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Quarkonium measurements in heavy-ion collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV with the STAR experiment

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We present the latest J/ψ and Υ measurements in p+p, p+Au and Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV by the STAR experiment. In p+p collisions, the inclusive Υ cross section is measured through the di-electron decay channel, while the inclusive J/ψ polarization parameters are obtained from both the di-muon and di-electron channels. The later are compared to the Non-Relativistic QCD (NRQCD) models. In p+Au collisions, the measured nuclear modification factor for J/ψ suggests additional suppression mechanism besides the nuclear PDF (nPDF) effect. The latest Υ measurements in Au+Au collisions reach a higher precision by combining the data sets taken in 2011, 2014 and 2016, compared to previous results. The nuclear modification factors for the ground and excited Υ states in Au+Au collisions are shown as a function of the number of participants, and compared to the results at the LHC as well as to theoretical calculations.

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1. Introduction

Measurements of quarkonium production are an important tool for studying the properties of the Quark-Gluon Plasma (QGP) formed in relativistic heavy-ion collisions. J/ψ suppression due to the color-screening effect was proposed as a strong evidence of the QGP formation [1]. However, other effects, such as cold nuclear matter effects (CNM) and regeneration, complicate the interpretation of the observed suppression. At RHIC collision energies, Υ mesons are believed to be a cleaner probe of the color-screening effect compared to J/ψ, since the additional competing effects are predicted to be much smaller. Moreover, different bottomonium states with different binding energies are expected to dissociate at different temperatures, and therefore measurement of this "sequential melting" can help constrain the temperature of the medium. In elementary collisions, J/ψ polarization measurements provide valuable insights into its production mechanism, which in turn helps to clarify the picture of quarkonium behavior in the QGP. Quantifying these medium effects as well as understanding the quarkonium production mechanism requires precise measurements of quarkonium production in p+p, p+Au, and Au+Au collisions. With the di-muon trigger enabled by the Muon Telescope Detector (MTD), the STAR experiment recorded data sets corresponding to integrated luminosities of 14.2 nb^{-1} and 12.8 nb^{-1} for Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV in 2014 and 2016, as well as 122 pb^{-1} for p+p collisions and 409 nb^{-1} for p+Au collisions in 2015. Di-electron channel measurements are based on data triggered by the Barrel ElectroMagnetic Calorimeter (BEMC) corresponding to integrated luminosities of 1.1 nb^{-1} for Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV in 2011, 300 nb^{-1} for p+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV in 2015, as well as up to 23.5 pb^{-1} and 97 pb^{-1} for p+p collisions at $\sqrt{s}$ = 200 GeV in 2012 and 2015.

In these proceedings, we present (i) measurements of the inclusive Υ cross section as well as J/ψ polarization parameters in p+p collisions; (ii) nuclear modification factor for inclusive J/ψ in p+Au collisions; and (iii) nuclear modification factors for ground and excited Υ states in Au+Au collisions.

2. Inclusive J/ψ and Υ production in p+p collisions

Figure 1 shows the cross section of Υ(1S+2S+3S) times the $\Upsilon \to e^+e^-$ branching ratio (B) from 2015 BEMC-triggered p+p data. It follows the trend of world-wide experimental data and can be described by the Next-to-Leading Order (NLO) Color Evaporation Model (CEM) calculation [3]. STAR has recently published results on the inclusive J/ψ cross section in p+p collisions at $\sqrt{s} = 200$ GeV [4]. The results show good agreement with the CEM [3] and NLO NRQCD [5, 6] calculations in the applicable transverse momentum ($p_{\rm T}$) ranges. Meanwhile, the results are close to the lower uncertainty boundary of the CGC+NRQCD [7] calculations at low $p_{\rm T}$.

Figure 2 shows the inclusive J/ψ polarization parameters λ_θ, λ_φ in p+p collisions. λ_θ and λ_φ are measured in the helicity and Collins-Soper frames via the di-muon decay channel within $|y| < 0.5$ for $0 < p_{\rm T} < 5$ GeV/c (red circles), along with the λ_θ measurement in the helicity frame via the di-electron channel within $|y| < 1$ for $2 < p_{\rm T} < 8$ GeV/c (blue circles). The J/ψ polarization is found to be consistent with zero in the measured kinematic range. These results are compared to the NRQCD model calculations using two sets of Long Distance Matrix Elements (LDMEs) (NRQCD1 [8] and NRQCD2 [9]). While both model calculations can qualitatively describe data within uncertainties, the substantial difference at low p_T suggests a potential to constrain the LDMEs once the precision of such measurements is improved.

