Proc. 24th Winter Workshop on Nuclear Dynamics (2008) 000–000

24th Winter Workshop on Nuclear Dynamics
South Padre, Texas, USA
April 5–12, 2008

Progress Towards Understanding Quarkonia at PHENIX

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Abstract. Quarkonia (J/ψ, ψ', χ_C, Υ) production provides a sensitive probe of gluon distributions and their modification in nuclei; and is a leading probe of the hot-dense (deconfined) matter created in high-energy collisions of heavy ions. We will discuss the physics of quarkonia production in the context of recent $p+p$ measurements at PHENIX. We next discuss Cold-Nuclear Matter (CNM) effects as seen in our measurements in $d + Au$ collisions - both for intrinsic physics such as gluon saturation and final-state dissociation, and as a baseline for studies in nucleus-nucleus collisions. Then we review the latest nucleus-nucleus results in the light of the expected CNM effects, and discuss two leading scenarios for the observed suppression patterns. Finally we show the latest data from PHENIX, including new $d + Au$ data from the 2007-2008 run; and then look into the future.

Keywords: quarkonia, heavy-quarks, quark-gluon plasma, gluon saturation, cold nuclear matter.
PACS: 24.85.+p, 13.85.-t, 25.75.-q, 25.75.Nq

1. Introduction

We discuss our present understanding of Quarkonia (J/ψ, ψ', χ_C, Υ) based on the measurements by PHENIX at RHIC. We discuss 1) production, 2) cold nuclear matter (CNM) effects, 3) the effect of the Quark Gluon Plasma (QGP), and then comment on prospects for the future as RHIC luminosities increase and detector upgrades are installed. As shown in Figure 1, the numbers of J/ψ obtained in recent runs has increased dramatically, with over 70,000 in the just completed $d+Au$ run.

2. How are Quarkonia Produced

Quarkonia are produced primarily via gluon-fusion, but it has proven difficult for theoretical predictions to reproduce both the cross section and the polarization

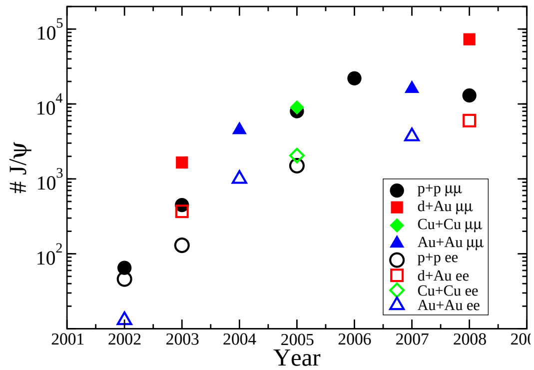

Fig. 1. Approximate Number of J/ψs per year for different types of collisions at PHENIX. Close symbols are for dimuons at forward rapidity, and open symbols are for dielectrons at mid rapidity.

of the J/ψ. The configuration of the initially produced $c\bar{c}$ state remains unclear, and casts uncertainty on what CNM effects it will experience in nuclei. NRQCD models produce a $c\bar{c}$ in a color-octet state and are able to reproduce the cross section, but predict large transverse polarization at large p_T - unlike the data from E866/NuSea[1] and CDF[2] which show only small longitudinal polarization. However, a recent color-singlet model[3] claims good agreement for both cross section and polarization.

Another complication in quarkonia production, particularly for the J/ψ, is that about $\sim 40\%$ of the J/ψs come from decays of higher mass resonances, namely the ψ' and χ_C. Until recently, these fractions have been inferred from measurements at other energies. Now PHENIX has started to quantify these itself with initial results indicating $8.6 \pm 2.5\%$ from the ψ' and $< 42\%$ from the χ_C. Another PHENIX measurement[5] shows that $4^{+3}_{-2}\%$ of the J/ψs come from decays of B-mesons, a contribution which is strongest at larger p_T.

