PROCEEDINGS OF SCIENCE

Nuclear matter effects on J/ψ production in Cu+Au and U+U collisions in PHENIX

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The Phenix experiment at RHIC has produced high quality J/ψ measurements in heavy ion interactions for various energies and collision systems. These measurements allow us to study the mechanisms which may modify the charmonium production in the nucleus. During 2012 run, the flexibility of RHIC to provide collisions with different nuclei have led to the first experimental study of two new collision systems with unique initial collision geometries. The initial asymmetry of the Cu+Au system leads to differences in the J/ψ suppression along the beam axis. The Phenix detector, with its extensive kinematic coverage, is well suited to measure the J/ψ production in both forward and backward rapidities, 1.2 $<y<$ 2.2 and –2.2 $<y<$ –1.2. Such studies, along with a comparison to the d+Au and Au+Au systems, provide insight into the interplay of cold and hot nuclear matter on the J/ψ modification, and whether such effects could be factorized. The second system, U+U, extends further the maximum energy density reached in heavy ion collisions at RHIC and presents the possibility to study how this increase may alter the particle production.

XXII. International Workshop on Deep-Inelastic Scattering and Related Subjects
28 April - 2 May 2014
Warsaw, Poland

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PoS(DIS2014)191

1. Heavy quarks and heavy-ion collisions

The hot, dense state of nuclear matter – the Quark Gluon Plasma – is a deconfined, color charged state of quarks and gluons. The conditions needed for its creation, high temperature and baryon density, are experimentally achievable with heavy-ion collisions. Heavy quarks are an important probe for studying the QGP. The original idea by Matsui and Satz [1] stated that the color (Debye) screening of the hot quark-gluon plasma will prevent the $c\bar{c}$ binding; the screening will modify the quarkonium potential due to the charge density of the surrounding medium, making it shallower. With increasing temperature different $c\bar{c}$ states are expected to melt sequentially. Some states, e.g J/ψ , may become unbound. Thus suppression of the J/ψ yield in heavy-ion collisions with respect to collisions where QGP is not created, may be used as a confirmation of the QGP formation.

The mechanisms which modify the J/ψ production in heavy-ion collisions can be split into two broad groups: cold nuclear matter effects (CNM), modifications due to the nuclear target when no QGP is present (in systems like d+Au), and hot nuclear matter effect (HNM), modifications in the created QGP.

To learn about the QGP mechanisms which modify the charmonium the current experimental approach has been to try to "remove" the CNM effects from A+A collisions by measuring the quarkonia production and parametrizing the CNM effects in collision systems like $p(d)$+Au. This relies on the assumption that CNM and HNM effects can be factorized. Phenix has made substantial contributions to the world's J/ψ measurements. The energy range varies from =39–200 GeV and the collision systems include p+p, d+Au, Cu+Cu, Cu+Au, Au+Au, and U+U collisions. The J/ψ are measured in the Central arms of the Phenix detector via the electron decay channel, and at forward rapidity via the di-muon channel. Each forward rapidity arm covers $1.2<|\eta|<2.2$ and $\Delta\phi = 2\pi$. The muons are identified and their momentum is measured with the help of three detector sub-systems: the Muon Tracker, the Muon Magnet, and the Muon Identifier. For more information please refer to [2].

2. J/ψ in cold nuclear matter

The d+Au system is not only "cold", where no QGP is created, but also an asymmetric collision system. Due to this initial asymmetry a rapidity dependent suppression of the J/ψ yield compared to the yield in p+p collisions is observed [3]. More suppression is observed at forward (d-going) rapidity, which can be seen in Fig. 1 . The ratios of the yield in the two systems is known as the nuclear modification factor:

$$R_{AA} = \frac{1}{N_{coll}} \frac{d^2N_{AA}/dydp_T}{d^2N_{pp}/dydp_T} \tag{2.1}$$

where the $d^2N/dydp_T$ is the yield in the d+Au / p+p, and N_{coll} is the number of binary collisions in the former. If the ratio is unity, then no modification of the J/ψ production in the heavy-ion system is observed. The nuclear modification factor in Fig. 1 is compared to two CNM models. EPS09 [4] accounts for the modification of the gluon densities in the Au and d nuclei (gluon shadowing) and describes the data reasonably well. The model, which considers the gluon saturation in the

