

Latest Results of Open Heavy Flavor and Quarkonia from the PHENIX Experiment at RHIC

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Abstract. The PHENIX Collaboration carries out a comprehensive physics program which studies heavy flavor production in relativistic heavy ion collisions at RHIC. The discovery at RHIC of large high- p_T suppression and flow of electrons from heavy quarks flavors have altered our view of the hot and dense matter formed in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. These results suggest a large energy loss and flow of heavy quarks in the hot, dense matter. In recent years, the PHENIX has installed a silicon vertex tracker both in central rapidity (VTX) and in forward rapidity (FVTX) regions, and has collected large data samples. These two silicon trackers enhance the capability of heavy flavor measurements via precision tracking. This paper summarizes some of the latest PHENIX results concerning open heavy flavor and quarkonia production as a function of rapidity, energy and system size.

1. Physics Motivation

Understanding the properties of strongly interacting matter at high temperatures has been a central goal of many researchers' numerical simulations of lattice QCD. Recent results from lattice QCD calculations were presented in Refs. [1, 2, 3], wherein the energy density is normalized by temperature (T^4) as a function of temperature for a system of $n_f = 2 + 1$ flavors of dynamical quarks. These calculations reveal a rapid increase in the number of degrees of freedom associated with this deconfinement of quarks and gluons from the hadronic chains. The transition point is at a temperature $T_c = 154 \pm 9$ MeV and energy density $\epsilon_c = 0.18$ to 0.5 GeV/fm³ [3]. Therefore, scientists have experimentally searched for the signatures both of QGP formation and the in-medium effects of hadron properties. For instance, the Relativistic Heavy Ion Collider (RHIC) was designed as a heavy ion machine, able to provide collisions over a large range of energies. We have attained collisions of gold-gold (Au + Au), copper-copper (Cu + Cu), uranium-uranium (U + U), copper-gold (Cu + Au), deuteron-gold ($d + Au$), helium-gold ($^3\text{He} + Au$), proton-gold ($p + Au$), proton-Aluminum ($p + Al$) and proton-proton $p + p$ at center of mass energies from $\sqrt{s_{NN}} = 7.7$ to 200 GeV. Figure 1 summarizes the achievements of RHIC accelerator over the years [4]. Researchers at RHIC have made a major physics discovery, namely the creation of a new form of matter in high-energy central gold-gold collisions. This matter, dense and strongly interacting, is called the strongly coupled quark-gluon plasma, or sQGP. This finding of a new form of matter was published in four independent white papers [5] from the four RHIC experiments. Without a doubt, the physics program at RHIC has enabled remarkable advances in the study of hot strongly interacting matter [5, 6, 7]. The extended particle momentum range at RHIC allowed the use of hard probes to study the behavior of the created medium that was difficult to access at lower collision energies. The hard penetrating probes now such as open heavy flavor and quarkonia production are one of the major experimental tools successfully exploited by RHIC and LHC collaborations [5, 8, 9].



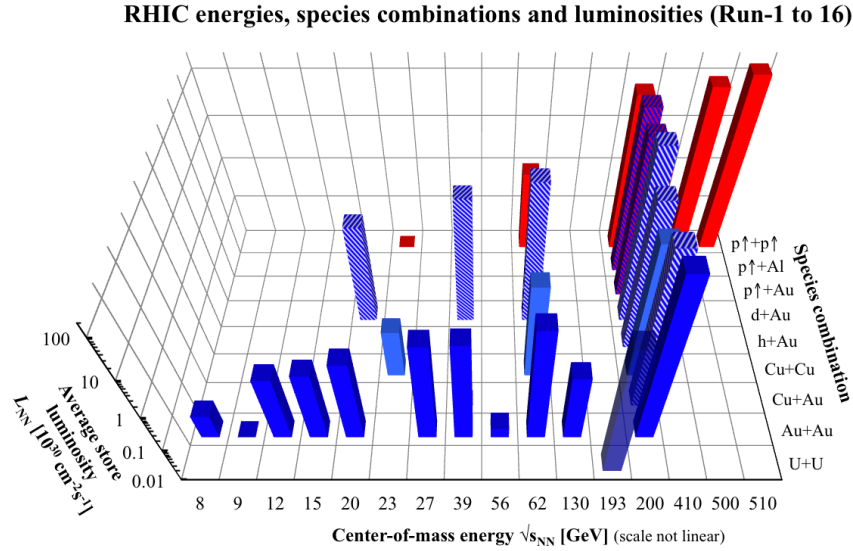


Figure 1. RHIC operating modes and total integrated luminosity delivered to all experiments for each run [4].

