Recent heavy flavor measurements from PHENIX at RHIC

T O S Haseler for the PHENIX collaboration

Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30303, USA

E-mail: `thaseler1@student.gsu.edu`

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 rapidity ranges. 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 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, $\Lambda^{QCD} << mass_{c,b}$, 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 loss and ultimately experiencing the full space-time evolution of the medium.

Open heavy flavor is studied not only in heavy ion collisions, in which QGP forms. It is also measured in small asymmetric collision systems in which no QGP is expected to form 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

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

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 $\sqrt{s_{NN}} = 200$ 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 $\sqrt{s_{NN}} = 200$ GeV. Finally the last measurement discussed is that of $\sigma_{b\bar{b}}$ in $p+p$ collisions, at $\sqrt{s_{NN}} = 500$ GeV, via the like sign di-muon signal that will use the unique properties of B^0 oscillation.

2. Single 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 $c\tau_{D^{\pm}} = 318\ \mu m$, $c\tau_{D^0} = 123\ \mu m$ and B mesons lifetimes are $c\tau_{B^{\pm}} = 491\ \mu m$, $c\tau_{B^0} = 456\ \mu m$ 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.

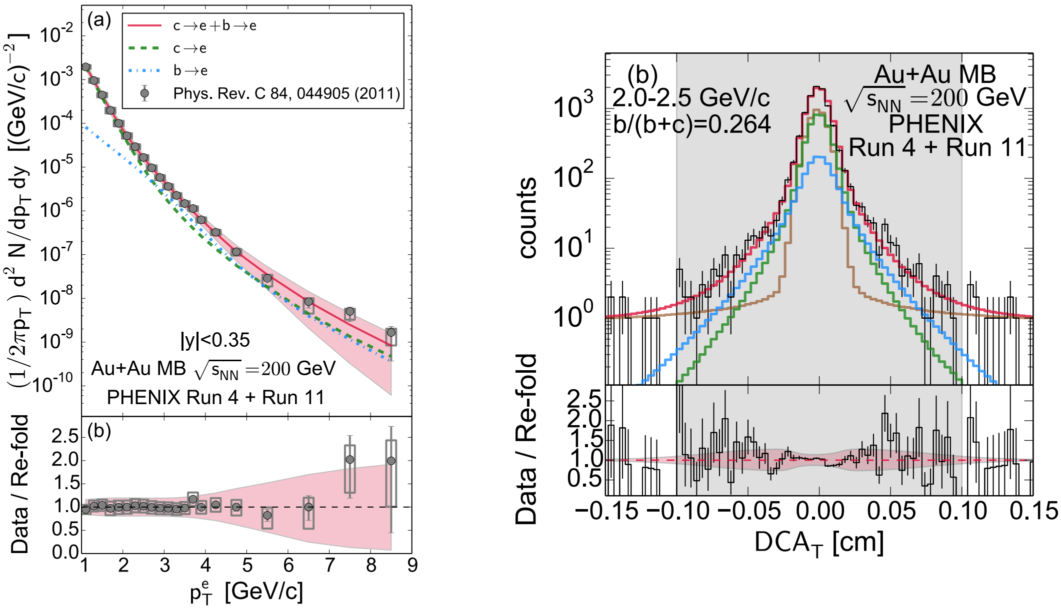

Figure 1. (a) The sampled inclusive invariant yield from heavy flavor single electrons as measured in [2]. (b) A sample DCA$_T$ distribution in the 2.0-2.5 GeV/c p_T kinematic window. The black curve is data, brown is the combined background contributions, green is the separated charm contribution, blue is the bottom contribution and red is the combined signal and background. 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 b decays to the inclusive heavy flavor contribution of the single electron yield. The result is compared to FONLL calculations and previous STAR and PHENIX 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 [3].

