Recent heavy flavor measurements from PHENIX at RHIC

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Abstract. Heavy flavor quarks are an important probe of the initial state of the Quark Gluon Plasma formed in heavy-ion collisions. Bottom and charm quarks are primarily produced through hard interactions, early in the collision and experience the full time evolution of the medium. Measuring their production in \( p + p \) collisions can also give a baseline reference to study larger collision systems, including asymmetric systems and can directly test pQCD calculations. At PHENIX open heavy flavor states can be measured through leptonic decay channels. Some measurements have utilized silicon vertex detectors to determine meson decay lengths in order to separate \( D \) mesons from \( B \) mesons. Recent measurements have been made at \( \sqrt{s_{NN}} = 200 \) and 500 GeV, with a variety of collision species, in both forward/backward and central rapidities. A review of the recent heavy flavor measurements from PHENIX will be presented in this proceeding.

1. Introduction

The Quark Gluon Plasma (QGP) is a strongly coupled state of matter composed of “free” quarks and gluons that is produced through heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC). The Pioneering High Energy Nuclear Interaction eXperiment (PHENIX) is positioned to study QGP through a variety of observables including open heavy flavor. Charm and bottom quarks are produced early in the collision system due to their large masses, \( \Lambda_{QCD} \ll \text{mass}_{c,b} \), through the initial hard scattering phase of the collision process. They are a good probe of the QGP matter since they interact with it through scattering, leading to energy losses and ultimately experiencing the full space-time evolution of the medium. Open heavy flavor is studied in heavy ion collisions in which the QGP forms and it is also measured in small asymmetric collision systems in which no QGP is expected to form in order to understand Cold Nuclear Matter (CNM) effects. These effects are those associated with the presence of normal nuclear matter in a collision. Baseline measurements need to be made in \( p + p \) collisions to serve as a reference to both Hot Nuclear Matter (HNM) and CNM effects and can be used to directly test pQCD theory. One such way of quantifying the HNM and CNM effects is through a parameter known as the nuclear modification factor

\[
R_{AA} = \frac{dN^{AA}/dp_T}{<N_{coll}> dN^{pp}/dp_T}.
\] (1)

Recent results of open heavy flavor measurements made at PHENIX will be presented. The first result relies on the secondary displaced vertex from a silicon vertex detector in order to separate
charm and bottom contributions due to their hadronic decay lengths in \(Au + Au\) collisions at \(\sqrt{s_{NN}} = 200\ \text{GeV}\). The second result will detail production via a di-electron measurement in \(p + p\) collisions as well as explore CNM in \(d + Au\) collisions both measured at \(\sqrt{s_{NN}} = 200\ \text{GeV}\). Finally, the last measurement discussed is that of \(\sigma_b\) in \(p + p\) collisions, at \(\sqrt{s_{NN}} = 500\ \text{GeV}\), via the like sign di-muon signal that will use the unique properties of \(B^0\) oscillation.

2. Electrons from Semi-Leptonic \(D\) and \(B\) Meson Decay in \(Au + Au\) Collisions

This measurement utilizes a new silicon vertex (VTX) detector installed for the RHIC 2011 run, in order to measure displaced vertices of heavy flavor contributions in the single electron yield. \(D\) mesons have known lifetimes of \(c\tau_{D^+} = 318\ \mu\text{m}\), \(c\tau_{D^0} = 123\ \mu\text{m}\) and \(B\) mesons lifetimes are \(c\tau_{B^+} = 491\ \mu\text{m}\), \(c\tau_{B^0} = 456\ \mu\text{m}\) which are then used to help separate the contributions through a distance of closest approach (DCA) analysis [1]. The analysis procedure breaks down the DCA distribution in the transverse plane (DCA\(_T\)) into five \(p_T\) bins and accounts for known backgrounds using a variety of data driven and Monte Carlo methods. It then samples the inclusive heavy flavor invariant \(p_T\) distribution from a previous PHENIX measurement [2], shown in Fig. 1 (a), and uses a Bayesian inference (a.k.a. unfolding) method to separate the charm and bottom contributions. One such \(p_T\) bin is shown in Fig. 1 (b) that also includes the results of the unfolding procedure.

