Au+Au spectra relative to p+p.
Figure 1.9: (a): The $m_T$ spectrum for light for various particle species in 200 GeV Au+Au central collisions. A fit using the Blast Wave model are shown. The arrows show the expected increase in freeze out temperature, with decreasing average radial flow velocity. (b): Blast Wave fit parameters $T_{fo}$ versus $\langle \beta_T \rangle >$ contour plot from the fits to light hadrons spectra in 5-10% and 0-5% Au+Au collisions and fits to the multi-strange hadrons in 0-10% Au+Au collisions.

The model assumes local thermal equilibrium, and the only variables that modify the spectrum are the temperature and mass of the particle. After the initial collision, the system expands out and cools. As this happens, the particles collective velocity continues to increase. A Blast Wave fit to the momentum spectra allows for the extraction of model parameters, such as kinetic freeze out temperature ($T_{fo}$) and average radial flow velocity ($\langle \beta_r \rangle$).

$$\frac{dN}{m_T dm_T} \propto \int_0^R r \, dr \, m_T \, I_0 \left( \frac{p_T \sinh \rho}{T} \right) K_1 \left( \frac{m_T \cosh \rho}{T} \right)$$  \hspace{1cm} (1.4)

Here $\rho = \tanh^{-1} \beta_r$

STAR has measured $p_T$ for various particle species. Figure 1.9 shows $m_T$, where $m_T \equiv \sqrt{p_T^2 + m^2}$, spectra for light hadrons ($\pi$, K, p), $\Lambda$, $\Xi$, multi-strange hadrons ($\phi$, $\Omega$) in 200 GeV Au+Au central collisions [19, 20, 21, 22] and the open charm hadron
(D0) in 200 GeV Au+Au minimum bias collisions [23]. The fit to the lighter flavors indicates a large flow velocity, with a small freeze out temperature, meaning that lighter hadrons kinetically freeze out relatively late with strong collective motion. On the other hand, the fit to the heavier, multi-strange baryon spectrum gives a larger temperature, with a smaller flow velocity, indicating that the multi-strange freeze out earlier than the bulk as the system evolves. The multi-strange baryons have smaller hadronic scattering cross sections, meaning that their momentum distributions won’t drastically change after chemical freeze out. The chemical freeze out temperature is near to the critical temperature, indicating that the temperature of the initial system is greater than the critical temperature. Therefore, a phase transition may have taken place.

1.5.3 Momentum Space Azimuthal Anisotropy

In a typical non-central heavy ion collision the two nuclei are Lorentz-contracted along the beam axis, so they look like two circular disks. In a non-central collision the overlap region will have the shape of an almond. The shape creates an initial azimuthal anisotropic source in coordinate space. A reference plane called the reaction plane is defined by the beam axis and the vector connecting the centers of the two colliding nuclei. As the system develops, the particles traveling parallel to the reaction plane traversing less medium than those moving perpendicular to the reaction plane, which causes their momentum distributions to be different, if those particles interact with the medium. In that case, an azimuthal anisotropy in momentum space is observed in the final state. Mathematically, the particle distribution in momentum space can be expanded into a Fourier series [24],

\[ E \frac{d^3N}{dp^3} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left( 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\phi - \Psi_{RP})] \right) \]  

(1.5)
\[ \nu_n \text{ is the anisotropy parameter of the nth harmonic, } p_T, y, \text{ and } \phi \text{ are respectively transverse momentum, rapidity, and azimuthal angle. } \Psi_{RP} \text{ is the reaction plane azimuthal angle. The second harmonic coefficient } \nu_2 \text{ is called elliptic flow. In order to develop momentum space anisotropy from coordinate space azimuthal anisotropy, multiple interactions are necessary. If each nucleon-nucleon collision was totally independent, the final particles momentum distribution would be a superposition of many isotropic momentum distributions resulting from completely uncorrelated nucleon-nucleon collisions. The result would be an isotropic momentum distribution.} \]

\[ \text{STAR has reported on } \nu_2 \text{ in minimum bias Au+Au collisions [25]. Figure 1.10 shows } \nu_2 \text{ for identified particles. There is a mass ordering at low transverse momentum } p_T. \text{ At a given } p_T, \nu_2 \text{ decreases with increasing particle mass. A hydrodynamic model, which assumes ideal fluid flow, describes the mass ordering of } \nu_2 \text{ at low } p_T \text{ very well. The dot-dashed lines are hydrodynamic calculations [26]. The ability to use the hydrodynamic model in this } p_T \text{ range indicates that a strongly interacting} \]
thermalized quark matter has been created. However, $\nu_2$ is not a tell-tale sign of the formation of a quark-gluon plasma [27].

Models of hadron formation by coalescence or recombination successfully describe hadron production in the intermediate $p_T$ region ($1.5 < p_T < 5 \text{ GeV}/c$). It is predicted that in this $p_T$ region $\nu_2$ will scale with the number of constituent quarks. When the hadronization mechanism is dominated by coalescence the $\nu_2$ distribution can be described by a universal curve. This curve represents that momentum space anisotropy of constituent quarks prior to hadronization. It has been observed that the $p_T$ dependence of $\nu_2$ scales with the number of constituent quarks, see Figure 1.11. This is evidence that flow originated in the deconfined phase [25].

1.6 Thesis Outline

This thesis discusses the use of charm to study the QGP and its evolution, the theoretical motivations will be outlined in Chapter 2. This will be followed by a chap-
ter on charm meson reconstruction methods currently used by STAR and PHENIX and the physics results observed. Chapter 4 describes the experimental facilities used to create and investigate the QGP. Then the procedures used for data reconstruction and analysis will be discussed. Following that, we outline various methods used for background subtraction in this analysis. The measurements of $D$ mesons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV will be presented in Chapter 7. To conclude, future directions in charm quark measurements will be discussed.
Chapter 2

Open Charm - Theoretical Framework

The matter produced in heavy ion collisions at RHIC is primarily composed of gluons and light flavor quarks (u, d, s). The energy available for heavy flavors (c, b) pairs, $Q\bar{Q}$, mostly goes into charm production. Bottom production is also present, but it is estimated to be 1-2% of charm production. The typical time scale for the formation of heavy quark pairs is of order $1/2m_Q$, for charm this is near 0.1 fm/c. It is estimated, using hydrodynamic calculations, that the QGP has a formation time 0.6 fm/c, so the charm forms well before the plasma, making it an excellent probe of the earliest stages of the collision.

In this chapter the theoretical framework for charm quark production, the subsequent fragmentation to hadrons, and their later decay is discussed. Following this, we will describe the current pQCD total charm cross section predictions, along with theoretical predictions of how strongly charm (and bottom) interact with the QGP medium.

2.1 Charm Production Framework

The creation of charm and its evolution can be described by a sequence of several different processes. First, the hard scattering of partons is thought to be the process responsible for charm production. This scattering occurs as a result of the individual inelastic collisions of nucleons. The charm quarks then fragment into charm hadrons,
which eventually decay into the final particles that are observed experimentally.

2.1.1 Charm Production

The energy threshold for the production of a charm and anti-charm pair is much larger than $\Lambda_{QCD}$, which means that the cross section can be calculated using perturbative QCD (pQCD). In this framework calculations of the charm quark cross section are performed using what is known as the QCD factorization theorem \cite{28}. The theorem gives the production cross section as

$$E \frac{d\sigma_{AB \to Q}}{d^3p} = f_{i/A}(x, \mu) \otimes f_{j/B}(x, \mu) \otimes E \frac{d^3\bar{\sigma}_{ij}(s)}{d^3p} \quad (2.1)$$

where $f_{i/A}(x, \mu)$ is the probability distribution function for the $i^{th}$ parton inside hadron $A$ for the energy scale $\mu$ and the momentum fraction $x$ that the parton carries from hadron. The cross section of charm quark production in the collision of the $i$ and $j$ partons is denoted by $\hat{\sigma}_{ij}(s)$.

The assumption that heavy quarks are essentially produced from the parton-parton interaction in hadron-hadron collisions is inherent in the QCD factorization theorem. For charm production the leading order processes are $q\bar{q} \to c\bar{c}$ and $gg \to c\bar{c}$, see Figure 2.1. However, at RHIC energies the dominant process is gluon fusion, $gg \to c\bar{c}$. The $q\bar{q}$ annihilation process should not significantly contribute since the density of light anti-quarks inside the nuclei are considerably smaller compared to the
2.1.2 Hadronization

After charm production comes hadronization, were charm quarks fragment into charmed hadrons. Two outcomes are possible. If the momenta of the charm and anti-charm pair are aligned the $c\bar{c}$ pair combine and form a charmonium meson, also known as "closed" charm. On the other hand, the created charm combines with lighter flavors, forming "open" charm hadrons. The quark and anti-quark pair are called $D$ mesons.

The mechanism responsible for parton fragmentation is unknown. However, it is important to understand what happens to the initial momentum of the charm when it combines with lighter flavors. This is generally specified by the fragmentation function $D^H_Q(x)$, which represents the fragmentation of quark $Q$ into a final-state hadron $H$. It tells about the distribution of energy carried by the hadron with respect to the charm quark energy density, $z = E_H/E_Q$. Bjorken was the first to undertake a theoretical explanation of the hadronic production by a heavy quark \cite{Bjorken}. The conclusion was the the distribution $dN/dz$ of produced hadrons from a heavy quark $Q$ would peak near $z = 1$, meaning that the heavy quark is hardly slowed down when picking up a light quark to form a heavy meson. Other attempts followed this, which led to a popular, fully phenomenological model given by Peterson et al \cite{Peterson}. Here the fragmentation function behaves as $(1-z)^2$ for large values of $z$, whereas the behavior for light quarks goes like $z^{-1}(1-z)^2$. The Peterson fragmentation function is defined as

$$D^H_Q(z) = \frac{N}{z(1-(1/z) - \epsilon_Q/(1-z)^2)} \quad (2.2)$$

where $N$ is fixed by summing over all hadrons containing $Q$, and the parameter $\epsilon_Q$ is approximately $m_q^2/m_Q^2$, the ratio of effective light and heavy quark masses. Other
methods, such as pQCD alone, Heavy Quark Effective Theory (HQET), and pQCD plus non-perturbative parameterization approaches have also been employed.

<table>
<thead>
<tr>
<th></th>
<th>$f(c \to D^0)$(%)</th>
<th>$f(c \to D^+)$ (%)</th>
<th>$f(c \to \Lambda^+_c)$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO (MeV/c)</td>
<td>54.9 ± 5.4 ± 6.1</td>
<td>23.0 ± 3.2 ± 2.1</td>
<td>8.1 ± 1.2 ± 1.4</td>
</tr>
<tr>
<td>ARGUS</td>
<td>46.2 ± 7.0</td>
<td>22.6 ± 3.6</td>
<td>7.3 ± 1.0 ± 1.0</td>
</tr>
<tr>
<td>ALEPH</td>
<td>55.9 ± 1.7 ± 3.5</td>
<td>23.8 ± 0.8 ± 1.3</td>
<td>7.8 ± 0.8 ± 0.4</td>
</tr>
<tr>
<td>OPAL</td>
<td>58.5 ± 4.1 +3.9 -3.7</td>
<td>23.1 ± 3.0 +1.6 -2.0</td>
<td>4.8 ± 2.2 ± 0.8</td>
</tr>
<tr>
<td>DELPHI</td>
<td>54.4 ± 1.5 ± 3.2</td>
<td>22.6 ± 0.8 ± 1.4</td>
<td>8.6 ± 1.8 ± 1.0</td>
</tr>
<tr>
<td>Average</td>
<td>54.9 ± 2.3 (± 1.3)</td>
<td>23.2 ± 1.0 (± 1.5)</td>
<td>7.6 ± 0.7 (± 2.0)</td>
</tr>
</tbody>
</table>

Table 2.1: Measured and average probabilities that a charm quark hadronizes into a $D^0$, $D^+$, and $\Lambda^+_c$. The average probability errors in parentheses are due to the uncertainties in the charm hadron branching ratios.

The fragmentation function should not depend on the manner in which charm has been produced. $e^+e^-$ collisions offer extremely precise measurements of the fraction of charm quarks hadronizing as a particular charm hadron [31] (shown in Table 2.1). These fractions are used to extract the fragmentation functions that are used in hadronic collisions.

2.1.3 Decay

An interesting feature of most particles is that they decay into lighter particles, unless conservation laws prevent them from doing so. For instance, there is no lighter lepton for the electron to decay to so it is stable, the proton is also safe because it is the lightest baryon and conservation of baryon number prevents its decay. Most of the particles created in heavy ion collisions will be unstable and eventually decay. Each particle has a characteristic mean lifetime, $\tau$, and will decay into a variety of different channels. The probability of decay for each individual channel is called the branching ratio.

The particles that are produced in the collisions will move radially away from the interaction region, into the detectors of the specific experiment. However, charmed
mesons have a relatively short mean lifetime and decay before reaching the detectors. Instead they are measured through the reconstruction of their decay products. By choosing a specific decay channel to measure and knowing the branching ratio for that channel we can determine the production of the $D$ meson we are attempting to measure.

There are three types of decay channels to consider for reconstruction. They are the leptonic; semi-leptonic, and hadronic. Measuring the purely leptonic decay is not very attractive since the branching ratio is at most $10^{-3}\%$. The semi-leptonic decay of $D$ mesons goes to a hadron, lepton, and neutrino, as do the $B$ mesons. Both STAR and PHENIX detect the electron from these decays, which results in an indirect measurement of heavy flavor production. The hadronic decays are processes where $D$ mesons decay exclusively to hadrons. An example is the $D^+$ and $D^+_s$ decay.
to $K^+K^-\pi^+$. In this case the $D$ meson can be directly identified by calculation of the invariant mass using measured momentum information from the decay products. An example of such a measurement can be seen in Figure 2.2. Measuring $D$ mesons in heavy ion collisions from their hadronic decay is the main goal of the research presented in this thesis.