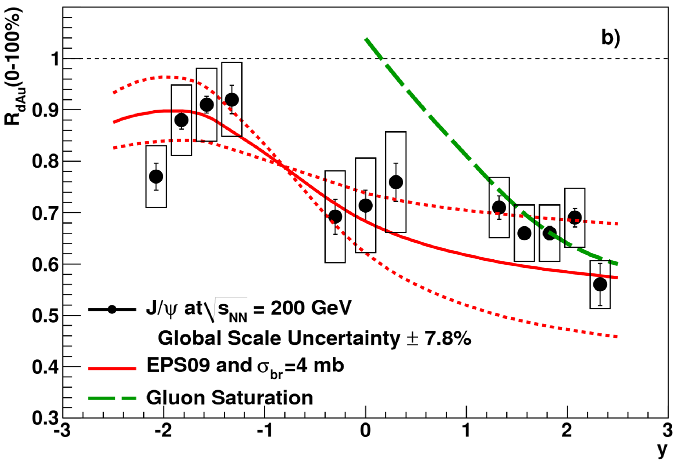

Figure 1: R_{dAu} nuclear modification factor as a function of rapidity, y. The lines show models prediction. Figure from [3].

Au and d nuclei [5] describes the yield ratio well only at forward rapidity. These are only two of the many models considering the role of the CNM on the J/ψ production. Others consider effects such as initial parton energy loss, transverse momentum broadening, and more. As a whole, the CNM effects are a complex admixture of different mechanisms, which strongly depend on the rapidity. Independent of our preference for a specific model, the open question which still remains unanswered is: can we factorize the CNM effects? There have been recent measurements in $p(d)$+Au showing collective phenomenon [6, 7], which may be indicative of a presence of HNM effects. If there are other effect in this "cold" system, do they affect the J/ψ production?

3. Hot nuclear matter effects

The hot, dense region in a heavy-ion collision is created when the two nuclei overlap. The *centrality* of the collision is a measure of this initial overlapping volume and through simulations can be connected to the number of the shared nucleons between the two nuclei – the number of participants, N_{part}. To control the properties of the created state experimentally, we can select the collisions by their centrality. The head-on collisions overlap almost fully and produce the most particles. They are *central* collisions and have large N_{part} values. The collisions which are glancing have small overlapping regions, small N_{part} values, and are referred to as *peripheral* collisions.

Another experimental handle on the created matter is varying the collision system size, e.g colliding Cu+Cu creates a smaller system compared to Au+Au. We can also create a hotter system by increasing the center of mass energy. For example, for the Au+Au system, RHIC has provided collisions at minimum of 7.7 GeV to the nominal collision energy of 200 GeV.

The hot matter properties seen through the global particle production have well established features. The charged particle density, $dN/d\eta$, can be used as a measure of the initial energy density of the created state, ε_B. $dN/d\eta$ increases with collision energy [8]. An increase in $dN/d\eta$ for more central collisions compared to the peripheral at all collision energies is also observed. The energy density has a maximum at mid-rapidity and decreases at higher rapidity [9].

J/ψ production in hot nuclear matter has been well studied by Phenix. The measurements in Au+Au collisions can be closely examined via their energy and rapidity dependence.

The nuclear modification factor in Au+Au collisions for three center of mass energies in Phenix is shown in Fig. 2. At forward rapidity there is suppression for J/ψ with respect to p+p collisions. This suppression increases slightly with increasing N_{part} but there is very little, if any, energy dependence. Comparison with HNM models [10] show competing effects of dissociation and regeneration of the $c\bar{c}$ state. Latest results from Alice at LHC [11] study J/ψ suppression at a much higher energy of 2.7 TeV. When compared to the Phenix forward rapidity results the suppression is much reduced, pointing to the importance of recombination at LHC energies [12]

