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HEAVY FLAVOR MEASUREMENTS IN PHENIX*

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Heavy quarkonia suppression is one of the highly cited signatures of quark-gluon plasma (QGP) formed in relativistic heavy ion collisions. However, theoretical predictions remain diverse due to lack of precise knowledge of heavy flavor meson production, suppression, regeneration in hot and dense medium and other cold nuclear effects. PHENIX has carried out a comprehensive study of heavy flavors which includes baseline measurements of heavy flavor, J/ψ and Upsilon in $p+p$ collisions, and the measurements from d+Au, Cu+Cu and Au+Au collisions over the past decade. This paper will give an overview of the PHENIX heavy flavor measurements with a focus on the most recent and exciting results from PHENIX. An outlook of the PHENIX effort on heavy flavor studies will also be presented in this talk.

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1. Introduction

The experimental study of matter properties at extremely high temperature and high density at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) is approaching its 12th year since the first RHIC physics run in 2000. Data from these runs clearly demonstrate that a high temperature and density state of matter has been achieved at RHIC. This state of matter, called QGP, provides exciting possibilities of experimentally exploring the phase transition from hadronic to partonic degrees of freedom, which is estimated to have occurred in the first few microseconds after the Big Bang. This state of matter, contrary to early

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suggestions of a quasi-ideal state of free quarks and gluons, behaves like a dense fluid with very low kinematic viscosity, exhibiting strong hydrodynamic flow, and nearly complete absorption of high momentum hadronic particles initially created from the colliding nuclear matter [1, 2].

Heavy quarkonia suppression is one of the highly cited signatures of QGP formed in relativistic heavy ion collisions [3]. The modification in the quark pair potential by the hot dense medium will lead to quarkonium suppression in comparison with quarkonium production in $p+p$ collisions. Because of different binding energies of the quarkonium states, one could gain access to the temperature of the medium [4]. However, theoretical predictions remain diverse due to the lack of precise knowledge of heavy flavor meson production, suppression, regeneration in hot and dense medium and other cold nuclear effects. The understanding of the modification of the properties of the quarkonium states is very crucial for exploring the onset of a deconfined state in the hot and dense nuclear medium. In the PHENIX experiment J/ψ mesons are measured from $p+p$, d+Au and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV and several energy scans of Au+Au collisions [5]. In this paper, we highlight the most recent J/ψ measurements including feed-down contributions, cold nuclear matter effects in d+Au collisions and energy dependence of J/ψ suppression in Au+Au collisions following a brief description of the PHENIX detector systems.

2. PHENIX experiment

The PHENIX experiment was designed and optimized for the measurement of rare probes in heavy ion collisions [6]. Figure 1 shows the PHENIX detector setup in beam and side views. The beam view (left) shows the

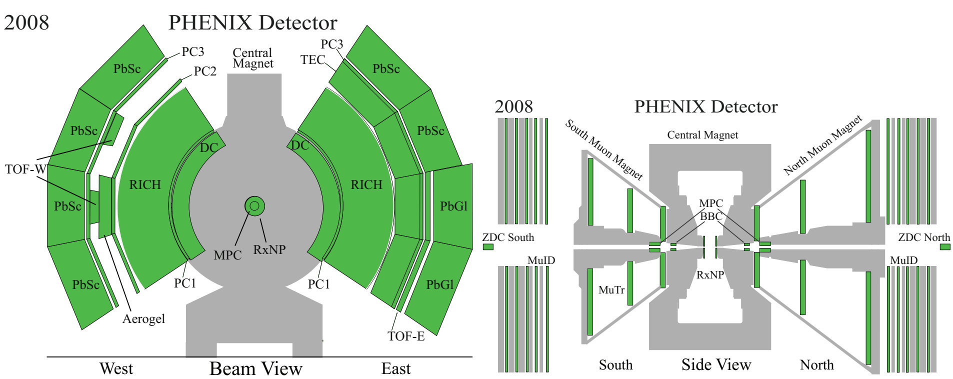

Fig. 1. PHENIX detector setup: (left) Central Arms in beam view; (right) Muon Arms in side view.

West and the East arm detectors in the central rapidity region, which covers $|\eta| < 0.35$ and $90°$ in azimuth for both arms. The side view (right) shows the South and the North muon arms in the forward and backward rapidity region, which covers $1.2 < |\eta| < 2.4$ and $360°$ in azimuth for both arms. The J/ψ results reported in this paper, were measured in both the central arms and the muon arms.