2.2 pQCD Cross Section Estimates

We found it relevant to outline the processes involved, starting from the production of charm quarks to the final decay particles we detect, because a strong understanding of these steps is needed to extract the total charm cross section from data. Experimentally, we start with a finite number of measured $D$ mesons and extrapolate back to estimate the total charm cross section, making many assumptions along the way.

The charm cross section can be calculated by summing up the terms of the Feynman diagrams (shown in Figure 2.1) to find a transition amplitude. The evaluation of the distribution $E^{d\sigma_{AB \rightarrow Q}}_{d^2p}$ has been done to the Fixed-Order Next-to-Leading-Log (FONLL) level which includes terms of order $\alpha_s^2(\alpha_s \log(p_T/m))^k$ and $\alpha_s^3(\alpha_s \log(p_T/m))^k$ and to the Next-to-Leading-Order (NLO) level which includes orders of $\alpha_s^2$ (LO) and $\alpha_s^3$ (NLO). The NLO calculation is the most accurate of the total charm cross section over all energies. Here the perturbative parameters are the heavy quark mass $m$ and the value of the coupling constant $\alpha_s$, described in [6].

Both STAR and PHENIX have measured heavy flavor mesons through their semi-leptonic decay, thus the total charm cross section is obtained using the calculated single electron spectrum from heavy flavor decays. The fragmentation of the heavy quark to a heavy meson is extracted from $e^+e^-$ data in the context of FONLL calculations [32]. It should be noted that the fragmentation function given by Peterson et al, using standard parameter choices for charm and bottom, can not describe the fragmentation to FONLL. The measured $p_T$ spectra for electrons from $D$ and $B$ mesons
are modeled and assumed equal for all charm and bottom electrons. Contributions
of feed-down from $B$ decays is also taken into account. Finally, the decay spectrum
is normalized using the branching ratios for the $D$ and $B$ decay to $e + X$ and for the
decay of $B$ to $D$ which then goes to $e + X$.

One method used for the cross section calculation takes $dp_T$ slices of the distri-
bution, which are then integrated. Results using FONLL and NLO calculations at
$\sqrt{s_{NN}} = 200$ GeV are consistent and are,

\begin{equation}
\alpha_{cc}^{FONLL} = 256_{-146}^{+400} \mu b \tag{2.3}
\end{equation}

\begin{equation}
\alpha_{cc}^{NLO} = 244_{-134}^{+381} \mu b \tag{2.4}
\end{equation}

For the above calculations the heavy quark is treated as an active light flavor
when $p_T > m$, this means that the number of light flavors used in the calculation of
$\alpha_s$ is "3+1", where the three light flavors are the u, d, and s quarks.

Another method calculates the cross section to NLO by evaluating the entire $p_T$
range in one step. In this calculation, the quark is massive and the renomalization
scale is fixed and proportional to the quark mass, and the resulting cross section with
three light flavors is,

\begin{equation}
\alpha_{cc}^{NLO} = 301_{-210}^{+1000} \mu b \tag{2.5}
\end{equation}

The uncertainties are considerably larger than the previous results. This arises
from how $\alpha_s$ is calculated and the low $x$ behavior of the parton densities.
2.3 Charm as a QGP Signature

In the previous chapter, we outlined results from light flavor measurements that are characteristic to QGP formation. Similarly, we should perform these same measurements for heavier flavors. What is most telling is how the charm (and bottom) interact with the medium, either through observed energy loss or through collective effects that arise from traversing a thermally equilibrated medium.

2.3.1 Energy Loss

The energy loss experienced by charm quarks in a QGP was expected to be much lower than the lighter flavors because of the larger mass of charm. This effect is called the ”dead-cone” phenomena. Energetic, light quarks will lose energy in the QGP medium through gluon bremsstrahlung. The charm quark energy loss differs from the lighter flavor case because gluon radiation is suppressed at angles smaller than the ratio of the charm mass $M$ and its energy $E$. Basically, the large mass of charm and bottom reduce the phase space for gluon radiation. Aside from inelastic collisions, energy loss from elastic collisions was predicted to not play a large roll in heavy flavor energy loss.

Results from the measured energy loss via $R_{AA}$ from both STAR and PHENIX show a greater quenching of the high $p_T$ heavy flavor quarks than was predicted using the dead-cone argument. This observed suppression was quite surprising, since $B$ meson decays should make a significant contribution in this $p_t$ region, and $B$ mesons should experience even less energy loss with the bottom quark mass more that 3 times than of the charm because of the dead-cone effect.

In an effort to reproduce these findings energy loss through elastic collisions was folded in to the calculations. It was found that using a fixed path length $L = 5$ fm and $dN_g/dy = 1000$ that the impact of collisions on $R_{AA}$ for charm, bottom and also the lighter flavors is large (see Figure 2.3). Although the observed $R_{AA}$ can not be
describe using inelastic and elastic collisional energy loss for both charm and bottom, it does demonstrate that the energy loss of charm may reach that of the light quarks.

The magnitude of single electron $R_{AA}$ can also be reproduced using calculations of radiative energy loss if a large enough transport coefficient $\hat{q}$ is used \[^{32}\]. As $\hat{q} \approx \langle h_i^2 \rangle / \lambda$, a large $\hat{q}$ requires a small mean free path $\lambda$, which implies a high gluon density. In addition to showing a comparison of FONLL calculation of single electrons to data from $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV (right), Figure 2.4 shows $R_{AA}$ of single electrons in central Au+Au collisions with $\hat{q} = 14$ GeV$^2$/fm, solid line. The shaded band is the theoretical uncertainty. The red dashed and blue dotted curve show $R_{AA}^e$ for charm and bottom quark, respectively. However, one may intuitively think that if the density becomes great enough that elastic collisional energy loss should also increase.

The previous models discussed here assume that heavy quarks have fully traversed
Figure 2.4: Left: A comparison of single non-photonic electron spectrum calculated in the framework of FONLL [6] to $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV [7]. The upper and lower curves are estimates of theoretical uncertainties. Right: $R_{AA}$ of electrons in central Au+Au collisions using a transport coefficient $\hat{q} = 14$ GeV$^2$/fm. The red and blue curves represent $R_{AA}$ for bottom and charm decay contributions, respectively.
Figure 2.5: Suppression of heavy flavor single electrons from $D$ and $B$ meson $p_T$ spectrum that has been softened by collisional dissociation in central Au+Au collisions compared to data from STAR [8] and PHENIX [9].

the QGP and hadronize in vacuum. In one theoretical approach the observed suppression at high $p_t$ of the measured single heavy flavor electrons arises from QGP induced dissociation of heavy mesons [34]. If the lifetime of the QGP is taken to be $L_T^{QGP} \leq 6$ fm, they find for a pion with $p_T = 10$ GeV at mid-rapidity a formation time of $\tau_{form} \approx 25$ fm, which is considerably larger than that of the QGP. However, the $B$ and $D$ mesons with the same $p_T$ will have formation times $\tau_{form} \approx 0.4$ and 1.6 respectively, which is significantly smaller than that of the QGP. The consequence of this is that the heavy flavor mesons form inside the medium, which then induces their dissociation and this interaction shifts the mesons to a lower $p_T$. This model offers a good description of the non-photonic electron suppression (see Figure 2.5).

2.3.2 Collective Motion

Aside from measured energy loss and the total cross section estimations, $D$ mesons can be utilized to probe the thermodynamic properties of the medium. In the previ-
Figure 2.6: The transverse momentum spectrum of charm quarks at a freeze out time of 6 fm for a Bjorken expansion with an initial formation time of 1 fm and initial temperature of 300 MeV and freeze out temperature of 165 MeV. The initial $p_T$ spectrum is given by Leading Order (LO) pQCD. The red curves represent the change in the spectra shape using various diffusion coefficients. [10, 35]

ous chapter, we described the collective behavior of light flavors in a system that is in thermal equilibrium. One measurement mentioned was elliptic flow, which when scaled with the number of constituent quarks, is evidence of a deconfined phase. In addition, the appearance of radial flow being predicted to appear after the hydrodynamic evolution of the QGP. If heavy flavor mesons do not interact with the medium as strongly as their lighter counterparts do then we expect to observe less collective motion. Of course, if they interact strongly they should move in the same manner as the rest of the mostly light flavored medium.

Theoretical calculations find that if the charm quarks interact with the lighter quarks in the QGP kinematics could be altered [10, 35]. They observe that for a small
diffusion coefficient (D) the charm $p_T$ spectrum approached the thermal spectrum (see Figure 2.6). This implies a boost to the radial flow of charm quarks. A charm quark, although heavy, may acquire flow if sufficient interactions occur in a dense, thermal QGP. This is not expected for the bottom quark because of its extremely large mass and even smaller interaction cross section, with respect to charm. A small diffusion coefficient also implies a substantial suppression in the high $p_T$ region of the spectrum.

The measurement of radial flow, based on the blast wave model discussed in the previous chapter, is interesting for two reasons: the extraction of the average radial flow velocity can tell us how strongly the charm interacts, and at what temperature the system freezes out. Considering the relatively large mass of the charm and the small interaction cross section, it is expected to freeze out early and not greatly participate in collective motion.
Chapter 3

Charm Reconstruction Methods and Experimental Findings

There are a variety of methods used to detect particles produced in nuclear collisions. Some particles live for a considerable amount of time, and can reach the detectors. These particles are tracked by measuring energy deposition through processes such as ionization and electromagnetic showers. By combining spatial and energy measurements an accurate description of the particles properties can be obtained. These measurements are a slightly more complicated when the particle is short lived. The $D$ mesons are of such a type. On average, the lifetime ($\tau$) is approximately $10^{-12}$ s, so after traveling a few hundred microns they will decay. The decay products, or ”daughters”, can be used to reconstruct the ”parent” particle. If the daughters live long enough to reach the detectors they can be used to study the parent.

At RHIC, STAR and PHENIX reconstruct $D$ mesons by measuring the decay products. As discussed in the previous chapter the creation of charm quarks and the subsequent production of experimental observables can be described by a sequence of three different processes, shown in 3.1. First, the initial hard scatterings of partons are thought to be the process responsible for $c\bar{c}$ production. The charm quarks will hadronize into charm hadrons, which quickly decay to the final particles that we detect. Figure 3.1 also demonstrates two types of decay. The right side depicts the semi-leptonic decay, where $D^0$ goes to a kaon, electron, and electron neutrino. The
branching ratio for this mode is $3.55 \pm 0.05\%$. The left side shows the decay of $D^0$ to a kaon and pion, with a branching ratio of $3.89 \pm 0.05\%$.

In this chapter, we will describe the methods used by STAR and PHENIX to identify charm quarks. The technique used for measuring the semi-leptonic decay using non-photonic electron will be discussed, along with the direct reconstruction of $D^0$ mesons, which utilizes mixed event and rotational techniques for background subtraction. Finally, we present previous physics results from these two measurements, that include the total charm cross section, collective motion, and the observed energy loss of non-photonic electrons from heavy flavor decays and discuss the consequences of these measurements.

3.1 Non-photonic Electrons

Charm, together with bottom quarks can be identified through the measurement of single electrons that come from semi-leptonic decay of $D$ and $B$ mesons. STAR
has studied the spectrum of single electrons, $e^\pm$. The main background sources in the single electron spectrum are primarily $e^+e^-$ pairs from photon conversions in detector material and $\pi^0$ and $\eta$ Dalitz decays. For this reason the single electron signal is called non-photonic and the background is called photonic. It is important to note that the electrons only carry a fraction of the total $D$ and $B$ momentum, meaning the parent particle momentum is unknown. In addition, the electrons measured come from both $D$ and $B$ decays, therefore the relative fraction that each heavy flavor meson contributes to the measured electron spectrum is uncertain.

STAR identifies $e^\pm$ using the Time Projection Chamber (TPC), the Electromagnetic Calorimeter (EMC), and the Shower Maximum Detector (SMD). Electrons are identified using the ionization energy loss ($dE/dx$) information from the TPC, the energy ($E$) deposited into the EMC, and the shape of the shower in the SMD. An energy loss cut is used to isolate $e^\pm$. Compared to hadrons, $e^\pm$ produce a different shower and deposit more energy into the EMC, so additional cuts on $E/p$ and shower size in the SMD aid in hadron rejection. Finally, the photonic background is rejected using an invariant mass technique. The $e^+e^-$ invariant mass distribution due to photonic conversions and $\pi^0$ and $\eta$ Dalitz decays has a maximum near zero, and a tail at nonzero. A cut of $M_{inv} (e^+e^-) < 150 \text{ MeV}/c^2$ can be applied to subtract off most of photonic contribution.

PHENIX identifies $e^\pm$ using a Drift Chamber (DC), Pad Chambers (PC1), a Ring Imaging CHeRenov detector (RICH), and an ElectroMagnetic Calorimeter (EMCal). The DC and PC1 are used to track charged particles. It is required that these tracks also have a hit in the EMCal. Electrons are identified by requiring at least two associated hits in the RICH. Similar to STAR, cuts on shower shape and the $E/p$ ratio are used to eliminate background from photonic and hadronic sources. Additional background is subtracted off using what is called the ”cocktail subtraction”, which considers the inclusive $e^\pm$ yield to be composed of electrons from heavy flavor decays,
photonic background electrons, and non-photonic background electrons that come from the semi-leptonic decay of kaons.

