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Nuclear Physics B Proceedings Supplement 00 (2014) 1–5

Nuclear Physics B Proceedings Supplement

PHENIX Results on Heavy Flavor Physics

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Abstract

The PHENIX experiment at the Relativistic Heavy Ion Collider has measured a suite of observables for open and closed heavy flavor in a variety of collision systems, p+p, d+Au, Cu+Cu, Au+Au, U+U, and at different beam energies. These results indicate substantial modification in the yields of quarkonia, including J/ψ, ψ', and Υ states, and a substantial redistribution in momentum space of open heavy flavor quarks. We discuss the latest results and comparisons to theoretical interpretations.

Keywords:

1. Introduction

Heavy flavor probes in heavy-ion collisions are important as they access all phases of the collision interaction. Such probes are created in hard partonic scattering and are subject to the extremes of hot and dense QCD matter during the creation and freeze-out of the Quark-Gluon Plasma (QGP).

It was originally suggested by Matsui and Satz [1] that a signature of the formation of the QGP would be that J/ψ states that are initially bound may disassociate due to color screening in the high temperature QGP matter. It has also been proposed that the sequential melting of the bound bottomonium states $b\bar{b}$ $\Upsilon(1S, 2S, 3S)$ may lead to a firm restriction on the temperature of the formed nuclear matter (see for example [2]).

In determining any heavy flavor modification, one can measure the relative yields in heavy-ion collisions to those observed in pp interactions, scaled by the number of expected binary collisions ($N_{\rm coll}$). This is known as the nuclear modification factor, R_{AA}:

$$R_{AA} = \frac{1}{N_{\rm coll}} \frac{d^2N_{AA}/dydp_T}{d^2N_{pp}/dydp_T} \quad (1)$$

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 effects. These include modification of the parton density functions in a nucleus, parton energy loss in cold nuclear matter, and (for quarkonia states), breakup due to collisions with nucleons in the target.

To disentangle such effects, multiple measurements are needed, such as collisions of different ions and at different collision energies. RHIC has the unique ability to store and collide nuclei of different mass, for example Au+Au and Cu+Cu, and also collide asymmetric systems such as $p(d)$+Au and Cu+Au. By observing the modification in more elementary systems ($p(d)$+Au), one may hope to understand the initial modifications before the QGP is formed.

PHENIX utilizes several techniques to identify heavy flavor. By measuring the daughter decay products from, for example J/ψ, the invariant mass can be calculated to positively identify the original, parent, particle. For J/ψ in PHENIX, both the electron ($J/\psi \rightarrow e^+e^-$) and muon ($J/\psi \rightarrow \mu^+\mu^-$) decay channels are used. The identification of electrons is made in the central arms of the detector at midrapidity ($|y|<0.35$), utilizing an electromagnetic calorimeter and drift chamber system. The muons are measured at forward rapidity ($1.2<|y|<2.2$) using a spectrometer and a muon identifier. For more information see Ref. [3].

For open heavy flavor measurements, PHENIX has employed single electron/muon measurements [4, 5], coupled with a background cocktail to remove non-heavy-flavor backgrounds. In addition, an invariant mass calculation method [6] is also used, along with both a converter and a cocktail method to determine the non-heavy-flavor background, to measure correlated electron pairs at mid-rapidity ($|\eta|<0.35$). The systematic removal of known particles, via the cocktail, leaves a remnant spectrum due to only heavy flavor decays.

2. Υ measurement in Au+Au

The heaviest particle measured in PHENIX to date is the Υ [7, 8]. The Υ is sensitive to the temperature of the QGP, and subsequently to color screening. The different states, Υ(1S), Υ(2S), and Υ(3S) are sequentially more loosely bound, meaning that the relative abundance (to each other and to that measured in *pp* collisions) is directly sensitive to the temperature of the QGP. Owing to the available statistics and limitations of the momentum resolution, a measurement of the combine Υ(S1+S2+S3) is made, see Fig. 1.

