PROCEEDINGS OF SCIENCE

Heavy quarkonium production at the STAR experiment

Petr Chaloupka* **for the STAR collaboration** †
Faculty of Nuclear Sciences and Physical Engineering Czech Technical University in Prague, Prague, Czech Republic
E-mail: petr.chaloupka@fjfi.cvut.cz

In the collisions of heavy ions the nuclear matter can undergo a phase transition from hadrons to a state of deconfined quarks and gluons, the Quark-Gluon Plasma (QGP). Suppression of heavy quarkonia due to Debye-like screening of the quark-antiquark potential has been predicted to be a sensitive indicator of the thermodynamical properties of the created QGP. However, cold nuclear matter effects and secondary production in the QGP via heavy quark recombination could also alter the observed suppression picture. Measurements of J/ψ production at different collision energies, collision systems, and centralities can shed new light on the interplay of these effects on J/ψ production and medium properties. Moreover, Υ production is expected to be less affected by b-$\bar{\text{b}}$ recombination and interactions with hadrons in the final state. It hence provides a cleaner probe for studying the interaction of heavy quarkonia with the partonic medium.

In this paper recent results from the STAR experiment on J/ψ and Υ production in p+p collisions at $\sqrt{s}$=500 GeV and heavy-ion collisions at various energies are presented. The energy dependence of J/ψ production in Au+Au collisions at $\sqrt{s_{NN}}$ =39, 62.4 and 200 GeV and in U+U collisions at $\sqrt{s_{NN}}$=193 GeV is discussed together with Υ production in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV and in U+U collisions at $\sqrt{s_{NN}}$=193 GeV.

The European Physical Society Conference on High Energy Physics
22–29 July 2015
Vienna, Austria

*Speaker.

†This work was supported by the grant of the Grant Agency of Czech Republic n.13-20841S and by the Grant Agency of the Czech Technical University in Prague, grant No. SGS 13/215 OHK 4/3 T/14.

PoS(EPS-HEP2015)203

1. Introduction

Suppression of heavy quarkonia due to Debye-like screening of the quark-antiquark potential, has been predicted to be an indicator sensitive to the presence of the QGP [1]. The Debye screening length depends on the temperature attained by the QGP medium. Since different quarkonium states have different binding energies (hence sizes), they are expected to melt at different QGP temperatures. The observed quarkonium suppression pattern can then be linked to the thermodynamical properties of the created QGP.

However, there are other effects that can alter the quarkonium production with respect to the baseline of p+p collisions. These effects include secondary production of quarkonia in the QGP via heavy quark recombination together with cold nuclear matter effects (CNM) such as shadowing/anti-shadowing of parton distribution functions, initial-state parton energy loss and final state nuclear absorption. Since these mechanisms have different dependence on variables such as p_T or energy density, differential measurements of quarkonium production at different collision energies, collision systems, and centralities can help to disentangle the interplay of these effects and to study properties of the created medium.

It should be noted that the experimentally measured yields of J/ψ and Υ contain contributions from feed-down. Inclusive J/ψ production is a combination of prompt and non-prompt J/ψ. The prompt J/ψ are either direct ($\sim$ 60%) or from feed-down from higher excites states ($\psi(2S)$and χ_C). The non-prompt J/ψ originate from B-hadron decays. This contribution has been estimated by the STAR experiment to be $10 \sim 25\%$ in the range of $4<p_T<12$ GeV/c [2]. It is hence important to study the production of higher charmonium states in both p+p and nucleus-nucleus collisions.

2. Data analysis and results

The STAR experiment [3] is a large-acceptance detector which excels at tracking and identification of charged particles at mid-rapidity ($|\eta| < 1$) with full azimuthal coverage. In the majority of the analyses discussed below J/ψ, ψ(2S) and Υ were reconstructed at mid-rapidity in the di-electron decay channel. Electrons and positrons are reconstructed using the Time Projection Chamber (TPC) which also provides particle identification by measuring ionization energy loss (dE/dx). Furthermore, the particle identification is enhanced by the Time of Flight detector (TOF) in the low-p_T region. At high p_T, the Barrel Electromagnetic Calorimeter (BEMC) can further improve electron identification by requiring E/p$c\sim$1, where E is the energy deposited in the BEMC and p is the momentum of the TPC track matched to the BEMC signal. The Vertex Position Detectors (VPD) is used for triggering on minimum bias data sample while the BEMC is used for triggering on high-p_T electrons.

