PHENIX measurements of bottom and charm quark production

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Abstract.

Heavy quarks are produced primarily in the early stage of high-energy collisions, before the formation of any quark-gluon plasma (QGP). Therefore heavy quarks provide valuable insight to the properties of the QGP, especially by changing the mass of the heavy quark. PHENIX is able to measure the nuclear modification factor of electrons from bottom and charm composed hadrons. PHENIX has also made measurements of the momentum integrated nuclear modification factor of $B \rightarrow J/\psi$ and prompt $J/\psi$ production, observing no nuclear modification for $B$ mesons and a significant suppression of prompt $J/\psi$ due to its breaking in the medium. Additionally, the $b \bar{b}$ cross-section was measured in p+p collisions where it shows a factor of two larger than the center value of the Fixed-Order-Next-to-Leading-Log (FONLL) prediction.

1. Introduction

Heavy Flavor quarks are a valuable probe of the Quark Gluon Plasma (QGP) at RHIC, this is due to the fact that at RHIC energies Heavy Flavor quarks, such as bottom and charm, are produced predominately in the initial hard scattering collision. Since heavy flavor quarks observe the full evolution of the collision system, modification of heavy flavor production in larger systems compared to p+p can provide valuable insight to effects of the medium [1].

In hard scattering p+p collisions it is possible to use perturbative Quantum Chromodynamics (pQCD) to calculate heavy flavor production. One such Monte Carlo which is used in PHENIX is PYTHIA, which uses leading order calculations to calculate particle generation. Using Fixed-order plus Next-to-Leading-Log (FONLL) [2] one can make more accurate predictions on open heavy flavor productions. Using the Color Evaporation Model (CEM) [3], which allows for the calculation of closed heavy flavor production such as $J/\psi$, there is a fairly comprehensive collection of models for comparison of heavy flavor quark production at PHENIX. These models have been probed by PHENIX through various avenues. FONLL/CEM have been studied by looking at $J/\psi$ production for both prompt and through B decays. Additionally, FONLL was probed through its estimation of the $b \bar{b}$ cross section. Using pythia as a Monte Carlo model of p+p collisions, PHENIX was able to probe and understand the various production modes of heavy flavor at RHIC energies through the study of $q \bar{q}$ azimuthal correlations.

In heavy ion collisions there are two main effects whose contributions can be studied: initial state effects which are modeled to first order using parton distribution functions such as EPS09[4]; and final state interactions with the nuclear matter which can be modeled using transport calculations [5]. PHENIX has probed the effects of interactions with the nuclear
medium by looking at heavy flavor production of separated charm and bottom in Au+Au collisions. By comparing measurements to calculations done using a Transport Matrix approach one is able to gain insights onto the strength of coupling within the QGP. By looking at the nuclear modification factor \( R_{AA} \) of separated bottom and charm quarks we can learn about the mass dependence of interactions within the nuclear medium. The nuclear modification factor of integrated momentum B mesons at forward/backward rapidity in Cu+Au collisions can tell us if initial state effects can affect the production of b-quarks.

2. Nuclear Modification of electrons from bottom and charm decays

PHENIX has measured electrons from the semi-leptonic decays of bottom and charm hadrons in 0-10% central Au+Au events at \( \sqrt{s} = 200\text{GeV} \). In PHENIX electrons candidates are identified at mid rapidity using a combination of a ring imaging Cherenkov detector and an energy/momentum cut to remove charged hadrons, a schematic of the central arm of PHENIX is seen in Figure 1. This electron candidate sample has contributions from many sources including but not limited to heavy flavor decays, photonic, non-photonic (such as J/\(\psi\)), and hadron contamination. For each electron the distance of closest approach in the transverse direction (\( dca_T \)) was measured using the Silicon Vertex Tracker (VTX). Due to life time and decay kinematics the \( dca_T \) allows PHENIX to distinguish between electrons from bottom, charm, and various background sources as seen in Figure 1.

![Figure 1](image-url)

**Figure 1.** Left: Diagram of the Central arm of the PHENIX detector. Right: Measured electron \( dca_T \) with separated contributions from bottom, charm, and background sources.

The separated bottom and charm measurement was done using Bayesian Inference Techniques to simultaneously fit previously published inclusive heavy flavor electron invariant yields and measured electron \( dca_T \) distributions, the details of this technique are discussed in reference [6]. The b-fraction, as defined as \( b \rightarrow e/ (b \rightarrow e + c \rightarrow e) \) and shown in shown in Figure 2, agrees with a model implying strong coupling in the QGP, and at \( p_T > 5\text{GeV/c} \) it observes agreement with DGLV predictions implying both radial and collisional energy loss occurring within the QGP.

Combining the measured heavy flavor electron invariant yields in central Au+Au with STAR measurements in p+p done using electron-hadron correlations PHENIX was able to extract an \( R_{AA} \) for both electrons from charm and bottom, as seen in Figure 2. We observe that electrons from bottom are less suppressed than those from charm at \( p_T \) between 3 and 4 GeV/c. This would imply that there is a mass dependence to the energy loss experienced due to interactions.
within the QGP. In PHENIX there is currently an effort underway to measure a continuous p+p baseline using a similar technique for the range of 1-9 GeV/c in combination with analyzing the full 2014 Au+Au statistics (4x) one can expect an updated $R_{AA}$ result with reduced uncertainties soon.