3.2 Direct Hadron Reconstruction

Neutral and charged $D$ mesons can be reconstructed through their hadronic decays, with $D^0$ decaying to $K + \pi$ and $D^\pm$ to $K + \pi + \pi$. The pions and kaons can be identified by their energy loss in the TPC. The reconstruction is performed using a combinatorial technique. For example, for $D^0$ all kaons and oppositely charged pions are paired in the same event and each pair is considered a $D^0$ candidate. The invariant mass can be determined knowing the momenta of the tracks and assuming the pion and kaon masses. The invariant mass distribution contains contributions from real $D^0$ and combinatorial background from random positive-negative pairs. For the results that will be discussed in the following section, the background is estimated using the event mixing and rotational methods. These techniques will be described in Chapter 6.

The main advantage of the direct hadron reconstruction technique over the non-photonic is complete kinematics, since the entire momentum of the parent is reconstructed. However, this method comes with a large combinatorial background compared to the signal size and above some $p_T$ particle identification is not possible. In an attempt to obtain a statistically significant signal an upper bound of 1.9 GeV/c is placed on the momentum of the $D^0$ candidate. It should be noted that if the decay topology was available additional topological cuts could be used to suppress the background, but these previous measurements were performed using the TPC alone, which can not offer track position resolution satisfactory enough to fully reconstruct the decay.
3.3 Previous Experimental Results

Light flavor hadron measurement strongly point to the creation of a quark-gluon matter in heavy ion collision at RHIC. Theoretical descriptions of the light flavor quarks interaction with the QGP predict that heavy flavor, because of their relatively large masses, will not exhibit the same behavior as their lighter counterparts. In this section we will present previous measurements of heavy quarks via heavy flavor hadron measurements and outline the possible theoretical implications.

3.3.1 Total Charm Cross Section

The study of charm quark production in heavy ion collisions is done mostly through the detection of charm mesons, a bound state of a quark and anti-quark. Table 3.1 lists some of the open charm mesons, quark content, mass, and mean decay length.

<table>
<thead>
<tr>
<th>Meson</th>
<th>Quark content</th>
<th>Mass (MeV/c²)</th>
<th>cτ(μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D⁰(D⁰)</td>
<td>cū(čū)</td>
<td>1864.84 ± 0.17</td>
<td>122.9 μm</td>
</tr>
<tr>
<td>D⁺(D⁻)</td>
<td>cd(čd)</td>
<td>1869.62 ± 0.20</td>
<td>311.8 μm</td>
</tr>
<tr>
<td>Dˢ⁺(D&lt;sub&gt;s&lt;/sub&gt;⁻)</td>
<td>cš(čš)</td>
<td>1968.49 ± 0.19</td>
<td>149.9 μm</td>
</tr>
<tr>
<td>D⁰(D⁰*)</td>
<td>cū(čū)</td>
<td>2006.97 ± 0.19</td>
<td></td>
</tr>
<tr>
<td>D&lt;sup&gt;+&lt;/sup&gt;⁺(D&lt;sup&gt;-&lt;/sup&gt;⁻)</td>
<td>cd(čd)</td>
<td>2010.27 ± 0.17</td>
<td></td>
</tr>
<tr>
<td>D&lt;sup&gt;+&lt;/sup&gt;⁺(D&lt;sub&gt;s&lt;/sub&gt;⁻)</td>
<td>cš(čš)</td>
<td>2112.3 ± 0.5</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: A list of charm mesons along with their quark content, masses, and mean decay lengths.

Ground state D mesons alone are used to calculate charm cross sections. The excited states primarily decay to neutral and charged D mesons. The charm mesons that contain a strange quark, D<sub>s</sub>, decay to hadrons and semi-leptonically. Charm baryons also exist. The lowest mass charm baryon, Λ<sub>c</sub>⁰, decays primarily to Λ, but also semi-leptonically and to charged hadrons. The heavier ground state baryons and the excited states (Σ<sub>c</sub>) decay to Λ<sub>c</sub>. It is assumed that the charm baryons do not
contribute a significant amount to the total charm cross section.

The STAR experiment has measured open charm meson spectra from hadronic decay channels and non-photonic electron spectra from charm and bottom decays. The measured $p_T$ spectra obtained from the semi-leptonic decay of charm and bottom in $p+p$, d+Au, and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and $D^0(\bar{D}^0) \rightarrow K^-\pi^+(K^+\pi^-)$ in $p+p$, d+Au, and Au+Au collisions can be seen in Figure 3.2 [36, 37]. In addition, the $p_T$ spectrum in Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV has been measured [\]. The total cross section per nucleon-nucleon collision ($\sigma_{c\bar{c}}^{NN}$) using the spectrum obtained from the hadronic channel in d+Au is $\sigma_{c\bar{c}}^{NN} = 1.3 \pm 0.2(stat.) \pm 0.4(sys.)$ mb and is $\sigma_{c\bar{c}}^{NN} = 1.4 \pm 0.2(stat.) \pm 0.4(sys.)$ mb with the non-photonic electron spectrum included in the fit. The cross section obtained using Au+Au collisions, using a com-
bined fit to the $D^0$ mesons and the muons and electrons from heavy flavor decays, is 
\[ \sigma_{_{c\bar{c}}}^{NN} = 1.29 \pm 0.12(stat.) \pm 0.39(sys.) \text{ mb}. \]  The cross section using Cu+Cu collisions was measured to be 
\[ 1.06 \pm 0.26(stat.) + 0.29(sys.) - 0.38(sys.) \text{ mb}. \]  Within errors, these results are consistent indicating that the charm cross section scales with the number of binary collisions. The scaling implies that the presence of the QGP has no effect on charm quark production. A measurement of $D^0$ in Au+Au collisions will provide an additional check of these cross section results.

At RHIC, PHENIX has measured the electron spectrum from heavy flavor decays in $p+p$ and Au+Au collisions at $\sqrt{s_{_{NN}}} = 200$ GeV. Their measured cross section in $p+p$ collisions at $\sqrt{s_{_{NN}}} = 200$ GeV is 
\[ \sigma_{_{c\bar{c}}}^{NN} = 0.567 \pm 0.057(stat.) \pm 0.193(sys.) \]  and 
\[ \sigma_{_{c\bar{c}}}^{NN} = 0.622 \pm 0.057(stat.) \pm 0.160(sys.) \text{ in Au+Au collisions at } \sqrt{s_{_{NN}}} = 200 \text{ GeV}. \]  If we ignore the results from STAR, the measured cross sections from PHENIX are also consistent with binary scaling. Both STAR and PHENIX measurements, along with Next to Leading Order (NLO) calculations are shown in Figure 3.3. The measured cross section from PHENIX is a factor of two below the results from STAR and are not consistent within systematic and statistical errors. Both collaborations have made efforts to understand this discrepancy. Recent preliminary STAR results indicate that the background contribution had been previously underestimated, which means the more recent analysis yields cross sections that are closer to the PHENIX results.

3.3.2 Thesimalization

Assuming that a thermal QGP is created, we can use certain thermodynamic models to describe the spectrum and extract parameters such as freeze out temperature, $T_{fo}$, and average radial flow velocity, $\langle \beta \rangle$. As discussed in Chapter 1, the blast wave model is used to extract such parameters. If the $D^0$ mesons are fully coupled to the lighter species hadrons in the late stages of the QGP, they will also take on the same
Figure 3.3: The inclusive total charm cross section for various collision systems measured by STAR and PHENIX. Next to Leading Order (NLO) pQCD calculations are shown.

parameters, found for pions, kaons, and protons.

The $p_t$ spectrum obtained using $D^0$ measured in Cu+Cu collisions has been fit to extract the blast wave parameters. However, the blast wave function, has three free parameters and with only three $p_T$ bins it is difficult to extract all three parameters from the spectrum. Instead, a comparison with the lighter particle species in the Cu+Cu system is made. Figure 3.4 shows that the blast wave curve using the lighter flavor fit parameters is inconsistent with the data (light brown curve). If instead, the freeze out temperature is kept constant, a value of the average radial velocity can be extracted (green curve). The $\langle \beta \rangle$ from the fit is $0.35 \pm 0.07$. A comparison to the lighter flavor species value of $\langle \beta \rangle = 0.470 \pm 0.001$ suggests that the $D$ mesons do not have as strong a radial flow as the light quark hadrons. One interpretation is that the charm decouples from the medium in a different manner than that of the lighter species. A cross check of this result will be made with the $D^0$ measurement presented in this thesis.
Figure 3.4: The $D^0 + \bar{D}^0$ spectrum in 200 GeV Cu+Cu collisions at 0-60 %, fit with a thermal fit (red curve), a blast wave fit derived from $T_{fo}$ and $\langle \beta \rangle$ of pions, kaons, and protons in 0-60 % Cu+Cu collisions (light brown), and a blast wave fit from fixing $T_{fo}$ obtained from the light species and allowing $\langle \beta \rangle$ to be a free parameter (green).

3.3.3 Energy Loss

STAR and PHENIX have both reported on $R_{AA}$ measurements of heavy flavor decay electrons (non-photonic electrons) in $p + p$ and Au+Au collisions [?, ?]. These heavy flavor electrons do not reveal the dramatic differences in energy loss for charm and bottom that were originally predicted, and at $p_T > 4$ GeV/c show a similar magnitude of suppression as light flavor in Au+Au collisions, see Figure 3.5. Models using only radiative energy loss predict significantly less suppression, and those that include other components such as collisional energy loss also underpredict the observed suppression. The only radiative plus collisional theoretical model that describes the data well is one where only charm is contributing to the non-photonic electron spectrum. Other avenues have been explored to explain the suppression. One model where open heavy flavor mesons can form early and collisional dissociation in the medium, multiple times. The prediction using this model can been seen in the figure as the dashed turquoise line and describes the observed energy loss quite well. More details
Figure 3.5: $R_{AA}$ as a function of $p_T$ of heavy flavor electrons measure by STAR (red) and PHENIX (blue). The curves represent various calculations using radiative and collisional energy loss models for heavy flavor electrons.

regarding the relevant energy loss models were given in Chapter 2.3.1.

All theoretical predictions are sensitive to the bottom contribution to the electron spectrum. Recent Fixed Order Next to Leading Log (FONLL) calculations for heavy flavor production in $p+p$ collisions show the bottom contribution to the non-photonic electron spectrum becoming comparable to charm near intermediate $p_T$ above 3-4 GeV/c, shown in Figure 3.6. It is crucial, in order to understand the observed heavy flavor energy loss from heavy flavor electrons, to determine the contribution from $D$ and $B$ mesons experimentally. A direct measurement of $D$ mesons alone could allow us to separate out the charm contribution to the non-photonic electron spectrum.
Figure 3.6: Results from FONLL estimates of the charm and bottom contribution to non-photonic electron spectrum in $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV.

3.3.4 Electron-Hadron Azimuthal Correlations

Electron-hadron ($e-h$) azimuthal correlations have been studied with the objective of disentangling the $D$ and $B$ meson contributions to the non-photonic electron spectrum. Momentum conservation implies that the heavy quark anti-quark pairs produced in the initial hard scatterings of the collision are correlated azimuth ($\Delta \phi$), here a back-to-back orientation arises. $D^0$ mesons will predominately decay hadronically ($D^0 \rightarrow K+\text{anything}$, B.R. $\sim 55\%$) and bottom, via $B$ meson, will decays into $D^0$ mesons. In addition, both the $D$ and $B$ mesons will decay semi-leptonically. With the $D^0$ also decaying to $K+\text{anything}$, azimuthal correlations can be made between electrons and charged hadrons. The expected charm and bottom contributions are simulated using PYTHIA. Figure 3.7 shows the predicted distributions using PYTHIA and the correlation for electrons and hadrons in $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV for two different $p_T$ bins. The width of the near side ($\Delta \phi = 0$) peak for electrons from $B$ decays is much wider compared to $D$. The energy released in the $B$ me-
Figure 3.7: $\Delta\phi$ for non-photonic electron and hadron pairs, where the trigger electron has (top) $2.5 < p_T < 3.5 \text{ GeV}/c$ and (bottom) $5.5 < p_T < 6.5 \text{ GeV}/c$. The curves represent PYTHIA calculations for $D$ (red dotted curve) and $B$ (blue dashed curve) decays. The fit is shown as the black solid curve.

The semi-leptonic decay leads to this broader angular correlation between the decay electron and hadron daughters. The measured distribution is then fit with a linear combination of the PYTHIA curves with $N_{\epsilon_B}/(N_{\epsilon_D} + N_{\epsilon_B})$ as a parameter in the fit function. Figure 3.8 shows the relative bottom contribution (closed symbols) to the total non-photonic electron yield as a function of $p_T$ using this method. The open symbol is from an independent method, which studied $e$-$D^0$ azimuthal correlations in $p+p$ collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$ [38].

The experimental results are consistent with FONLL estimates. The measurements suggest that the $B$ meson contribution to the non-photonic electron spectrum increases with $p_T$ and is comparable to the $D$ meson contribution above 5 GeV/c. This indicates that theoretical models that try to describe the observed high $p_T$ non-photonic electron suppression must also take bottom’s contribution to the heavy flavor spectrum into account as well.