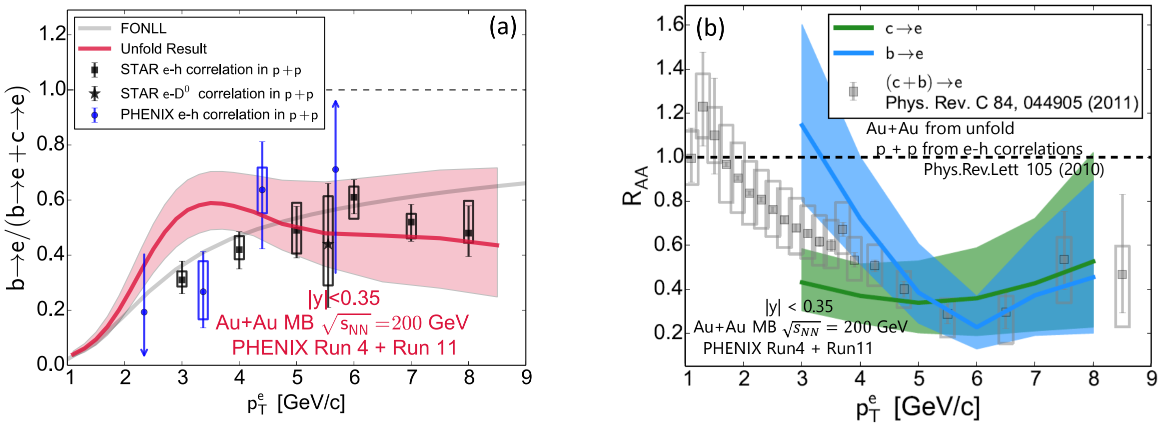

Figure 2. (a) The bottom fraction determined from the unfolding method, compared to FONLL calculations and previous $p + p$ measurements. (b) The R_{AA} calculation for individual charm and bottom contributions compared to previous inclusive heavy flavor R_{AA} results from single electrons.

3. Heavy flavor production via e^+e^- in $d + Au$ and $p + p$ collisions

Di-electron measurements 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 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.

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 [4]. 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.

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 then 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

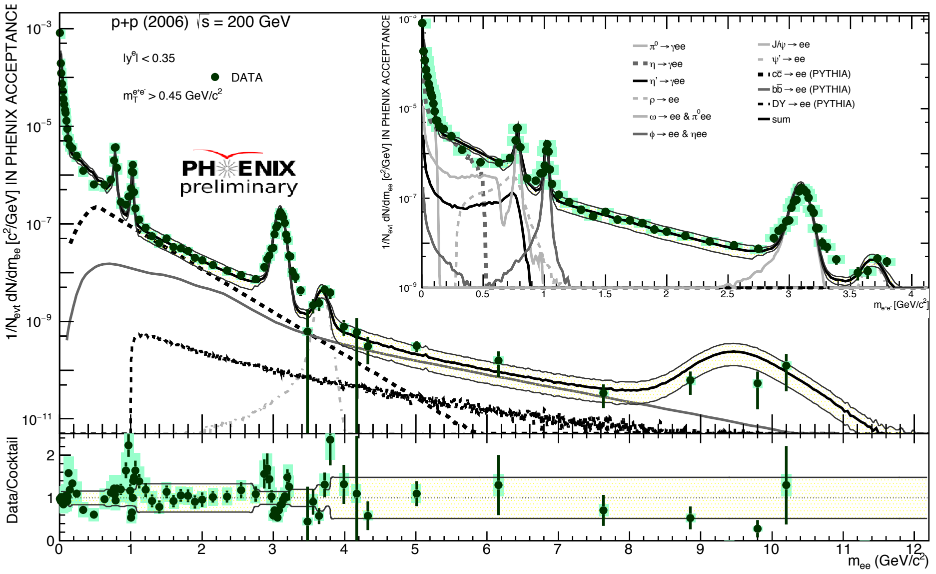

Figure 3. Correlated invariant e^+e^- mass distribution. The individual components of the hadronic cocktail and the total cocktail are shown alongside the data. The insert in the upper right corner shows the low mass region and the lower plot is the ratio of data to the total cocktail.

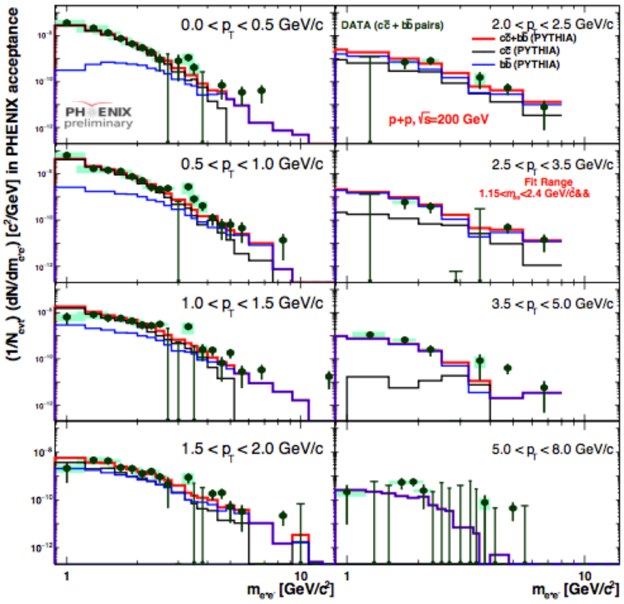

Figure 4. Inclusive heavy flavor invariant e^+e^- mass shown in eight p_T bins. An example of the simultaneous fitting procedure is shown with the PYTHIA model where the total model is fit to the data in the individual bins, shown in red, the charm and bottom contributions are shown as black and blue,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

