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Excess of J/ψ yield at very low transverse momenta in Au+Au and U+U collisions measured by the STAR experiment

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J/ψ suppression in heavy-ion collisions due to color screening of quark and antiquark potential in the deconfined medium has been proposed as a signature of the QGP formation. Other mechanisms, such as the cold nuclear matter effect and charm quark recombination, are likely to contribute to the observed modification of J/ψ production in heavy-ion collisions. Recently, a significant excess of J/ψ yield at very low transverse momentum (p_T) ($<$ 0.3 GeV/c) in peripheral hadronic Pb+Pb collisions at $\sqrt{s_{\rm NN}}$= 2.76 TeV at forward-rapidity has been observed by the ALICE collaboration, which can not be explained within the scenarios mentioned above. The excess observed may originate from the coherent photoproduction of J/ψ, which would be very challenging for the existing coherent photoproduction models. Measurements of J/ψ production at very low p_T in different collision energies, collision systems, and centralities can shed new lights on the origin of the excess.
In this article, we report the STAR measurements of J/ψ production at very low p_T in hadronic Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV and U+U collisions at $\sqrt{s_{\rm NN}}$ = 193 GeV at mid-rapidity. Centrality dependence of J/ψ yields and nuclear modification factors at very low p_T are presented.

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1. Introduction

The Relativistic Heavy Ion Collider (RHIC) is built to search for the Quark-Gluon Plasma (QGP) and to study its properties in laboratory through high energy heavy-ion collisions [1]. J/ψ suppression in "hadronic" heavy-ion collisions, due to color screening of quark and antiquark potential in the deconfined medium, has been proposed as a signature of the QGP formation [2]. In addition, other mechanisms absent in p+p collisions are likely to make significant contributions to the observed J/ψ yield modification in heavy-ion collisions. These mechanisms include the recombination of charm quarks in the QGP [3, 4], cold nuclear matter (CNM) effects, such as nuclear parton distribution function modification [5], energy loss of partons in the colliding nuclei [6], Cronin effect [7], and final state effects as nuclear absorption [8] and dissociation by co-movers [9]. The interplay of these effects can qualitatively describe the experimental measurements of Jψ production modification in heavy-ion collisions observed at the SPS [10, 11, 12], RHIC [13, 14] and LHC [15, 16, 17].

J/ψ can also be produced via the strong electromagnetic fields generated by heavy ions, e.g. photon-nucleus coherent or incoherent interactions [18], in ultra-relativistic heavy-ion collisions. In the coherent photoproduction process, quasi-real photons, coherently produced by the electromagnetic field from one of the colliding nuclei, interact coherently with the gluon field of the other nucleus to create a J/ψ. This process in heavy-ion collisions is expected to probe the gluon distribution in the nucleus [19], for which currently there exist considerable uncertainties in the low Bjorken-x region [20]. The coherence conditions require the production of J/ψ at transverse momentum (p_T) on the order of one over the nuclear radius. This has been studied in detail in Ultra-Peripheral Collisions (UPC), where the impact parameter can reach several tens of femtometers and no hadronic interactions occur.

Recently, a significant excess of J/ψ yield at $p_T < 0.3$ GeV/c has been observed by the ALICE collaboration in peripheral hadronic Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV at forward-rapidity [21], which cannot be explained by the hadronic J/ψ production modified by the cold or hot medium effects. The observed excess may originate from the coherent photon-nucleus interactions, which would be very challenging for the existing models. Measurements of J/ψ production at very low p_T in different collision energies, collision systems, and collision geometries can shed new lights on the origin of the excess.

In this article, we report the measurements of J/ψ production at very low p_T in hadronic Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV and U+U collisions at $\sqrt{s_{\rm NN}}$ = 193 GeV at mid-rapidity by the STAR experiment. Centrality dependence of J/ψ yields and nuclear modification factors at very low p_T are presented.

2. Experiment and Analysis

The STAR experiment is a large-acceptance multi-purpose detector which covers full azimuth and pseudorapidity of $|\eta| < 1$ [24]. The Au+Au and U+U events were recorded using a minimum-bias trigger which requires coincidence signals in the Vertex Position Detector (VPD) [22] and the Zero Degree Calorimeter (ZDC) [23]. In this analysis, the J/ψ's are reconstructed through their decays into electron-position pairs, J/$\psi \rightarrow e^+ + e^-$ (branching ratio equal to 5.97 $\pm$ 0.03%

[25]). The primary detectors used in this analysis are the Time Projection Chamber (TPC) [26], the Time-of-Flight (TOF) detector [27], and the Barrel Electromagnetic Calorimeter (BEMC) [28]. The electron identification and J/ψ reconstruction techniques are similar to those described in [29, 30].