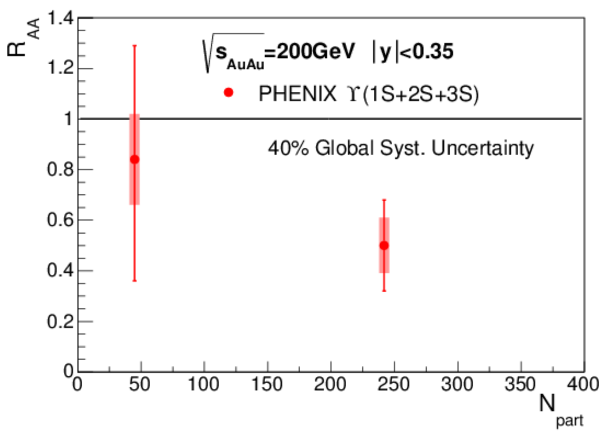

Figure 1: Υ(1S+2S+3S) nuclear modification factor, R_{AA} measured at mid-rapidity as a function of collision centrality in Au+Au collisions at $\sqrt{s} = 200$ GeV. From Ref. [7].

The results indicate that there is a significant suppression in central collisions. This is a trend which is observed in the centrality distribution of other hadrons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Assuming that the more tightly bound (i.e. requires the highest temperature to be suppressed, see Ref. [7]) Υ(1S) is unmodified, the measured R_{AA} is consistent with a full suppression of the excited Υ(2S) and Υ(3S) states [7].

3. J/ψ production versus system size

3.1. J/ψ in d+Au collisions

The abundance of J/ψ observed in PHENIX allows for a much more detailed examination of the modification effects in the nuclear environment.

At $\sqrt{s_{NN}} = 200$ GeV, the J/ψ is primarily produced from gluon fusion interactions, and the initial production is modified due to the modification of the PDFs in the target. At forward (*d*-going) rapidity in PHENIX J/ψ production involves low-Björken-x gluons in the target, where suppression due to shadowing is expected, while at backward rapidity it involves high-x gluons, where enhancement due to anti-shadowing is expected. Measurements of J/ψ in *d*+Au collisions [9], i.e. cold-nuclear matter only, show a suppression at all rapidities, see Fig. 2. This suppression is consistent with a model [10] which couples the EPS09 [11] nPDFs with a $c\bar{c}$ break-up cross-section.

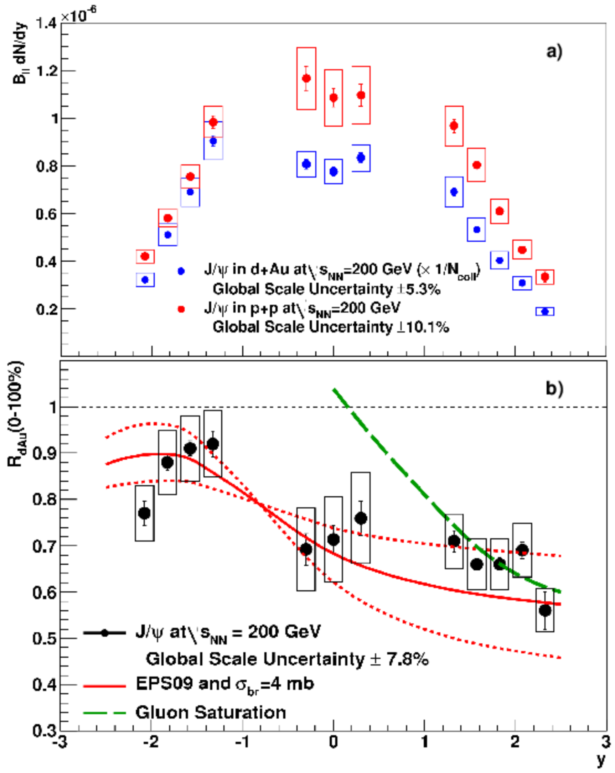

Figure 2: Panel (a) shows the measured J/ψ yields in *pp* (red) and *d*+Au (blue) collisions at $\sqrt{s} = 200$ GeV as a function of rapidity. Panel (b) shows the nuclear modification factor, R_{dA} as a function of rapidity. The red lines show the effect of shadowing coupled to a nuclear break-up cross-section [10], the green shows the expectation from a Gluon saturation Model [12]. From Ref. [9].