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. $b\bar{b}$ production via $\mu^\pm\mu^\pm$ 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

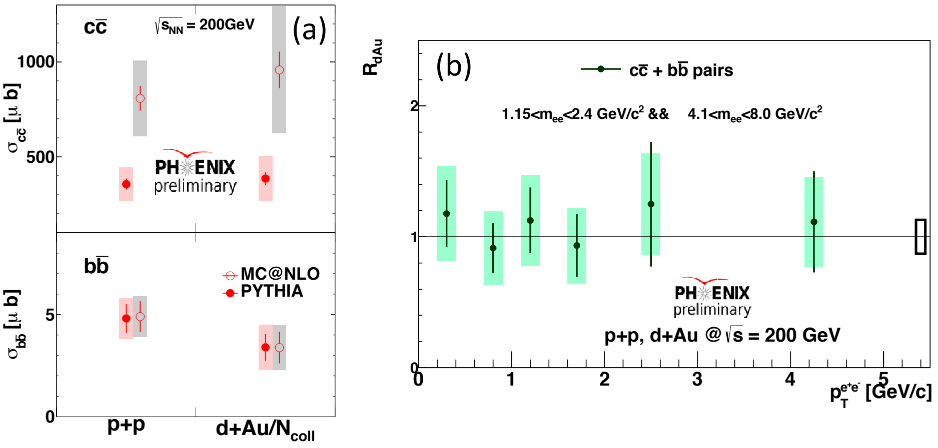

Figure 5. (a) The total charm and bottom cross sections as determined through each model. Shown along side is the cross section as found in $d + Au$ collisions normalized by the average number of nucleons involved in a collision. (b) The R_{dAu} vs p_T of inclusive heavy flavor e^+e^-.

mesons oscillate with known frequencies, $B_s^0 \sim 17\%$ and $B_d^0 \sim 50\%$ [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 then 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 $\mu^{\pm}\mu^{\pm}$ 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.

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 μ 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).

5. Summary

In this proceeding recent heavy flavor measurements from PHENIX have been presented. Using a variety of collision species at center of mass energies of 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

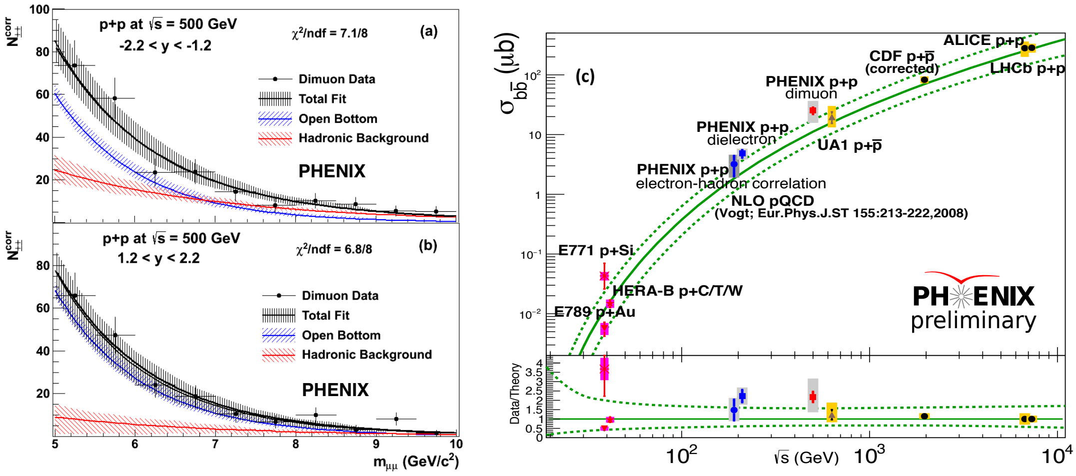

Figure 6. (a) Like sign mass distribution in the the 5-10 GeV/c^2 mass region for the $-2.2 < y < -1.2$. (b) Like sign mass distribution in the the 5-10 GeV/c^2 region for the $1.2 < y < 2.2$. For both (a) and (b) the correlated data are the points, the jet background is shown in red and the difference between them is the open bottom signal in blue. 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* center of mass energies is plotted along side pQCD theory with other world data. The bottom panel is the ratio of the data to the pQCD theory.

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 within the known uncertainties.

Acknowledgments

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6. References

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