![Image](image.png)

**Figure 1.** (a) The sampled inclusive invariant yield from heavy flavor single electrons as measured in [2]. (b) A sample DCA\(_T\) distribution in the 2.0-2.5 GeV/c \(p_T\) kinematic window. The distribution is broken into charm, bottom and background contributions and summed together. The shaded region is the region of interest for the analysis. On the bottom of both plots are the ratios of the data and final results from the unfolding method.

Once the two contributions are separated, the bottom fraction, shown in Fig. 2 (a), is calculated as the ratio of heavy flavor from bottom decays to the inclusive heavy flavor contribution of the single electron yield. The result is compared to FONLL calculations and previous STAR [3] and PHENIX [4] results. There is good agreement in the ratio to the data in the higher \(p_T\) region (5-8 GeV/c) which will have implications in the \(R_{AA}\) calculation. This fraction is then used to determine the individual charm and bottom \(R_{AA}\) distributions as shown in Fig. 2 (b). It was found that charm is more suppressed than the bottom in the 3-5 GeV/c region and that they have similar suppression in the 5-8 GeV/c region [5].
Figure 2. (a) The bottom fraction determined from the unfolding method, compared to FONLL calculations and previous $p+p$ measurements. (b) The $R_{AA}$ calculation for charm and bottom contributions compared to previous inclusive heavy flavor $R_{AA}$ results from single electrons.

3. Heavy Flavor Production via $e^+e^-$ in $d + Au$ and $p + p$ Collisions

Measurements of electron pairs are made in the PHENIX central arm spectrometers, $|y| < 0.35$, without the capabilities of the VTX detector, and the heavy flavor contributions are separated through a phase space analysis. The unlike sign pair mass spectrum consists of a variety of contributions that need to be accounted for including the inclusive heavy flavor signal, combinatorial pairs, and correlated background. After like sign pairs are used to estimate the combinatorial background and subtracted off, a hadronic cocktail is used to determine and remove correlated background signals such as vector mesons, pseudo scalar mesons and Drell-Yan pairs. See Fig. 3 for the correlated invariant mass distribution and the hadronic cocktail.

Figure 3. Correlated invariant $e^+e^-$ mass distribution. The individual components of the hadronic cocktail and the total cocktail are shown alongside the data. The insert in the upper right corner shows the low mass region and the lower plot is the ratio of data to the total cocktail.

The inclusive heavy flavor signal is then simultaneously fit, using PYTHIA and MC@NLO
models, to mass distributions in $p_T$ bins. An example of this process can be seen in Fig. 4 and the method is detailed in [6]. As expected, charm contributions dominate the low mass and low $p_T$ regions and the bottom contributions dominate the high $p_T$, low mass and low $p_T$, high mass regions of phase space. A total fit to mass and $p_T$ is then determined. The fit is shown to match data and from it a total cross section can be determined for both the charm and bottom quarks.

![Figure 4](image)

Figure 4. Inclusive heavy flavor invariant $e^+e^-$ mass shown in eight $p_T$ bins. An example of the simultaneous fitting procedure is shown with the PYTHIA model where the separate charm and bottom model contributions are shown and the total model is fit to the data in the individual $p_T$ bins.

Shown in Fig. 5 (a), the models are in agreement in the bottom cross section determination but not in the charm cross sections. This is due to the handling of the decay kinematics of the $D$ and $B$ mesons and the differences in their masses relative to the decay electron. The bottom quark mass is much greater than that of the electron and therefore has a larger uncertainty associated with the electrons decay angle relative to the bottom quark. The charm quark mass is smaller and there is less uncertainty associated with the kinematics of the electrons relative to the charm quark. The differences in mass smear the opening angles of the electrons relative to the opening angle of the heavy flavor quarks differently. These cross sections are then used as the baseline measurement for the $d+Au$ measurement. The $R_{dAu}$ for the heavy flavor di-electron pairs, shown in Fig. 5 (b) is consistent with 1 which indicates there is no modification in the inclusive heavy flavor production.

