Heavy Flavor Measurements at STAR

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Abstract

We present a selection of recent heavy flavor results from the STAR experiment. Measurements of D⁰ and D* meson production in √s=200 and 500 GeV p+p, as well as in √s_{NN}=200 GeV d+Au, Au+Au and 193 GeV U+U collisions are presented and implications on the production mechanism are discussed. We report on the production and elliptic flow of electrons from semi-leptonic decays of heavy flavor hadrons in √s_{NN}=39, 62.4 and 200 GeV Au+Au collisions. Nuclear modification of J/ψ production in √s_{NN}=39, 62.4 and 200 GeV Au+Au, and 193 GeV U+U, and of Υ in 200 GeV d+Au, Au+Au, and 193 GeV U+U collisions are compared to theoretical models. Finally we discuss the prospects of heavy flavor measurements with the recent detector upgrades.

Keywords:

1. Introduction

In ultrarelativistic heavy ion collisions, a phase transition occurs from hadronic matter into a state of deconfined quarks and gluons [1, 2]. Properties of this latter state of matter, dubbed as the strongly interacting Quark Gluon Plasma (sQGP), have been a subject of extensive measurements at the Relativistic Heavy Ion Collider (RHIC) in the past decade and a half. The RHIC Beam Energy Scan (BES) program Phase I. was dedicated to the search of turn-off signatures of the sQGP [3]. On the other hand, significantly improved luminosity of RHIC in the recent years, paired with continuous detector development allows one to turn to rare probes, such as heavy flavor production, which are complementary to observables of light hadrons and provide us with a deeper understanding of the strong interaction.

1.1. Heavy flavor at RHIC energies

Charm and bottom quarks are produced in hard QCD processes early in the interaction, and, due to their large masses, their number is virtually unaffected in the later stages of the reaction. Heavy flavor quarks therefore provide a unique means of exploring the properties of the sQGP. Open heavy flavor yields at different momenta are sensitive to the energy loss mechanism of partons. Azimuthal anisotropy measurements may supply us with additional information about the degree of thermalization of the medium.

Quarkonium states are expected to be subject to sequential melting due to the screening of the q̅q potential in the sQGP, and provide access to thermodynamical properties of the medium [4]. Production of charmonia is abundant and therefore it is relatively easy to measure them with precision. However, several effects concurrent to sequential melting, such as feed-down, recombination in the sQGP and co-mover absorption in the hadronic phase, influence measured yields [5]. The interplay between these effects can be understood by comprehensive measurements at different energies and in different colliding systems. Bottomonium measurements are of special interest because, contrary to charm quarks, the effect of bottom pair recombination and co-mover absorption is negligible at RHIC energies [6].

1.2. Experiment

The STAR detector at RHIC is a compound experiment of several subsystems that provides a full azimuthal coverage at mid-rapidity (|η|<1). In the analyses discussed below, momentum measurement of charged particles, as well as particle identification based on energy loss via ionization, is done using the Time Projection Chamber (TPC). Charged particle identification is aided by the Time of Flight detector (TOF) at low p_T. The Barrel Electromagnetic Calorimeter (BEMC) is used for energy measurement and further identification of electrons. The Vertex Position Detector (VPD) provides trigger for the minimum bias (MB) data. A
2. Open heavy flavor measurements

Currently, STAR measures open heavy flavor through two different channels. One is the direct reconstruction of charmed mesons from their hadronic decays ($D^0 \rightarrow K^- \pi^+$ or $D^{*-} \rightarrow D^0 \pi^- \rightarrow K^- \pi^+ \pi^-$ and their charge conjugated counterparts) [8,9]. $D^0$ and $D^*$ meson production was measured in $\sqrt{s} = 200$ and 500 GeV p+p, as well as $D^0$ in $\sqrt{s_{NN}} = 200$ GeV Au+Au and $\sqrt{s_{NN}} = 193$ GeV U+U MB collisions. The invariant yields are determined in the following way: the invariant mass peak is reconstructed from the decay products, the combinatorial background is subtracted using event mixing, and their charge conjugated counterparts) [8, 9]. $D^0\rightarrow K^-\pi^+$ or swapped-sign background ($D^{*}\rightarrow K^-\pi^+$). Such processes typically have branching ratios two times larger than hadronic channels, and high-$p_T$ electrons are easily triggered on the BEMC using a high tower (HT) trigger. It is, however, not possible to directly separate charm and bottom contribution without secondary vertex reconstruction. The main background for this process is the so-called photonic electrons (PE), $e^+e^-$ pairs from decays of light hadrons and from photon conversion in detector material. The PE contribution is determined from data.

