Overview of Open Heavy Flavor Measurements in STAR

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Abstract. We present an overview of measurements related to open heavy flavor production. Results from indirect reconstruction of heavy flavor via semi-leptonic decays in \( p + p \) and minimum bias \( \text{Au+Au} \) collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \), and results from \( D \) meson measurements via their hadronic decay channel in minimum bias \( \text{Cu+Cu} \) and \( \text{Au+Au} \) collisions are discussed. For the semi-leptonic decays the focus is on partonic energy loss, \( R_{AA} \), and the use of \( e^{-}h \) and \( e^{-}D_{0} \) azimuthal correlation measurements to extract the \( B \) meson contribution to the non-photonic electron spectrum. For the hadronic decay the focus is on open charm yields in \( \text{Cu+Cu} \) collisions and first measurements of \( D \) meson in heavy ion collisions using a secondary vertexing technique.

1. Introduction

Measurements using data taken at the Relativistic Heavy Ion Collider (RHIC) point to the production of a near perfect Quark Gluon Liquid [1, 2], that is opaque to the passage of light partons [3, 4, 5]. In this hot and dense medium, it is believed that the partons lose energy via gluon radiation before fragmenting into hadrons. A method used to quantify this energy loss is through the nuclear modification factor, \( R_{AA} \). Heavy quarks, because of their large masses, are expected to be produced predominately from the initial gluon fusion in parton-parton hard scatterings in nuclear collisions at RHIC energies [6]. This makes heavy flavor a powerful probe of the QCD properties of the matter created in heavy ion collisions. It was expected that heavy quarks would lose energy in the same manner as their lighter counterparts, via gluon radiation. However, a suppression of radiative energy loss should occur because of the dead cone effect, which states that gluonic radiation of a massive parton should be suppressed at angles \( \theta < M_{q}/E_{q} \) [7]. This would indicate that the \( R_{AA} \) for heavy quarks in central nucleus-nucleus collisions is larger than that of lighter quarks.

RHIC experiments have reported the measurement of heavy quarks using semi-leptonic decays (non-photonic electrons) in \( p + p \) and \( \text{Au+Au} \) collisions [8]. These heavy flavor decay electrons do not reveal the dramatic differences in energy loss for charm and beauty that was originally predicted, and at \( p_T > 4 \text{ GeV/c} \) show a similar magnitude of suppression as light flavor in \( \text{Au+Au} \) collisions. Models using only radiative energy loss predict significantly less suppression [9, 10], and those that include other components for energy loss, i.e. collisional [13, 12], 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 [11].
Alternatively, it has been shown that the observed energy loss can be described quite well using a model where open heavy mesons can form early and collisionally disassociate in the medium, multiple times. This may be a significant contribution to the non-photonic electron energy loss observed [14].

These theoretical predictions are sensitive to the beauty contribution to the electron spectrum. Recent Fixed Order Next to Leading Log (FONLL) calculations for heavy flavor production in $p+p$ collisions show the beauty contribution to the non-photonic electron spectrum becoming comparable to charm near intermediate $p_T$ (4-5 GeV/c) [15]. The relative contribution is experimentally unknown at $p_T$ above 3-4 GeV/c. In order to understand heavy flavor energy loss observed from the non-photonic electrons the contribution of $D$ and $B$ mesons needs to be determined experimentally.

Another probe of the Quark Gluon Liquid is radial flow, which is described in the so-called Blast-Wave model [16]. STAR has reported the radial flow of the lighter flavor hadrons in Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV [17], and the observed flow suggests a strongly interacting liquid. If heavy flavor quarks also interact strongly with the light flavor medium they will exhibit a similar flow.

In this article, the focus will be on extracting beauty’s contribution to the non-photonic electron spectrum using $e^{-}h$ azimuthal correlations and by measuring $D$ mesons directly through their hadronic decay channel. In addition, the $D$ meson measurements can be compared to the Blast-Wave model and the Statistical Hadronization model predictions [18], which state that a large strangeness production and "free" charm in the medium will enhance the $D_s$ yield compared to $e^{+}e^{-}$ collisions.

2. Data Analysis

2.1. Single Electrons

Charm and beauty quarks can be identified through the measurement of single electrons that come from semi-leptonic decays of $D$ and $B$ mesons. The electrons will carry a fraction of the total $D$ momentum. The STAR Collaboration has studied the spectrum of single electrons, $e^{\pm}$. The main background sources in the single $e^{\pm}$ spectrum are primarily $e^{+}e^{-}$ pairs from photon conversions in detector material and $\pi^{0}$ and $\eta$ Dalitz decays. For this reason the single $e^{\pm}$ signal is called non-photonic and the background $e^{\pm}$ is called photonic.