3.2. J/ψ in Au+Au collisions

In Au+Au collisions, the effect of cold nuclear matter is entangled with effects from the QGP. Figure 3 shows the nuclear modification factor from Au+Au collisions at forward (red) and central (blue) rapidities [13]. The lines represent which accounts for several nuclear effects [14, 15]. For example, the upper dashed lines show the expected effect from cold nuclear matter, an effect which is similar to the model of d+Au data described above.

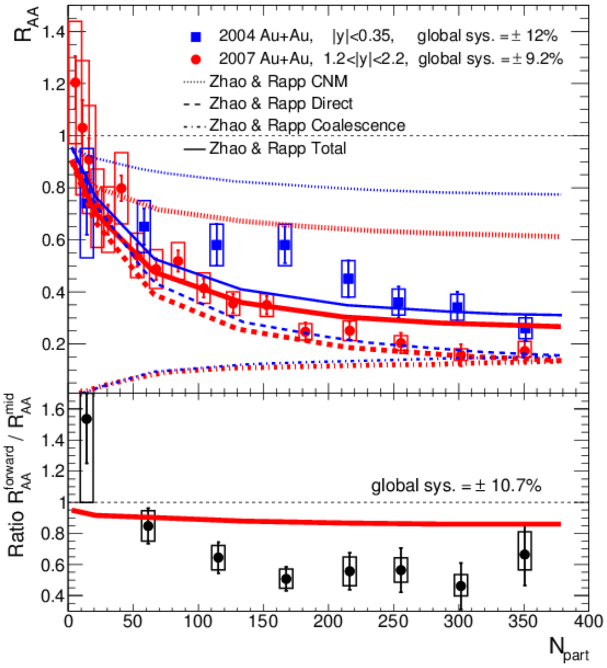

Figure 3: The upper panel shows the nuclear modification factor, R_{AA} as a function of centrality. The lines show the effect of cold nuclear matter (dotted, uppermost pair), direct production (dashed), and coalescence (dot-dashed). The solid lines represent the sum of all effects considered. The lower panel shows the ratio of forward to midrapidity R_{AA}. From Ref. [13].

The suppression observed at forward rapidity is stronger than that at mid-rapidity, even though the energy density is expected to be slightly larger at midrapidity. This could be due to stronger cold nuclear matter effects at forward rapidity, or possibly stronger coalescence of charm quarks at hadronization at midrapidity, or both.

3.3. J/ψ in Cu+Au collisions

In symmetric systems, it is not possible to differentiate forward and backward particle production. However, one of the strengths of RHIC is to collide large ions of asymmetric mass. By colliding ions of different sizes, the cold nuclear matter effects will be different at forward and backward rapidities. Figure 4 shows the nuclear modification factor from Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [16]. The red symbols depict the nuclear modification at forward rapidity, the blue shows R_{AA} at backward rapidity. The forward rapidity data are observed to be systematically lower than the backward rapidity points, a similar trend to that found in d+Au collisions. For comparison, Au+Au data are shown. The backward Cu+Au data are similar in magnitude to the Au+Au data.