The motivation for the analysis presented in this thesis is two part. First, we
Figure 3.8: $p_T$ dependence on the relative contribution from $B$ mesons to the non-photonic electron spectrum. The solid curve is the FONLL calculation and theoretical uncertainties are represented by the dashed curves.

attempt to expand on the direct reconstruction of $D$ mesons by using the same combinatorial technique as used in the previous analysis but through a secondary vertex technique that reconstructs the full decay topology of the $D$ meson. This type of measurement is possible because of the added track position resolution achieved by including the inner silicon detectors in STAR and can contribute as a cross check to measured values of the total charm cross section. Secondly, we expect to measure $D$ mesons out to a higher momentum and hope to contribute to separating out the charm contribution to the heavy flavor electron spectrum.
Chapter 4

Experimental Facilities

4.1 Introduction

The Relativistic Heavy Ion Collider (RHIC) is a colliding beam facility that has the ability to collide a range of ions, of both the same and different species. The collider is located in Upton, New York at Brookhaven National Laboratory. RHIC is multipurpose, and has been the first to provide beams of colliding relativistic heavy ion beam and polarized protons. The latter collisions are performed in order to study the spin structure of hadrons. The main goal for construction of RHIC was to investigate a hot and dense medium of quarks and gluons that should arise from the collision of heavy nuclei, at high energy. The RHIC ring has six interaction points, and four of these points are dedicated to the STAR\textsuperscript{1}, PHENIX\textsuperscript{2}, PHOBOS\textsuperscript{3} and BRAHMS\textsuperscript{4} experiments. In 2000 RHIC started running and since this time BRAHMS and PHOBOS have completed their physics programs and have been decommissioned. The two multipurpose, larger detectors, STAR and PHENIX, are still in operation and will be well into this decade. In this chapter the RHIC facility will be described along with a description of STAR.

\textsuperscript{1}Solenoidal Tracker At RHIC

\textsuperscript{2}Pioneering High-Energy Nuclear Interactions eXperiment

\textsuperscript{3}Is not a acronym. Phobos is a moon of Mars, which was the name of the original proposed detector, Modular Array for RHIC Spectra (MARS)

\textsuperscript{4}Broad Range Hadron Magnetic Spectrometer
4.2 The RHIC Facility

RHIC has been designed to collide a variety of ion beams. Table 4.2 lists the basic design parameters for RHIC. For this thesis, Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV were used, so I will describe the process of accelerating Au ions, although this process for other ions is similar. A schematic of the set-up of the facilities needed to collide these ions is describe below and Figure 4.1 shows these facilities schematically.

The Au ions, produced using a cesium sputter source, start off with a $+1e$ charge before entering the Tandem Van de Graaff accelerator. There the beam passes through a carbon stripper foil, leaving the ion in a $+12e$ charge state. Before the 1 MeV/u gold beam is transported to the Booster Syncrotron it moves through a thicker object stripper foil that leaves the ion in a $+31e$ charge state. In the Booster the beam is accelerated to a kinetic energy of 95 MeV/u. Before exiting the Booster the ions are further stripped before injection in to the Alternating Gradient Syncrotron (AGS).
In the AGS the ions are accelerated to the RHIC injection energy of 8.86 GeV/u. At this energy, the fully ionized bunches, containing approximately $1 \times 10^9$ ions each, are injected into the two counter-rotating rings of RHIC through the AGS-to-RHIC (ATR) Beam Transfer Line.

RHIC has two rings that intersect at six points. These points are the collision regions where experiments can be placed. STAR is located at the 6 o’clock position of the rings. Inside RHIC, two Radio-Frequency (RF) systems are used for additional acceleration and storage. One system, operating at 28 MHz, accelerates the beam bunches to a final energy of 100 GeV/u. At this energy the second system, operating at 197 MHz, keeps the ions at top energy. Superconducting magnets are used to steer the ion beams around the 3.8 km rings.

<table>
<thead>
<tr>
<th></th>
<th>Au+Au</th>
<th>p + p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>$100 \rightarrow 5$ GeV/u</td>
<td>$250 \rightarrow 30$ GeV</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$2 \times 10^{26}$ cm$^{-2}$ s$^{-1}$</td>
<td>$1.4 \times 10^{31}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Number of bunches/ring</td>
<td>60($\rightarrow 120$)</td>
<td>60($\rightarrow 120$)</td>
</tr>
<tr>
<td>Luminosity lifetime</td>
<td>10 h</td>
<td>&gt; 10 h</td>
</tr>
</tbody>
</table>

Table 4.1: Performance specifications of RHIC.

4.3 Particle Tracking using Semiconductor Detectors

For the analysis presented in this thesis, the primary detectors utilized were the STAR Time Projection Chamber (TPC), the Silicon Vertex Tracker (SVT), and the Silicon Strip Detector (SSD). The TPC is a gas detector that does particle tracking and energy loss measurements from charged tracks ionizing as they pass through the chamber. The SVT is a large area silicon strip detector. A charged particle goes through they create electron hole pairs. The charges drift to the electrodes and
the drift generates a signal. A short introduction to semiconductor detector devices follows.

4.3.1 A Brief History of Semiconductor Detectors

Semiconductor detectors have been known for about 60 years. In 1949 McKay investigated the use of very pure germanium and silicon as a detector of charged particles[39]. As incident particles pass through the detector charge is produced and needs to be collected. For this, the application of an electric field is needed. The initial problem was that germanium and silicon are not insulators, therefore the applied electric field caused large leakage currents. McKay eventually found that by using a reversed-biased diode structure high electric fields could be used at room temperature without excess noise. The advantage of using germanium or silicon is that there is no serious trapping problem or recombination, which was the problem with previously fabricated particle detectors that were made using crystal.

Throughout the 1950s, McKay, at Bell Laboratories, reported on a few measurements involving the use of germanium and silicon as particle detectors [40,41]. During this time a group at Purdue was pioneering the use of thin, large-area surface barrier junctions [42,43,44]. By the end of the 1950s, largely pushed by the work of the Purdue group, the successful application of germanium junctions to a low energy nuclear experiment by Dabbs, Walter, and Roberts were implemented [45]. Following this, labs throughout the United States, Canada, and Europe began intensive development of particle detectors using silicon or germanium.

The discovery of heavy quarks, that travel only a few hundred microns before decaying, made the high energy physics community focus their interest on the tracking abilities of silicon detectors [46]. During the late 1970s groups from the SPS at CERN were involved in charm production and needed an device that would be able to detect a particle that had a mean lifetime on the order of $10^{-13}$ seconds. Silicon
won over germanium and the Pisa group investigated silicon for use on an active target. By observing steps in amplitude of signals in the detector secondary vertices could be identified. Simultaneously the CERN group constructed strip detectors for high precision tracking using silicon wafers, tested at the NA11 setup [17]. Both of the prototypes were constructed as surface barrier silicon diodes on high resistivity n-type silicon.

By 1981, the NA11/32 experiments successfully installed and used silicon strip detectors for tracking and vertex measurements [18–19]. The NA11 experiment installed six planes of silicon strip detectors, and in the second set-up for the NA32 experiment eight detectors, grouped into four pairs (one in the front of the target and three behind). The detector gave a vertex position reconstruction resolution (along the beam) of 130 µm and a track impact parameter resolution of 24 µm.

In 1984 silicon detectors were successful. NA32 measured neutral and charged $D$ mesons along with $D_s^±$ mesons [50,51]. The goal of these measurements was a better understanding of the charm production mechanism in charm particle hadronic decays. In addition, a better grasp on decay properties such as lifetimes and branching ratios was achieved.

4.4 The STAR Experiment

In a heavy ion collision at RHIC a considerable amount of particles are produced, along with high momentum particles that originate from parton-parton hard scattering. The simultaneous study of many observables must be achieved in order to study the many signatures of a QGP. The Solenoidal Tracker at RHIC (STAR) was designed with that in mind. The large acceptance of STAR allows for event-by-event studies using bulk particles along with the detection of hadron jets. Measurements of hadron production over a large solid angle can be performed with high precision tracking, momentum determination, and particle identification.
The detector layout of STAR, during the 2007 run, can be seen in Figure 4.2. The room temperature solenoidal magnet provides a 0.5 T field that bends the charged hadron tracks for momentum measurement. The TPC and SVT yield high precision charged particle tracking near the interaction region. An additional layer of silicon, the SSD is located between the SVT and TPC. The large volume TPC performs tracking with and without the SVT and SSD, and also can be used for particle identification. For the data shown in this thesis the main detectors utilized were the TPC, SVT, and SSD. In the next sections a more detailed discussion of the detectors follows.

4.4.1 The STAR Magnet

The particles that come streaming out after the collision of two heavy ions can best be understood through tracking. A magnetic field parallel to the beam direction is provided by the STAR Magnet. The field is used for particle tracking and momentum
determination of charged particles. From the Lorentz Force Law

\[ F_{\text{Magnetic}} = q(\vec{v} \times \vec{B}) \]  

(4.1)

where \( \vec{v} \) is the particle velocity and \( \vec{B} \) is the magnetic field. The magnetic force will be equal to

\[ F_{\text{Centrifugal}} = m \frac{\vec{v}^2}{r} \]  

(4.2)

For a particle of mass \( m \) we find

\[ p = qBr \]  

(4.3)

The momentum, \( p \), can be extracted knowing the magnetic field, the helical trajectory of the charged track, and by assuming that the charged particle is \( \pm 1e \). The large solenoidal magnet that surrounds STAR provides a uniform magnetic field of 0.5 T inside of the TPC. The field strength was chosen with two things in mind: high kinematic acceptance at low \( p_T \) and good momentum resolution at high \( p_T \).

4.4.2 The STAR Time Projection Chamber

The TPC is the primary tracking device in STAR. The 4.2 m long TPC does radial tracking at distances of 50-200 cm from the beam axis. It covers \( |\eta| < 1.8 \) and \( \Delta \phi = 2\pi \), giving complete azimuthal symmetry. The TPC is divided in two halves by a thin conductive Central Membrane (CM), and its volume constrained by two concentric field-cage cylinders and readout end caps (see Figure 4.3). In these two volumes a gas composed of 90% argon and 10% methane sits in a uniform electric field of 135 V/cm at a pressure of 1 atmosphere. This gas mixture, called P-10, is used in order to have fast drift velocities in a low electric field. As the charged particles pass through the gas they continuously ionize allowing us to map the tracks trajectories. The secondary electrons from the ionizing particles will drift to the readout end caps of the chamber.
Figure 4.3: Cut-away view of the Time Projection Chamber. The TPC diameter is 4 m, with a length of 4.2 m. The high voltage membrane is located at $z = 0$. There are 12 pairs of inner and outer sectors of pads at each end for readout.

The readout system is based on Multi-Wire Proportional Chambers (MWPC) with 136,608 read out pads. The electrons will avalanche in the high fields near the 20 $\mu$m gold plated tungsten anode wires, giving an amplification of 1000 to 3000. The positive ions created will induce a temporary image charge on the read out pads. The measured induced charge from this is shared over a few adjacent pads and this is how the reconstruction of the original track position is performed. The track multiplicities will be greater in the inner anode pads, so the individual pads have been divided into two sectors.

The outer sector, see Figure 4.4 is composed of 32 pad rows with a total of 3,942 pads (6.2 mm x 19.5 mm). There is virtually no space between pad rows. The continuous design of the pads yields optimal ionization energy loss ($dE/dx$) resolution. Here the full track ionization signal is collected and the more electrons collected, the greater the the statistics, improving the $dE/dx$ resolution. Additionally, the
Continuous pad coverage improves the tracking resolution by anti-correlating errors between pad rows.

The highest track density lies in the inner sector. Therefore, the design is optimized for good two-hit resolution. The inner sector consists of 13 pad rows with a total of 1,750 small pads (2.85 mm x 11.5 mm). The space between the pad plane and the anode wire is also reduced, in comparison to the outer sector. This reduction in spacing reduces induced surface charge width to improve two track resolution. The main improvement in the two track resolution is from the shorter pad length. This helps with reconstruction of lower momentum tracks crossing the pad row far from the perpendicular and tracks with a large dip angle. The inner sector does not do much for improving $dE/dx$ resolution. However, it does improve position measurements along the track to small radii, and this improves the momentum resolution and matching to the inner detectors of STAR.
Figure 4.5: Functional diagram of a generic silicon drift detector (SDD).

4.4.3 The Silicon Vertex Tracker

The STAR Silicon Vertex Tracker (SVT) is a 3 layer Silicon Drift Detector (SDD) that can be used in conjunction with the TPC for charged particle tracking. Silicon drift technology was chosen in order to handle high multiplicities and to minimize the number of readout channels. In a central Au+Au collision near 1000 primary particles are produced per unit of pseudorapidity, and many secondary particles are present from the primaries interaction with detector material and the decay of short lived primaries. The SVT is situated around the interaction region to improve on primary vertexing and add to secondary vertexing capabilities. By including track information from the SVT in the tracking the primary vertex resolution and impact parameter resolution of the tracks is greatly improved.

The geometry of a generic linear SDD is shown in figure 4.5. Each detector is fabricated on a thin n-type silicon wafer. On the top and bottom of the wafer p+ cathode strips are implanted. The n+ anodes lie parallel to the cathode strips at the end of the wafer. The detector can be thought to consist of two parts: a drift region and a focusing region. The drift region takes up most of the detector area, while
the focusing region lies near the last few millimeters before the anodes. In the drift region the p+ strips a symmetrically biased (top and bottom) with the potential gradient along the drift direction (x). When an energetic charged particle passes through ionized electrons are generated. These electrons will drift to the middle of the detector (in z) because of the potential valley that arises from the p/n junction. This valley keeps electrons from the surface of the detector, which helps to ensure that all charge is collected. In the focusing region an asymmetrical potential is applied to the p+ strips. This is done to guide the electron cloud to the readout anodes. The electrons are readout through pre-amplification electronics. The hit anodes determine the y-coordinate, while the drift time determines the x-coordinate.