The $e^{\pm}$ are identified using the Time Projection Chamber (TPC), the Electromagnetic Calorimeter (EMC), and the Shower Maximum Detector (SMD). For $p > 1.5$ GeV/c, $e^{\pm}$ are identified through measurements of ionization energy loss ($dE/dx$) in the TPC, the energy ($E$) deposited into the EMC, and the shape of the shower in the SMD. An energy loss cut of $3.5$ keV/cm $< dE/dx < 5.1$ keV/cm is used to isolate $e^{\pm}$. Compared to hadrons, $e^{\pm}$ produce a different shower and deposit more energy into the EMC. Thus, additional cuts on shower size in the SMD and a $p/E < 2$ cut aids 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 [20]. A cut of $M_{inv}(e^{+}e^{-}) < 150$ MeV/$c^2$ can be applied to subtract off most of photonic contribution. The non-photonic electrons are identified with an efficiency near 70%.

2.2. Direct Hadronic Reconstruction

$D^{0}$ and $\bar{D}^{0}$ have been reconstructed through their hadronic decay $D^{0}(\bar{D}^{0}) \rightarrow K^{\mp} + \pi^{\pm}$ (B.R. = 3.91% [20]). The pions and kaons are identified by their energy loss in the TPC. All primary kaons and oppositely charged pions are paired in the same event and each pair is then considered a $D^{0}$ candidate. The invariant mass of the $D^{0}$ candidate can then be determined from the
momenta of the tracks and assuming the daughter masses. The invariant mass spectra contains the contribution from real $D^0$ and combinatorial background from random positive/negative pairs. This background can be estimated by the rotational or event mixing technique. The impact parameter resolution of the track is much greater than $c\tau(D^0) = 123 \mu m$ [20] so when using the TPC alone, STAR can not obtain a full reconstructed $D^0$ decay topology.

$D^0$ has also been measured in 200 GeV Au+Au collisions using a secondary vertexing and tracking technique that utilizes the Silicon Vertex Tracker (SVT) and the Silicon Strip Detector (SSD) alongside the TPC. The inclusion of 2 or more hits from the SVT and SSD improves the impact parameter resolution of the global tracks to the primary vertex (PV). For example, at $p_T = 1$ GeV/c the resolution improves by a factor of 10, compared to the TPC alone [21]. The resolution is comparable to $c\tau(D^0)$, so a full reconstruction of the decay topology can be achieved. The topology contains variables such as, $D^0$ distance of closest approach (DCA) to the PV, $D^0$ decay length, DCA of the decay daughters to the PV, and the DCA of the daughters to one another. These geometrical variables are used as cut parameters to distinguish between $D^0$ signal and combinatorial background.

A secondary vertexing technique reconstructs the $D^0$ by pairing all oppositely charged tracks and projecting them toward the primary collision vertex. If the two track trajectories cross at some point away from the primary vertex they are considered candidates for the $D^0$ decay. Again, the $D^0$ is identified through an invariant mass analysis. The difference here is that a set of decay topology cuts can be applied. These cuts discriminate between the signal and the background.

3. Results and Discussion

3.1. Electron-Hadron Azimuthal Correlations

Since charm and beauty have large masses, pQCD can be used to predict their production. FONLL predicts heavy flavor decay electrons from charm to dominate at low $p_T$, with beauty’s contribution becoming comparable to charm near 5 GeV/c.

Electron-hadron ($e$-$h$) azimuthal correlations have been studied with the objective of disentangling the $D$ and $B$ meson contributions to the non-photonic $e^\pm$ 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 (Figure 1 (right)). $D^0$ mesons will predominately decay hadronically ($D^0 \rightarrow K^+anything$, B.R. ~ 55%) and beauty, via $B$ meson, will decays into $D^0$ mesons. In addition, both the $D$ and $B$ mesons will decay into $e^\pm$. With the $D^0$ also decaying to $K^-\pi^+$, azimuthal correlations can be made between electrons and charged hadrons. The expected charm and beauty contributions are simulated using PYTHIA. Figure 1 (left) shows the predicted distributions using PYTHIA and the correlation for $e^\pm$ and hadrons in $p+p$ collisions at $\sqrt{s} = 200$ GeV for a single $p_T$ bin. 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 $B$ meson 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 $B/(B+D)$ as a parameter in the fit function. Figure 2 (right) shows the relative beauty contribution (blue symbols) to the total non-photonic $e^\pm$ yield as a function of $p_T$ using this method.