3. Most recent results

The study of particle production in heavy-ion collisions is typically characterized by the so-called nuclear modification factor, R_{AA}, which is defined as the ratio of the particle yield in heavy-ion collisions to the yield in $p+p$ collisions scaled by the number of binary nucleon–nucleon collisions. If the nuclear medium effects are negligible, one would expect that $R_{AA} = 1$, especially for point-like processes. Otherwise, one would get an enhanced particle production for the case of $R_{AA} > 0$ or a suppressed one if $R_{AA} < 0$. It is also common to use $R_{\rm CP}$ to study the nuclear medium effect, which shows the ratio of the particle yields between the central and the peripheral collisions scaled to the per binary collision basis.

3.1. J/ψ suppression puzzle

PHENIX experiment reported in a recent publication [7] on J/ψ suppression at forward rapidity in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV with high statistics as shown in Fig. 2 (left) together with the PHENIX J/ψ result measured in the central rapidity region. The R_{AA} is presented as a function of the number of participants ($N_{\rm part}$) in the collisions, which is determined by a Glauber model calculation and a simulation of the PHENIX beam–beam counter response. Also shown in Fig. 2 (right) is R_{AA} *vs.* $N_{\rm part}$ for J/ψ production in Cu+Cu and Au+Au collisions [5].

In order to study the energy dependence of the nuclear modification factor for J/ψ production in heavy ion collisions, PHENIX took data from Au+Au collisions both at $\sqrt{s_{NN}} = 39$ and 62 GeV in 2010. This was one of the critical steps of the RHIC heavy ion program for studying the onset of the phase transition from the normal hadronic matter to QGP. Unfortunately, there were no baseline measurements of J/ψ productions in $p+p$ collisions at these two energies yet at RHIC, we are not able to determine the R_{AA} from these measurements. Instead, we present here the PHENIX preliminary results of $R_{\rm CP}$ *vs.* $N_{\rm part}$ from Au+Au collisions at $\sqrt{s_{NN}} = 39$ and 62 GeV as shown in Fig. 3. A comparison of the $R_{\rm CP}$ results from these two lower energy data sets with the 200 GeV result is also shown in Fig. 3.

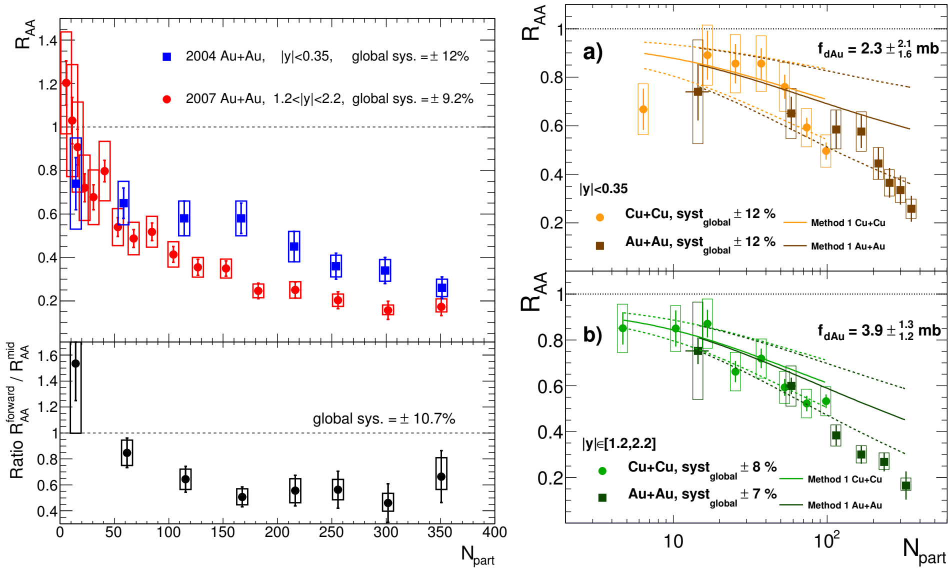

Fig. 2. (Color online) J/ψ R_{AA} as a function of the number of participants in Au+Au (left) and Cu+Cu (right) collisions at $\sqrt{s_{NN}} = 200$ GeV.

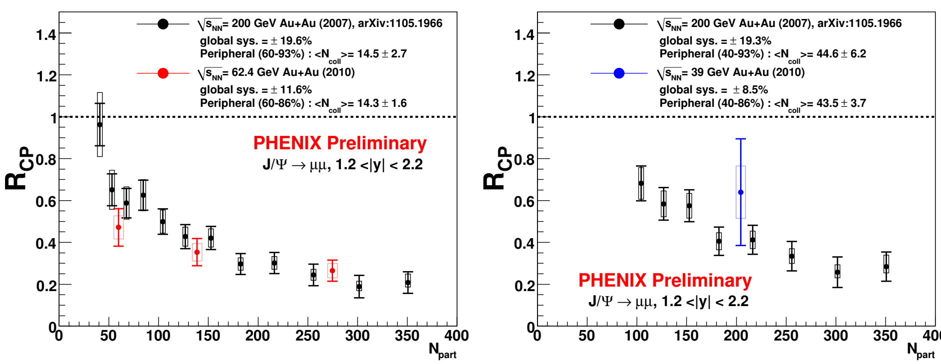

Fig. 3. J/ψ $R_{\rm CP}$ at $\sqrt{s_{NN}} = 62$ GeV (left) and 39 GeV (right) compared to the corresponding $\sqrt{s_{NN}} = 200$ GeV using the same peripheral bin as reference.