The drift velocity $v_e$ depends on the electric field $E$ that is applied. The relationship is

$$v_e = \mu_e E$$

(4.4)

where $\mu_e$ is the electron mobility in silicon. The electric field is usually limited to less than 1000 V/cm, below which the electron mobility is independent of $E$ and is equal to 1350 cm$^2$/V at 300 K. For a detector with dimensions on the order of a centimeter, this gives characteristic drift times on the order of a microsecond.

The STAR SVT is composed of a total of 216 SDD wafers that are arranged as three concentric barrels around the beam pipe at radii of 6.9, 10.8, and 14.5 cm (See Figure 4.7). The SDD are supported on structures called "ladders". A total of 36 ladders (with four, six, or seven detectors) lie along the direction of the beam pipe with length 25.2, 37.8, and 44.4 cm, respectively. Each ladder consists of three mechanical components: a detector carrier (DC) and two electronics carriers (ECs). Each SDD is attached to a DC. Each DC is 1.8 mm thick, 63 mm wide, and 530 or 560 mm long. The ECs are 1.8 mm thick, 20 mm wide, and either 530 or 560 mm long. The different length DC and EC yield different length ladders. This difference is present in order to have a compact detector.
The SDD design is illustrated in figure 4.6. The bottom of the figure shows the layout of the SDD on 4” Wacker NTD wafer that is 280 $\mu$m thick and has 3 k$\Omega$cm resistivity. The detector is cut using lasers to be of size 63 mm x 63 mm. The detector is separated by what is called the ”continental divide”. This so called divide is the central cathode and it receives the maximum voltage bias. The half-detectors, called ”hybrids”, formed by this divide will drift electrons in opposite directions from one another.

Figure 4.6 (top) also shows a magnified corner of an SDD. The segmented anodes, 200 $\mu$m x 200 $\mu$m in size, are at a 250 $\mu$m pitch. This pitch is appropriate for the range of signal gaussian widths $70 \mu m < \sigma < 200\mu m$ that are expected for drift distances up to 3 cm and ionization from 1-10 Minimum Ionizing Particles (MIPs). For each drift direction there are 240 anodes. The p+ cathodes are at 135 $\mu$m pitch, which is sufficient to maintain an acceptable linear electric field in the bulk of the detector. The p+ implants with aluminum coating serve as guard strips and are connected to every tenth cathode. They serve two purposes. The first is that each tenth cathode on one hybrid connects to that of the other hybrid. This ensures that only one hybrid needs external bias, making it so the other half is automatically bias. The second
purpose is the guard strips provide a controlled voltage step down gradient between the high voltage implants near the central cathode and the edge of the detector. This is important for preventing breakdown voltage gradients on the detector where voltage gradients are greatest. The optimized design of the guard areas resulted in detector with a 94.5% active area.

The nominal working voltage of the SDD is -1500 V. Each hybrid has a maximum drift distance of about 3 cm. The resultant electric field from this is 500 V/cm. This is well within the range where electron mobility is independent of E. Then the drift velocity is approximately 6.75 \( \mu \)m/ns, giving a total drift time near 4.5 \( \mu \)s.

As ionized electrons reach the anodes, the front-end electronics will amplify and shape the signal. This is done to measure the time of arrival and total charge deposited. The front-end must also minimize the noise introduced into these measurements. All of this is done with the SVT front-end multichip module (MCM). The MCM is 63 mm long and 20.5 mm wide. 240 input pads are spaced at the detector anode pitch of 250 \( \mu \)m and are wire bonded to the SDD anodes. Each pad had a second wire bond to and input pad of the PreAmplifier ShaPer (PASA). There are 15 PASAs on each MCM, and each PASA contains 16 channels. The PASA sends
the output to a Switched Capacitor Array (SCA), which stores the output in analog form. The data can now be converted to digital format.

4.4.4 The Silicon Strip Detector

The STAR Silicon Strip Detector (SSD) was added to provide addition tracking precision to the SVT. The SSD lies 23 cm from the beam line, between the TPC and SVT. It gives an extra space point that helps with the extrapolation of tracks determined using the TPC toward the interaction point via the SVT hits. The cylindrical SSD holds 20 ladders, which are 106 cm long. Each ladder consisted of 16 detection modules. The detection modules are double sided, and have an area of 75 mm x 42 mm, with a thickness of 300 µm. A module consists of one detector, 12 readout chips placed on two hybrids. The SSD has a position resolution below 20 µm in the radial direction and 750 µm in the direction of the beam.

The SSDs are n-type semiconductors that are ionized with the passage of energetic particles. The ionization electrons travel to the anodes, and a two dimensional reconstruction of the hit is performed. The readout anodes and cathodes are located on the top and bottom of the detector. Whereas the readout for the SVT is located at the ends of the wafer. This allows the relaxation of the electric field requirement because the ionization does not need to be propagated as far as in the SVT. Therefore the SSD operating voltage ranges from 20 to 50 V.

4.4.5 Triggering System

At RHIC, luminosities range from \( L \approx 6 \times 10^{30} \text{ cm}^{-2} \) for p+p collisions to \( L \approx 2 \times 10^{26} \text{ cm}^{-2} \) for Au+Au collisions. RHIC can deliver approximately 2000 Hz collisions, but STAR can only take data at the rate of 100 Hz, so triggering detectors are essential. A triggering system also improves on operational efficiency by taking data on those events that are of interest, based on the geometry of the Au+Au event. The
triggers are divided into Levels 0, 1, 2, 3, based on order of operation and response speed. Level 0, 1, and 2 take information from STAR’s fast detectors, while the level 3 trigger utilizes data taken from slow detectors. The detectors used for triggering in this thesis are the Zero Degree Calorimeter (ZDC) and the Vertex Position Detector (VPD). The ZDC and VPD are fast detectors, which means that they have a readout time on the order of $1 \mu s$.

The ZDC is a sampling calorimeter, which is placed at a distance of $18 \text{ m}$ from the interaction point in the RHIC tunnel on both sides of STAR’s experimental hall. The ZDCs [50, 49] are used to provide the minimum bias trigger and to measure centralities in heavy ion collisions. Identical ZDC detectors are installed at each of the four RHIC experiments providing comparable collision rate measurements to monitor the RHIC luminosity. Figure [4.8] shows the configuration of the detectors. The ZDC detector measures the total energy of the unbound neutrons emitted from the nuclear fragments after a collision. The charged fragments of the collision are bent away by the RHIC dipole magnets. Each ZDC contains hadron calorimetry that consists of tungsten plates with alternating layers of optical fibers. The Cherenkov light from shower electrons, which originated from the energy deposition of the neutrons, is measured.
The Vertex Position Detector (VPD) was used to select on the primary vertex position of the collision. The cut of $\pm 5$ cm was to ensure that the vertex was well constrained into to the acceptance to the SVT. This cut effectively sampled $1/10$ the luminosity.
Chapter 5

Data Reconstruction and Analysis Methods

Neutral \( D \) mesons can be identified through their hadronic decay \( D^0(\bar{D}^0) \rightarrow K^{\mp}\pi^{\pm} \) (B.R. = 3.89 ± 0.5\% [1]), and charged \( D \) through their hadronic decay \( D^+(D^-) \rightarrow K^{\pm}\pi^{\mp}\pi^{\mp} \) (B.R. = 9.4 ± 0.4\% [1]) using the STAR TPC, SVT, and SSD detectors. The identification of \( D \) mesons is done using an invariant mass technique that utilizes the decay vertex topology. The daughter pions and kaons are identified by their energy loss measured in the TPC and momentum measured using the TPC, SVT, and SSD. Additional cuts are placed on the daughters in order to improve signal-to-background ratio. In this chapter we will discuss track and event reconstruction, along with event and track selection used for this analysis. In addition, a description of the reconstruction process and cut selection using simulations will be discussed.

5.1 Track and Event Reconstruction

As charged particles move away from the collision region they traverse the SVT, SSD, and TPC volume. The particles are reconstructed by using the ionization points. As a particle passes through these detectors it will ionize the material, be it the gas mixture of the TPC or the silicon of the SVT and SSD. The ionized electrons are used to create clusters in the detectors and the clusters are used to determine the "hits" the particle made in each detector, which are used to identify the path of the
particle. The algorithm for track reconstruction starts with the TPC hit that lies the farthest away from the center of STAR, and moves inward. Each of the 45 TPC rows can place one hit on a track, the SSD is only one layer, and the SVT has three layers. Therefore, the maximum number of hits a track can have associated with it is 49. Although, in the SVT there are ladders that slightly overlap, so it is possible, but unlikely, that a track can have more than 3 hits in the SVT. Initially tracking is performed using the TPC hits alone. The points in space that lie close to one another are used to extrapolate a curve. As each point is added to the curve the extrapolated curve is refit. The points that lie off of the curve are removed, while the points that are added to the track are marked as used. The curve extrapolation recognizes that the path of a charged track in the STAR magnetic field can be described with a helix. The helix can be parameterized as a function of the track length and describe in Cartesian coordinates as:

\[
x(s) = x_0 + R[\cos (\Psi_0 \pm \frac{s}{R} \cos \lambda) - \cos \Phi_0] \tag{5.1}
\]

\[
y(s) = y_0 + R[\sin (\Psi_0 \pm \frac{s}{R} \sin \lambda) - \sin \Phi_0] \tag{5.2}
\]

\[
z(s) = z_0 + s \sin \lambda \tag{5.3}
\]

where \(s\) is the path along the helix, illustrated in Figure 5.1(a), \(\lambda\) is the dip angle, see Figure 5.1(b), \(R\) is the radius, the value of \(\pm 1\) depends on the magnetic field and the charge of the particle, and \(\Psi = \Phi + \pi/2\), which is the azimuthal angle of the track direction.

In the \(xy\) plane the arc of a circle represents the projected helix. In any plane parallel to the \(z\)-axis, the track trajectory is a section of a sinusoidal curve and a straight line approximation can be used. By eye, high momentum tracks \((p_T > 3 \text{ GeV/c})\) can be approximated as a straight line, because the curvature is small. The bulk of the particles seen by STAR are low momentum and are visibly curved.

At this stage, all of the tracks are considered to be "global" tracks. The name
global means that the fit used for the track is composed from information extracted from several tracking detectors. All global tracks will be refit using a Kalman filter algorithm. A track is put through the Kalman filter three times. In the first pass, the proximity of points to the curve is calculated. In the next pass, energy loss, distortions from non-uniform fields, and multiple scatterings experience by the electrons in the detector material are taken into account. Finally, the least $\chi^2$ fit is used to calculate the trajectory of the particle.

After obtaining the global tracks of an event the space point of where the collision occurred must be determined. This point is called the primary vertex of the event. It is the space point where the beams collide. The ions travel in bunches and due to the long length of the bunches ($\sim 20$ cm in a Au bunch), the collision can occur at any position along the beamline inside STAR. At $\sqrt{s_{NN}} = 200$ GeV the beam is collimated to a few mm, which helps to restrict the primary vertex in the transverse direction. Locating the primary vertex $z$ is more challenging, but it can be performed
by looking for a crossing region of the tracks in a given event and extracting a common point. The procedure involves projecting the tracks back to the collision line, and using the Least Squares method to calculate the primary vertex location [54].

Once a primary vertex is reconstructed, the tracks originating from this point are refit using the addition point of the collision vertex. These tracks are called primary tracks. The addition fit point improves the accuracy of the direction and momentum determination of the track. Global tracks that point back to the primary vertex will also be primary tracks, but they are not dropped from the global track group. The result is that all primary tracks correspond to certain global track, but not every global has a corresponding primary track, because not all tracks will point back to the collision vertex.

5.2 Event Selection

As discussed in the previous chapter, collisions or events are selected using certain triggers. When using certain triggers to select on an event a certain bias can arise. To avoid such biases one can select events satisfying the “minimum bias” trigger. These events were chosen using the VPD trigger, which ensures that the events are in the acceptance of the SVT. The coincidence triggering of the ZDC was used alongside the VPD. The ZDCs lie on the beamline, +18 m and -18 m from the interaction point. A coincidence between both detectors serve as the minimum bias trigger. The resulting distribution of the $z$ vertex position can be seen in Figure 5.2 (right).

One way to classify a heavy ion collision is through what is called the centrality of the event. The centrality is correlated with the multiplicity of particles in an event. The STAR experiment defines the centrality using a value called reference multiplicity. Figure 5.2 (left) shows the reference multiplicity distribution for year 7 Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV. Reference multiplicity is defined as the approximate number of charged particles at mid-rapidity ($|\eta| < 0.5$). These tracks
must also have a Distance of Closest Approach (DCA, the minimum distance of a
tracks trajectory to the primary vertex) of 3 cm, and a minimum of 10 points in the
TPC that are used in the track fit. The event centrality and reference multiplicity are
related through the Glauber model, which describes nuclear collisions as an ensemble
of nucleon-nucleon collisions in an overlap region located in a plane that is transverse
the beamline.

For this analysis, a more restrictive cut of ±10 cm primary vertex $z$ cut is used in
order to ensure that all decay daughter tracks pass through each layer of the SVT. In
addition, the events are selected using what is called a minimum bias trigger. This
means that all events, regardless of centrality, are used. However, for specific types
of physics analyses certain centralities would be selected. The most central collision
would create the hottest, densest matter. A measurement of the energy loss of charm
through the reconstruction of $D$ mesons would require a reference multiplicity cut in
order to analyze the most central collisions. On the other hand, to measure the elliptic
flow of charm through the measurement of $D$ mesons mid-central events would be
selected on. In run 7 Au+Au collisions STAR triggered on 69M minimum bias events
Figure 5.3: Energy loss per unit length \((dE/dx)\) in the STAR TPC as a function of momentum \((p)\) of charged tracks. (a) The grey points are all charged particles. (b) The identified pion and kaon tracks are marked using a 2\(\sigma\) cut on their Bethe-Bloch parameterization fits.