2. Recent Open Heavy Flavor and Quarkonia Results

The measurement of inclusive hadron yields in central Au+Au collisions at RHIC led to the discovery of the suppression of hadron production at large transverse momenta (p_T) compared to $p + p$ collisions [5]. This is generally attributed to the energy loss of light partons in the dense nuclear matter created at RHIC. Heavy quarks, i.e. charm and beauty, are believed to be mostly created in initial hard scattering processes of partons [10] and thus are excellent probes of the hot and dense matter formed in nucleus–nucleus collisions at high energy. Adding to this discovery, two very striking results were seen for open heavy flavor from the PHENIX experiment via the measurement of electrons from the semi-leptonic decays of hadrons carrying charm or bottom quarks [7, 11, 12, 13]. First, heavy mesons, despite their large mass, exhibit a suppression at high transverse momentum compared to that expected from $p + p$ collisions. This suppression is similar to that of light mesons, which implies a substantial energy loss of fast heavy quarks while traversing the medium. Second, an elliptic flow is observed for heavy mesons, electrons from semi-leptonic decays of hadrons carrying charm or bottom quarks, that is comparable to that of light mesons like pions. This implies that the heavy quarks in fact are sensitive to the pressure gradients driving hydrodynamic flow giving new insights into the strongly coupled nature of the QGP fluid at these temperatures. However, the interpretation of heavy ion collision data is complicated by the fact that heavy quark production is modified in a nuclear target by cold nuclear matter (CNM) effects. These include modification of the parton density functions in a nucleus, parton energy loss in CNM, and (for quarkonia states), breakup due to collisions with nucleons in the target. To disentangle such effects, multiple measurements were made, such as collisions of different ions and at different collision energies.

Heavy quark production has been studied by the PHENIX experiment via measurements of single leptons from semi-leptonic decays in both the electron channel at mid-rapidity and in the muon channel at forward-rapidity. In recent years, the PHENIX has installed a silicon vertex tracker both in central rapidity (VTX) and in forward rapidity (FVTX) regions, and has collected large data samples. These two silicon trackers enhance the capability of heavy flavor measurements via precision tracking.