3. What Cold Nuclear Matter (CNM) Effects are Important

For Quarkonia produced in nuclei, e.g. in $p+A$ or $d+A$ collisions, several interesting effects - usually called cold nuclear matter (CNM) effects, can occur. These include modifications of the initial gluon density either according to traditional nuclear shadowing models[7, 8] that involve fits to deep-inelastic scattering and other data, or gluon saturation models[9]. In addition the initial-state projectile gluon may lose energy before it interacts to form a J/ψ. Both of these effects can cause suppression of the produced J/ψs per nucleon-nucleon collision at large rapidity (or small x) relative to that observed in p+p collisions. Finally, the J/ψs can be suppressed by dissociation of the $c\bar{c}$ by the nuclear medium in the final state.

A new analysis of the 2003 PHENIX $d + Au$ data, along with the new 2005 baseline $p + p$ data have been put together to produce new nuclear modification

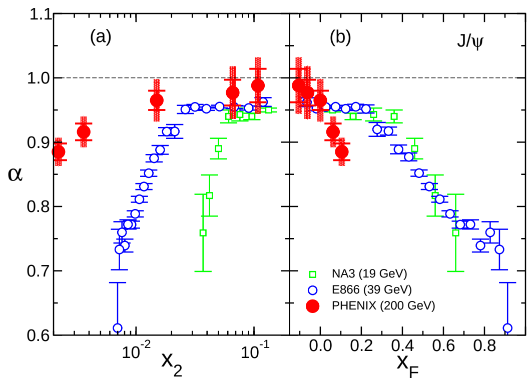

Fig. 2. Nuclear dependence of J/ψ production for three different energies vs x_2 and x_F. Where $x_F = x_1 - x_2$ and x_1 and x_2 are the momentum fractions in d and Au respectively. α is a representation of the nuclear dependence in terms of a power law, i.e. $\sigma_A = \sigma_N A^\alpha$.

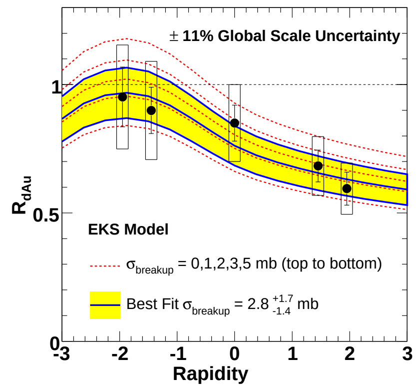

Fig. 3. Nuclear modification factor versus rapidity for $d+Au$ collisions. The yellow band bordered by black lines represents a fit to a model that contains EKS[7] shadowing and a dissociation cross section.

factors for CNM[6], as shown in Figure 2, where they are compared to similar data at lower energies. The lack of scaling with x_2 shown in the left panel of the figure suggests that traditional shadowing models, which should have a universal x_2 dependence, are not the dominant physics. The approximate scaling with x_F (right panel), at least for the lower energy data that extends to large x_F, hints that initial-state energy loss or gluon saturation may be the dominant physics.

In Figure 3 an approximate constraint using a simple CNM model (with shadowing and dissociation)[10] is shown. This model can then be used to give an extrapolated constraint for $Au+Au$ collisions, as shown in Figures 4 and 5. Clearly the $d+Au$ data from 2003 used to constrain the CNM extrapolation here suffers from large uncertainties, and results in a large uncertainty for $Au+Au$ collisions. For $Au+Au$ at mid-rapidity the CNM band is almost consistent with the observed suppression - except for the most central collisions ($n_{part} \sim 340$); while at forward rapidity the suppression seen for $Au+Au$ is substantially stronger. The just completed 2008 $d+Au$ run has approximately 30 times more J/ψ's than before and, once analyzed, will dramatically improve the knowledge of the CNM baseline in $A+A$ collisions, and allow precision studies of the additional physics beyond CNM that comes from the hot-dense matter created in heavy-ion collisions. The CNM constraint is expected to narrow by approximately a factor of three with the new $d+Au$ data.