4. Production of $b\bar{b}$ via $\mu^+\mu^-$ in $p+p$ Collisions $\sqrt{s_{NN}} = 500$ GeV

This measurement takes advantage of $B^0$ oscillation in the 5-10 GeV/$c^2$ di-muon mass window which are measured in the muon arm spectrometer rapidity acceptance of $1.2 < |y| < 2.2$. $B^0$ mesons oscillate with known frequencies, $B^0_{s} \sim 17\%$ and $B^0_{d} \sim 50\%$ [1], and $b\bar{b}$ pairs in which a $B$ meson oscillates will produce like sign di-muons. In the case of $b\bar{b}$ pairs not oscillating only unlike sign pairs are produced. In the like sign di-muon high mass region the signal is dominated by primary-primary decay $B$ mesons and pairs that include a $D$ meson decay chain, $B \to D \to \mu$. Charm contributions are negligible in the mass region greater than 5 GeV/$c^2$ and within the PHENIX forward and backward muon arms acceptance. Like sign pairs also have an additional benefit of few other background contributions that would otherwise be found in unlike sign pairs such as Quarkonia and Drell-Yan pairs.

To separate out the open $B$ signal from the $\mu^+\mu^-$ pairs in the invariant mass distribution, a mixed event background subtraction technique is used and the remaining correlated signal includes two components which are the open $B$ meson signal and hadronic jets. Simulation is used to account for this jet background and a fit to both the total correlated signal and hadronic
background is performed. The correlated like sign mass distributions are shown in Fig. 6 (a) and (b). The difference between the correlated signal and the hadronic background is the signal from open bottom mesons.

Figure 5. (a) The total charm and bottom cross sections as determined through each model. Shown along side is the cross section as found in $d + Au$ collisions normalized by the average number of nucleons involved in a collision. (b) The $R_{dAu}$ vs $p_T$ of inclusive heavy flavor $e^+e^-$. 

Figure 6. (a) Like sign mass distribution in the the 5-10 GeV/$c^2$ mass region for $-2.2 < y < -1.2$ (a) and $1.2 < y < 2.2$ (b). For both (a) and (b) the correlated data are the points and the jet background is subtracted to get the open bottom signal. There is some difference between the two panels and that is due to the differences of absorber material in the muon detectors. (c) The total measured cross section vs mass energies is plotted along side pQCD theory [7] with other world data [4,7–15]. The bottom panel is the ratio of the data to the pQCD theory.

Once the open bottom signal is determined from the like sign pairs and through the use of MC@NLO and PYTHIA models, the signal is further separated into like sign pair muons in which at least one $\mu$ comes from a neutral $B$ meson that has oscillated. Then, from the fraction of like sign pairs from oscillation to total $\mu\mu$ pairs, a total yield is extracted, the cross section is calculated and then extrapolated to full phase space. The total $\sigma_{b\bar{b}}$ cross section is shown to be in agreement with theory within uncertainties and is plotted alongside the pQCD theory curve.
as well as with other world data in Fig. 6 (c) [4,7–15].

5. Summary
In this proceeding recent heavy flavor measurements from PHENIX have been presented. Using a variety of collision species at $\sqrt{s_{NN}} = 200$ and 500 GeV, an understanding of HNM effects and CNM effects was obtained by comparison with baseline measurements in $p + p$ collisions.

In 2011 PHENIX began running with the VTX silicon vertex detector in order to separate contributions from their secondary displaced vertex measurements. In the first such measurement to do so, individual charm and bottom $R_{AA}$ measurements were made from the single electron signal. It was found that the bottom quark was less suppressed than the charm in the lower $p_T$ region but they both had similar suppression levels in the higher $p_T$ region.

To understand CNM effects $p+p$ baseline cross section measurements were made as a reference to $d + Au$ measurements through the $e^+e^-$ decay channel. It was found that there is no modification within uncertainties across the 0-5 GeV/c $p_T$ range. This analysis focused on extracting the signal through a phase space separation.

$b\bar{b}$ production was studied at $\sqrt{s_{NN}} = 500$ GeV through the di-muon decay channel. This analysis technique separated out contributions in the 5-10 GeV/c$^2$ mass region and relied on the $B^0$ oscillation properties of the mesons. The measured cross section was found to be consistent with pQCD calculations [7] within the known uncertainties.

Acknowledgments
The author would like to thank the organizers of the BEACH 2016 conference for giving him the opportunity to present these results and for their financial support.

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