Measurements of J/ψ Production and Polarization in p+p and p+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV with the STAR Experiment

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We present the measurements of J/ψ production at mid-rapidity via the di-muon decay channel in p+p and p+Au collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR experiment at RHIC. In p+p collisions, the measured inclusive J/ψ cross section can be qualitatively described by model calculations. The J/ψ polarization parameters, λ_θ , λ_ϕ as well as the frame-invariant quantity λ_{inv} , are presented as a function of transverse momentum in both the helicity and Collins-Soper frames. No significant polarization is observed. In addition, the nuclear modification factor for inclusive J/ψ in p+Au collisions is similar to that measured in d+Au collisions and favors an additional nuclear absorption effect on top of the nuclear PDF effect.

Keywords: J/ψ cross section; J/ψ polarization; cold nuclear matter effect.

1. Introduction

Understanding J/ψ production mechanism in elementary collisions has been a long-term interest both experimentally and theoretically¹. It provides an excellent laboratory to study the hadronization process². Measurements of the J/ψ cross section³ and polarization, both of which are sensitive to the J/ψ production mechanism, can be used to distinguish among different models⁴. Moreover, quarkonia serve as an important tool to study the properties of the Quark-Gluon Plasma (QGP) formed in relativistic heavy-ion collisions. In particular, suppression of the J/ψ meson production due to the color-screening effect in the medium was proposed as a direct evidence of the QGP formation⁵. However, interpretation of the J/ψ suppression measured in heavy-ion collisions is still challenging due to the presence of other

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effects, including the cold nuclear matter effects^{6–7}. The Muon Telescope Detector (MTD)⁸, which is used to trigger on and identify the muons at mid-rapidity, opens the door to measuring quarkonia via the di-muon decay channel at the STAR experiment. With the MTD di-muon trigger, the STAR recorded two data sets corresponding to integrated luminosities of 122 pb^{-1} for p+p collisions and 409 nb^{-1} for p+Au collisions at $\sqrt{s_{\text{NN}}} = 200 \text{ GeV}$ during the RHIC 2015 run. In these proceedings, we present: (i) measurements of inclusive J/ψ cross section and polarization in p+p collisions at $\sqrt{s} = 200 \text{ GeV}$; and (ii) measurements of nuclear modification factor (R_{pAu}) for inclusive J/ψ in p+Au collisions at $\sqrt{s_{\text{NN}}} = 200 \text{ GeV}$.

2. J/ψ measurements in p+p collisions at $\sqrt{s} = 200 \text{ GeV}$

2.1. J/ψ p_T spectrum

Figure 1 shows the differential cross section of inclusive J/ψ in p+p collisions at $\sqrt{s} = 200 \text{ GeV}$ in both the di-electron and di-muon decay channels for $0 < p_T < 14 \text{ GeV}/c$. The results in these two decay channels are consistent with each other in the overlapping p_T range. The Non-Relativistic QCD (NRQCD) formalism coupled with the color glass condensate effective theory (CGC)⁹ at low p_T together with the next-to-leading order NRQCD (NLO NRQCD)¹⁰ calculations at high p_T for prompt J/ψ production can qualitatively describe data in the full p_T range. There seems to be a tension towards very low p_T though. The Improved Color Evaporation Model (ICEM)¹¹ for direct J/ψ production describes data fairly well at low p_T . However,

Fig. 1. Inclusive J/ψ cross section multiplied by the branching ratio B as a function of p_T in the di-muon (red circle) and di-electron (blue square) decay channels.

it leaves room for improvements in the range of $3.5 < p_T < 12$ GeV/ c , for which feed-down contributions need to be taken into account.

2.2. J/ψ polarization measurements

J/ψ polarization can be extracted from the angular distribution of the decayed leptons, which can be expressed using three polarization parameters λ_θ , λ_ϕ and $\lambda_{\theta\phi}$ as

$$W(\cos\theta, \phi) \propto \frac{1}{3 + \lambda_\theta} \cdot (1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi). \quad (1)$$

The polar angle θ and azimuthal angle ϕ are identified by the direction of μ^+ with respect to the chosen coordinate frame. Two reference frames are used in this analysis which differ in the definition of the z axis:

- (1) Helicity frame (HX): the direction along the J/ψ momentum in the center-of-mass system of the colliding beams;

Fig. 2. Inclusive J/ψ polarization parameters as a function of p_T in both HX and CS frames for p+p collisions at $\sqrt{s} = 200$ GeV.