The 50M events satisfied a primary vertex cut of \(\pm 10\) cm. Along with these cuts, half of the physics runs were not used for this analysis due to detector inefficiencies that arose from areas of the silicon detectors becoming problematic during physics running.

5.3 Charged Particle Identification

Charged particles, such as \(\pi\), K, p and e, lose energy via interaction with the medium inside the TPC. The energy loss per unit length \((dE/dx)\) of a track can be determined using a fit of all clusters and the energy loss measured on all TPC rows associated with a given track. The energy loss \(dE/dx\) of a particle with charge \(Z\) and speed \(\beta = v/c\) can be calculated using the Bethe-Bloch formula, defined as:

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

(5.4)

Here \(\kappa\) is \(4\pi N_A r_e^2 m_e c^2 = 0.307\) MeV cm\(^2\), with \(N_A\) being Avogadros number, \(r_e\).
the classical radius, $m_e$ the rest mass of the electron. $Z$ is the atomic number and $A$ is the atomic mass of the absorbing material. $I$ corresponds to the mean excitation energy, and $T_{\text{max}}$ is the maximum transferable kinetic energy in one collision. Both $\beta$ and $\gamma$ are the kinematic variables with their usual meanings, $\delta/2$ is the density effect correction to ionization energy loss.

Different Bethe-Bloch distributions will correspond to different particles. For this analysis, the variable $N_\sigma$ is used as a particle identification cut. $N_\sigma$ corresponds to the standard deviation of a Gaussian between the energy per unit length of a measured track and the expected value. For a particle $x$, $N_\sigma$ is defined as:

$$N_{\sigma,x} = \frac{1}{R} \log \frac{(dE/dx)_{\text{meas.}}}{\langle dE/dx \rangle_x}$$

(5.5)

where $(dE/dx)_{\text{meas.}}$ is the measured energy loss, $\langle dE/dx \rangle_x$ is the expected mean energy loss of particle $x$, and $R$ is the $dE/dx$ resolution of the TPC, which is around 7%. Pions and kaons with momentum below 750 MeV/c can be cleanly identified using this $dE/dx$ technique.

The $dE/dx$ distribution for all charged particles as a function of momentum is shown in Figure 5.3 (a), along with the identified pions (blue) and kaons (pink) using a $2\sigma$ cut about the mean energy loss Bethe-Bloch parameterization (b). For $p_T > 750$ MeV/c the distributions completely overlap and the particle type is no longer identifiable.

### 5.4 Secondary Vertex Reconstruction

The secondary vertexing technique is a standard method employed for the reconstruction of neutral particles. When a neutral particle decays into two charged particles, often called ”daughters”, a pattern appears from the trajectories of tracks in the detectors that has the shape of a ”vee”. These ”V0” decays and their mea-
measurement is performed by pairing all oppositely charged tracks, and projecting them
toward the primary vertex. If the two trajectories cross at some point away from the
event vertex the pair is considered a candidate for a V0 decay.

The V0 particle can be identified using an invariant mass analysis. The momentum
components of the two daughters are then used, assuming the daughter particles
masses for the V0 decay, to calculate the invariant mass using Equation $E_1$ and
$E_2$ represent the two daughter energies and $p_{x1}$, $p_{x2}$, $p_{y1}$, $p_{y2}$, $p_{z1}$, and $p_{z2}$ represent
their individual momentum components.

$$M_{\text{invariant}} = \sqrt{(E_1 + E_2)^2 - ((p_{x1}^2 + p_{x2}^2) + (p_{y1}^2 + p_{y2}^2) + (p_{z1}^2 + p_{z2}^2))}$$ (5.6)

For this analysis, the V0 method has been utilized to reconstruct $D^0$ mesons.
The reconstruction of charged $D$ mesons has been performed using a variation of this
method.

5.4.1 $D$ Meson Reconstruction

A few things need to be consider when choosing the decay channel to measure $D$
mesons. The most important considerations are the branching ratio, mean lifetime
($\tau$), and the statistical significance of the measured signal. Charmed mesons are
short lived and decay before reaching the tracking detectors. In addition, there is
no way to identify neutral particles using the TPC and SVT, so the decay channels
chosen must have final products containing only charged particles.

In order to perform a $D$ meson measurement using the secondary vertexing tech-
nique, the pointing resolution of the daughter tracks must be comparable to the $\tau$
of the $D$. The pointing resolution is defined as the resolution of the two-dimensional
distance of closest approach of a global track to the primary vertex. When tracking is
performed using the TPC alone a resolution of $\sim 2.6$ mm is obtained for a track with momentum 1 GeV/c. With the inclusion of the silicon detectors in the tracking a resolution of 210 $\mu$m is achievable at 1 GeV/c. Figure 5.4, which shows the pointing resolution as a function of inverse momentum, demonstrates this.

For this analysis the $D^0$ is reconstruct using the $\pi K$ decay channel which has a branching ratio of $3.89 \pm 0.05$ % and a $c\tau$ of 122.9 $\mu$m, which is comparable to the pointing resolution. Choosing a decay channel with only two daughters is important because, to first order, the background goes like $N^i$, where $N$ is the number of tracks and $i$ represents the number the decay daughters.

To measure the charged $D$ mesons we reconstruct the $K\pi\pi$ channel, which has a branching ratio of $9.63 \pm 0.3$ % and a $c\tau$ of 311.8 $\mu$m. The three particle decay channel was chosen over the two particle channel because the two particle hadronic decay results in one neutral and one charged daughter, and as previously mentioned
neutral particle detection is not possible in the TPC. Unfortunately, requiring three tracks for reconstruction will increase the background. However, this decay channel comes with some advantages. The branching ratio is a factor of three higher than the channel chosen for $D^0$. Also, the charged $D$ lifetime over a factor two greater than the neutral $D$ and above the pointing resolution of the detectors.

5.4.2 Track Selection Cuts

The candidate selection for neutral $D$ is performed in a similar manner as the V0 method previously described. We start with tracks from the TPC that have hits in the SVT and identify the species of the daughter tracks using a $2\sigma$ cut on the Bethe-Bloch curves. Additional particle selection is performed using certain topological criteria from the decay. An illustration of the decay topology can be seen in Figure 5.5. The $D^0$ originates at the primary vertex (PV). It will travel some distance, called the decay length, at which point it will then decay to a kaon and pion. At this point we have a set of $D^0$ candidates, which include signal and background contributions.

Once the candidates are selected, the next process involves discriminating between the $D^0$ signal and the background. This can be achieved through certain geometrical cut variables placed on the daughter tracks of the candidate. An example of this would be the decay length. A fraction of the background will be filtered out because most of the topological variables for the candidates will have a geometrical pattern incompatible with the $D$ decay. However, the finite resolution of the detectors creates a reconstruction that is not perfect and a significant number of the real $D$ meson and background will have similar kinematics. This makes unambiguous signal determination an even more difficult task. Ideally, what ends up being filtered out is mostly background and what is kept is mostly signal.

The particle selection is made based on five topological variables, shown in Figure 5.5. The possible topological cuts are:
Figure 5.5: The decay vertex topology of $D^0$. DCA is an acronym for the Distance of Closest Approach. The black dot represents the primary collision vertex. The dot-dash line represents the $D^0$ path from the primary vertex. The daughter can be projected back to the primary vertex and each will have a DCA to the vertex.

1. Distance of closest approach of the $D^0$ to the primary vertex ($D^0$ DCA to PV)
2. $D^0$ decay length
3. Pion distance of closest approach to the primary vertex ($\pi$ DCA to PV)
4. Kaon distance of closest approach to the primary vertex (K DCA to PV)
5. Distance of closest approach of the daughters to one another (DCA between daughters)

The candidate selection for $D^\pm$ is performed using a variation of the V0 method. Again, track species is identified using $dE/dx$ information from the TPC and each decay daughter must have hits in the SVT. For the reconstruction we start with two $K\pi$ pairs, and require that both pairs contain the same kaon and that the pion in pair #1 is not the pion in pair #2. The $D^\pm$ is reconstructed using the invariant mass
equation for three particles. The number of topological cut variables is now doubled, for example, there will be a DCA between daughters for pair #1 and pair #2.

Although the decay vertices for both $D$ decays lie at some finite distance from the primary vertex, a large combinatorial background remains. The secondary vertexing technique allows for the use of topological cuts to suppress as much background as possible.

5.5 Simulation Studies

Monte Carlo simulation studies are a useful tool for many reasons. One important use of these studies is to investigate what topological cuts should be place on the decay daughters and the parent particle that should decrease the background while retaining a statistically significant signal. In addition, the study of simulations can aid in a better understanding of the shape of the background compared to the signal.

In the initial stages of the analysis, it was necessary to compare the topological cut variable distribution of $D^0$ alone to the background in a Au+Au collision and also investigate possible background sources. We start with Monte Carlo (MC) simulations of events consisting of one $D^0$ per event in vacuum We can call these pure $D^0$ events because no other particles are present. The event generator, PYTHIA, was used to produce $2.5 \times 10^5$ events, containing 1 $D^0$ within $|y| < 1.0$ and $p_t < 5$ GeV/c. The particles are then moved through detector simulation, followed by event reconstruction using GEANT. In this case, the studies were done with ”perfect” detectors, meaning that dead areas and other effects were not present.

5.5.1 Topological Cut Investigation

The background for charm meson reconstruction in Au+Au events is quite large compared to the signal size. To discriminate between signal and background an investigation of the topological variable distributions should be performed. in addition,
the effect of $N_\sigma$ cuts used for particle identification should also be studied, but the recreation of the $dE/dx$ for tracks in the TPC using GEANT is very difficult, so $N_\sigma$ can not be studied using these MC simulations.

Figure [5.6] demonstrates the differences of the topological variable distributions between the simulated $D^0$ and real Au+Au background. Here the blue distributions are the pure $D^0$ and the red represent the background distributions for $D^0$ candidates. The background is scaled down to the number entries in the pure sample in order to do a one to one comparison. We require that the tracks used for reconstruction have at least 15 TPC hits and at least 2 SVT hits. The comparison allows us to select initial cuts to be used in this analysis. For example, the upper left plot is the D0 DCA to the PV, the pure $D^0$ distribution is peaked closer to zero and has a different shape that the background. Below 300 $\mu$m the signal dominates, and above 300 $\mu$m the background dominates. Therefore we choose D0 DCA to PV to be less than 300 $\mu$m as the starting cut for this variable. For each plot, the gray region demonstrates the area that is cut out for that particular variable. The base topological cuts used in this analysis are:

1. D0 dca PV $< 300 \mu$m
2. D0 decay length $< 500 \mu$m
3. Dca Daughters $< 300 \mu$m
4. Daughter dca PV $< 300 \mu$m

These cut variables are correlated. For example, by using a 300 $\mu$m cut on the D0 dca PV we change the shape of the D0 decay length distribution for both the signal and the background and this can be seen in Figure [5.7] (right). However, this cut does not effect the the signal or background distribution of DCA of the daughters to one another (left). In fact, by applying a cut of Dca Daughters $< 300 \mu$m the shape
of the other three distributions pretty much stays the same, making this a useful cut since its application does not alter the background such that it takes on the same shape as the signal (see Figure 5.8).

If we apply the base topological cuts, excluding the daughters dca to the primary vertex cut, we find the shape of Daughter dca PV for the pure $D^0$ and background are identical (see Figure 5.9), and because of this we do not use this cut for this analysis.

5.5.2 Kinematic Cut Investigation

It is common to use momentum based cuts in V0 type analyses. Two variables of interest are the momentum asymmetry of the decay daughters and angular distribu-
Figure 5.7: Decay length and Daughters DCA distributions after requiring the D0 dca PV < 300 µm.

Figure 5.8: D0 dca PV and Decay length distributions after requiring the Dca Daughters < 300 µm.
tions. In a $\Lambda$ decay to $p+\pi$ the proton, because of it’s significantly large mass relative to the pion, typically carries most of the momentum of the parent and an asymmetry will be present when comparing the momentum of the decay daughters. In the $K_s^0$ decay to two pions both daughters will on average carry the same momentum. These kinematic properties can be illustrated using the Armenteros-Podolanski plot. The two dimensional distribution is a plot of $p_T$ of the oppositely charged daughters with respect to the longitudinal asymmetry, defined as,

$$\alpha = \frac{p_{+}^{L} - p_{-}^{L}}{p_{+}^{L} + p_{-}^{L}}$$

(5.7)

Figure [5.10] demonstrates the Armenteros-Podolanski distribution of $\Lambda$ and $K_s^0$. The parabola distribution centered at $\alpha = 0$ represents $K_s^0$, while the other parabolas (centered at $\alpha = \pm0.7$) are from $\Lambda$ decays. One can see that the $\Lambda$ candidates could contaminate the $K_s^0$ particles and visa versa. In most V0 analyses, the solution for suppressing contaminating V0s (those that have similar topologies) is done using an invariant mass cut in the range of the unwanted particle.

For this analysis, we did not find this cut to be useful. The main reason is that
Figure 5.10: Armenteros-Podolanski plot for $\Lambda, \bar{\Lambda}$, and $K^0_s$ candidates.

Figure 5.11: Right: Armenteros-Podolanski plot for $D^0$ from simulation. Left: Armenteros-Podolanski plot for Au+Au background candidates.
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Figure 5.12: \( \cos \theta \) distributions of \( D^0 \) from simulation and Cu+Cu HIJING background for both daughters.