![Figure 2.](image1)

**Figure 2.** Left: Preliminary b-fraction result for 0-10% central Au+Au.
Right: Preliminary $R_{AA}$ result for electrons from bottom and charm in 0-10% central Au+Au

### 3. Nuclear Modification of Prompt J/ψ and J/ψ from B decays

PHENIX has measured muons from J/ψ decays within a rapidity range of $1.2 < |\eta| < 2.2$. The muons are measured using a combination of a muon identification detector, which provides rejection of charged pions, and a muon tracking detector, used to measure the muon momentum from the trajectory in the magnetic field. J/ψ’s were reconstructed as opposite charge muon pairs with $2.8 < \text{mass} [\text{GeV}/c^2] < 3.5$. For each muon from a di-muon pair within the J/ψ mass region the distance of closest approach along the radial distance ($dca_R$) was measured using the forward silicon vertex detector. This quantity allows one to distinguish muons from prompt J/ψ and those from $B \rightarrow J/\psi$ decays, as those come from a displaced vertex, as seen in Figure 3.

By doing a fit to the measured $dca_R$ distributions using templates for the shapes of prompt and non-prompt J/ψ’s PHENIX was able to extract measurements of both prompt and $B \rightarrow J/\psi$ in both p+p and Cu+Au. Specific details on the analysis method can be found in reference [7]

![Figure 3.](image2)

**Figure 3.** Left: di-muon mass spectrum
Right: $dca_R$ distribution of simulated muons from prompt J/ψ and those from B to J/ψ decays
PHENIX measurements of the fraction of $J/\psi$'s which come from B decays show agreement in p+p with FONLL/CEM predictions, while in Cu+Au we observe a significant increase in the $B \rightarrow J/\psi$ fraction. This indicates that $B \rightarrow J/\psi$ observe less suppression than prompt $J/\psi$. By combining the $B \rightarrow J/\psi$ fraction with an inclusive $J/\psi$ $R_{CuAu}$ an $R_{CuAu}$ was extracted for both prompt and $B \rightarrow J/\psi$. It is observed that the $B \rightarrow J/\psi$ is consistent within uncertainties with no nuclear modification, while prompt $J/\psi$ observe significant suppression. This is consistent with the number of b-quarks being conserved or having small modification in nuclear collisions, whereas prompt $J/\psi$ are breaking/melting within the nuclear medium.

**Figure 4.** Left: Fraction of $J/\psi$ which come from B decays  
Right: Nuclear modification factors $R_{CuAu}$ for both prompt $J/\psi$ and $B \rightarrow J/\psi$

4. **Heavy Flavor measurements through Di-Muons**

PHENIX has made a measurement of separated bottom and charm at forward and backwards rapidity in p+p by studying di-muon pairs. This analysis, similar to the $J/\psi$ analysis, uses the same detector systems to look at the di-muon mass spectra of both opposite sign and same sign di-muon pairs. This analysis takes advantage of the fact that although D mesons decay to $\mu^+\mu^-$ B mesons are able to decay into $\mu^+\mu^-$. This allows for the use of the like sign di-muon pairs to be used to measure $b\bar{b}$. As seen in Figure 5 we are able to get a very clean measurement of $b\bar{b}$ in the like sign high mass region as there are very few sources of like sign di-muon pairs in PHENIX. Additionally, by looking at the intermediate mass region in un-like sign pairs we are able to make a measurement of $c\bar{c}$. These measurements were made by combining the measured di-muon mass spectra with a di-muon mass cocktail to account for the various background sources and applying a fit to extract the contributions from $b\bar{b}$ and $c\bar{c}$. 


Using this measurement PHENIX was able to extract the $b\bar{b}$ cross-section at both forward and backwards rapidity. Combining this result with PHENIX measurements at mid rapidity we observe good agreement across the full rapidity coverage with MC@NLO and POWHEG, however there is an apparent factor of two larger than the center value of FONLL calculation for the $b\bar{b}$ cross-section as seen in Figure 6.

Looking at azimuthal correlations between the two muons from $b\bar{b}$ or $c\bar{c}$ decays it was observed that heavy flavor at PHENIX is well described by PYTHIA, this is seen in Figure 7. At RHIC at $\sqrt{s} = 200GeV$ pair creation and flavor excitation are the dominant modes of production, while the contribution due to gluon splitting is very small. This is in contrary to what is observed at the LHC, where gluon splitting is the dominant mode of heavy flavor production.
5. Summary

PHENIX has measured bottom and charm quarks in p+p, Au+Au, and Cu+Au providing valuable insight into both production mechanisms and nuclear matter effects. It was observed in central Au+Au collisions that electrons from bottom between 3 and 4 GeV/c are less suppressed than electrons from charm, which provides some indication of mass dependence to interactions within the QGP. PHENIX showed that $B \rightarrow J/\psi$ measurements are consistent with no nuclear modification in Cu+Au collisions, while prompt $J/\psi$ observe significant suppression consistent with $J/\psi$ experiencing melting/breaking in the medium. In p+p $b\bar{b}$ cross section measurements are consistent with the global data, a factor of two larger than the central FONLL prediction and mainly produced by pair creation and flavor excitation processes.

References

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