To improve the STAR capabilities, particularly in the heavy flavor sector, a new Muon Telescope Detector (MTD) [4] was commissioned in 2013 to detect and trigger on muons from heavy flavor decays. For quarkonium measurements, a dimuon trigger requiring at least two MTD hits was used to sample p+p collisions at 500 GeV. This allows reconstruction of J/ψ in the di-muon channel in $\sqrt{s}$=500 GeV p+p data.

PoS(EPS-HEP2015)203

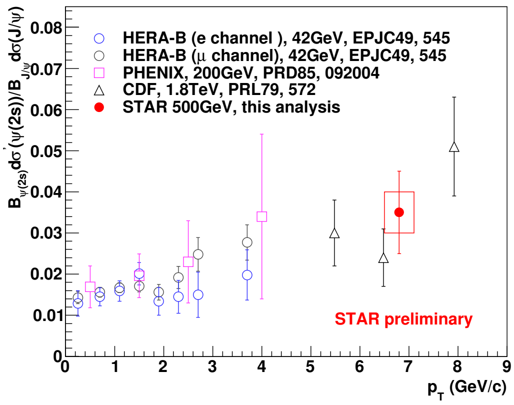

Figure 1: Ratio of $\psi(2S)$ to J/ψ yields in p+p at $\sqrt{s}$=500 GeV, compared to results from HERA-B, PHENIX and CDF experiments.

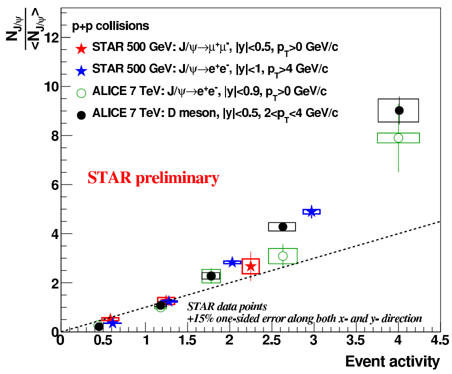

Figure 2: Relative J/ψ yield as a function of event activity from STAR at $\sqrt{s}$=500 GeV compared to ALICE [5, 6] measurements of J/ψ and D-meson yields at $\sqrt{s_{NN}}$=7 TeV.

2.1 J/ψ and $\psi(2S)$ production

For correct interpretation of results from heavy-ion collisions the J/ψ production in elementary p+p collisions needs to be understood. STAR has previously measured production of J/ψ in p+p and nucleus-nucleus collisions at $\sqrt{s_{NN}}$=200 GeV [2, 7]. To further study the charmonium production and constrain the feed-down from the higher states STAR has analyzed p+p collisions at $\sqrt{s}$=500 GeV, the highest collision energy achievable in p+p collisions at RHIC. The high statistics data recorded in the year 2011 allowed not only to extract differential cross section for inclusive J/ψ production up to $p_T = 20$ GeV/c [8], but also for the first time to study the production of ψ(2S) state in p+p at $\sqrt{s}$=500 GeV. The STAR result on the $\psi(2S)$ to J/ψ yield ratio at mid-rapidity, presented in Fig. 1, agrees with results from other experiments which exhibit an increasing trend with p_T with no significant dependence on the collision energy.

Minimum-bias (MB) p+p collisions can be classified into different event activity bins based on the charged-particle multiplicity of the event. At the STAR experiment this is done using the TOF, which is a fast detector hence insensitive to pile-up. In Fig. 2 relative J/ψ yield is shown as a function of event activity in p+p collisions at $\sqrt{s}$=500 GeV extracted from both the di-muon and the di-electron channels. An enhancement of J/ψ production at high event activity, especially at high-p_T, is evident. This is consistent with the ALICE observation [5, 6] of faster than linear rising trend for relative yields of J/ψ and D-mesons in p+p collisions at $\sqrt{s_{NN}}$=7 TeV.