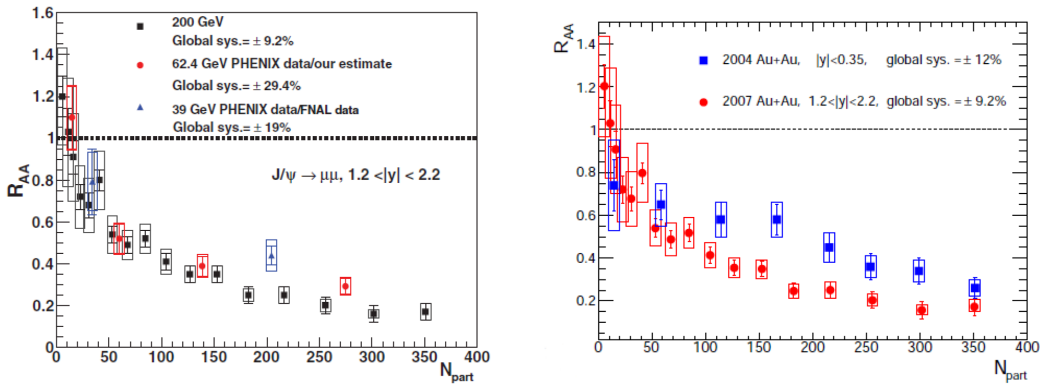

Figure 2: J/ψ R_{AA} versus N_{part} for different energies in Au+Au collisions at Phenix [13] (left). Comparison of the J/ψ R_{AA} measurements at forward and mid-rapidity [14] (right panel) at 200 GeV Au+Au collisions as a function of N_{part}.

Stronger suppression of J/ψ at forward (backward) rapidity is observed compared to mid-rapidity at the same center of mass energy, see Fig. 2 (right). Intriguingly, the suppression does not increase with increasing energy density at mid-rapidity, as seen in the charged particle multiplicity. This may be a result of higher coalescence at higher energy density. CNM effects may also play role as they are different at forward and mid-rapidity.

In general, the HNM effects are a complex admixture of different mechanisms, which strongly depend on rapidity and collision energy. They could lead to destruction, formation, or a change of the observed properties of J/ψ in the medium. One of the open questions which still remain is: can we factorize the CNM and HNM effects? Studies of new collision systems with unique initial geometries may provide more insight into the J/ψ production in hot matter.

4. J/ψ in the Cu+Au collision system

Cu+Au is an asymmetric collision system. It adds variation to the initial state. The initial asymmetry of the size of the two nuclei should translate into asymmetry along the beam axis and should be evident in the distribution of the final particle density. J/ψ production in Cu+Au collisions is expected to be similar to that in d+Au, with asymmetric CNM effects. There should be HNM effects as in symmetric A+A systems, but this could also be asymmetric along the beam axis.

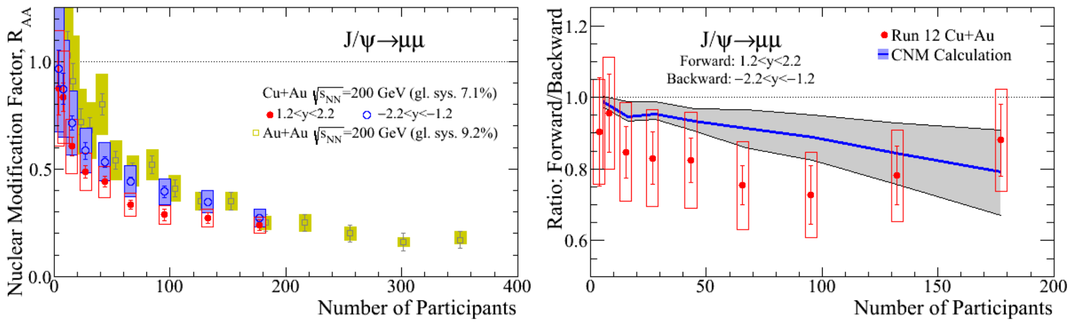

Figure 3: Nuclear modification factor for J/ψ as a function of number of participants in Cu+Au at 200 GeV (left) for Cu-going direction (closed circles) and Au-going direction (open circles) [15]. The open squares show the J/ψ results in the Au+Au collisions at the same center of mass energy. Ratio of forward/backward J/ψ (right) versus N_{part} in Cu+Au collisions.