Additionally, STAR had studied $e$-$D^0$ azimuthal correlations in $p+p$ collisions at $\sqrt{s} = 200$ GeV. Here the $D^0$ is fully reconstructed from the $K\pi$ decay. Azimuthal correlations are made between like sign $e$-$K$ pairs. Figure 1 (right) shows the fragmentation of charm and beauty, respectively. The figure demonstrates that a like sign $e$-$K$ correlation with $\Delta\phi$ near $\pi$ would arise mostly from the $cc$ diagram and a $\Delta\phi$ near 0 would come from the $bb$ diagram. Figure 2
Figure 1. Left: $\Delta \phi$ for non-photonic $e^\pm$ and hadron pairs in $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV, where $2.5 < p_T^{(\text{trig})} < 3.5$ GeV/c and $p_T^{(\text{assoc})} > 0.3$ GeV/c. The vertical axis is the number of charged tracks per $e^\pm$ trigger. Right: Diagram of the fragmentation of $c\bar{c}$ and $b\bar{b}$ pair.

(left) shows PYTHIA and MC@NLO simulations [19] as a comparison to data. The away side ($\Delta \phi = \pi$) correlation peak is a feature of prompt charm pair production $\sim 75\%$ $D$ and $\sim 25\%$ $B$ decays. The near side peak largely represents contributions for $B$ decays. From this, the relative beauty contribution to the non-photonic $e^\pm$ can be extracted, and the result (red symbols) is shown in Figure 2 (right) along with the results from $e^-h$ azimuthal correlations [23, 24].

Figure 2. Left: $\Delta \phi$ of non-photonic $e^\pm$ and $D^0$ mesons, for like sign $e$-$K$ pairs in $p + p$ collisions at $\sqrt{s} = 200$ GeV. Right: Relative beauty contribution to the total non-photonic $e^\pm$ yield for $e^-D^0$ (red symbols) and $e^-h$ (blue symbols) correlations. The uncertainty band from a FONLL calculation (green curves)

All experimental results are consistent with FONLL estimates. The measurements suggest that the $B$ meson contribution to the non-photonic spectra increases with $p_T$ and is comparable to the $D$ meson contribution at and above 5 GeV/c. This indicates that theoretical models that try to describe the observed non-photonic $e^\pm$ suppression must take beauty’s suppression into account as well.

Due to incomplete kinematics of reconstructing heavy flavor meson from their semi-leptonic decays, there is an uncertainty in the relative fraction of charm and beauty. A direct measurement of charm through the $D$ meson hadronic decay could resolve this. In the next sections measurements of this type will be discussed.
3.2. \(D^0\) in Cu+Cu collisions

\(D^0\) and \(\bar{D}^0\) yields have been measured in Cu+Cu collisions at \(\sqrt{s_{NN}} = 200\) GeV [25]. Figure 3 (left) shows the invariant mass distribution of K+\(\pi\) pairs after the rotational background subtraction has been applied. The signal shown has been rebinned into 3 \(p_T\) bins. The result is the \(p_T\) spectrum, Figure 3 (right). A blast wave fit to a \(p_T\) spectrum allows the temperature at thermal freeze out, \(T_{fo}\), and the average radial velocity, \(<\beta>\), to be extracted. However, the blast wave function, has three free parameters and with only three \(p_T\) bins it is difficult to extract all three from the spectrum. Instead, a comparison with the lighter particle species in the Cu+Cu system can be made.

Figure 3. Left: K\(\pi\) invariant mass distribution after background subtraction using a rotational method. Right: 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 \(<\beta>\) of pions, kaons, and protons in 0-60% central Cu+Cu collisions (brown), and a blast wave fit from fixing \(T_{fo}\) to the light species and allowing \(<\beta>\) to be a free parameter (green).

If the \(D^0\) mesons are fully coupled to the lighter species hadrons in the late stages of the quark-gluon medium, they will also take on the parameters, \(T_{fo}\) and \(<\beta>\), that were found for pions, kaons, and protons. Figure 3 (right) shows that the blast wave curve using the lighter flavor fit parameters is inconsistent with the data. If instead, the freeze out temperature is kept constant, a value of the average radial velocity can be extracted. The \(<\beta>\) from the fit is 0.35 \pm 0.07. A comparison to the lighter flavor species value of \(<\beta> = 0.470 \pm 0.001\) 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.