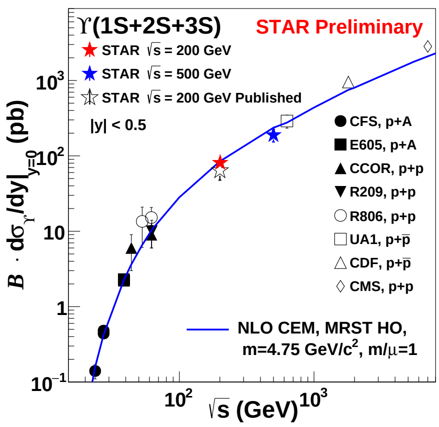


Figure 1: Integrated cross section of the ϒ(1S+2S+3S) at mid-rapidity in p+p collisions at $\sqrt{s} = 200$ GeV (red star), compared to the world-wide data and NLO CEM calculations.

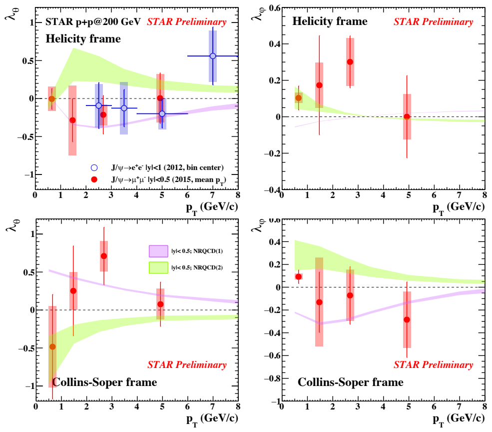
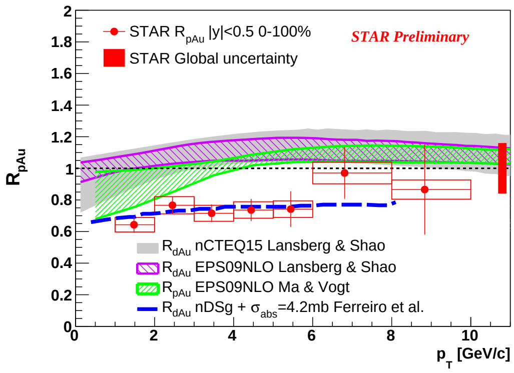


Figure 2: Inclusive J/ψ polarization parameters, λ_θ and λ_φ, as a function of p_T in helicity and Collins-Soper frames measured in p+p collisions at $\sqrt{s} = 200$ GeV.

3. Inclusive J/ψ measurement in p+Au collisions

Figure 3 shows the nuclear modification factor R_{pAu} of inclusive J/ψ in minimum-bias p+Au collisions for $0 < p_T < 10$ GeV/c within $|y| < 0.5$ using MTD-triggered data in 2015. The R_{pAu} is suppressed at lower p_T, and increases to be close to unity at higher p_T. Various theoretical models are proposed to describe the modification of the J/ψ production caused by the CNM effects. Model calculations, taking into account the nPDF effect using the nCTEQ15 [10, 11, 12] or EPS09NLO [10, 11, 12, 13] nuclear PDF sets (bands), can barely describe data within uncertainties. A different model calculation, including additional nuclear absorption effect on top of the nPDF effect [14] (blue dashed line), seems to be favored by data.

Figure 3: Nuclear modification factor R_{pAu} as a function of p_T for inclusive J/ψ, compared to various model calculations.



4. Υ suppression in Au+Au collisions

To improve the precision of Υ measurements, we have combined the results from both the di-electron (BEMC-triggered data in 2011) and the di-muon (MTD-triggered data in 2014 and 2016) decay channels. Figure 4 shows the resulting nuclear modification factor R_{AA} of inclusive Υ(1S) and Υ(2S+3S) as a function of the number of participants N_{part} within $|y| < 0.5$ for $p_T > 0$ in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Suppression increases from peripheral to central collisions for both the ground and excited Υ states. Υ(2S+3S) is more suppressed than Υ(1S) in central collisions, consistent with the expectation of sequential melting. The STAR results are compared to the CMS measurement [15] in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV within $|y| < 2.4$ (black diamonds). While the R_{AA} of Υ(1S) is similar, there seems a hint that Υ(2S+3S) is less suppressed at RHIC than at the LHC.