2.1. $D^0$ and $D^*$ production

Precision p+p measurements are essential as a benchmark for theoretical calculations as well as a baseline for nuclear modification. Uncertainty in extrapolation of the $D^0$ and $D^*$ spectra towards lower momenta used to be one of the main sources of the systematic uncertainty on the total production cross section [8]. Recent high-statistics measurements at $\sqrt{s} = 200$ GeV constrained the shape of the spectrum by extending the range with a new $0 < p_T < 0.7$ GeV/c point. Fig. 1 shows previously published charm production cross sections $d\sigma^{c\bar{c}}_{NN}$ at $\sqrt{s_{NN}} = 200$ GeV, as well as new 200 and 500 GeV data. STAR data points follow the trend of world data and are described by pQCD FONLL calculations [16].

Fig. 2 shows a comparison of $d\sigma^{c\bar{c}}_{NN}$ in $\sqrt{s_{NN}} = 200$ GeV p+p, d+Au and Au+Au collisions. The total cross section follows scaling with the number of binary collisions ($N_{bin}$), supporting the picture that charm is produced early, in perturbative processes. Accordingly, nuclear modification factor $R_{AA}$ of the $D^0$ mesons, in Fig. 3 (a), exhibit no significant modification in peripheral collisions at $\sqrt{s_{NN}} = 200$ GeV [9]. In more central collisions, however, a different structure emerges: while higher-$p_T$ $D^0$ $R_{AA}$ shows similar suppression to that of light mesons [17, 18], a characteristic hump-shaped enhancement appears in the $1 < p_T < 2$ GeV/c range. The 10% most central data are compared to several models in Fig. 3 (c). High-$p_T$ suppression of the charmed mesons indicates a strong charm–medium interaction [27]. The low-momentum enhancement can be understood by models that include charm–light quark coalescence [20–22] and allow for charm to pick up radial flow. A model prediction without charm–light quark coalescence [24] differs significantly from observations in the low-momentum range [9]. Model calculations of Ref. [22] hint that cold nuclear matter (CNM) effects play an important role.

Uranium ions are heavier than gold and have a prolate shape, and therefore they extend the STAR measurements up to higher number of participant nucleons $N_{part}$. It is estimated [15] that, on average, an approximately 20% higher Bjorken energy density is achieved in central U+U than in central Au+Au collisions. The $R_{AA}$ of $D^0$ mesons with $p_T > 3$ GeV/c in top-energy Au+Au collisions is...
Figure 2: The STAR results at $\sqrt{s} = 200$ and 500 GeV are compared to different experiments and an NLO model. Right: Charm production cross section in STAR p+p, d+Au and Au+Au collisions versus the number of binary collisions $N_{\text{bin}}$.

2.2. Non-photonic electrons at different energies

Fig. 5 shows a significant suppression of non-photonic electron yield in central $\sqrt{s_{\text{NN}}} = 200$ GeV Au+Au collisions, that is similar to light mesons. The results are compared to several energy loss mechanism models [24–28]. Although gluon radiation scenario [24] is quite successful in describing energy loss of light hadrons, it appears not to be enough alone to explain the observed high-p$_T$ NPE suppression. The azimuthal anisotropy parameter $v_2$ (also called elliptic flow) is found to be non-zero, and significantly above the non-flow estimation at low momenta [10]. It is to be noted that those models that are in better agreement with the NPE $R_{AA}$ come short in describing $v_2$ at the same time.

The picture emerging from recent lower energy measurements is, however, radically different from top RHIC energy. Fig. 6 shows the $R_{AA}$ of NPE in $\sqrt{s_{\text{NN}}}=62.4$ GeV Au+Au collisions. The p+p reference used here is from pQCD calculations with $k_T$-factorization technique [29], which gives an upper limit for NPE production in p+p collisions [10]. The $R_{AA}$ is generally flat, showing no NPE suppression in $\sqrt{s_{\text{NN}}}=62.4$ GeV Au+Au collisions. Fig. 7 shows the NPE elliptic flow in $\sqrt{s_{\text{NN}}} = 39, 62.4$ and 200 GeV Au+Au collisions. While at top RHIC energy one observes substantial flow, $v_2$ is consistent with zero in the case of the two lower energies, and differs significantly from top energy results in the 0.5<p$_T$<1 GeV/c range. These results suggest that the effect of the thermalized, hot matter does not dominate heavy flavor production anymore at 62.4 GeV and below.

3. Quarkonium results

Quarkonia are reconstructed via the dielectron decay channel ($J/\psi \rightarrow e^-e^+$, $\Upsilon \rightarrow e^-e^+$). Minimum bias data were used in the BES $J/\psi$ analyses [11], with an event mixing background subtraction. At $\sqrt{s_{\text{NN}}}=200$ GeV, both MB and HT triggered data were used to maximize luminosity at high-p$_T$ [12]. HT triggered data were used in the $\Upsilon$ analyses [14]. Like-sign pair combinatorial background subtraction was applied. There is a substantial background contribution from Drell-Yan and open $b\bar{b}$ processes, which are accounted for using a simultaneous fit with templates of pre-set shapes from models, together with the signal.