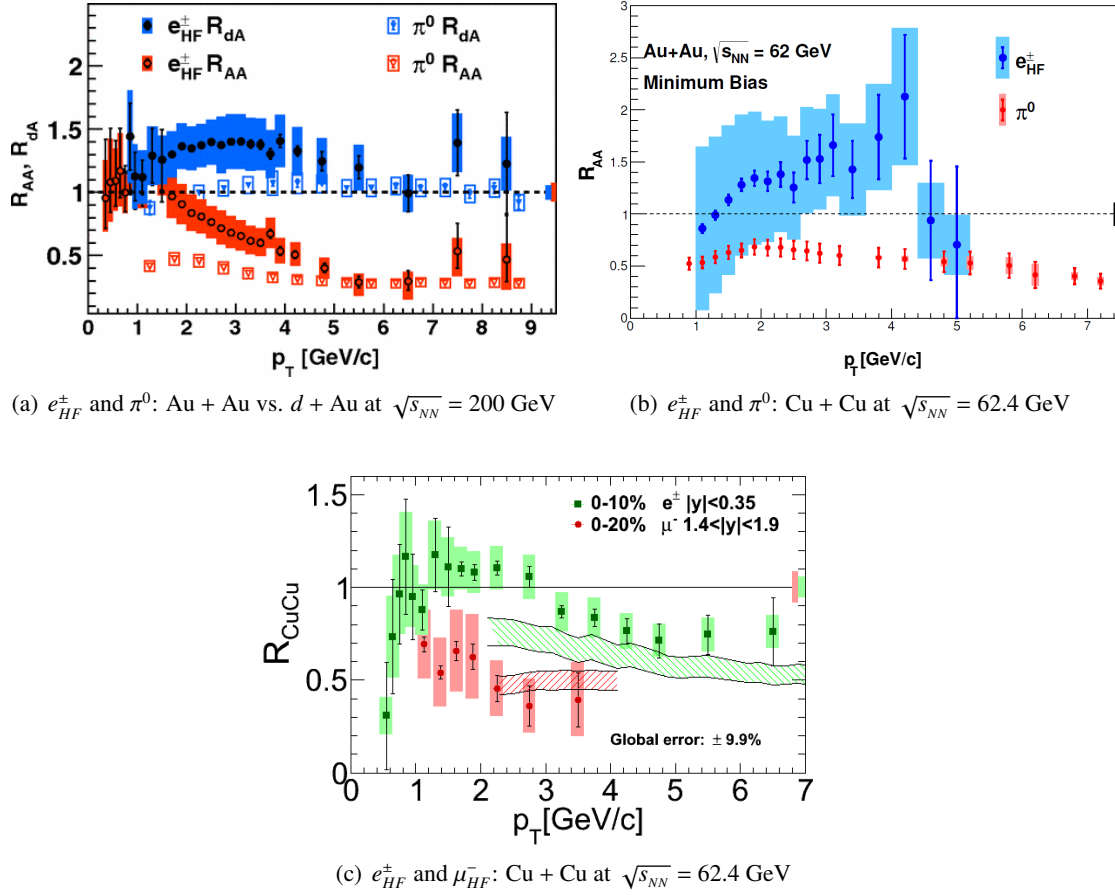


Figure 2. The nuclear modification factors $R_{dAu}(p_T)$ and $R_{AA}(p_T)$ for the π^0 , e_{HF}^{\pm} and μ_{HF}^- : panels (a) and (b) for minimum-bias $d + Au$, $Au + Au$ and panel (c) for central collisions $Cu + Cu$ [12, 13].

2.1. Open Heavy Flavor - Single Electron/Muon Measurements

Open heavy flavor production is measured in PHENIX through the measurement of inclusive electrons or muons [14, 15]. These analyses use a cocktail method to remove fake and real electrons/muons from the data sample. i.e. for the electron measurement, the electrons that come from either meson decay or photon conversions are measured and subtracted from the inclusive spectrum and the remainder is attributed to electrons coming from the semi-leptonic decay of D and B mesons. The effects of CNM are expected to be present in the initial state of $A + A$ collisions; however, this CNM enhancement is convolved with the suppressing effects of hot nuclear matter. Figure 2(a) shows $R_{dAu}(p_T)$ and $R_{AA}(p_T)$ for e_{HF}^{\pm} and the neutral pion (π^0), for which only small CNM effects are observed between e_{HF}^{\pm} and π^0 for $p_T < 5$ GeV/c. Above $p_T \approx 5$ GeV/c, where the CNM effects on both species, e_{HF}^{\pm} and π^0 , are small, their $R_{AA}(p_T)$ values are consistent within uncertainties. However, in the range where CNM enhancement is large for e_{HF}^{\pm} and small on π^0 , the corresponding $e_{HF}^{\pm} R_{AA}(p_T)$ values are consistently above the π^0 values. This could suggest that the difference in the initial state cold nuclear matter effects due to the mass-dependent Cronin enhancement is reflected in the final state spectra of these particles in $Au + Au$ collisions, although alternate explanations involving mass-dependent partonic energy loss in the hot medium are not ruled out. To study the interplay between initial-state effects and final-states effects for heavy flavor (e_{HF}^{\pm}) productions, PHENIX measured the $R_{AA}(p_T)$ in $Au + Au$ collisions at low beam energy, $\sqrt{s_{NN}} = 62.4$ GeV. These $R_{AA}(p_T)$ values for e_{HF}^{\pm} in $Au + Au$ collisions at 62.4 GeV are compared to $\pi^0 R_{AA}(p_T)$ at the same energy as shown in Figure 2(b). At 62.4 GeV, the competition, if present, favors heavy flavor enhancement over suppression. This is consistent with previous results