- (2) Collins-Soper frame (CS): the bisector of the angle formed by one beam direction and the opposite direction of the other beam in J/ψ rest frame.

In both frames the λ_θ is extracted from a distribution $W(\cos\theta) \propto 1 + \lambda_\theta \cos^2\theta$ which is obtained by integrating over the azimuthal angle ϕ , while λ_ϕ is extracted from $W(\phi) \propto 1 + \frac{2\lambda_\phi}{3+\lambda_\theta} \cos 2\phi$ obtained by integrating over the polar angle θ . The $\lambda_{\theta\phi}$ term vanishes in both integrations. A simultaneous fit to the $W(\cos\theta)$ and $W(\phi)$ distributions is performed to obtain the polarization parameters. Figure 2 shows the polarization parameters for inclusive J/ψ from the di-muon decay channel in both the HX and CS frames for $0 < p_T < 5$ GeV/c. The λ_θ and λ_ϕ are consistent with 0 in both frames.

A frame invariant quantity¹², $\lambda_{inv} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$, is used to cross check measurements performed in different frames. Any arbitrary choice of the experimental observation frame should give the same value of this quantity. As shown in Fig. 3, the measured λ_{inv} values as a function of p_T are consistent between the HX and CS frames.

Figure 4 shows the comparison of the measured λ_θ parameter in the HX frame. The new results using 2012 (via di-electron decay channel) and 2015 (via di-muon decay channel) data are consistent in the overlapping region and are consistent with 0 for $0 < p_T < 8$ GeV/c. Current data are also consistent with previous publication using 2009 data¹³⁻¹⁴, even though the overall trend seems a bit different.

3. J/ψ measurements in p+Au at $\sqrt{s_{NN}} = 200$ GeV

Figure 5 shows the first results on inclusive J/ψ nuclear modification factor, R_{pAu} , in 0-100% p+Au collisions at RHIC. The measured R_{pAu} is consistent with unity at high p_T and is less than unity at low p_T . It is generally consistent with the previous R_{dAu} result¹⁵ within statistical and systematic uncertainties. There seems

Fig. 3. λ_{inv} as a function of p_T in HX (red circle) and CS (blue circle) frames.

Fig. 4. The newly measured λ_θ parameters using 2012 (blue open circle) and 2015 (red circle) data compared to previous publication with 2009 data (black open square for STAR¹⁴ and black open star for PHENIX¹³).

Fig. 5. Inclusive J/ψ nuclear modification factor R_{pAu} as a function of p_T measured via the di-muon decay channel (red circle).

to be a small tension at 3.5-5 GeV/ c with a significance of only 1.4σ though. This overall consistency suggests similar cold nuclear matter effects in p+Au and d+Au collision systems. Calculations, taking into account the nuclear PDF effect using the nCTEQ15^{16–18} or EPS09NLO^{16–19} nuclear PDF sets, can touch the upper limit of the measured R_{pAu} within the uncertainties. On the other hand, the measured R_{pAu} favor a model calculation which includes an additional nuclear absorption effect²⁰ on top of the nuclear PDF effect.

4. Summary

In summary, we present the J/ψ production measurements through the di-muon decay channel at mid-rapidity at RHIC. In p+p collisions at $\sqrt{s} = 200$ GeV, inclusive J/ψ cross section is measured for $0 < p_T < 10$ GeV/ c , which can be described by CGC+NRQCD and NLO NRQCD within the uncertainties. ICeM describes data at low p_T while underestimates data at $p_T > 3.5$ GeV/ c . The J/ψ polarization parameters are measured in the HX and CS frames via the di-muon channel for $0 < p_T < 5$ GeV/ c . Both λ_θ and λ_ϕ parameters are consistent with 0 in both frames. In p+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, inclusive J/ψ R_{pAu} is consistent with R_{dAu} suggesting similar cold nuclear matter effects, and R_{pAu} favors an additional nuclear absorption effect on top of nuclear PDF effect.

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