PROCEEDINGS OF SCIENCE

Measurements of the Υ meson production in Au+Au collisions at the STAR experiment

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In ultra-relativistic heavy-ion collisions, creation of a novel state of matter, consisting of deconfined quarks and gluons, has been observed. Quarkonium suppression in the medium due to the colour screening effect has been viewed as a direct evidence of the formation of such matter. Moreover, different quarkonium states are expected to dissociate at different temperatures, which can be used to constrain the medium temperature. At RHIC energies, other effects, such as regeneration and co-mover absorption, are expected to be very small for the bottomonium family, which makes it a cleaner probe compared to the J/ψ meson. The nuclear modification factors for the Υ states measured in Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV via both the di-muon and di-electron channels by the STAR experiment at RHIC are reported and compared with similar measurements at the LHC as well as theoretical calculations. Moreover, measurements of the Υ production in p+p and p+Au collisions are presented as well, providing a p+p reference with significantly improved precision and a quantification of the cold nuclear matter effects, respectively.

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1. Introduction

Lattice QCD calculations predict that under extreme conditions, hadronic matter undergoes a phase transition and forms a new state of matter consisting of deconfined quarks and gluons, the so-called Quark Gluon Plasma (QGP). This form of matter is hypothesised to comprise the Universe in its earliest stages. Such conditions are believed to be achievable in ultra-relativistic heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). Due to its short lifetime ($\sim$fm/c), the properties of the QGP are experimentally very challenging to measure.

One of the key probes to the QGP properties is the measurement of suppression for heavy quarkonia, e.g. J/ψ or Υ. The $c\bar{c}$ or $b\bar{b}$ pairs, due to their large masses, are created primarily before the QGP formation and their production cross-sections can be well calculated based on perturbative QCD. In the presence of the QGP, a quarkonium is expected to dissociate by the *colour screening* effect when its radius exceeds the Debye radius $r_{\mathrm{Debye}} \propto 1/T$ [1]. This dissociation is dependent on the quarkonium binding energy, and thus is expected to occur for different states at different temperatures. Thanks to this *sequential melting*, quarkonia can serve as a “QGP thermometer” [2].

Other phenomena can also influence the quarkonium production in heavy-ion collisions, such as the *statistical recombination* by coalescence of deconfined quarks at the QGP phase boundary and the *cold nuclear matter (CNM)* effects, like the inelastic interactions with co-moving hadrons. The CNM effects can be investigated in p+A collisions. Compared to J/ψ, the Υ mesons are believed to be a cleaner probe of the colour screening effect at RHIC energies, due to less susceptibility to the co-mover absorption [3] and virtually no production by recombination thanks to the b and $\bar{b}$ scarcity in the medium [4].

2. Υ reconstruction with the STAR experiment

At the Solenoidal Tracker At RHIC experiment (STAR), Υ’s are reconstructed via both the di-electron and di-muon decay channels at mid-rapidity. The Time Projection Chamber (TPC) serves as the primary tracking sub-detector with full coverage in azimuth $0 < \varphi < 2\pi$ within pseudorapidity $|\eta| < 1$. It also provides particle identification (PID) via measurement of the energy loss $\mathrm{d}E/\mathrm{d}x$. For the di-electron channel, the Barrel Electromagnetic Calorimeter (BEMC) is employed. It has the same φ and η coverage as the TPC. Apart from providing electron PID via the E/p, it is also used for triggering on high-p_{T} electrons from Υ decays. Since 2013, STAR can also measure quarkonium production through the di-muon channel thanks to the instalment of the Muon Telescope Detector (MTD) placed behind the solenoidal magnet. It covers approximately 45% in azimuth within $|\eta| < 0.5$ and can be used for both identifying and triggering on muons. Whenever possible, results obtained from both of the channels are combined to enhance the statistical precision of the measurement.

3. Results

In all figures presented in this section, statistical uncertainties are shown as vertical bars and systematic ones as open boxes around the data points. Full boxes around unity denote the global uncertainties.

3.1 Υ production in p+p and p+Au collisions

Production of Υ(1S+2S+3S) has been measured via the di-electron channel in p+p collisions at $\sqrt{s} = 200$ GeV using BEMC-triggered data with an integrated luminosity of 97 pb^{-1} from 2015. Within $|y| < 0.5$, the p_{T}-integrated cross-section is measured to be $B \cdot \mathrm{d}\sigma/\mathrm{d}y = 81 \pm 5(\mathrm{stat.}) \pm 8(\mathrm{syst.})$ pb, where B is the branching ratio. As shown in the left panel of Fig. 1, the new result is consistent with the previously published result by STAR [5], but the precision is improved by a factor of 2. The new result is also in a good agreement with the trend of world-wide experimental data as well as the NLO CEM prediction [6].