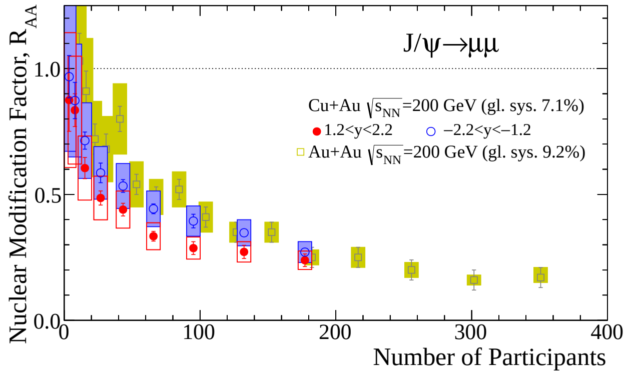

Figure 4: Nuclear modification factor, R_{AA} as a function of centrality in Cu+Au collisions at forward (red) and backward (blue) rapidity. For comparison, the Au+Au (gold) data are also shown, averaged over forward and backward rapidities. From Ref. [16].

A more detailed way to look at these data is via the ratio of forward and backward yields. Figure 5 shows the forward/backward ratio as a function of collision centrality, compared to a model prediction using EPS09 nPDFs for each nucleus and a break-up cross-section for the $c\bar{c}$ pair. This simple model contains no hot matter effects. The fact that it reproduces the trend of the data and has about the right magnitude is consistent with cold nuclear matter effects being responsible for most of the difference in the of suppression forward and backward rapidity. More detailed theoretical calculations will be required to properly account for hot and cold nuclear matter effects on this collision system.

3.4. J/ψ in U+U collisions

J/ψ production has also been studied in the heaviest-ion collisions recorded at RHIC: U+U at $\sqrt{s_{NN}} = 193$ GeV. The centrality dependence of this dataset shows a similar trend to the lighter systems, with a slightly lower suppression in the most central collisions, see Figure 6. The most central collisions from

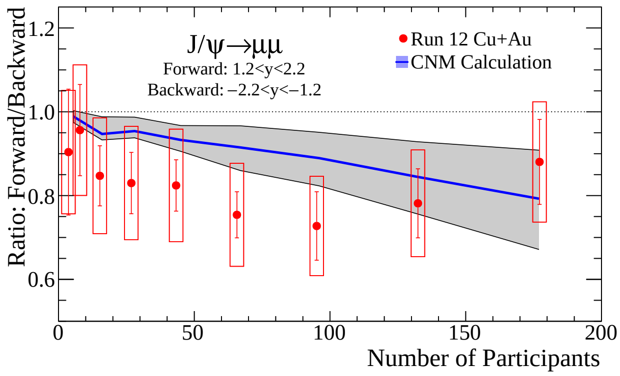

Figure 5: Ratio of yields measured at forward / backward rapidity in Cu+Au collisions, compared to a model prediction. From Ref. [16].

$U+U$ include data at the highest measured energy densities at RHIC [17].

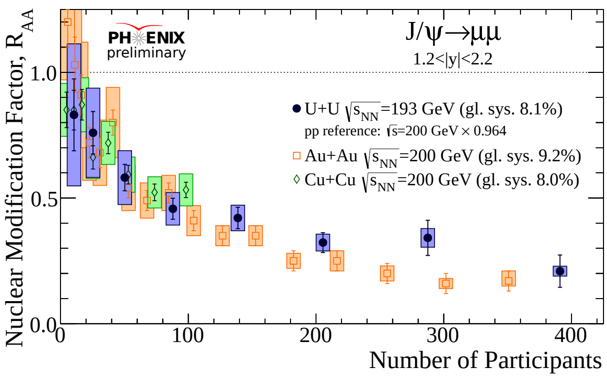

Figure 6: Nuclear modification factor, R_{AA}, measured in $U+U$ collisions as a function of centrality (blue). For comparison, Au+Au (red) and Cu+Cu (green) data are also shown. Results are preliminary.