Fig. 3 (left) shows the J/ψ nuclear modification factor as a function of N_{part} in Cu+Au at 200 GeV compared to Au+Au collisions. The strong suppression in Au+Au with respect to p+p is also seen in the Au-going direction (backward rapidity, –2.2<y<–1.2). More importantly, the suppression is the same at the same N_{part} values. On the other hand less suppression than that in Au+Au at same N_{part} is seen in the Cu-going direction (forward rapidity, -2.2<y<-1.2).

The ratio of forward to backward J/ψ (Fig. 3, right) shows that the difference for non-peripheral data is $\sim$20 %. To try to explain this observation one has to consider different CNM effects, which are asymmetric in rapidity. At forward rapidity (Cu-going direction) the gluon modification (shadowing) will be due to both Cu and Au nuclei, where J/ψ probes gluons at high-x in Cu and low-x in the Au nucleus. There will be interplay between dynamical processes: the quark energy loss in the Au nucleus has to be considered, as the J/ψ has short crossing proper time in the Au. The long crossing proper time in Cu will give rise to $c\bar{c}$ breakup by nucleon collisions. At backward rapidity the CNM effects will be reversed. The CNM model calculation shown in Fig. 3 (right) is comparable in magnitude to the data, and has the same sign. This calculation only includes differences in shadowing between Cu and Au nuclei from EPS09 nPDFs and a 4mb break-up effective cross-section. No other mechanisms are considered in this model, for example HNM effect like color screening should be larger in the Au and should increase the ratio.

5. First measurements of J/ψ in U+U collisions

U+U is the largest collision system at RHIC. It reached the record RHIC energy density of ε_B=6.15 GeV/fm^2/c [8]. Only a moderate increase was observed in ε_B from central Au+Au to central U+U (20%), in contrast to some earlier predictions [16] which expected up to 55% increase in ε_B for the special tip-tip orientation of the colliding nuclei.

The effects which modify J/ψ production in U+U at 200 GeV were predicted by [17]. This model expected that the higher energy density in U+U compared to Au+Au (15-10%) should lead to stronger suppression due to color screening. On the other hand, for a given centrality, a larger N_{coll} value in U+U (compared to Au+Au) should increase charm production by statistical coalescence. As for the CNM effects the shadowing is expected to be similar in both systems.

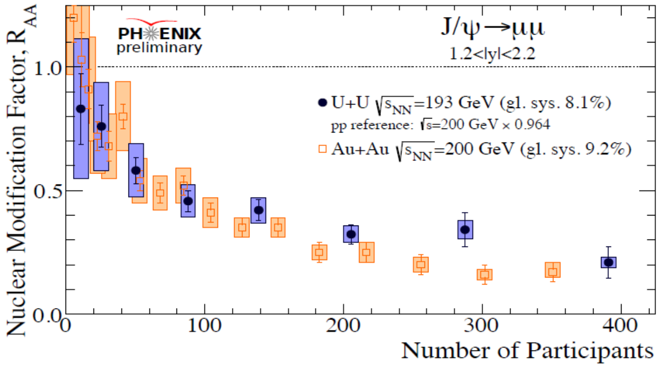

Figure 4: J/ψ nuclear modification factor as a function of number of participants in U+U at 193 GeV at forward rapidity (closed circles). The open squares show the J/ψ results in the Au+Au collisions at 200 GeV center of mass energy.

The J/ψ nuclear modification factor for forward rapidity in U+U collisions at 193 GeV is shown in Fig. 4. The results are very close to the Au+Au at 200 GeV, with a hint of a weaker suppression in central U+U collisions. This may be due to the higher coalescence rate in U+U as predicted by [17].

6. Conclusion

Phenix has measured J/ψ production at forward rapidity in two new collision systems at RHIC. These new measurements add more information about the hot and cold nuclear matter effects which modify the J/ψ yield in heavy-ion collisions.

Cu+Au, as an asymmetric system, adds variation in the studied initial geometry. The R_{AA} results show significantly stronger suppression in the Cu- going direction, consistent with the direction and magnitude expected from differences in EPS09 shadowing between Cu and Au (cold nuclear matter effects).

U+U is a larger system compared to the nominal Au+Au collision system at RHIC. At forward rapidity the J/ψ suppression with respect to p+p seems to be slightly less than in Au+Au for the central data. This is a hint that the coalescence (hot nuclear matter effect) is important when the collision system size increases.

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