STAR published results [2, 7] on J/ψ production in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV exhibit strong suppression at low p_T in central (0-30%) and mid-peripheral (30-60%) events. For high-p_T J/ψ the suppression is observed only in central collisions while in peripheral and mid-peripheral collisions the nuclear modification factors R_{AA} are consistent with unity. The strong suppression of high-p_T J/ψ is likely to come from suppression in the QGP (due to color screening or other dynamical effects) since for p_T>5 GeV/c J/ψ are expected to be less affected by the recombination and CNM effects. To further study the pattern of quarkonium suppression STAR recorded collisions of Uranium nuclei at $\sqrt{s_{NN}}$=193 GeV. It is expected that approximately 20% higher energy density can be reached in U+U collisions in comparison with Au+Au collisions [9].

STAR preliminary results on J/ψ invariant yield at mid-rapidity in U+U collisions at $\sqrt{s_{NN}}$= 193 GeV are shown in Fig. 3 with p_T reaching up to 6 GeV/c. The presented data are from 0-80% minimum bias events and at high-p_T from events triggered by a signal from high-p_T electrons in the BEMC. The p_T dependence of the extracted R_{AA} using $\sqrt{s_{NN}}$=200 GeV p+p data is shown in Fig. 4. The R_{AA} in U+U, similarly as in Au+Au, shows a strong suppression at low p_T. There is also a remaining suppression even in the high-p_T region.

The R_{AA} obtained from the low-p_T dominated 0-80% U+U minimum bias events is compared in Fig. 5 to the centrality (expressed through number of participants N_{part}) dependence of R_{AA} from Au+Au collisions at $\sqrt{s_{NN}}$=200, 62.4 and 39 GeV. It should be noted that STAR did not measure p+p data at 62.4 and 39 GeV and hence model was used for these collision energies as a reference instead. The uncertainties due to this p+p reference are shown as boxes in Fig. 4 and 5. As can be seen, the U+U results are consistent within uncertainties with the suppression pattern observed in Au+Au which exhibits very weak dependence on the collision energy. Theoretical models [10] which are able to reproduce the data incorporate an interplay of two competing effects. In these models, as the collision energy increases, the higher suppression of primordial J/ψ is countered by an increasing number of J/ψ produced by recombination of thermalized charm quarks.

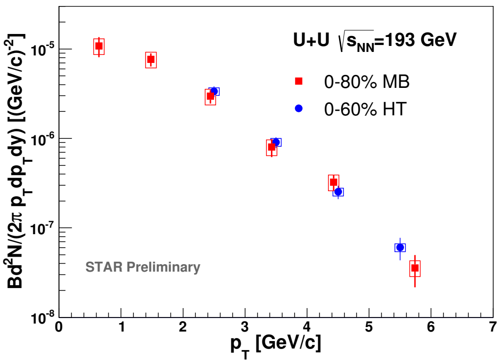

Figure 3: J/ψ invariant yield versus transverse momentum in U+U collisions at $\sqrt{s_{NN}}$=193 GeV from minimum bias (red) events and events triggered by high-p_T electron in BEMC (blue).

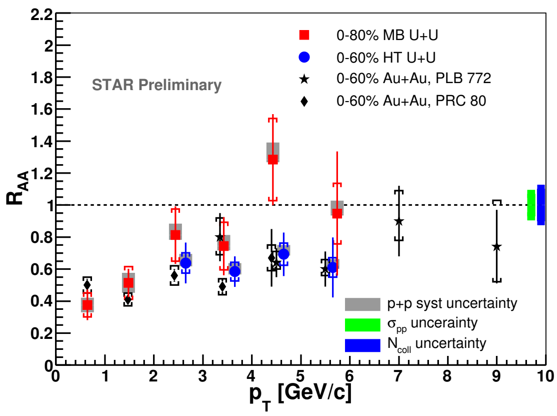

Figure 4: J/ψ nuclear modification factor in U+U collisions at $\sqrt{s_{NN}}$=193 GeV as a function of p_T, compared to results form Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV.

2.2 Υ production in Au+Au and U+U collisions

At RHIC collision energies Υ production, in contrast to that of J/ψ, is expected to be less affected by quark-antiquark recombination and interactions with hadrons in the final state [12]. The Υ hence provides a cleaner probe for studying the interaction of heavy quarkonia with the partonic medium.