The PHENIX results do indicate as much as a factor of five of J/ψ suppression in the most central Au+Au collision at all colliding energies of 200, 62 and 39 GeV. The similarity of the suppression scale at these colliding energies and species poses a significant challenge in disentangling the hot and dense medium (*i.e.*, QGP) effects on J/ψ suppression from the effects of normal cold nuclear medium both in theory and experimental studies. The same trend of J/ψ suppression has also been reported at SPS and even at LHC experiments [8].

3.2. J/ψ feed-down measurements

Inclusive J/ψ measurement has feed-down contributions from higher charmonium states ψ', χ_c as well as B meson decays. PHENIX has measured ψ' and χ_c productions in the baseline $p+p$ collisions at $\sqrt{s} = 200\,\text{GeV}$, which not only provide the reference measurement of R_{AA} for these charmonium states but also allow us to quantitatively estimate their feed-down contributions to the inclusive J/ψ measurements in PHENIX. The results are shown in Fig. 4. The total feed-down contribution to J/ψ from ψ' is $9.6 \pm 2.4\%$ and $32 \pm 9\%$ from χ_c in $p+p$ collisions at 200 GeV in the central rapidity region of the PHENIX experiment [9].

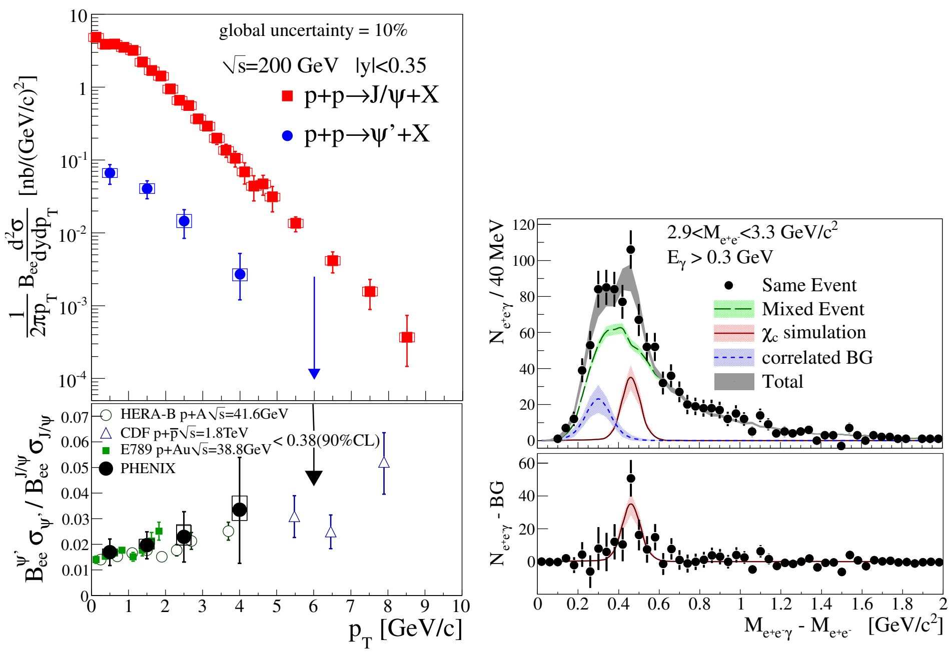

Fig. 4. (Color online) (left) Transverse momentum dependence of J/ψ and ψ' in $|y| < 0.35$ and their ratio at the bottom panel. (Right) $e^+e^-\gamma$ invariant mass distribution and bottom panel is the χ_c signal after like-sign background subtraction.

3.3. Cold nuclear matter effects

In order to explore cold nuclear matter effects, PHENIX also measured the nuclear modification factor ($R_{d\text{Au}}$) of J/ψ in d+Au collisions at $\sqrt{s_{NN}} = 200\,\text{GeV}$. It is expected that there will be no QGP medium created in d+Au collisions at RHIC energies but the measurement allows us to quantify the level of J/ψ production modification in cold nuclear medium environment. This measurement is imperative for studying the signals of the color-screening effect in a deconfined QGP medium [3]. Figure 5 shows $R_{d\mathrm{Au}}$ for two d+Au colliding centralities: 60–80% (top) and 0–20% (middle) and the ratio of central to peripheral $R_{d\mathrm{Au}}$ (*i.e.*, R_{CP}). A substantial level of suppression both in the forward and in the mid-rapidity has been observed.