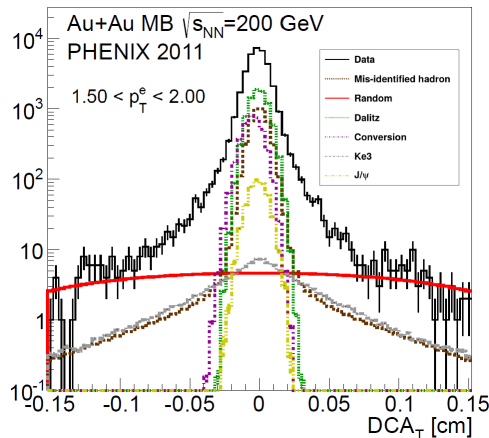


Figure 3. DCA_T distribution for electrons with $1.5 < p_T^e < 2.0$ GeV/c in Au + Au minimum-bias collisions at $\sqrt{s_{NN}} = 200$ GeV. Also shown are the normalized contributions for the various background components detailed in Ref. [19].

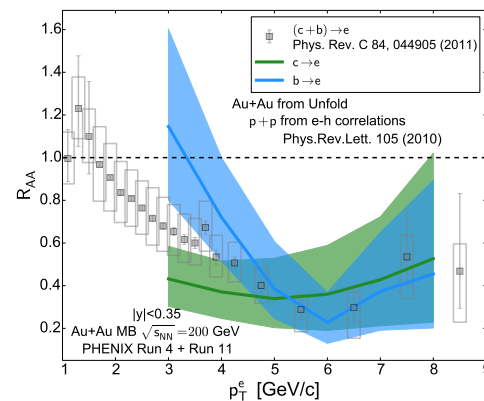


Figure 4. R_{AA} of electrons from charm ($c \rightarrow e$), bottom ($b \rightarrow e$) decays and combined heavy flavor as a function of p_T^e in Au + Au minimum-bias collisions at $\sqrt{s_{NN}} = 200$ GeV. For more details see Ref. [19].

with hadrons where the Cronin enhancement increases as the collision energy decreases [16]. PHENIX measurements of heavy flavor muons (μ_{HF}^\pm) at forward rapidity ($1.4 < y < 1.9$) in central Cu+Cu collisions at $\sqrt{s_{NN}} = 62.4$ GeV show a significant suppression [16]. The magnitude of this suppression at forward-rapidity in Cu + Cu (shown in Fig.2(c)) is compared to the suppression of e_{HF}^\pm in central Au+Au collisions at mid-rapidity at the same energy. As open heavy flavor is significantly more suppressed at forward-rapidity than at mid-rapidity in Cu + Cu, additional nuclear effects, such as gluon shadowing at low-Björken- x or partonic energy loss in the nucleus, may be significant. The heavy flavor e_{HF}^\pm and μ_{HF}^\pm are compared in Fig.2(c) to a theoretical prediction that combines the effects of partonic energy loss, energy loss from fragmentation and dissociation, and includes nuclear matter effects such as shadowing and Cronin enhancement due to parton scattering in the nucleus [17]. While consistent within uncertainties, the model predicts more suppression for heavy flavor electrons than seen in the data.