STAR has published results on Υ production in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV [13]. In Fig. 6 the R_{AA} from Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV of Υ(1S) in central events together with the excited states Υ(2S+3S) at 0-60% centrality are compared to high-p_T J/ψ mesons from [2]. The Υ(1S) suppression in $\sqrt{s_{NN}}$=200 GeV Au+Au collisions is observed to be similar to the suppression of high-p_T J/ψ. However the higher excited states Υ(2S+3S) show stronger suppression.

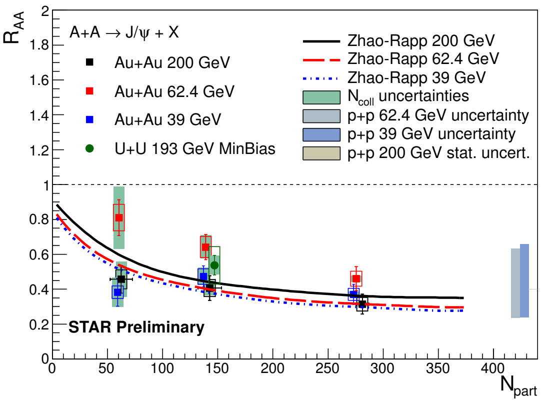

Figure 5: Centrality dependence of J/ψ R_{AA} for p_T<5 GeV/c in Au+Au collisions at different collision energies and U+U (p_T<6 GeV/c) at $\sqrt{s_{NN}}$=193 GeV.

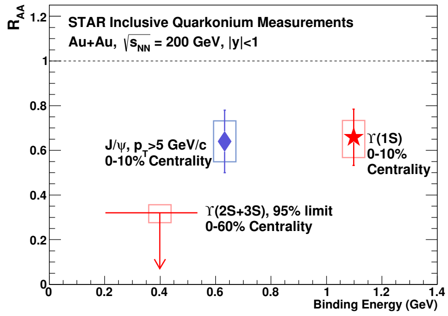

Figure 6: The R_{AA} from Au+Au at $\sqrt{s_{NN}}$=200 GeV of quarkonia as a function of their binding energy. The ϒ(1S) and the high-p_T J/ψ are from of 0-10% centrality, while the ϒ(2S+3S) 95% upper limit (arrow) is from 0-60% central events.

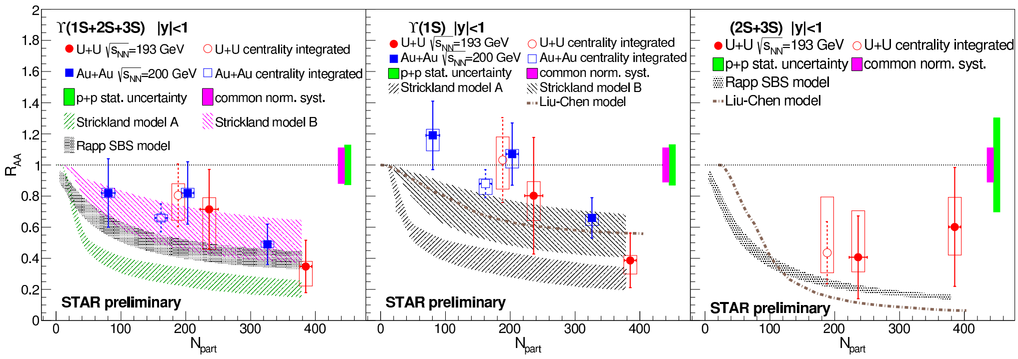

Figure 7: The R_{AA} of the ϒ(1S+2S+3S), ϒ(1S) and the ϒ(2S+3S) states as a function of N_{part}, in $\sqrt{s_{NN}}$=200 GeV Au+Au and $\sqrt{s_{NN}}$=193 GeV U+U collisions, compared to different models [11]. Open symbols represent the 0-60% integrated centrality.

Fig.7 shows the preliminary results on the modification of bottomium production in U+U collisions at $\sqrt{s_{NN}}$=193 GeV [11]. The R_{AA} for ϒ(1S+2S+3S), ϒ(1S) and ϒ(2S+3S) as a function of centrality(N_{part}) are compared to results from Au+Au at $\sqrt{s_{NN}}$=200 GeV. The measurements from U+U are in agreement with the suppression observed in Au+Au and extend the range of R_{AA} measurements to higher N_{part}. Most importantly the ϒ(1S) shows significant suppression beyond the level expected from cold nuclear matter effects in both, Au+Au and U+U, collisions.