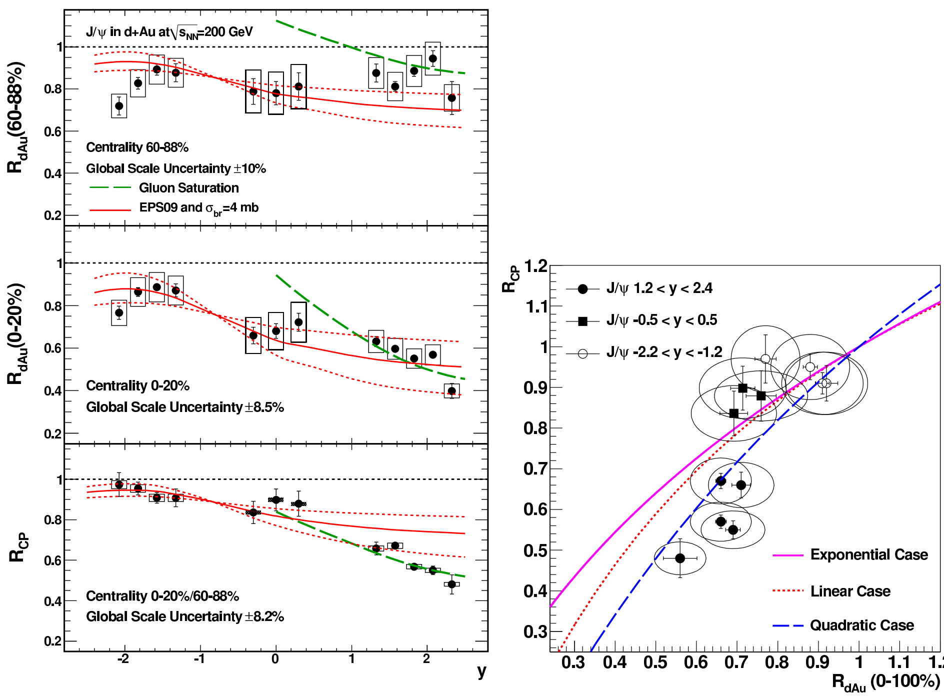

Fig. 5. (Left) Rapidity dependence of nuclear modification factors. (Right) Unbiased $R_{d\mathrm{Au}}$ *vs.* R_{CP} with different geometric dependencies of the nuclear modification.

J/ψ production at RHIC is dominated by gluon–gluon fusion and thus is sensitive to the nuclear modification of the gluon parton distribution function (PDF). For quantifying the sensitivity of the modified PDF on J/ψ production, we have utilized the EPS09 nuclear PDF set [10], assuming that the modification is linear in the longitudinal density-weighted thickness (Λ) through the nucleus [11], and added an additional J/ψ break-up cross-section of 4 mb to fit the PHENIX $R_{d\mathrm{Au}}$ data. The fit results are shown in the left panel in Fig. 5, where the dotted (red) lines are the maximum variations of the EPS09 parameterization. It is clear to see that this fit is not in good agreement with the most peripheral $R_{d\mathrm{Au}}$ and R_{CP} in forward rapidity. The dashed (green) lines in Fig. 5 (left panel) are calculations from a gluon saturation model [12] which fits the PHENIX data in the forward-rapidity region but failed completely in the mid-rapidity and the backward-rapidity regions.

In order to further explore the centrality dependence, we categorize each d+Au centrality class with transverse radial position of the struck nucleons in Au and impose different geometric dependence as described in details in [13]. In Fig. 5 (right), we plotted the $R_{\rm CP}$ *vs.* $R_{d\rm Au}$ for three different geometry dependences and revealed a large disagreement between the PHENIX data and either the linear or exponential dependence of the nuclear modification scenarios. The PHENIX data in the forward rapidity region favors a higher than linear geometric dependence of J/ψ production in Au nucleus.

4. Summary

We presented here a few highlights of J/ψ measurements in the PHENIX experiment at RHIC. We want to point out that in order to extract the signals of J/ψ suppression due to color-screening effect in QGP, one has to consider cold nuclear matter effects such as initial state energy loss and shadowing, corrections for feed-down contribution from higher mass states, and many other factors including secondary production mechanisms as well as recombination of initially uncorrelated $c\bar{c}$ pairs [14]. Given the limited space, many of the important and unique PHENIX measurements on heavy flavor production in heavy ion collisions at RHIC are intentionally discarded here. PHENIX is currently working on its decadal plan to upgrade and even redesign its detector systems to continue exploring the heavy flavor physics in heavy ion collisions.

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