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# Cold Nuclear Matter Effects on J/$\psi$ and $\Upsilon$ Productions at RHIC with the STAR Experiment

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Quarkonia are excellent probes for studying the properties of quark-gluon plasma formed in relativistic heavy-ion collisions at RHIC. In order to fully understand the observed suppression of quarkonium production in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, it is essential to understand the contribution from the cold nuclear matter (CNM) effects on the quarkonium production. Collisions of p+Au at the same energy can be used to study the CNM effects since these effects are expected to be dominant in such systems. We present the measurements of inclusive J/$\psi$ and $\Upsilon$ production modification in p+Au collisions (the nuclear modification factor $R_{\mathrm{pAu}}$) at $\sqrt{s_{NN}}$ = 200 GeV. The results are extracted from data recorded by the STAR experiment in 2015 using the di-electron decay channel of the quarkonia. Comparisons are made to results from other experiments as well as to model calculations and physics implications are also discussed.

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## 1. Introduction

Quarkonia are considered as excellent probes of quark-gluon plasma (QGP) properties. The sequential melting of quarkonia is dependent on the properties of medium created in the collision, as the dissociation temperature varies among different quarkonium states. The resulting modification in yields of quarkonia is often quantified by the nuclear modification factors. Modifications caused by existence of QGP medium is categorised as the hot nuclear matter (HNM) effects, and those not from the QGP are named by the cold nuclear matter (CNM) effects. One has to study CNM effects and isolate its contribution from the total amount of modification in order to extract the HNM effects. The CNM effects include [1]: 1) modification of parton distribution function in the nuclei compared to free protons, the *nPDF effects*; 2) inelastic interaction between the quarkonia and nucleons, the *nuclear absorption*; 3) interaction of the quarkonia with co-moving particles, leading to the dissociation of quarkonia, the *co-mover dissociation*; 4) the parton *energy loss* during multiple scattering process.

Suppression of quarkonia production in heavy-ion collisions has already been observed. Result of J/$\psi$ production in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV by the STAR experiment [2] shows suppression across collision centrality in high transverse momentum ($p_{\mathrm{T}}$) range ($p_{\mathrm{T}}$ > 5 GeV/c). The result indicates a trend of less suppression but with large uncertainties in more peripheral collisions. Meanwhile, production of $\Upsilon$ family has been studied at STAR as well. Suppression of $\Upsilon(2S+3S)$ in Au+Au collisions is significantly stronger than that of $\Upsilon(1S)$ in the most central collisions [3].

The following will present our study of CNM effects on J/$\psi$ and $\Upsilon$ productions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV with the STAR experiment with data taken in 2015. J/$\psi$ and $\Upsilon$ are reconstructed via di-electron decay channel, utilizing the Time Projection Chamber (TPC) and the Barrel Electromagnetic Calorimeter (BEMC) with full azimuthal coverage over the pseudo-rapidity range of $|\eta| < 1$. Electrons and positrons, referred to collectively as "electrons" in the following, are identified with the ionization energy loss ($dE/dx$) in the TPC, as well as the ratio between energy deposition in the BEMC and momentum ($E/p$). One of the electrons in the di-electron pair is required to pass the trigger threshold of transverse energy ($E_{\mathrm{T}}$) at 4.3 GeV.

## 2. CNM Effects in J/ψ Production

The J/$\psi$ yields in p+p and p+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV are obtained from data corresponding to integrated luminosities of around 97 pb$^{-1}$ and 310 nb$^{-1}$, respectively. The integrated invariant mass distributions of di-electron pairs over $4 < p_{\mathrm{T}} < 12$ GeV/c in p+p and p+Au collisions are shown in the top left and top right panels of Fig.1. The ratios between p+Au and p+p collisions, of electron detection efficiency vs. $p_{\mathrm{T}}$ and the electron triggering efficiency above $p_{\mathrm{T}}$ threshold are shown in the bottom panel of Fig.1. We calculate the $R_{\mathrm{pAu}}$ of J/$\psi$ by taking ratio of raw yields in p+Au and p+p collisions modified by number of binary collisions. A global scale factor is added in order to correct for the small difference in electron detection and trigger efficiencies between p+p and p+Au collisions. A global systematic uncertainty of about 2.3% is included, corresponding to the deviation of electron trigger efficiency near the trigger threshold from the average value at higher $p_{\mathrm{T}}$.