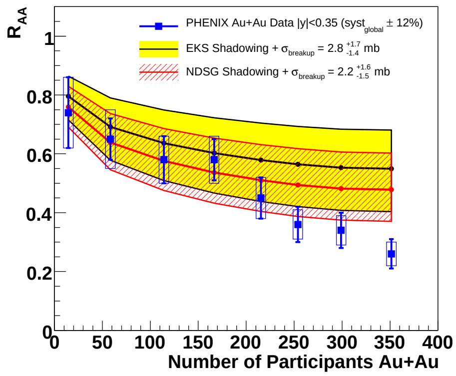

Fig. 4. Extrapolation of the simple CNM model shown in Figure 3 to Au+Au collisions at mid rapidity. Results for both EKS[7] and NDSG[8] shadowing are shown.

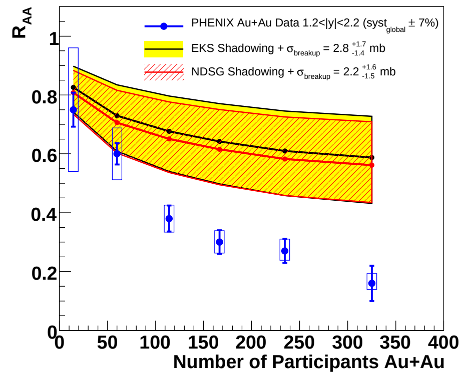

Fig. 5. Extrapolation of the simple CNM model shown in Figure 3 to Au+Au collisions at forward rapidity. Results for both EKS[7] and NDSG[8] shadowing are shown.

4. How does the QGP affect Quarkonia

Quarkonia are thought to be a definitive probe of the QGP through the screening process in the deconfined colored medium[11]. Different quarkonia states, because of their different binding energies, are expected to "melt" at different temperatures of the medium. E.g. in some lattice calculations the J/ψ would melt at $1.2T_C$, but the Υ only at over $2T_C$. Nuclear modification factors observed by PHENIX in $Au+Au$ collisions are shown in Figure 6. The suppression at mid-rapidity is about the same as that observed for lower energies at the SPS[12], despite the expectation that the hotter medium created at RHIC would cause a larger suppression. The suppression at forward rapidity is stronger than that at mid rapidity, and the ratio of the nuclear modification factors, forward/mid, shown in the bottom panel of the figure, reaches an approximately constant level of 0.6 for $n_{part} > 100$.

Several scenarios can be considered in trying to understand the observed trends: 1) CNM effects, as discussed above, should always be accounted for as a baseline. 2) Sequential screening[13] - where, as suggested by some lattice calculations, only the ψ' and χ_C are screened and the J/ψ itself is not - not at RHIC or at SPS energies. Then the observed suppression beyond CNM comes only from loss of the feeddown ($\sim 40\%$) from the two higher mass quarkonia states. 3) Regeneration models[14], where the large density of charm quarks created in the collisions (~ 20 in a central $Au+Au$ collision) can produce charmonia in the latter stages of the expansion.

In the sequential screening picture, if the CNM suppression at mid rapidity and the "melting" of the higher mass charmonia states was the same at RHIC and at the SPS, this would provide a natural explanation for the nearly identical suppression at RHIC and the SPS. It would also agree with some lattice calculations that indicate no melting of the J/ψ until over $2T_C$[15]. The stronger forward rapidity suppression seen at RHIC could then be explained by gluon saturation that gives stronger forward suppression than that from standard shadowing models. For traditional shadowing models the shadowing of the gluon from one nucleus is largely canceled by the anti-shadowing from the gluon from the other nucleus - resulting in an approximately flat rapidity dependence. For gluon saturation a "shadowing-like" effect is produced for the gluon in the small-x region, but no anti-shadowing for the other gluon, resulting in a stronger suppression at forward rapidity. Since screening and gluon saturation might have different centrality dependences, it is unclear whether they would balance to produce the approximately flat ratio observed for $n_{part} > 100$ (Figure 6).