Aside from resonances, no other particles that are present in heavy ion collisions share topologies that are similar to \( D \) mesons. Figure 5.11 is the Armenteros-Podolanski distribution of \( D^0 \) from simulations (right) and \( D^0 \) candidates in Au+Au collisions (left). The background shape, in the same mass range, is identical to that of the \( D^0 \) so we did not include any Armenteros-Podolanski like cut for this analysis.

In addition, cuts based on angular distributions were studied. More specifically, the angle between the \( D^0 \) momentum in the lab frame with respect to the decay daughter momentum in the center of mass (CM) frame. We looked at the cosine value of the angle, defined as

\[
\cos \theta = \frac{\vec{p}_{D^0} \cdot \vec{p}_{\text{daug,CM}}}{|\vec{p}_{D^0}| |\vec{p}_{\text{daug,CM}}|}
\]  

(5.8)

Figure 5.12 compares this distribution for simulated \( D^0 \) and background from Cu+Cu HIJING events. Initially, by requiring the \( \cos \theta > -0.6 \) for the negatively charged daughter and \( \cos \theta < 0.6 \) for the positive daughter proved extremely useful for background suppression. Unfortunately, we found that these cuts created a bias that enhanced the background near the \( D^0 \) mass.

A comparison was made using the pure \( D^0 \) and the Cu+Cu sample with the sim-
ulated $D^0$ embedded in to the HIJING events. When running over the same number of events, and using the exact same cuts on TPC hits, SVT hits, and topological distributions we would expect that the signal remaining after the cut application in both samples should be near equal. However, we found that if a background was present the signal was artificially enhanced. This is shown in Figure 5.13: the black distribution represents the background without the cut, while the red is the background shape after applying the $\cos \theta$ cuts. There is a clear enhancement of the background near the $D^0$ mass, most likely caused by mis-identification. If the kaon candidate is in actuality a pion, the energy of this track is over estimated because of the kaon mass assumption, and this causes the magnitude of the candidate daughter’s momentum in the CM frame to decrease. The tracks that should in fact be sitting in the lower mass region of the invariant mass distribution are pushed to higher mass region. Since this cut biased the $D^0$ invariant mass distribution it was not used in this analysis.
Chapter 6

Background Subtraction Methods

For this analysis the combinatorial background present using a secondary vertexing technique is quite large. However, an excess in entries in the $D$ invariant mass spectrum should be present near the $D$ mass if a statistically significant signal is present. It is not necessary that the peak be visible by eye, because given a large enough background the peak will disappear underneath. In order to observe any peak near the actual $D^0$ mass a method of background subtraction is essential. We have studied three possible techniques that can be utilized to subtract off the background. In this chapter, we will describe the mixed event, rotational, and polynomial background subtraction methods. To simplify the discussion, each method will be described for the $D^0$ decay to $\pi^+$ and $K^-$.  

6.1 Mixed Event Technique

The mixed event technique can be used to generate a random background. For this analysis, a large source of the background comes from uncorrelated $\pi$ and $K$ pairs. In a mixed event all correlations should vanish. This technique starts with $K\pi$ pairs in an event, then either the $K$ or $\pi$ from that pair is placed in a different, but similar event. Here similar refers to events where multiplicities and primary vertex $z$ locations are within a given range of the original event. The ranges chosen should be as small as possible, but computing resources do put a limit on the range. If
we choose to mix the kaons, the background is created by combining the K from
the original event with the π in the mixed event. An advantage of this method, is
that a large number of statistics can be obtained using this technique, since the K
from the original event can be mixed into multiple events. This greatly decreased the
statistical error, which goes like $\sqrt{1 + 1/N}$ where N is the number of events mixed.
It should be noted that even after the generated background has been subtracted off
a residual background remains. If a signal is present, the invariant mass distribution
will have a linear shape with a gaussian centered at the $D^0$ mass. This distribution
can be fit with a polynomial function plus a gaussian to extract the signal strength.

This technique has been successful for $D^0$ measurements in d+Au, Cu+Cu, and
Au+Au collisions. These measurements employ a reconstruction technique that uses
a combinatorial method where the invariant mass is calculated using positive and
negative primary tracks, that have been identified using $dE/dx$ information from the
TPC. It is also required that the tracks have a 3 cm DCA to the primary vertex and
that they have 15 hits in the TPC. Compared to a secondary vertexing technique,
few cuts are applied and the inner silicon detectors are not used in the tracking.

However, attempting to use this technique for this analysis was challenging and has
a few disadvantages. The main issue is that the tracks used for $D^0$ reconstruction are
global tracks and placing these tracks in different events changes the local position
of the track. For instance, a track with a DCA to the primary vertex of 300 $\mu$m
(in the original event) placed into an event where, for example, the primary vertex
location has changed by 1 cm will not be used in our reconstruction because the tight
topological cuts applied will reject this track. In the end, a significant amount of the
mixed pairs will not satisfy our topological requirements. However, we could choose
events where the primary vertex z positions are close to identical, but then we also
will have to require that these events also contain similar multiplicities of tracks. As
mentioned, the computing resources put a limit on the ranges chosen. In the end, we
opted to explore other avenues of background subtraction.

6.2 Rotational Technique

An uncorrelated background can also be generated using what is called the rotational background method. In the same event, the $x$ and $y$ momentum components of one of the daughter tracks from the candidate $D^0$ decay is rotated. The rotation is performed so to remove any correlations. Figure 6.1 demonstrates this for the $\pi$ using multiple rotations.

Before attempting to use this method on the real data we first looked at the $D^0$ MC simulation used for topological cut studies in the previous chapter. We want to study the angles available for rotation. Figure 6.2 shows what the invariant mass distribution looks like after a series of rotations, starting from 30 degrees and going out to 180. It is clear that a 30 degree rotation does not remove all the correlations
Figure 6.2: The MC $D^0$ invariant mass distribution after rotating the daughter pion using various angles. Large angle rotations are necessary to create a distribution that is similar to the background seen in real data, which has a linear behavior because the distribution, although widened, still peaks at the $D^0$ mass. As does the distribution using the 60 and 90 degree rotation. We find that the angles of rotation chosen should be larger than 120 degrees (smaller than 240 degrees), in order to destroy any invariant mass peak near the actual $D^0$ mass. In addition we observe that a single rotation does not provide enough statistics needed to lower the statistical error. To increase the statistics multiple rotations are needed.

To describe the background in Au+Au events, the $x$ and $y$ components of the pion candidate momentum are rotated every 5 degrees, starting from an angle of 150 out to 210 degrees, making 13 total rotations. The result using this method for the pure $D^0$ can be seen in Figure 6.3. The black peak is the invariant mass reconstruction of the pure $D^0$ and the red is the distribution after the 13 rotations, centered at 180 degrees. It is clear that this method removes all correlations, creating an linear distribution, not at all peaked at the real mass.
For the Au+Au data, the rotational background is normalized using the number of entries in a certain region of the real background distribution, away from where a $D^0$ mass peak should be present. The normalized rotational background is then subtracted off from the original invariant mass distribution. Similar to the mixed event technique, a residual background remains. We use a polynomial fit to side bands that sit away from the real mass value to estimate the remaining background. Figure 6.4 shows the invariant mass distribution of $D^0$ candidates for Au+Au collisions after the normalized rotational background is subtracted. The red lines are the fit to the side bands. The parameters from this fit are input into a polynomial that is fit over the entire distribution, shown by the blue curve. Each data point sits near the fit, and an excess in counts is observed near the $D^0$ mass.
Figure 6.4: The $D^0$ and $\bar{D}^0$ invariant mass distribution after a rotational background subtraction. The red fit is used to estimate the parameters of final polynomial fit that is used to subtract off the residual background.
Figure 6.5: The $D^0$ and $\bar{D}^0$ invariant mass distribution fit using a polynomial function to estimate the background.

6.3 Polynomial Fit Technique

Estimating the background using a polynomial fit alone is the most simple yet effective approach to background subtraction. Without creating an uncorrelated background as performed in the mixed event and rotational methods, the invariant mass distribution is directly fit using a polynomial function. We look at various orders until the best $\chi^2$ fit is obtained. Again, we fit to side bands of the invariant mass spectrum that lie away from the actual $D^0$ mass, as demonstrated in Figure 6.5. The $n$ parameters from the fit are input into another polynomial function that is used to fit the entire invariant mass distribution (also shown in Figure). The fit represents the background and can be subtracted off. Unlike the previously described techniques, there is no significant, residual background after the subtraction is perform, so in the end the final invariant mass distribution should be flat at the side bands and a signal in the shape of a gaussian present at the $D^0$ mass.
For this analysis we used the polynomial background subtraction method to describe the background. The background obtained using this fit has also been confirmed through independent studies using a rotational technique. Figure 6.6 (right) shows the invariant mass spectrum after background subtraction, where the background is estimated using a 4\textsuperscript{th} order polynomial fit and (left) the spectrum after rotational background subtraction. The signal yields, Gaussian widths, and means are consistent within the statistical errors. Once again, because of the decay geometry the mixed event technique was not employed.
Chapter 7

Experimental Results

7.1 The $D^0$ and $\bar{D}^0$ Invariant Mass Spectrum

The $D^0$ and $\bar{D}^0$ were reconstructed from measurement of the $K\pi$ decay channel daughters in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The optimized topological cuts used are listed in Table 7.1. Invariant mass peaks near the known $D^0$ mass were present after the background subtraction using a $4^{th}$ order polynomial fit to sidebands away from the expected peak region to estimate the background, shown in Figure 7.1. Since the polynomial is fit to the actual combinatorial background, after subtraction, invariant mass regions away from the peak are nearly flat. The peak is fit with a Gaussian in order to calculate raw yields. Although the signal-to-background is quite large the $D^0 + \bar{D}^0$ signal significance is 5.0 where significance ($\sigma$) is defined as,

$$\sigma = \frac{S}{\sqrt{S + 2B}} \quad (7.1)$$

where $S$ signal and $B$ background. The signal is determined by the area under the Gaussian, which goes out to $3\sigma$ from the actual $D^0$ mass. The background is estimated in the same region, before it is subtracted off.

The mean of the Gaussian distribution is $1870 \pm 10$ MeV/$c^2$, which is consistent within errors of the $D^0$ published mass value of $1864.83 \pm 0.14$ MeV/$c^2$. The sigma of the Gaussian is $31.9 \pm 6.9$ MeV/$c^2$, which is wider than that found in simulation of
14.3 ± 0.01 MeV/c². Broadening can arise from detector effects that are not present in the simulation ("perfect" detectors are used for the simulation). Another reason, also detector related, is that invariant mass distributions will shift downward when reconstructed from particles with lower momentum and shift upward for particles with higher momentum. This invariant mass shifting has been seen in the mass spectra of other particles measured in STAR, for instance the $K^0_s$ and $\phi$. Finally, $D^0$ spectrum was split into 3 $p_T$ bins ranging from 0.2-0.7, 0.7-1.0, and 1.0-5.0 Gev/c, shown in Figure 7.2.

The measured signal of $D^0$ alone is 14,525 ± 5173 (stat.) and the $\bar{D}^0$ signal is 22,586 ± 5738 (stat.) and both distributions are shown in Figure 7.3. The ratio of $D^0$ to $\bar{D}^0$ is consistent with unity within the statistical errors. We expect this to be so, since the $c$ and $\bar{c}$ quarks form in pairs. The Gaussian sigma for $D^0$ is 26.78 ± 10.66 MeV/c² and for $\bar{D}^0$ is 31.27 ± 8.90 MeV/c², and although they do differ, they are consistent within the errors. The mean value for the $\bar{D}^0$ is 1856 ± 9 MeV/c², which is slightly below the PDG mass. The $D^0$ mean value is 1891± 12 MeV/c², which is slightly above PDG mass.

<table>
<thead>
<tr>
<th>Cut Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daughter track momentum (MeV/c)</td>
<td>&gt; 200</td>
</tr>
<tr>
<td>TPC hits</td>
<td>&gt; 20</td>
</tr>
<tr>
<td>SVT hits</td>
<td>&gt; 1</td>
</tr>
<tr>
<td>dE/dx</td>
<td>&lt; 2.0 σ</td>
</tr>
<tr>
<td>DCA D0 to the primary vertex (μm)</td>
<td>&lt; 300</td>
</tr>
<tr>
<td>D0 decay length (μm)</td>
<td>&lt; 200</td>
</tr>
<tr>
<td>DCA between daughters (μm)</td>
<td>&lt; 200</td>
</tr>
</tbody>
</table>

Table 7.1: Optimized cuts applied for $D^0$ identification.
Figure 7.1: The $D^0 + \bar{D}^0$ invariant mass distribution in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, after background subtraction using a 4th order polynomial fit. The distribution is fit with a Gaussian function, which is used to estimate the signal.

Figure 7.2: The $D^0 + \bar{D}^0$ in three $p_T$ bins. Background is subtracted using a polynomial fit.
7.2 The $D^+ + D^-$ Invariant Mass Spectrum

The $D^+$ and $D^-$ were reconstructed from measurement of the $K\pi\pi$ decay channel daughters in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV using cuts listed in Table 7.2. Invariant mass peaks near $D$ mass were present after the background subtraction using a 6th order polynomial fit, shown in Figure 7.4. The order polynomial was chosen, as in the $D^0$ case, based on the $\chi^2$ of the fit. The estimated signal significance is 4.0.