The large suppression R_{AA} of e_{HF}^\pm at high- p_T shown in figure 2(a) in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, and similar to that of light mesons π^0 , is the more striking because perturbative QCD calculations indicate a substantial contribution from bottom quark decays for $p_T > 5$ GeV/c [18]. For the specific purpose of separating the contributions of charm and bottom quarks at mid-rapidity, the PHENIX collaboration has added micro-vertexing capabilities in the form of a silicon vertex tracker (VTX). The different lifetimes and kinematics for charm and bottom hadrons decaying to electrons enables separation of their contributions with measurements of displaced tracks. Figure 3 shows the DCA_T distribution (in transverse plane) for electrons (e^\pm) in $1.5 < p_T^e < 2.0$ GeV/c range obtained in Au + Au minimum-bias collisions at $\sqrt{s_{NN}} = 200$ GeV. In order to extract the heavy flavor contributions, all background components, as shown in figure 3, were fully accounted for and their DCA_T shapes as a function of p_T incorporated. The nuclear modifications, $R_{AA}^{c \rightarrow e}$, and $R_{AA}^{b \rightarrow e}$, for charm and bottom hadron decays respectively are presented in figure 4 and detailed in Ref [19]. We find that electrons from bottom hadron decays are less suppressed than those from charm for the region $3 < p_T < 4$ GeV/c. We note that a significantly larger data set of Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV was collected in 2014 with an improved performance of the VTX detector. The 2014 Au + Au data coupled with the $p + p$ data taken in 2015 should yield both an important baseline measurement of the bottom electron fraction and a more precise measurement in Au + Au.

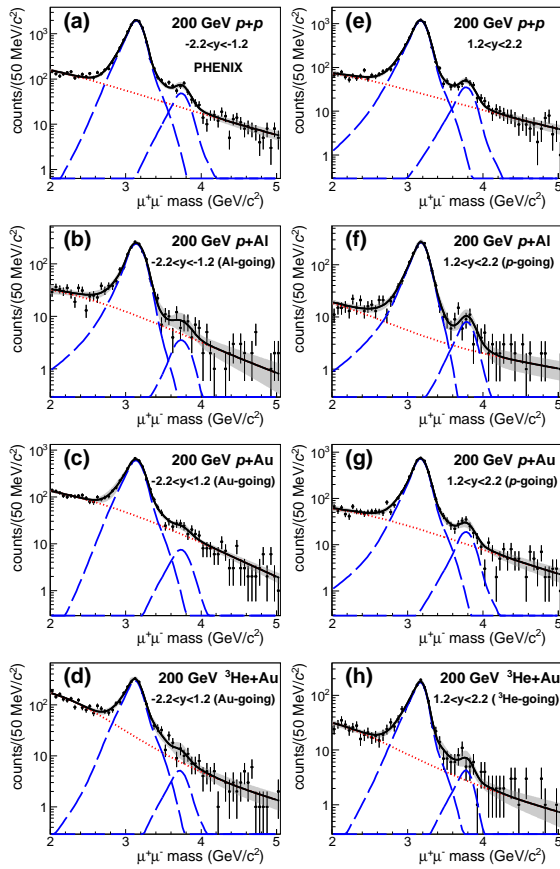


Figure 5. The measured dimuon mass spectra with fits from the (a–d) South and (e–h) North PHENIX muon arms, for $p + p$, $p + \text{Al}$, $p + \text{Au}$, and $^3\text{He} + \text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV. The total fit is the solid [black] line with a shaded [gray] band representing the 90% confidence level. The dashed [blue] and dotted [red] lines represent the contributions from the resonances and background, respectively. For more details see Ref. [21].

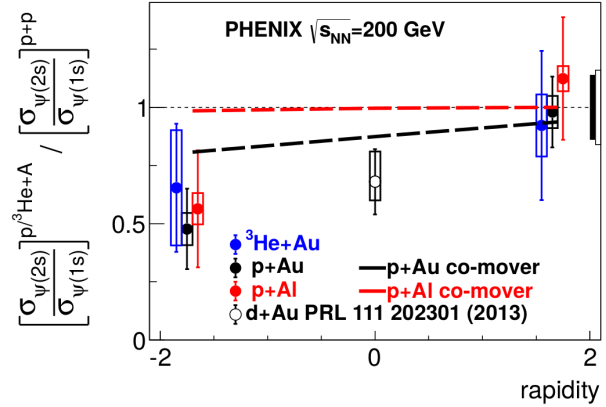


Figure 6. The double ratio of $\psi(2S)/\psi(1S)$ mesons measured in $p + \text{Al}$, $p + \text{Au}$, and $^3\text{He} + \text{Au}$ collisions to that same ratio in $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV, with a calculation based on breakup by comoving particles. The bars (boxes) on the data points represent the statistical (systematic) uncertainties, and the shaded (open) box around unity represents the global uncertainty on the forward/backward (mid) rapidity data. For more details see Ref. [21].