3. Result

Figure 1 shows the J/ψ invariant yields for Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV and U+U collisions at $\sqrt{s_{NN}}$= 193 GeV as a function of p_T for different centralities at mid-rapidity ($|y| < 1$). The error bars depict the statistical errors while the boxes represent the systematic uncertainties. The solid lines in the figure are the fits to data points in the range of $p_T > 0.2$ GeV/c using Eq. 3.1, wherein a, b, and n are free parameters. The dashed lines are the extrapolations of the fits. As shown in the figure, the fits describe the data above 0.2 GeV/c very well, but significantly underestimate the yield belows 0.1 GeV/c for all three centrality bins.

$$\frac{d^2N}{2\pi p_T dp_T dy} = a \times \frac{1}{(1+b^2p_T^2)^n} \tag{3.1}$$

The J/ψ R_{AA} as a function p_T for 60-80%, 40-60% and 20-40% centrality bins are shown in Fig. 2,

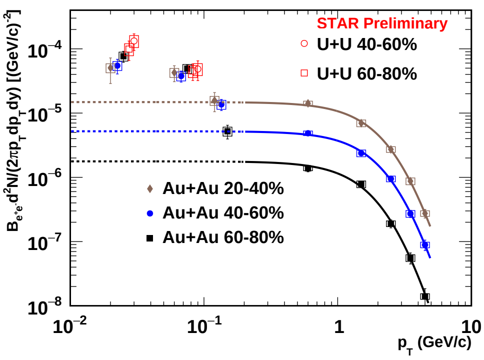

Figure 1: (color online) J/ψ invariant yields in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV and U+U collisions at $\sqrt{s_{NN}}$ = 193 GeV as a function of p_T for different centralities at mid-rapidity.

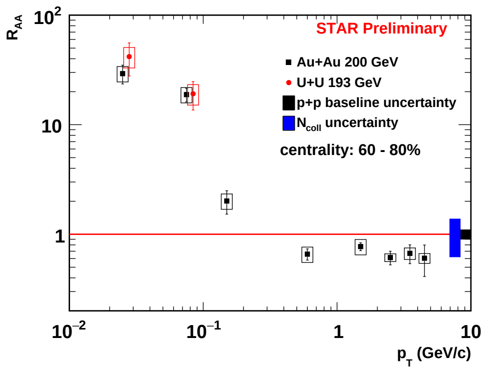

Figure 2: (color online) J/ψ R_{AA} as a function of p_T for centrality 60-80%.

Fig. 3 and Fig. 4, respectively. The pp baselines used for R_{AA} calculations are derived from [31]. Significant excess of J/ψ yield in the p_T range 0-0.1 GeV/c is observed for peripheral collisions (40-80%). The kinematic range of the enhancement is consistent with that of coherent photon-nucleus interactions, which indicates that the excess may originate from the coherent production.

The J/ψ yield as a function of the momentum transfer squared t ($t = p_T^2$) for 40-80% Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV is shown in Fig. 5. The structure of the distribution is very similar to that observed in UPC case [32]. An exponential fit has been applied to the distribution in the t range 0.002-0.015 (GeV/c)^2, and the extracted slope parameter is 196 ± 31 $(\mathrm{GeV}/c)^{-2}$, which

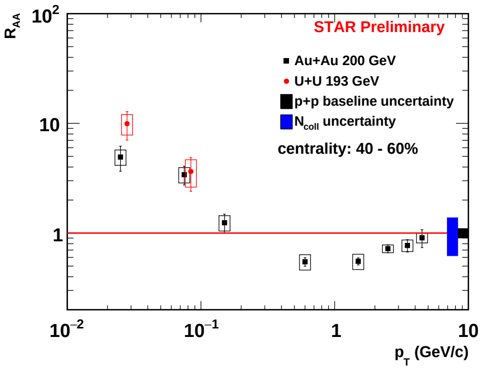

Figure 3: (color online) J/ψ R_{AA} as a function of p_T for centrality 40-60%.