3.1. Suppression and flow of the $J/\psi$

The $J/\psi$ nuclear modification factor is shown in Fig. 8 for $\sqrt{s_{\text{NN}}} = 39, 62.4$ and 200 GeV Au+Au collisions as a function of $N_{\text{part}}$. Minimum bias U+U data at $\sqrt{s_{\text{NN}}} = 193$ GeV is also shown on the plot. Due to the lack
Figure 4: Nuclear modification factor of $p_T > 3$ GeV/c $D^0$ mesons in Au+Au (dots) and in preliminary U+U measurements (squares) for minimum bias collisions (open symbols) as well as at different $N_{\text{part}}$ values (solid symbols).

Figure 5: Non-photonic electron $R_{\text{AA}}$ in central $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions compared to several models [24–28].

of p+p data with sufficient statistics, Color Evaporation Model (CEM) predictions [16] are used as 39 and 62.4 GeV references. A significant suppression is observed at all energies in mid-peripheral to central collisions, and all four datasets are consistent with each other within uncertainties. Model predictions from Zhao and Rapp [31] are consistent with data. This model includes in-medium dissociation of the $J/\psi$ as well as later regeneration from $c\bar{c}$ pairs. The weak dependence on collision energy predicted by the model and seen in the data suggests that different contributions that modify the $J/\psi$ yield largely cancel each other in the observed $R_{\text{AA}}$.

The different contributions to the $J/\psi$ suppression are, however, momentum-dependent. High-$p_T$ $J/\psi$ production is much less affected by CNM effects as well as regeneration in the later stages, and hot nuclear modification becomes the dominant factor [31]. Fig. 7 shows the $R_{\text{AA}}$ for high-momentum ($p_T > 5$ GeV) $J/\psi$ mesons. In central collisions one still observes a significant suppression that is consistent with the minimum bias data, while in the case of peripheral collisions it is gone and $R_{\text{AA}}$ is consistent with unity. It is to be noted that the current STAR $J/\psi$ measurements are inclusive, where the contribution from B meson feed-down can be as high as 15–25% above $p_T = 5$ GeV. The model of Ref. [31] underpredicts the change in peripheral $R_{\text{AA}}$ when going from $p_T$-integrated to high-momentum data. However, the model of Liu et al. [33], which includes the same main components but also considers melting of excited charmonium states feeding down to $J/\psi$, provides good description to the data.

Those $J/\psi$ mesons that are created late in the reaction may be thermalized and thus they may take part in the collective motion that the bulk of hadrons exhibit.
data, with an $R_\text{NN}$ served a suppression beyond model predictions of STAR results. It is to be noted, however, that STAR observed by Emerick, Zhao, and Rapp [38], which includes disfavoured. The strong binding scenario in model production to the number of participants in $\sqrt{s_{\text{NN}}} = 39, 62.4$ and 200 GeV Au+Au and 194 GeV U+U collisions (black, red, blue squares and a green dot, respectively), compared to a model calculation [31].

Fig. 10 shows the azimuthal anisotropy parameter $v_2$ of the $J/\psi$ mesons in minimum bias data. Above $p_T > 2$ GeV, STAR data shows complete consistency with the non-flow estimation, unlike $v_2$ of light mesons and the $\phi$ mesons [13]. This renders the scenario unlikely where $J/\psi$ mesons mainly stem from late, thermalized coalescence of $c\bar{c}$ pairs [34], and supports early production of a significant fraction of the $J/\psi$ mesons [35].

3.2. Suppression of the $\Upsilon$ states

Nuclear modification factors of the $\Upsilon(1S+2S+3S)$ in $\sqrt{s_{\text{NN}}}=200$ GeV $d+Au, Au+Au$ and new $\sqrt{s_{\text{NN}}}=193$ GeV U+U collisions are presented in Fig. 11 with respect to the number of participant nucleons. The trend observed in Au+Au is generally continued in the U+U data, with an $R_{AA}=0.35 \pm 0.01 \text{(stat.)} \pm 0.03 \text{(syst.)}$ measured for the 10% most central U+U collisions. The model of Strickland and Bazow [37] incorporates lattice QCD results on screening and broadening of bottomonium and the dynamical propagation of the $\Upsilon$ meson in the colored medium. Assuming an initial temperature between $428 < T < 443$ MeV, the scenario with a potential high-luminosity $p+Au$ run.