Within the experimental precision, the results on R_{AA} of excited states ϒ(2S+3S) from 0-60% U+U collisions are consistent with the strong suppression found in Au+Au collisions.

3. Summary

STAR experiment has measured ratio of ψ(2S) to J/ψ for the first time in p+p collisions at $\sqrt{s}$=500 GeV and found it consistent with the results at other collision energies. The first preliminary results on J/ψ suppression in U+U collisions at $\sqrt{s_{NN}}$=193 GeV are consistent with results from Au+Au collisions at different energies. Significant suppression of bottomium states in central heavy-ion collisions has been observed. The suppression of the ϒ(1S) in central Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV and the even stronger suppression of higher states is in agreement with the sequential melting hypothesis. The indication of significant ϒ(1S) suppression in central Au+Au collisions is further confirmed by the new measurements in U+U. In U+U collisions the ϒ suppression pattern generally follows the trends found in Au+Au and extends them towards higher N_{part} values.

References

[1] T. Matsui and H. Satz, *J/ψ Suppression by Quark-Gluon Plasma Formation*, *Phys.Lett.* **B178** (1986) 416.

[2] **STAR** Collaboration, L. Adamczyk et al., *J/ψ production at high transverse momenta in p+p and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV*, *Phys.Lett.* **B722** (2013) 55–62, [arXiv:1208.2736].

[3] **STAR** Collaboration, K. Ackermann et al., *STAR detector overview*, *Nucl.Instrum.Meth.* **A499** (2003) 624–632.

[4] L. Ruan, G. Lin, Z. Xu, K. Asselta, H. Chen, et al., *Perspectives of a Midrapidity Dimuon Program at RHIC: A Novel and Compact Muon Telescope Detector*, *J.Phys.G* **G36** (2009) 095001, [arXiv:0904.3774].

[5] E. G. Ferreiro and C. Pajares, *High multiplicity pp events and J/ψ production at LHC*, *Phys. Rev.* **C86** (2012) 034903, [arXiv:1203.5936].

[6] **ALICE** Collaboration, J. Adam et al., *Measurement of charm and beauty production at central rapidity versus charged-particle multiplicity in proton-proton collisions at $\sqrt{s} = 7$ TeV*, *JHEP* **09** (2015) 148, [arXiv:1505.00664].

[7] **STAR** Collaboration, L. Adamczyk et al., *J/ψ production at low p_T in Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}}$ = 200 GeV at STAR*, *Phys.Rev.* **C90** (2014) 024906, [arXiv:1310.3563].

[8] **STAR** Collaboration, R. Ma, *Measurement of jpsi production in p+p collisions at $\sqrt{=}$500 GeV at STAR experiment*, in *7th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions (Hard Probes 2015) Montréal, Québec, Canada, June 29-July 3, 2015*, 2015. arXiv:1509.06440.

[9] D. Kikola, G. Odyniec, and R. Vogt, *Prospects for quarkonia production studies in U + U collisions*, *Phys.Rev.* **C84** (2011) 054907, [arXiv:1111.4693].

[10] X. Zhao and R. Rapp, *Charmonium in Medium: From Correlators to Experiment*, *Phys.Rev.* **C82** (2010) 064905, [arXiv:1008.5328].

[11] **STAR** Collaboration, R. Vertesi, *Bottomonium production in heavy-ion collisions at STAR*, in *7th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions (Hard Probes 2015) Montréal, Québec, Canada, June 29-July 3, 2015*, 2015. arXiv:1509.05359.

[12] R. Rapp, D. Blaschke, and P. Crochet, *Charmonium and bottomonium production in heavy-ion collisions*, *Prog. Part. Nucl. Phys.* **65** (2010) 209–266, [arXiv:0807.2470].

[13] **STAR** Collaboration, L. Adamczyk et al., *Suppression of Γ production in d+Au and Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV*, *Phys. Lett.* **B735** (2014) 127–137, [arXiv:1312.3675]. [Erratum: Phys. Lett.B743,537(2015)].

PoS(EPS-HEP2015)203