<table>
<thead>
<tr>
<th>Cut Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daughter track momentum (MeV/c)</td>
<td>&gt; 200</td>
</tr>
<tr>
<td>TPC hits</td>
<td>&gt; 20</td>
</tr>
<tr>
<td>SVT hits</td>
<td>&gt; 1</td>
</tr>
<tr>
<td>dE/dx</td>
<td>&lt; 2.0 $\sigma$</td>
</tr>
<tr>
<td>DCA $D^0$ to the primary vertex ($\mu$m)</td>
<td>&lt; 300</td>
</tr>
<tr>
<td>$D^0$ decay length ($\mu$m)</td>
<td>$400 &gt; L &lt; 800$</td>
</tr>
<tr>
<td>DCA between daughters ($\mu$m)</td>
<td>&lt; 200</td>
</tr>
</tbody>
</table>

Table 7.2: Optimized cuts applied for $D^\pm$ identification.

The mean of the Gaussian distribution is $1872 \pm 7$ MeV/c$^2$, which is consistent within errors of the $D^0$ published mass value of $1869.60 \pm 0.16$ MeV/c$^2$. The sigma of the Gaussian is $26.79 \pm 6.05$ MeV/c$^2$, which is also wider than that found in simulation. Once again the widening is expected using the arguments given for the
The $D^+ + D^-$ invariant mass distribution in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, after background subtraction using a 6th order polynomial fit. The distribution is fit with a Gaussian function, which is used to estimate the signal.
observed $D^0$ distribution.

It is important to note that the optimized cut sets used for neutral and charged $D$ meson reconstruction are identical with the exception of the cuts placed on decay length. Recall that the $c\tau$ of $D^0$ is 122.9 $\mu$m, which is comparable to the track pointing resolution but unfortunately sits below it. On account of this, we found no justification to require a lower bound on the decay length. On the other hand, $D^+$ has a $c\tau = 311.8$ $\mu$m, which is comparable and greater than the resolution, which warrants the use of a lower bound cut on the decay length for the charged $D$ analysis.

7.3 Efficiency Corrections

The use of MC simulation studies is also used to estimate the acceptance of the detector and the reconstruction efficiency for each particle. The raw signals yields must be corrected to measure the yields produced in the collision. The acceptance correction accounts for the geometrical coverage of the detectors. The efficiency accounts for the reconstruction efficiency and the efficiency of detecting particles in the detectors. For example, we need to correct for particles that did not satisfy the topological cuts, did not reach the detector because it decayed in flight, and those
that went undetected because they did not deposit enough energy in the TPC volume.

The efficiency correction can be calculated as the ratio of the number of particles that satisfied the topological cuts and the number produced in the collision. For this analysis, MC simulated $D^0$ mesons are produced with flat $p_T$ over the interval $0 < p_T < 5$ GeV/c and over a flat rapidity interval $|y| < 1.0$. The MC $D^0$ decays to $K\pi$ with a branching ration of 100%. The decay is then embedded into 250k real Au+Au events to calculate efficiency. The number of $D^0$ mesons embedded into each event was chosen to be 5% of the event multiplicity. Previous V0 analysis found that choosing to embed 5% of multiplicity did not alter the event significantly.

With embedding, it is possible to simulate the tracking of the MC daughters in a realistic manner. The hits and the ionization of the MC tracks is simulated in embedding. The detector simulation packages calculate the particle’s interaction with detector materials and simulates the response of detector elements. The TPC Response Simulator and SVT Slow Simulator model the drift of the electrons, charge deposition, and electronics response.

Unfortunately, the study presented here was the first in STAR to use the SVT and also require an embedding sample for efficiency corrections. A few problems were encountered using the SVT Slow Simulator. Although these issues have been addressed and fixed, we were not able to produce the full embedding sample and could not calculate efficiency corrections and produced a corrected $D^0$ $p_T$ spectrum, which would have yielded a calculation of total charm cross section in Au+Au collisions. We expect that in the future, a sample of this size could be used to determine not only the cross section, but also to extract fit parameters, such as average radial flow velocity, using the Blast Wave thermal model fit to the spectrum.
Chapter 8

Future Directions

8.1 Corrected Spectrum

For any identified particle analysis, the use of an embedding sample to calculate efficiency corrections is crucial in order to discuss any resulting physics. It is unfortunate that a $D^0$ embedding sample was not available in time to correct the raw yields presented in this thesis. We hope to have a 250k event sample within a month and soon after we expect to have a corrected $D^0$ $p_T$ spectrum. As discussed throughout this thesis, the corrected spectrum will be used to extract the total charm cross section. This is performed by fitting the spectrum with an exponential function in $m_t - m_0$, defined as,

$$\frac{1}{2\pi N_{\text{events}}} \frac{d^2 N}{p_t dp_t dy} = \frac{dN_{D^0}}{dy} \frac{e^{-(m_t - m_0)/T_{\text{eff}}}}{2\pi T_{\text{eff}}(m_{D^0} + T_{\text{eff}})}$$ (8.1)

where $T$ is the effective temperature of the $D^0$ meson. From the fit one can extract the $D^0$ yield at midrapidity, $dN/dy$, and $T_{\text{eff}}$. The midrapidity measurement is then extrapolated to the full range using PYTHIA simulations of $D^0$ meson production in $p + p$ collisions [55]. The total cross section is calculated using,

$$\sigma_{\text{NN}}^{c\bar{c}} = \left( \frac{dN_{(D^0 + \bar{D}^0)/2}}{dy} \right) \times \left( \sigma_{pp}^{\text{inelastic}} / N_{\text{bin}}^{\text{AuAu}} \right) \times (f/R)$$ (8.2)

where $\sigma_{pp}^{\text{inelastic}}$ is the cross section of $p + p$ inelastic collisions and is 42 mb [56].
$N_{\text{Au-Au}}$ is the number of binary collisions in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. $f = 4.7 \pm 0.7$ accounts for the extrapolation to the full rapidity range. Finally, $R = 0.549 \pm 0.023 \pm 0.013$ is the ratio of $c\bar{c}$ pairs that hadronized to $D^0$ mesons in $e^+e^-$ collisions, taken from Table 2.1.

Finally, the total charm cross section can be calculated and compared to the pQCD predictions and the experimentally measured values from STAR and PHENIX, presented in Chapter 3. One thing that should be considered is that the ratio of $c\bar{c}$ pairs produced in heavy ion collisions which hadronize to $D^0$ mesons may not be equivalent to the ratio measured in $e^+e^-$ collisions. We mention this because the Statistical Hadronization Model (SHM) predicts that the large strangeness production and "free" charm in the medium will enhance the $D_s$ yield compared to $e^+e^-$ collisions [57]. This enhancement would cause the $c\bar{c}$ to $D^0$ ratio to be lower than 0.55.

In addition to a cross section measurement, we plan to use the corrected $p_T$ spectrum to study properties of the $D^0$ mesons at thermal freezeout. As in the Cu+Cu analysis discussed in Chapter 3, we only have three $p_T$ bins, which creates difficulties in the extraction of all three blast wave parameters. We will approach the Blast Wave fit in a same manner as the Cu+Cu analysis and assume the freezeout temperature and power-law dependence parameters are equivalent to those extracted for the light flavor hadrons. This will provide a cross check to the previous result, which estimates that the $D^0$ mesons do not have as strong a radial flow as the light species.

8.2 Future Charm Measurements

In the near future, STAR will be installing the Heavy Flavor Tracker (HFT). The proposed HFT aims to have a charged track pointing resolution of 50 $\mu$m. In a single year (6 months of RHIC running) an 500M event sample is expected. The key measurements the HFT can offer include charm spectra, $R_{AA}$, $R_{CP}$, and angular correlations. The goal is high-precision measurements of $D^0$, $D^{\pm}$, $D_s^{\pm}$, and $\Lambda_c^{\pm}$ in $p+p$, $p+\bar{p}$, $p+p$, and $p+\bar{p}$.
Figure 8.1: Left: Estimated statistical errors for $R_{CP}$ measurement of $D^0$ meson in 500M minimum bias Au+Au events. Right: Estimated errors on $\Lambda_c/D^0$ measurement, using 500M central and 500M peripheral events.

$p+A$, and $A+A$ using secondary vertexing techniques. A good $R_{CP}$ measurement requires 500M minimum bias Au+Au events, see Figure 8.1 (left). In addition, the enhancement of the $\Lambda_c/D^0$ ratio is believed to be a signature of a QGP, resulting from hadronization through coalescence rather than vacuum fragmentation, see Figure 8.1 (right).

The ALICE experiment at the LHC will be able to detect charm hadrons in $p+p$ and heavy ion collisions with use of the Inner Tracking System (ITS). The ITS is proposed to provide a resolution better than 60 $\mu$m in the bending plane ($r\phi$) for tracks with $p_T > 1.5$ GeV/c. Intensive simulation studies of $D$ mesons from hadronic decays in Pb+Pb have been performed on $D^0$, $D^+$, and $D_s$ and the study of $D^*$ and $\Lambda_c$ are underway. Charm reconstruction using the $D^0 \rightarrow K\pi$ channel is the most promising. Figure 8.2 demonstrated the potential statistical significance of $D^0$ meson reconstruction in $p+p$ and Pb+Pb collisions.

The reconstruction of the $D_s \rightarrow KK\pi$ decay channel should be challenging, since the signal relative to the background is estimated to be very low, but simulation studies found that it was feasible above $p_T$ of 3-4 GeV/c when the $D_s \rightarrow \phi\pi \rightarrow KK\pi$ decay channel was used. A successful $D_s^\pm$ measurement in ALICE will pro-
Figure 8.2: Projected $D^0$ signal significance as a function of $p_T$ for $p + p$ (14 TeV) collisions (left) and Pb+Pb (5 TeV) collisions (right) after one year of data acquisition.

provide information on the hadronization mechanism (fragmentation or recombination) through the comparison of the relative yield of $D_s$ to the inclusive $D$ yield, where $D_{inc} = D^0 + \bar{D}^0 + D^+ + D^-$. Measurements of open charm hadrons at ALICE look very promising. The projected yields should allow for unambiguous measurements of the energy loss and collective motion of the charm particles.
APPENDIX A

Kinematic Variables

The origin of the coordinate system is defined using the collision vertex, where the z-axis is along the beamline. All particles produced can be characterized using certain kinematic variables, such as energy $E$, momentum $\vec{p} = (p_x, p_y, p_z)$, and mass $m$. Therefore the longitudinal component of momentum is $p_z$ and the transverse component is defined as

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

The transverse mass, for a particle with mass $m_0$, is defined as

$$ m_T = \sqrt{m_0^2 + p_T^2} \quad (A.2) $$

The rapidity variable, $y$, is a dimensionless quantity, and is related to the energy and longitudinal momentum of a particle. In heavy ion physics, this variable is often used because of its additive property under Lorentz transformations along the beamline. It is defined as

$$ y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z} \quad (A.3) $$

The production angle of the particles relative to the beamline can be expressed using the pseudorapidity variable, $\eta$, defined as

$$ \eta = -\ln[\tan(\theta/2)] \quad (A.4) $$
It can also be written in terms of momentum as

\[ \eta = \frac{1}{2} \ln \frac{|p| + p_z}{|p| - p_z} \]  

(A.5)

When pseudorapidity in the form of equation 0.5 is compared to the rapidity defined in equation 0.3, it can be seen that they coincide for \(|p| \approx E\), i.e. the particles momentum is large. Other relations of rapidity, pseudorapidity, energy, and momentum include

\[ y = \tanh^{-1} \frac{p_z}{E} \]  

(A.6)

\[ p_z = m_T \sinh y \]  

(A.7)

\[ E = m_T \cosh y \]  

(A.8)

\[ \eta = \tanh^{-1} \frac{p_z}{|p|} \]  

(A.9)

\[ p_z = p_T \sinh \eta \]  

(A.10)

\[ |\vec{p}| = p_T \cosh \eta \]  

(A.11)
BIBLIOGRAPHY


[8] B. Abelev et al., (STAR Collaboration collaboration), Transverse momentum and centrality dependence of high-p(T) non-photonic electron suppression in


[17] J. Adams et al., (STAR collaboration), “Transverse momentum and collision energy dependence of high p(T) hadron suppression in Au + Au collisions at...


[54] D. Cebra and S. Margetis, “Main vertex reconstruction in star,”.


\[\text{arXiv:0811.2311 [nucl-ex]}\]


\[\text{arXiv:0311.004 [nucl-ex]}\]


At the Relativistic Heavy Ion Collider a hot and dense matter is produced in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV/c. This matter exhibits features of a new deconfined partonic matter, called the Quark-Gluon Plasma. Charm quarks are expected to be produced predominately from the initial gluon fusion in parton-parton hard scatterings. This indicates that the production of the charm occurs at the early stages of the collision. At this time the system is thought to be partonic, making the charm a powerful probe of the initial conditions. Non-photonic electron measurements in p+p, d+Au, and Au+Au provide some insight of the heavy flavor spectrum. However, because of incomplete kinematics, there is an uncertainty in the relative fraction of charm and bottom. A direct measurement of charm through hadronic channels could resolve this.

In this thesis, we present preliminary results from actual neutral and charged D-meson measurements in minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at STAR using existing silicon detectors (SVT and SSD). The measurements are performed using a secondary vertexing technique that exploits the resolution given
by the silicon detectors available in STAR. We will study D-meson yields, significances, and discuss the possible physics implications.
AUTOBIOGRAPHICAL STATEMENT

02 November, 1978
Born in Royal Oak
Michigan, USA

1999 – 2002
B.S. Physics
Wayne State University
Detroit, Michigan, USA

2003 – 2011
Graduate Research Assistant
High Energy Nuclear Physics Group
Wayne State University
Detroit, MI, USA