4. Future prospects

In recent years, two new detectors have been installed that facilitate the ongoing heavy flavor program of STAR, the Muon Telescope Detector (MTD) and the Heavy Flavor Tracker (HFT). Both the MTD and the HFT were operational and taking data with dedicated trigger setups in the 2014 high-statistics Au+Au run.

The MTD [39] is a multi-gap resistive plate chamber that is located outside the STAR magnet, and covers 45\% of the $|y|<0.5$ region. It is capable of detecting muons with $\approx 90\%$ efficiency up to $p_T = 20$ GeV/c along with good hadron rejection power. MTD allows for precision quarkonium production and flow, as well as for the separation of prompt and non-prompt $J/\psi$ con-
tributions. As an example, Fig. 13 shows the projected uncertainties of the D^0 v_2 measurements in \(\sqrt{s_{NN}}=200\) GeV Au+Au collisions.

5. Summary

A selection of recent heavy flavor measurements has been presented here. Total charm production cross sections from \(p+p\) D^0 and D^∗ measurements and Au+Au D^0 measurements at three different centralities are consistent with N_{bin} scaling, which supports the picture that charm is mainly produced in initial hard processes. The production of D^0 in top RHIC energy central heavy ion collisions at \(p_T>2\) GeV/c shows a substantial suppression similar to light hadrons, suggesting a strong charm–medium interaction, while the hump-like structure at \(1<p_T<2\) GeV/c suggests charm–light quark coalescence. While \(\sqrt{s_{NN}}=200\) GeV non-photonic electron measurements exhibit both a strong suppression and substantial anisotropy \(v_2\), \(\sqrt{s_{NN}}=62.4\) GeV \(R_{AA}\) shows no trace of suppression, and \(\sqrt{s_{NN}}=62.4\) and 39 GeV \(v_2\) measurements are consistent with no flow, suggesting a radical change in heavy flavor production and dynamics between \(\sqrt{s_{NN}}=62.4\) and 200 GeV energies.

The \(1/\psi\) \(R_{AA}\) also shows a strong suppression, but with a weak beam energy dependence. The U+U minimum bias data are consistent with the Au+Au measurements within errors. On the other hand, the measured \(v_2\) for \(1/\psi\) is consistent with non-flow, thus rendering the thermalized \(c\bar{c}\) coalescence scenario unlikely. The high-\(p_T\) \(1/\psi\) production, less influenced by regeneration and CNM effects, is also significantly suppressed in \(\sqrt{s_{NN}}=200\) GeV central Au+Au collisions, which is a clear signal of the sQGP. This conclusion is further supported by the quantitatively similar suppression of \(\Upsilon(1S)\), and that the \(\Upsilon(2S)\) and \(\Upsilon(3S)\) states are consistent with a complete suppression [14].

Cold nuclear matter effects, however, may play an important role in the case of \(\Upsilon\). The \(\Upsilon(1S+2S+3S) R_{AA}\) versus \(N_{part}\) seems to follow a universal trend in \(d+Au\), \(Au+Au\) and \(U+U\), which is consistent with an sQGP initial temperature \(428<T<443\) MeV, according to a model which assumes an internal energy based potential [37].

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References

[1] J. Adams et al. [STAR Collaboration], Nucl. Phys. A 757, 102 (2005) [nucl-ex/0501009].
[2] A. Adare et al. [PHENIX Collaboration], Phys. Rev. Lett. 104, 123201 (2010) [arXiv:1004.4108 [nucl-ex]].
[3] M. M. Aggarwal et al. [STAR Collaboration], arXiv:1007.2613 [nucl-ex].
[4] A. Mocsy and P. Petreczky, Phys. Rev. Lett. 99, 211602 (2007) [arXiv:0706.2185 [hep-ph]].
[5] M. I. Gorenstein, A. P. Kostyuk, H. Stöcker and W. Greiner, Phys. Lett. B 509, 277 (2001) [hep-ph/0010148].
Figure 12: Anticipated statistical uncertainties on $R_{AA}$ as a function of $N_{\text{part}}$ measured in $\sqrt{s_{NN}}=200$ GeV Au+Au collisions at the $\Upsilon$→$\mu^+\mu^-$ channel for $\Upsilon(1S)$ (red), $\Upsilon(2S)$ (blue) and $\Upsilon(3S)$ (green) separately. The $\Upsilon(1S)\rightarrow\mu^+\mu^-$ measured with the BEMC in the electron channel (black) is plotted for comparison purposes.

Figure 13: Anticipated $D^0_v^2$ statistical uncertainties versus $p_T$ in $\sqrt{s_{NN}}=200$ GeV Au+Au collisions for the scenario when charm and light quarks flow similarly (red) and when charm has no flow (green).