Quarkonium measurements via the di-muon decay channel in p+p and Au+Au collisions with the STAR experiment

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Abstract. We present the first $J/\psi$ and $\Upsilon$ measurements in the di-muon decay channel at mid-rapidity at RHIC using the newly installed Muon Telescope Detector. In p+p collisions at $\sqrt{s} = 500$ GeV, inclusive $J/\psi$ cross section can be described by CGC+NRQCD and NLO NRQCD model calculations for $0 < p_T < 20$ GeV/$c$. In Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, we observe (i) clear $J/\psi$ suppression indicating dissociation; (ii) $J/\psi R_{AA}$ can be qualitatively described by transport models including dissociation and regeneration with a tension at high $p_T$; and (iii) hint of less melting of $\Upsilon(2S + 3S)$ relative to $\Upsilon(1S)$ at RHIC compared to that at LHC.

1. Introduction
Quarkonia are an essential probe to study the properties of the Quark Gluon Plasma (QGP). The suppression of $J/\psi$ due to color-screening effects in the medium was initially proposed as a direct evidence of the QGP formation [1]. However, the interpretation of the $J/\psi$ suppression is still a challenge due to the contributions from the regenerated $J/\psi$ by the recombination of $c\bar{c}$ pairs in the medium and the cold nuclear matter effects. Therefore it is important to have more precise $J/\psi$ measurements over a broad kinematic range and even cleaner $\Upsilon$ state measurements. The latter do not suffer from the regeneration contribution due to the much smaller $b\bar{b}$ pair cross section, i.e. $\sigma_{b\bar{b}} \sim 2$ $\mu$b [2] while $\sigma_{c\bar{c}} \sim 800$ $\mu$b [3] at top RHIC energy. The newly installed Muon Telescope Detector (MTD), which provides both the di-muon trigger and the muon identification capability at mid-rapidity, opens the door to measuring quarkonia via the di-muon decay channel at STAR. Compared to the di-electron decay channel, the di-muon decay channel suffers much less from bremsstrahlung and thus provides much better invariant mass resolution to separate different $\Upsilon$ states. Using the MTD di-muon trigger, the STAR experiment recorded data corresponding to an integrated luminosity of 28.3 $pb^{-1}$ in p+p collisions at $\sqrt{s} = 500$ GeV in the RHIC 2013 run, and 14.2 $nb^{-1}$ in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV in the RHIC 2014 run. In these proceedings, we report (1) the measurements of $J/\psi$ production in p+p collisions at $\sqrt{s} = 500$ GeV; and (2) the measurements of the nuclear modification factor ($R_{AA}$) for $J/\psi$ and the production of different $\Upsilon$ states in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.
2. \(J/\psi\) measurements in \(p+p\) collisions at \(\sqrt{s} = 500\) GeV

Figure 1 shows the cross section of \(J/\psi\) in \(p+p\) collisions at \(\sqrt{s} = 500\) GeV in the di-electron and di-muon decay channels for \(0 < p_T < 20\) GeV/c. The di-muon decay channel extends \(p_T\) reach down to 0 GeV/c. The results in these decay channels are consistent in the overlapping \(p_T\) range of \(4 < p_T < 9\) GeV/c. The experimental results can be well described by CGC+NRQCD calculations at low \(p_T\) [4] and NLO NRQCD calculations at high \(p_T\) [5]. Figure 2 shows the \(x_T = 2p_T/\sqrt{s}\) scaling of \(J/\psi\) cross section [6]. The \(J/\psi\) cross section in \(p+p\) collisions at \(\sqrt{s} = 500\) GeV follows the common trend as a function of \(x_T\) at high \(p_T\). The breaking of the \(x_T\) scaling at low \(p_T\) can be attributed to the soft processes.

3. \(J/\psi\) measurements in \(Au+Au\) collisions at \(\sqrt{s_{NN}} = 200\) GeV

Figure 3 shows the invariant yield of \(J/\psi\) in \(Au+Au\) collisions at \(\sqrt{s_{NN}} = 200\) GeV for different collision centralities. The new results in the di-muon decay channel are consistent with previous results in the di-electron decay channel [7, 8] within uncertainties.

The nuclear modification factor \(R_{AA} = \frac{d^2N_{AA}/dy dp_T}{d^2N_{pp}/dy dp_T}\) of \(J/\psi\) in 0-40% central \(Au+Au\) collisions is shown in Fig. 4, compared with LHC results [13, 14]. The strong suppression at RHIC at low \(p_T\) indicates that dissociation plays a significant role in this \(p_T\) range. The hint of the increasing trend of \(R_{AA}\) at RHIC at high \(p_T\) can be explained by formation-time effects and feed-down of \(B\) hadrons. The less suppression of \(J/\psi\) at LHC at low \(p_T\) indicates larger regeneration contribution due to higher charm cross section, while more suppression of \(J/\psi\) at LHC at high \(p_T\) indicates larger dissociation rate due to higher temperature of the medium. Transport Models from Tsinghua [9, 10] and Texas A&M University (TAMU) [11, 12], including dissociation and regeneration effects, can qualitatively describe the \(p_T\) dependence of RHIC and LHC data.

Centrality dependence of \(J/\psi\) cross section is shown in Fig. 5 for integrated \(p_T\) and in Fig. 6 for \(p_T > 5\) GeV/c. For integrated \(p_T\), both models can describe centrality dependence at RHIC, but tend to overestimate suppression at LHC. For \(p_T > 5\) GeV/c, there is tension among models.
and data. New measurements in the di-muon decay channel provide a distinguishing power for these transport models.

4. \( \Upsilon \) measurements in Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \)

Figure 7 shows the di-muon mass spectrum in \( \Upsilon \) state mass range in Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). We observe signs of an indication of \( \Upsilon(2S + 3S) \) signals in the di-muon decay channel. The raw yields of \( \Upsilon \) states are obtained by a simultaneous fit to the like-sign and unlike-sign distributions. In this fit, (i) the \( \Upsilon \) state masses are fixed to the PDG values and their widths are determined by simulation; (ii) the ratio of \( \Upsilon(2S)/\Upsilon(3S) \) is fixed to the value in p+p collisions; and (iii) the shape of \( bb \) and Drell-Yan background is estimated using PYTHIA.

Figure 8 shows the fitted \( \Upsilon(2S + 3S)/\Upsilon(1S) \) ratio compared with the world-wide p+p data [16] and CMS data [17, 18]. There is a hint of less melting of \( \Upsilon(2S + 3S) \) relative to \( \Upsilon(1S) \) at RHIC
than at LHC.

5. Summary and Outlook

We present the first $J/\psi$ and $\Upsilon$ measurements in the di-muon decay channel at mid-rapidity at RHIC. In p+p collisions at $\sqrt{s} = 500$ GeV, inclusive $J/\psi$ cross section can be described by CGC+NRQCD and NLO NRQCD model calculations for $0 < p_T < 20$ GeV/c. In Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, we observe (i) clear $J/\psi$ suppression indicating dissociation; (ii) $J/\psi R_{AA}$ can be qualitatively described by transport models including dissociation and regeneration despite a tension at high $p_T$; and (iii) there is a hint of less melting of $\Upsilon(2S + 3S)$ relative to $\Upsilon(1S)$ at RHIC compared to that at LHC. These measurements in Au+Au collisions will have better statistical precision by combining the similar amount of data recorded in the RHIC 2016 run.

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