In order to study the CNM effects, Υ measurements have also been carried out in p+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV through the di-electron channel using BEMC-triggered data with an integrated luminosity of 300 nb^{-1} from 2015. The measured nuclear modification factor R_{pAu} within $|y| < 0.5$ is $0.82 \pm 0.10(\mathrm{stat.})^{-0.07}_{+0.08}(\mathrm{syst.}) \pm 0.10(\mathrm{norm.})$. The R_{pAu} is shown in the right panel of Fig. 1 as a function of rapidity. These results are consistent with previous STAR measurements in d+Au collisions [5] but have two times smaller relative uncertainties.

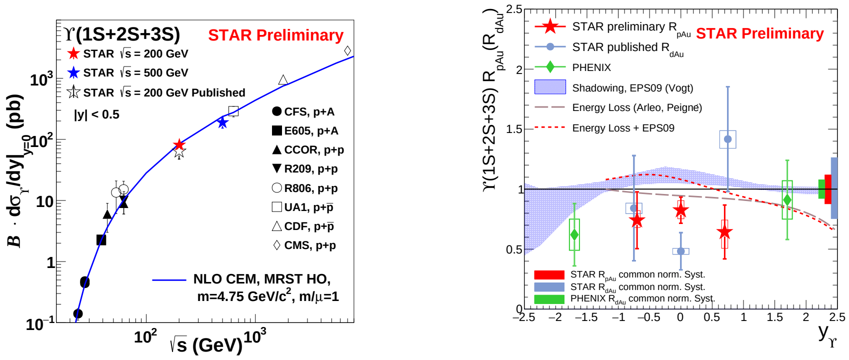

Figure 1: (*left*) Υ(1S+2S+3S) production cross-section at mid-rapidity from p+p collisions of $\sqrt{s} = 200$ GeV (red star) compared with global results and NLO CEM calculations [6]; (*right*) Υ(1S+2S+3S) nuclear modification factor R_{pAu} from p+Au collisions of $\sqrt{s_{\mathrm{NN}}} = 200$ GeV (red stars) as a function of rapidity.

3.2 Υ production in Au+Au collisions

In Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV, the Υ production has been measured both in the di-electron channel (BEMC-triggered data of 1.1 nb^{-1} from 2011) and the di-muon channel (MTD-triggered data of 14 nb^{-1} from 2014). Nuclear modification factors measured in both channels are found to be consistent with each other within uncertainties, and thus are combined to further increase the precision.

The combined R_{AA} is presented in Fig. 2 as a function of the mean number of participants N_{part} in each centrality bin for both Υ(1S) and Υ(2S+3S). The excited states are more suppressed in central collisions than the ground state. Shown are also results measured by CMS in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV [7]. Whereas the Υ(1S) results are consistent, the Υ(2S+3S) appears to be less suppressed at RHIC than at the LHC. The R_{AA} extracted from the di-muon channel is also shown in Fig. 3 as a function of p_{T}. In comparison with the CMS results [7], the Υ(1S) R_{AA} is again in agreement, whilst the Υ(2S+3S) R_{AA} seems to be larger at high-p_{T} at the RHIC.

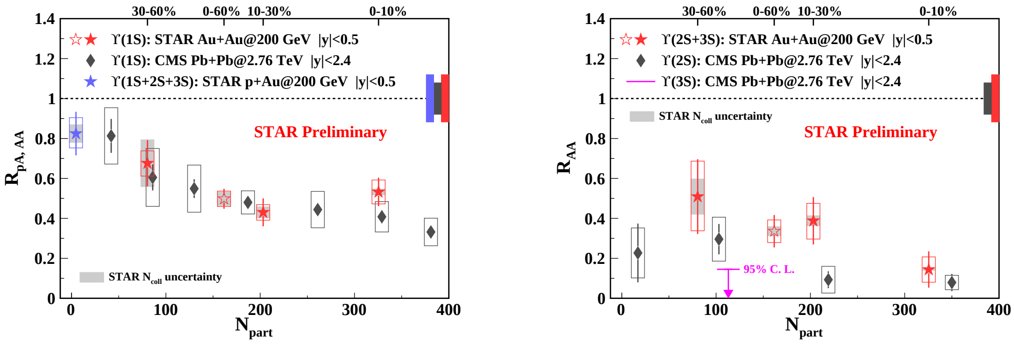

Figure 2: $R_{\rm AA}$ for the Υ(1S) (*left*) and the Υ(2S+3S) (*right*) at mid-rapidity as a function of $N_{\rm part}$ in Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV (red stars). Also portrayed are the centrality integrated result (open red star), the $R_{\rm pAu}$ from p+Au collisions (blue star), and CMS results from Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV (grey diamonds and magenta line) [7].