4. Open Heavy Flavor – single electron/muon measurements

Open heavy flavor is measured in PHENIX using single electrons at mid-rapidity [5] and single muons at forward rapidity [4]. These analyses use a cocktail method to remove fake and real electrons/muons from the data sample. In the muon channel, the resultant distribution of heavy-flavor muons can be compared at forward and backward rapidities to J/ψ production in the same system, see Fig. 7. The yields at forward rapidity are similar. At backward rapidity, the heavy-flavor muons are enhanced. This is most distinct in the lower p_T region which is dominated by charm production. Such a difference between closed and open heavy flavor may reflect an additional $c\bar{c}$ break-up or may be due to a higher co-mover density at backward rapidity.

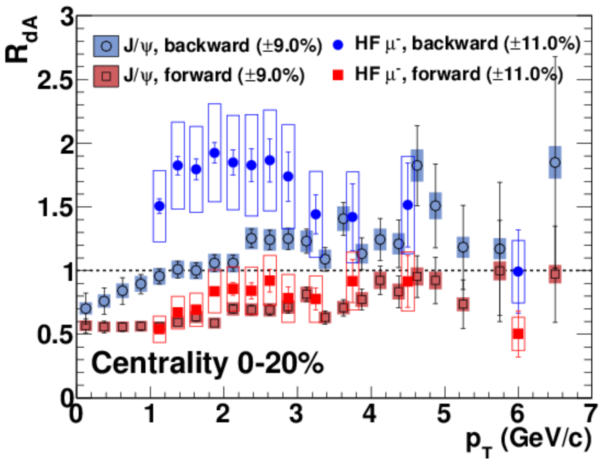

Figure 7: Nuclear modification factor, R_{dA}, of heavy-flavor muons (closed symbols) and J/ψ (open). The blue symbols depict the backward rapidity particle production, the red shows the forward rapidity. From Ref. [4].

At mid-rapidity, an enhancement of single electrons from heavy-flavor decays is observed [5] in central d+Au collisions. Figure 8 shows a comparison of the data from d+Au (closed/blue symbols) and for Au+Au [18] (open/red) collisions for both heavy-flavor electrons (circles) and π^0s (triangles). The heavy-flavor electrons show an enhancement up to $p_T \approx 5$ GeV in d+Au, whereas in Au+Au, heavy-flavor electrons are suppressed for $p_T > 2$ GeV.

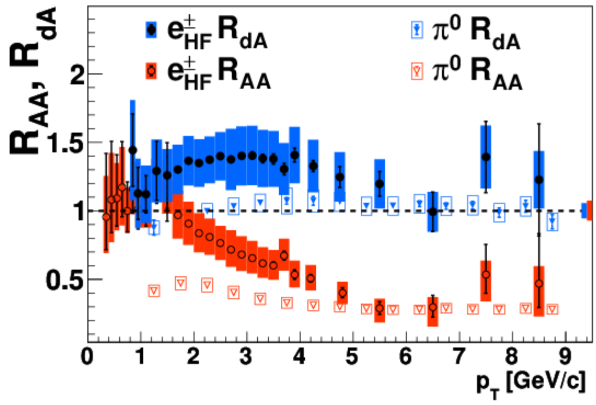

Figure 8: Nuclear modification factor of heavy-flavor electrons in d+Au (R_{dA} – closed blue circles) and Au+Au (R_{AA} – open red circles). Also shown for comparison are results from π^0s. From Ref. [5].

5. Summary

PHENIX has contributed a wealth of new data on heavy-flavor production over the past fourteen years of RHIC running. The broad kinematic reach of the detector coupled to the ability of RHIC to collide a diverse set of particles has led to unique measurements which shine light on some of the most intriguing questions in nuclear collisions. We have observed that heavy flavor is suppressed in heavy-ion collisions, with a similar suppression at similar numbers of participants. More subtle details are revealed in asymmetric collisions, with forward (small nucleus direction) exhibiting more suppression than the backward direction. Open heavy-flavor muons are found to be enhanced at backward rapidity compared to J/ψ, in the region p_T<2.5 GeV.

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