The measured $R_{\rm pAu}$ vs. $p_{\rm T}$ is consistent with $R_{\rm dAu}$ measured in d+Au collisions by PHENIX

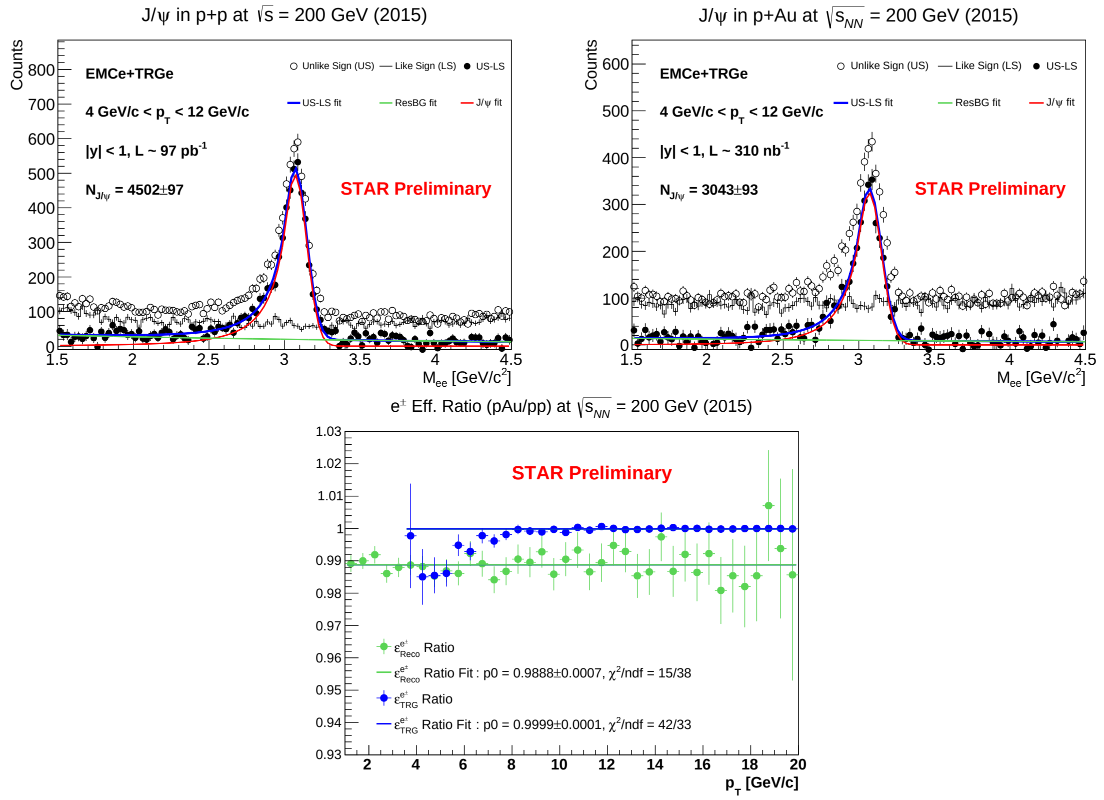


**Figure 1:** *Top left and right:* J/$\psi$ yield extraction for p+p and p+Au collisions achieved by fitting the invariant mass distribution to a Crystal Ball function with an exponential background. Open circle: unlike-sign (US) pairs; black histogram: like-sign (LS) pairs; solid circle: unlike-sign minus like-sign (US-LS) pairs; blue line: fitted US-LS; red line: J/$\psi$ signal from fit; green line: residual background from fit. *Bottom:* Electron detection efficiency ratio (green circle, fitted with green line) and triggering efficiency ratio (blue circle, fitted with blue line) between p+Au and p+p systems, studied with J/$\psi$ embeded into real data.

[4], and has significantly reduced uncertainties in the overlapping range, as shown in the left panel of Fig.2. The consistency indicates similar CNM effects in p+Au and d+Au collisions. Models utilizing nCTEQ and EPS09 nPDF sets at next-to-leading order (NLO) [5] predict a flat $R_{\rm pAu}$ around unity above 4 GeV/c which matches the experimental measurement well. Our measurement concludes that no significant suppression exists in this $p_{\rm T}$ range. The result in Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV published by STAR [2] shows a sizable J/$\psi$ suppression for $p_{\rm T}$ < 15 GeV/c. The measured $R_{\rm AA}$ is significantly smaller than the $R_{\rm pAu}$ for 4 < $p_{\rm T}$ < 12 GeV/c, as shown in the middle panel of Fig.2. An integrated $R_{\rm pAu}$ over $p_{\rm T}$ > 5 GeV/c is also calculated in order to be compared with $R_{\rm AA}$ in the same $p_{\rm T}$ range vs. number of participants ($N_{\rm part}$) [2], as shown in the right panel of Fig.2. These results suggest that J/psi suppression at $p_{\rm T}$ > 5 GeV/c in Au+Au collisions is dominantly from HNM effects.