2.2. Quarkonia Measurements - $\psi(1S)$ and $\psi(2S)$ mesons production versus system size

One way to isolate final-state effects is through studies of states with the same quark content but different binding energies, such as the charmonium states $\psi(1S)$ and $\psi(2S)$, with binding energies of 640 MeV and 50 MeV, respectively [20, 21]. While significant initial-state effects on open charm have been found in $d + \text{Au}$ collisions at RHIC, these should equally affect all charm pairs before projection onto a final state. Therefore any differences in the modification of $\psi(2S)$ and $\psi(1S)$ production are likely due to late time effects which are sensitive to differences in the fully-formed meson radius and binding energy. The measured dimuon mass spectra from $p + p$, $p + \text{Al}$, $p + \text{Au}$, and $^3\text{He} + \text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV are shown in figure 5. These distributions comprise peaks at the $\psi(1S)$ and $\psi(2S)$ masses (3.1 and 3.7 GeV/c^2 , respectively) on top of correlated background from charm and bottom hadron decays and Drell-Yan pairs, plus combinatorial background from light meson decays and hadrons which are not stopped in the absorbers. From figure 5 it is apparent that the $\psi(2S)$ peaks are suppressed

relative to the $\psi(1S)$ peak in the columns on the left (in the A-going direction). Quantitative comparisons are accomplished by calculating the double ratio of $\psi(2S)/\psi(1S)$ production in p/He+A collisions to the ratio found in $p + p$ collisions, as shown in figure 6. We see that at forward rapidity, the double ratio is consistent with unity in all three collision systems, indicating that any possible nuclear effects on the two charmonium states are comparable. Because these states are not fully formed until after they exit the nucleus, the fact that any nuclear effects have an equal magnitude on both states suggests that there are no significant final state effects on the pair which occur in this rapidity region. At backward rapidity, the ratios in all collision systems are suppressed by a factor of 2. The mechanism for this preferential suppression of the $\psi(2S)$ relative to the $\psi(1S)$ is expected to occur after the $\psi(1S)$ formation time. A significant difference in the late stages of the collision between this region and forward rapidity is the presence of a larger number of comoving hadrons.

3. Conclusions

RHIC is an amazing heavy ion machine, able to provide collisions over a large range of energies and system size. PHENIX Measurements of heavy flavor made in heavy ion collisions at RHIC have led to a broad and deep understanding of the properties of hot QCD matter. The large suppression R_{AA} of e_{HF}^{\pm} at high- p_T in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, and similar to that of light mesons π^0 , is the more striking because perturbative QCD calculations indicate a substantial contribution from bottom quark decays for $p_T > 5$ GeV/c. For the specific purpose of separating the contributions of charm and bottom quarks at mid-rapidity, the PHENIX Collaboration has added micro-vertexing capabilities in the form of a silicon vertex tracker (VTX). We find that electrons from bottom hadron decays are less suppressed than those from charm for the region $3 < p_T < 4$ GeV/c. The PHENIX experiments also established measurements of $\psi(1S)$ (or $\psi(1S)$) and $\psi(2S)$ production as a function of system size, $p + p$, $p + \text{Al}$, $p + \text{Au}$, and $^3\text{He} + \text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV. We have found that in $p^3\text{He} + \text{A}$ collisions at forward rapidity, we observe no difference in the $\psi(2S)/\psi(1S)$ ratio relative to $p + p$ collisions. At backward rapidity, where the comoving particle density is higher, we find that the $\psi(2S)$ is preferentially suppressed by a factor of two.

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