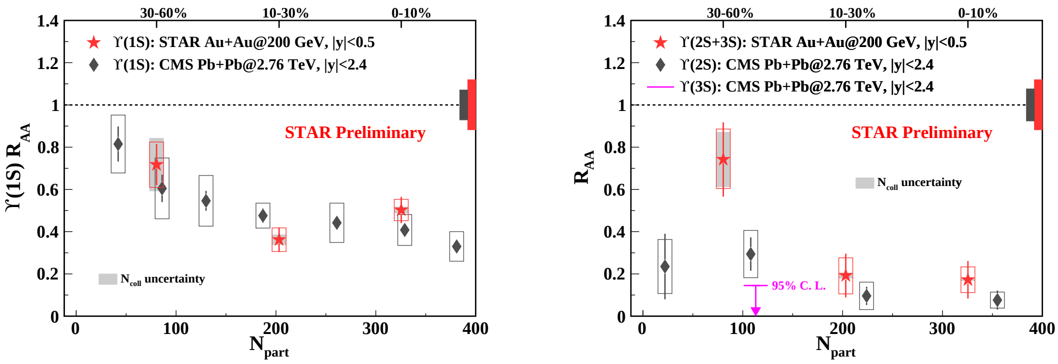


Figure 4: The R_{AA} of Υ(1S) (left panel) and Υ(2S+3S) (right panel) as a function of N_{part} within $|y| < 0.5$ in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV (red stars), compared to those measured in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV within $|y| < 2.4$ [15] (black diamonds).

The left panel of Fig. 5 shows a comparison between data and a theoretical calculation by Rothkopf et al. [16] which uses a lattice-vetted heavy-quark potential embedded in a hydrodynamically evolving medium. No CNM or regeneration is included. The model calculation agrees fairly well with the measured R_{AA} for Υ(1S), but seems to underestimate the Υ(2S+3S) R_{AA} in peripheral collisions. The right panel of Fig. 5 shows the comparison to the Rapp model [17] which uses temperature-dependent binding energies and a kinetic rate equation, and includes the regeneration and CNM effects at the same time. The Rapp model is able to qualitatively describe the results for both the ground and excited Υ states.

5. Summary

In summary, we present the latest J/ψ and Υ measurements in p+p, p+Au and Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV by the STAR experiment. In p+p collisions, models describe the Υ and J/ψ production cross section reasonably well. The J/ψ polarization is consistent with 0, and could help to constrain LDMEs once the statistical precision can be improved at low p_T in the future. In p+Au collisions, a significant suppression is seen at low p_T, which gradually goes away at high p_T. Comparison to model calculations suggest that additional suppression mechanism, such as nuclear

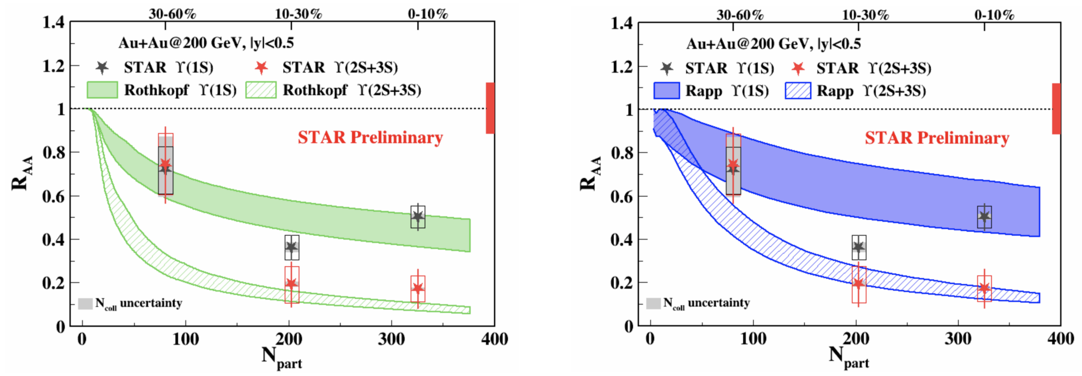


Figure 5: The R_{AA} of Υ(1S) (black) and Υ(2S+3S) (red) within $|y| < 0.5$ compared to theoretical predictions by Krouppa, Rothkopf, Strickland (left panel) and Du, He, Rapp (right panel). The full and dashed bands are theoretical predictions for Υ(1S) and Υ(2S+3S), respectively.

absorption, is favored on top of the nPDF effect. In Au+Au collisions, the excited Υ states are more suppressed than the ground state in central collisions, consistent with the sequential melting scenario. Comparing to similar measurements at the LHC, the level of suppression for Υ(1S) is similar, while Υ(2S+3S) seems to be slightly less suppressed at RHIC. Model calculations can qualitatively describe the data.

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