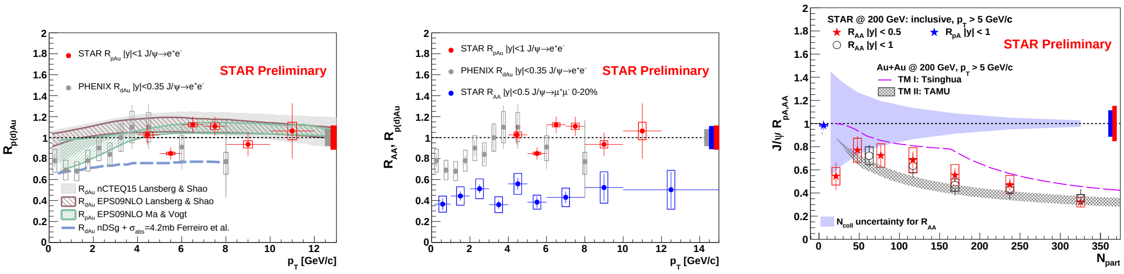


**Figure 2:** *Left:* $R_{\mathrm{p(d)Au}}$ vs. $p_{\mathrm{T}}$ for inclusive J/$\psi$. Red circle: this analysis; grey circle: PHENIX $R_{\mathrm{dAu}}$ |y| < 0.35 [4]; grey band: $R_{\mathrm{dAu}}$ nCTEQ15 [5]; brown shadowed: $R_{\mathrm{dAu}}$ EPS09 NLO [5]; green shadowed: $R_{\mathrm{pAu}}$ EPS09 NLO [6]; blue dashed line: $R_{\mathrm{dAu}}$ nDSg + $\sigma_{abs}$ = 4.2 mb [7]. *Middle:* $R_{\mathrm{p(d)Au}}$, $R_{\mathrm{AA}}$. Red circle: this analysis; grey circle: PHENIX $R_{\mathrm{dAu}}$ |y| < 0.35 [4]; blue circle: STAR $R_{\mathrm{AA}}$ |y| < 0.5 [2]. *Right:* $R_{\mathrm{pAu}}$, $R_{\mathrm{AA}}$ vs. $N_{\mathrm{part}}$. Blue star: this analysis; red star: STAR $R_{\mathrm{AA}}$ |y| < 0.5 [2]; violet dashed line: Tsinghua model [8]; black shadowed: TAMU model [9].

## 3. CNM Effects in ϒ Production

The ϒ(1$S$+2$S$+3$S$) production cross-sections in p+p and p+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV are obtained from data corresponding to integrated luminosities of around 97 pb$^{-1}$ and 310 nb$^{-1}$ [3]. Nuclear modification factor is calculated out of these cross-sections, as shown in Fig.3. The new results are consistent with those in d+Au collisions published by STAR [10], but have significantly improved precision [3]. Such a result indicates a non-negligible CNM effects beyond nPDF effects when compared to various theoretical calculations [11][12][13].

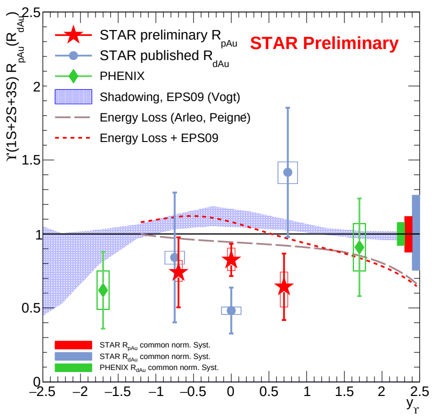


**Figure 3:** $R_{\mathrm{p(d)Au}}$ vs. rapidity for inclusive ϒ. Red star: STAR $R_{\mathrm{pAu}}$ [3]; blue circle: STAR $R_{\mathrm{dAu}}$ [10]; green rhombus: PHENIX $R_{\mathrm{dAu}}$ [14]; blue band: $R_{\mathrm{dAu}}$ EPS09 nPDF [11]; grey dashed line: $R_{\mathrm{dAu}}$ energy loss [12]; red dashed line: $R_{\mathrm{dAu}}$ energy loss + EPS09 [13].

## 4. Summary

We presented our studies of CNM effects on J/$\psi$ and ϒ production at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV with STAR experiment. The uncertainties are significantly reduced compared to previously published results. For J/$\psi$, $R_{\mathrm{pAu}}$ is flat around unity at $p_{\mathrm{T}}$ > 4 GeV/c, which is described by various theoretical calculations taking nPDF effects into account [5]. This indicates that the J/ψ suppression in Au+Au collisions [2] is dominantly from HNM effects at high $p_{\mathrm{T}}$ range. For Υ family, suppression is observed in p+Au collisions, which indicates non-negligible CNM effects beyond nPDF effects and energy loss [3].

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