Upsilon Production at the STAR Experiment with a Focus on New U+U Results

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We report recent Υ measurements in p+p, d+Au and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, and detail the analysis in U+U collisions at $\sqrt{s_{NN}} = 193$ GeV. Results on Υ production versus rapidity are consistent with pQCD predictions in p+p collisions. However, Υ production in mid-rapidity ($|y|$<0.5) d+Au collisions is suppressed with respect to p+p collisions beyond model predictions that take into account modification of parton distribution functions and initial parton energy loss inside nuclei. The nuclear modification factor R_{AA} shows a significant suppression in central Au+Au and U+U collisions, consistent with model calculations including color screening effects in a deconfined medium.

1 Introduction

Due to color screening, the production of quarkonia in high energy heavy ion collisions is expected to be sensitive to the energy density of the medium. Sequential suppression of different quarkonium states may therefore serve as a thermometer of the medium [1]. Although the suppression of charmonia was anticipated as a key signature of the Quark Gluon Plasma (QGP), the observed energy dependence of J/ψ suppression is rather weak [2]. This phenomenon is explained by J/ψ production via recombination (coalescence) of $c\bar{c}$ pairs in the QGP. Bottomonia, on the other hand, are less affected by recombination and can provide a cleaner probe of the strongly interacting medium. While p+p measurements provide a benchmark for pQCD and serve as a baseline for nuclear modification, d+Au collisions are generally considered as suitable to study cold nuclear matter (CNM) effects such as shadowing of the parton distribution functions and initial state parton energy loss. Central U+U data at $\sqrt{s_{NN}} = 193$ GeV, which is estimated to have a 20% higher average energy density than that of Au+Au [3], allow for further tests of the sequential suppression hypothesis.

2 Experiment and analysis

The STAR experiment at RHIC is a complex detector that provides a full azimuthal coverage at mid-rapidity ($|\eta|$<1). A detailed description of the STAR detector is in Ref. [4]. The $\Upsilon \to \mathrm{e}^-\mathrm{e}^+$ decay channel, with a branching ratio $B_{\mathrm{ee}} \approx 2.4$ %, was studied. Analysis of year 2012 $\sqrt{s_{NN}} =$ 193 GeV U+U data was done in a similar way to recently published Υ measurements in p+p, d+Au and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [5], with differences highlighted below. A total of 17.2 million *high-tower* triggered U+U events were collected requiring an energetic hit in the Barrel Electromagnetic Calorimeter (BEMC), corresponding to an integrated luminosity of 263.4 μb^{-1}. Momentum measurement and electron identification based on the energy loss $\mathrm{d}E/dx$ were done in the Time Projection Chamber (TPC). The projected position of the track is required to match the position of the hit in the BEMC to the extent $\Delta R = (\Delta\varphi^2 + \Delta\eta^2)^{1/2} < 0.04$ in the azimuth–pseudorapidity space. The three most energetic adjacent BEMC towers including the hit tower were combined into *clusters*. Electron candidates were required to have similar cluster energy and momentum ($0.75 < E_{cluster}/p < 1.35\ c$) with most of the energy in one tower ($E_{tower}/E_{cluster} > 0.7$ for those candidates that fired the trigger, $E_{tower}/E_{cluster} > 0.5$ for other candidates). They were then paired, and required to have an opening angle $\theta > 90°$. Fig. 1 shows the invariant mass distribution of the paired candidates. The combinatorial background was subtracted using like-sign combinations. In the peak region there is also a significant contribution from Drell-Yan and open $b\bar{b}$ processes. Templates of the $\Upsilon(nS)$ peaks and the Drell-Yan contributions obtained from simulations, and the $b\bar{b}$ contribution from pQCD model calculations were fitted simultaneously to determine their relative contributions. The reconstruction efficiency was determined using simulations and electron-enriched data samples as $\epsilon \approx 3\%$. The corrected p_{T}-spectrum is shown in Fig. 2. Bin-shift correction was done using a Boltzmann function with a slope $T = 1.16$ GeV, extracted from a parametrized interpolation over ISR, CDF and CMS data. A fit to the spectrum yields a slope $T = 1.32\pm0.21$ GeV, consistent with the interpolation. The measured Υ cross section in U+U collisions is $B_{\mathrm{ee}} \left.\frac{d\sigma^{\Upsilon}_{\mathrm{AA}}}{dy}\right|_{|y|<1} = 4.37\pm1.09(stat)\pm^{+0.65}_{-1.01}(syst)\ \mu\mathrm{b}$. The major systematic uncertainties are from signal extraction ($^{+4.8}_{-18}\%$), tracking efficiency (11.8%), electron identification in the TPC ($^{+4.0}_{-6.4}\%$) and in the BEMC (5.9%), TPC-BEMC matching (5.4%), trigger efficiency ($^{+1.1}_{-3.6}\%$), geometrical acceptance ($^{+1.7}_{-3.0}\%$) and input p_{T} and y spectrum in the simulations (2.1%).