3.3. \(D\) mesons in Au+Au Collisions

\(D^0\) and \(\bar{D}^0\) in Au+Au collisions at \(\sqrt{s_{NN}} = 200\) GeV have also been measured [26]. The main difference from the previous analysis is that a secondary vertexing technique is used. Figure 4 (left) shows the invariant mass obtained after identifying kaons and pions using dE/dx, requiring both daughter tracks to have 2 or more hits in the SVT, and applying cuts on the decay topology. At this stage the \(D^0\) peak is not easily visible, so the background is subtracted by fitting a polynomial to the side bands of the distribution (see Figure 4 (left)) and subtracting the background under the peak based on the \(\chi^2\) minimized polynomial fit. The background obtained by the fit can be confirmed through independent studies using a rotational technique. The preliminary result is Figure 4 (right). The signal has a statistical significance \(S/\sqrt{S+B} \simeq 4.5\).
Figure 4. Left: Kπ invariant mass after optimized cuts in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Right: Kπ invariant mass after background subtraction using a polynomial fit.

In addition, the secondary vertexing technique, that utilizes the SVT+SSD, has also been used to perform a $D^\pm_s$ measurement. $D^\pm_s$ decays to $\phi + \pi^\pm$, with $\phi \rightarrow K^+K^-$ (B.R. = 2.18%) [25]. Once again, kaons and pions are identified using dE/dx information from the TPC, and the daughter tracks must have at least 2 hits in the SVT. In addition to applying decay topology cuts, we can require that the reconstructed $K^+K^-$ pair invariant mass is near the $\phi$ mass peak. The $D^\pm_s$ signal, shown in Figure 5 (left), has a statistical significance of $3.1\sigma$. The yield, $dN/d\eta$, can be compared to the Statistical Hadronization Model (SHM) predictions. A comparison is made between the inclusive charm-strange yield, $D^\pm_s$, and the inclusive charm-light quark yield, $D_{inc}$, where $D_{inc} = D^0 + \bar{D}^0 + D^+ + D^-$ and $D_s = D^+_s + D^-_s$. STAR has measured the $D^0$ yield in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV using an mixed event technique [27].

Since RHIC has not yet published a $D^\pm$ spectra, the ratio of $D/D^0$ is extracted from Pythia or $e^+e^-$ collisions.

Figure 5 (right) shows the $D_{inc}/D_s$ ratio predicted using PYTHIA, $e^+e^-$ collider data, and STAR's measurement from Au+Au collisions. The value from STAR is consistent with SHM prediction of 2.8 at the conditions at RHIC, with $s/S \approx 0.03$ and $S^Q = S^H$, where $s/S$ is the strangeness to entropy ratio [18]. This result suggests an enhancement of $D_s$ in the QGP.

Figure 5. Left: $\phi\pi$ invariant mass after optimized cuts in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Right: $D_{inc}/D_s$ ratio (black line) compared to estimates from PYTHIA, $e^+e^-$ collisions, and the Statistical Hadronization Model.
4. Conclusions

We summarized the STAR collaboration measurements of open heavy flavor production in heavy ion and proton-proton collisions at RHIC. Results of non-photonic electrons from heavy flavor decays and $D$ meson reconstruction from the hadronic channel were shown. Heavy flavor electrons exhibit a similar suppression to that of the light hadrons at intermediate $p_T$. Currently, most theoretical models underpredict the observed suppression. One model that uses radiative and collisional energy loss, but for charm only, describes the data well. However, $e-h$ and $e-D^0$ azimuthal correlation measurements show that at a $p_T$ of 5 GeV/c and higher the contribution to the electron spectrum from beauty is comparable to that of charm.

In addition, $D$ mesons can be measured directly. The momentum distribution of $D^0$ in Cu+Cu collisions fit with a blast wave function indicates that the $D$ mesons do not have as strong a radial flow as the lighter quark hadrons. This suggests that the charmed hadrons interact with and decouple from the QCD matter differently than the light hadrons. We also show the first $D$ meson measurement in heavy ion collisions, using a secondary vertexing technique. The direct reconstruction of $D^0$ will further constrain the $D$ and $B$ contribution to the non-photonic electron spectrum and offer insight into the charm’s interaction with the medium. Finally, a preliminary $D^{±}$ measurement using secondary vertexing was shown. Its yield, compared to the inclusive $D$, hints at statistical hadronization. It is important to recognize that significant uncertainties are present in the data, as well as in current models. However, the measurements do provide constraints on theory, which will aid in a greater understanding of heavy flavors interaction with the hot and dense matter created in heavy ion collisions.

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