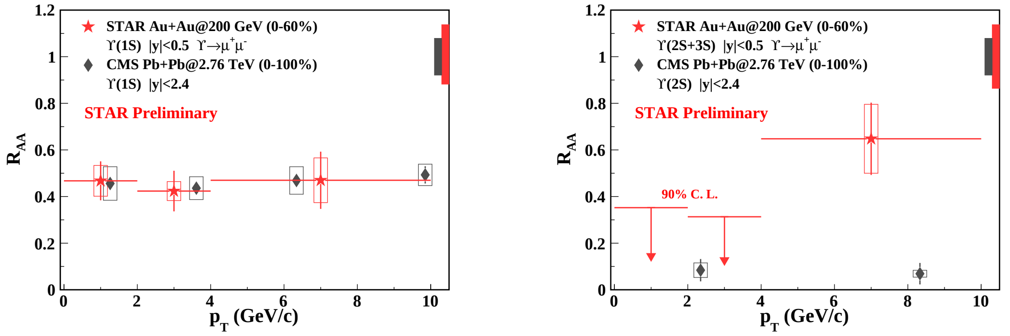

Figure 3: $R_{\rm AA}$ for the Υ(1S) (*left*) and the Υ(2S+3S) (*right*) at mid-rapidity as a function of $p_{\rm T}$ in Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV (red stars) together with CMS results for Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV (grey diamonds) [7].

Comparisons to theoretical predictions are shown in Fig. 4. These quarkonium production models in heavy-ion collisions differ mainly in the implementation of various CNM effects, recombination as well as their approaches to the quarkonium binding potential. The Strongly Binding Scenario (SBS) models use the internal energy as the heavy quark potential. It corresponds to a fast Υ dissociation and neglects random thermal energy transfers with the medium. Unlike SBS, the Weakly Binding Scenario (WBS) uses the free energy as the potential. The Strickland-Bazow model [8] studies the two scenarios with no CNM effects nor regeneration included. The model by Liu et al. [9] includes dissociation only for the excited states, and systematically under-predicts the suppression, hinting at further influence of CNM effects and/or direct Υ(1S) dissociation. Unlike the two previous models, the Emerick-Zhao-Rapp SBS model [4] takes into account CNM and regeneration effects. In summary, the data appear to favour the SBS-based model calculations.

4. Conclusions and outlook

We present recent measurements of Υ production at mid-rapidity with the STAR experiment. In p+p collisions of $\sqrt{s} = 200$ GeV, the new and more precise cross-section results are in solid agreement

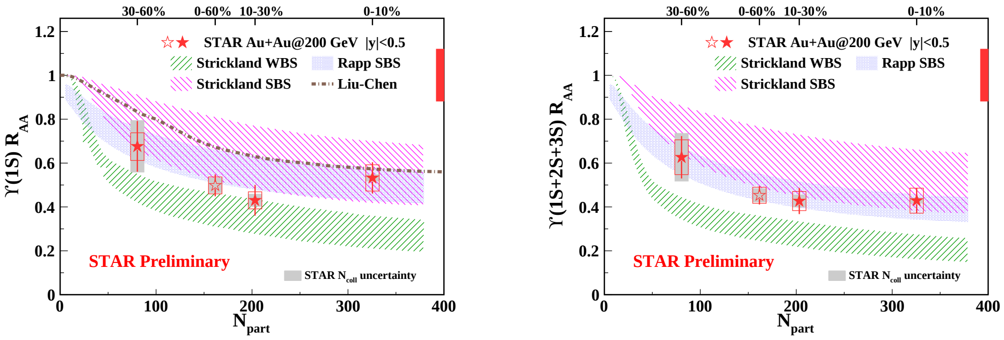

Figure 4: Nuclear modification factors for the $\Upsilon(1S)$ (*left*) and the $\Upsilon(1S+2S+3S)$ (*right*) in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at mid-rapidity are shown as a function of the mean number of participants N_{part}. Also shown are the predictions of theoretical models [4][8][9].

with NLO CEM predictions as well as with the world-wide experimental data trend [6]. In p+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, the CNM effects are quantified via R_{pA}, which is measured to be $0.82 \pm 0.10(\text{stat.})^{-0.07}_{+0.08}(\text{syst.}) \pm 0.10(\text{norm.})$.

In Au+Au collisions, we present R_{AA} as a function of N_{part} and p_T for the $\Upsilon(1S)$ and the $\Upsilon(2S+3S)$ separately. The $\Upsilon(1S)$ suppression at RHIC is similar to that at the LHC. Better understanding of CNM effects and the feed-down contribution is needed before drawing conclusions about direct $\Upsilon(1S)$ suppression. In the most central collisions, the Υ excited states are more suppressed than the ground state, which is in accordance with the sequential melting behaviour. The excited states also appear to be less suppressed at RHIC than at the LHC. These new Υ results can be further used to impose constraints on the QGP temperature at RHIC. Furthermore, analyses using other Au+Au data samples are under way, with a factor of two increase in statistics expected.

5. Acknowledgement

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