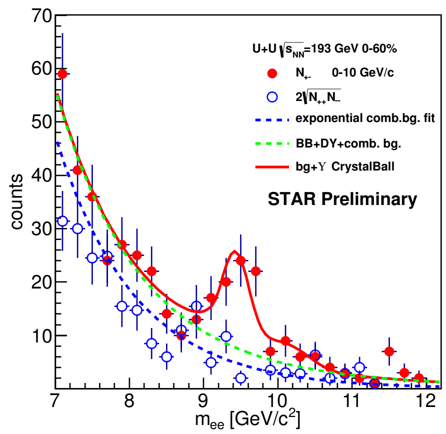

Figure 1: Invariant mass distribution of like-sign (filled dots) and unlike-sign (open points) electron pairs in $\sqrt{s_{NN}}$=193 GeV U+U collisions of 0–60% centrality at mid-rapidity, with background and peak fits.

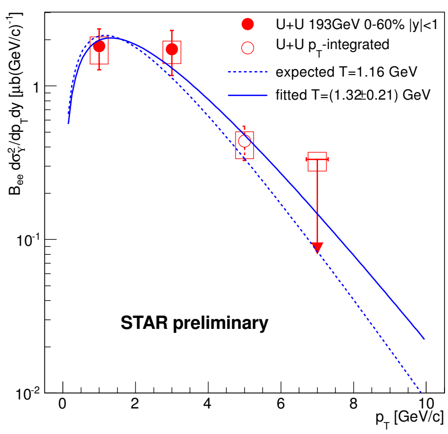

Figure 2: Υ p_{T}-spectrum in $\sqrt{s_{NN}}$=193 GeV U+U collisions of 0–60% centrality at mid-rapidity. The fit (solid line) to the data is compared to the expected slope (dashed).

3 Upsilon production in p+p and d+Au collisions

Fig. 3 shows the cross sections for Υ production in $\sqrt{s_{NN}}$=200 GeV p+p and d+Au collisions [5]. The data are compared to NLO pQCD color evaporation model predictions [6]. In Fig. 4 the nuclear modification factor in d+Au is compared to calculations including shadowing and/or parton energy loss [6, 7]. While the p+p data are consistent with pQCD, CNM effects alone may not be enough to explain the suppression in the d+Au mid-rapidity bin ($|y|<0.5$).

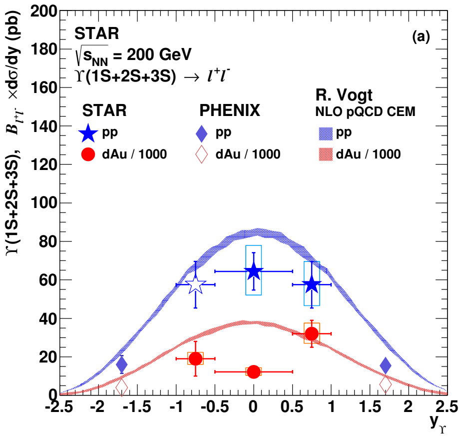

Figure 3: Υ yield $B_{\mathrm{ee}}\frac{d\sigma}{dy}$ for p+p and d+Au collisions [5] compared to a pQCD model [6].

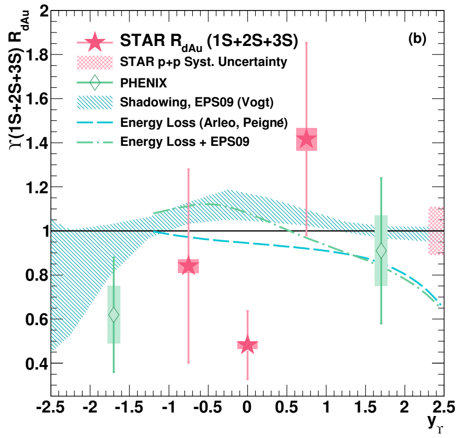

Figure 4: R_{dAu} versus y of Υ mesons [5] compared to theoretical calculations [6, 7].