An alternative is the regeneration picture, where the dissocation by the QGP at mid and forward rapidity would be similar, but the weaker suppression at mid rapidity would be due to regeneration effects being stonger here where the charm density is largest. In this case it would be an "accidental" compensation of screening and regeneration that leads to the same mid-rapidity suppression at RHIC and the SPS. At forward rapidity, where the charm density is smaller, the regeneration is reduced and stronger screening results. Again, whether the saturation in the forward to mid rapidity suppression could be reproduced by these two compensating effects is unclear.

The regeneration mechanism depends on the square of the open-charm cross section, so it is critical to resolve the present uncertainties there.[16] Also, since charm has been shown to exhibit flow for moderate p_T values, one would expect J/ψs that are produced by regeneration to inherit this flow. A first measurement of the J/ψ flow at mid rapidity is shown from part of the 2007 $Au + Au$ data in Figure 7; but is clearly quite challenging, and so far is consistent with zero flow.

5. Summary and Future

The suppression of J/ψ production in $Au + Au$ collisions at RHIC for mid rapidity is similar to that at lower energies, while for foward rapidity the RHIC suppression is stronger. Better cold nuclear matter constraints from the new $d + Au$ data are needed to establish an accurate baseline and allow quantitative analysis of the QGP effects. Two theoretical pictures, 1) sequential suppression with gluon saturation and 2) dissociation and regeneration, appear to offer explanations of the observed trends. Higher luminosities and silicon vertex upgrades will enable much more quantitative studies in the next few years. Over 100,000 J/ψs and 600 Υs are expected in a year with higher luminosities enabled by accelerator advances, while new silicon vertex detectors will allow explicit indentification of open-heavy and will improve both the background and mass resolution for the quankonia states - especially important to separate the ψ' from the J/ψ at forward rapidity.

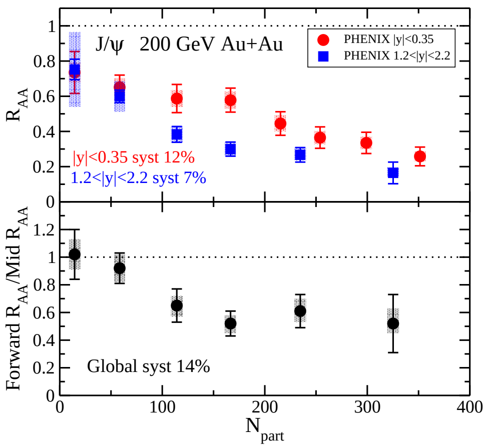

Fig. 6. Nuclear modification factor for Au+Au collisions at mid rapidity (red circles), and at forward rapidity (blue squares) versus centrality (top panel). In the bottom panel the ratio of the foward over mid rapidity nuclear modification factors from the upper panel is shown.

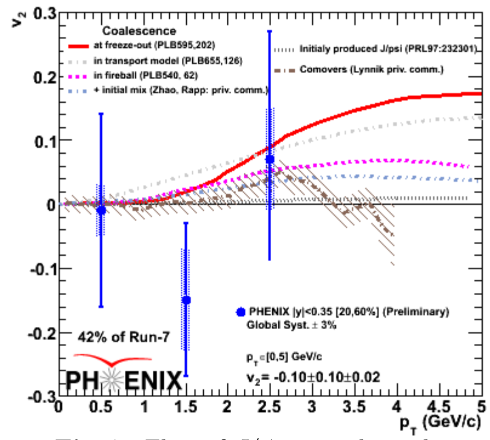

Fig. 7. Flow of J/ψs at mid rapidity vs p_T (preliminary result from 42% of the 2007 data), compared to several theoretical models.

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