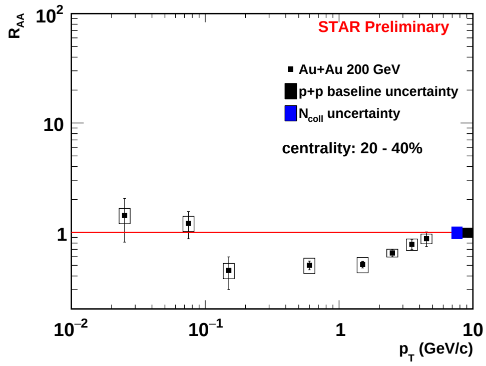

Figure 4: (color online) J/ψ R_{AA} as a function of p_T for centrality 20-40%.

is consistent with that of a Au nucleus (199 $[\text{GeV}/c]^{-2}$). As shown in the figure, the data point at the lowest t value is significantly lower than the extrapolation of the exponential fit, which may be an indication of interference. The theoretical calculation with interference for the UPC case [33], shown as the blue curve in Fig. 5, can describe the data very well ($\chi^2/NDF = 4.9/4$) for $t < 0.015$ $(\text{GeV}/c)^{-2}$.

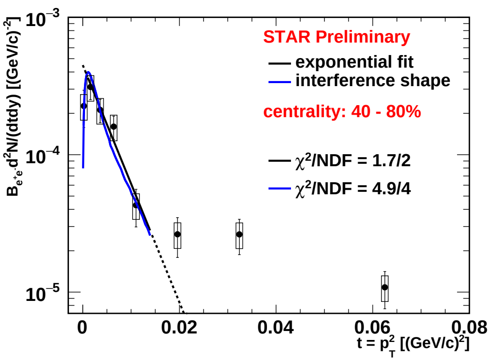

Figure 5: (color online) Measurement of J/ψ invariant yield as a function of the momentum transfer squared t for 40-80% central Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV.

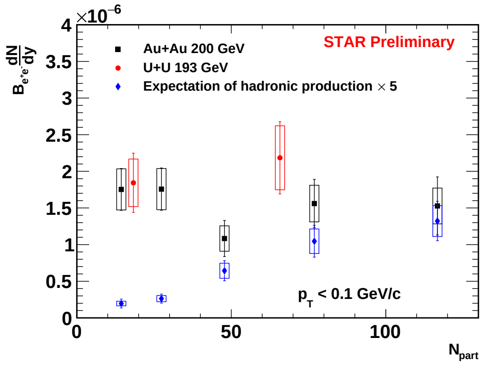

Figure 6: (color online) The p_T integrated J/ψ yields ($p_T < 0.1$ GeV/c) as a function of $N_{\rm part}$ for Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV. The expectation of hadronic production (scaled by a factor of 5) is also shown for comparison.

Figure 6 shows the p_T-integrated J/ψ yields ($p_T < 0.1$ GeV/c) as a function of N_{part} for 30-80% Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV. The integrated J/ψ yields show no significant centrality dependence. This is beyond the expectation of the hadronic production, which, scaled by a factor of 5, is also plotted for comparison. As depicted in the figure, the contribution of hadronic production is not dominant in the excess range. The integrated J/ψ yields at p_T interval 0-0.1 GeV/c in U+U collisions are similar to those in Au+Au collisions.

4. Summary

In summary, we report the recent STAR measurements of J/ψ production at very low p_T in hadronic Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV and U+U collisions at $\sqrt{s_{\mathrm{NN}}}$ = 193 GeV at mid-rapidity. Centrality dependence of J/ψ yields and nuclear modification factors, as well as dN/dt distributions in 40-80% centrality bin at very low p_T are reported. Significant excess of J/ψ yield at p_T interval 0-0.1 GeV/c is observed for peripheral collisions (40-80%). The excess for 30-80% centrality range shows no significant centrality dependence within uncertainties, which is beyond the expectation from the hadronic production. The characteristics of the excess are consistent with coherent photon-nucleus interactions. The existence of electromagnetically produced J/ψ in hadronic heavy-ion collisions merits theoretical investigations. In addition, coherent photoproduced J/ψ may be created in the initial stage of the collisions, and could therefore interact with the QGP, resulting in dissociation due to color screening of the heavy quark potential in the QGP. This makes the measurement of the excess a potential probe to study the hot medium created in heavy-ion collisions.

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