4 Upsilon suppression in heavy ion collisions

Nuclear modification factors of the Υ(1S+2S+3S) in d+Au, Au+Au and U+U collisions are presented in Fig. 5 with respect to the number of participants, and compared to model calculations [8, 9], as well as $\sqrt{s_{NN}}$=2.76 TeV Pb+Pb data from the CMS experiment [10]. The trend observed in Au+Au is generally continued in the U+U data, with an $R_{\mathrm{AA}} = 0.35 \pm 0.17(stat.)^{+0.03}_{-0.13}(syst.)$ in the 10% most central U+U collisions. The model of Strickland and Bazow [8] incorporates lattice QCD results on screening and broadening of bottomonium, as well as the dynamical propagation of the Υ meson in the colored medium. The scenario with a potential based on heavy quark internal energy is consistent with the observations, while the free energy based scenario is disfavoured. The strong binding scenario in a model proposed by Emerick, Zhao, and Rapp [9], which includes possible CNM effects in addition, is also consistent with STAR results. The measured R_{AA} at RHIC and at LHC are consistent within the sizeable uncertainties. However, the LHC data, which corresponds to higher energy densities, shows a trend that differs from RHIC: a strong suppression is present at all but the lowest N_{part} values.

Fig. 6 shows Au+Au R_{AA} for the ground state Υ(1S) and the excited states Υ(2S+3S) separately, compared to the R_{AA} of high-p_{T} J/ψ mesons in $\sqrt{s_{NN}}$ = 200 GeV Au+Au collisions [11]. The Υ(1S) shows a suppression similar to that of high-p_{T} J/ψ mesons, more than if only cold nuclear matter effects were present [5]. The excited state yields are consistent with a complete suppression within the precision of the measurement.

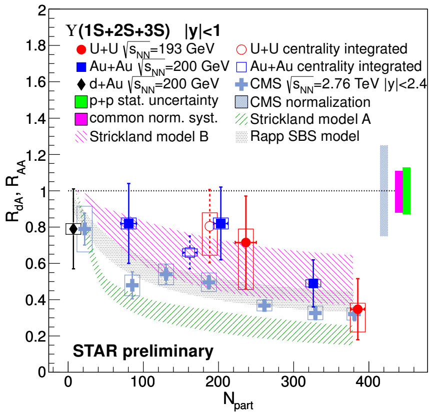

Figure 5: R_{AA} vs. N_{part} in $\sqrt{s_{NN}}$=200 GeV d+Au, Au+Au and 193 GeV U+U collisions, compared to models [8, 9] and LHC data [10].

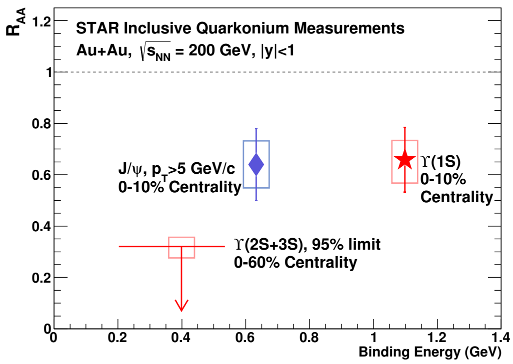

Figure 6: R_{AA} of the Υ(1S) and the Υ(2S+3S) states compared to high-p_{T} J/ψ R_{AA} [11], plotted against binding energy, in $\sqrt{s_{NN}}$=200 GeV Au+Au collisions.

5 Summary and outlook

We reported recent measurements of Υ production in p+p, d+Au and Au+A collisions at $\sqrt{s_{NN}}$ = 200 GeV, as well as U+U at 193 GeV. The slope of the p_{T}-spectrum in U+U collisions is consistent with interpolations from other experiments. We see a significant suppression in $|y|$<1 central Au+Au and U+U collisions, which attests to the presence of a deconfined medium and support the sequential melting hypothesis. However, the $|y|$<0.5 d+Au data also shows a suppression beyond model predictions, suggesting that CNM effects may also play an important role. The new Muon Telescope Detector has been completed by 2014, and will allow for a precise reconstruction of the three Υ states separately, through the dimuon channel. Future high-statistics p+Au collisions from 2015 will help us gain a deeper insight to the CNM effects.

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