Systematic study of the polarization effect on the measurements of the $J/\psi$ nuclear modification factor

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Abstract. Heavy quarkonium is one of the key candidates to study the fundamental properties of Quark-Gluon Plasma (QGP) created in heavy-ion ($A+A$) collisions. Comparing the production of the $J/\psi$ meson in proton-proton ($p+p$) and $A+A$ collisions, namely the nuclear modification factor ($R_{AA}$), provides the quantitative understanding of the QGP. Normally, the $R_{AA}$ is measured under the assumption that the quarkonium is unpolarized. However, the recent measurements on the $J/\psi$ polarization in the forward rapidity region in both $p+p$ and $A+A$ collisions from the LHC experiments suggest that the $J/\psi$ meson has small but non-negligible polarization. In this paper, we show the effects on the kinematic acceptance from the $J/\psi$ polarization to the measurement of $R_{AA}$ in the forward rapidity region using the available data from the ALICE and LHCb experiments and demonstrate the possible maximum effects from polarization in the central rapidity region at the RHIC and LHC energies. The results show that having precise measurements on the quarkonium polarization in heavy-ion collisions is important to obtain the full picture of how heavy quarkonium interacts with the QGP.

1. Introduction

Heavy quarkonia, the heavy flavor quark-antiquark pairs, are the important candidates to understand the fundamental properties of Quantum Chromodynamics (QCD). Studying the production of heavy quarkonium in proton-proton ($p+p$) and heavy-ion ($A+A$) collisions can provide fruitful information on QCD since it covers both the perturbative (hard scattering) and non-perturbative (hadronization stage) regions, as well as the knowledge of the new state of matter, Quark-Gluon Plasma (QGP), which is expected to be created in $A+A$ collisions. The $J/\psi$ meson is the $c\bar{c}$ bound state which was discovered in 1974 \cite{1,2} and it often serves as a standard candle for the studies of quarkonium properties.

Measuring the $J/\psi$ nuclear modification factor, $R_{AA}$, which is the ratio of the invariant production yields of $J/\psi$ in $A+A$ collisions normalized to the number of binary collisions to that in $p+p$ collisions, is one of the important ways to provide deep understanding of the QGP. The $R_{AA}$ for the $J/\psi$ meson in $A+A$ collisions (similarly for
$R_{pA}$ in proton-ion ($p+A$) collisions is defined as

$$R_{AA} = \frac{1}{\langle N_{\text{coll}} \rangle} \left( \frac{1}{2\pi p_T} \frac{d^2 N_{J/\psi}}{dy dp_T} \right)_{A+A} \left( \frac{1}{2\pi p_T} \frac{d^2 N_{J/\psi}}{dy dp_T} \right)_{p+p},$$

(1)

where $\langle N_{\text{coll}} \rangle$ is the average number of binary nucleon-nucleon collisions and $\left( \frac{1}{2\pi p_T} \frac{d^2 N_{J/\psi}}{dy dp_T} \right)_{A+A} (p+p)$ is the invariant yields of the $J/\psi$ meson in $A+A (p+p)$ collisions. The invariant yield can be expressed as

$$\frac{d^2 N_{J/\psi}}{2\pi p_T dp_T dy} = \frac{N_{J/\psi}^{\text{raw}}}{(2\pi p_T) \cdot A \cdot \varepsilon \cdot \Delta p_T \cdot \Delta y},$$

(2)

where $N_{J/\psi}^{\text{raw}}$ is the raw number of reconstructed $J/\psi$; $A$ is the $J/\psi$ kinematic acceptance which is defined as the ratio of number of events passed certain kinematic criteria which are based on the detector configuration to the number of events without any restrictions; $\varepsilon$ is the reconstruction efficiency of the $J/\psi$ candidates; $\Delta p_T$ and $\Delta y$ are the corresponding bin widths in $p_T$ and $y$ of the $J/\psi$ candidates, respectively. It is important to note that the angular distributions of the decayed leptons from $J/\psi$ are dependent on the polarization of $J/\psi$ as described in the following:

$$W(\cos \theta, \phi) \propto (1 + \lambda_\theta \cos^2 \theta + \lambda_\phi \sin^2 \theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos \phi),$$

(3)

where $\theta$ is the polar angle which is defined as an angle between the positive-lepton momentum vector in the $J/\psi$ rest frame and the given polarization axis, $\phi$ is the azimuthal angle, and $\lambda_\theta$, $\lambda_\phi$, and $\lambda_{\theta\phi}$ are the polarization parameters (the detailed definitions of them can be found in Ref. [3]). In other words, the kinematic acceptance of $J/\psi$ in Eq. 2 is also dependent on the polarization of $J/\psi$.

Obtaining the correct interpretation of the $R_{AA}$ measurement needs extra cares since there are many effects affecting it, for instance, the hot nuclear matter effects (HNM) which includes the suppression, regeneration, medium-induced energy loss, and formation time effect [4, 5] and the cold nuclear matter effects (CNM) which includes the modification of parton density function, nuclear absorption, and co-mover effect [6]. One way to distinguish the HNM and CNM effects is carefully by comparing the $R_{AA}$ and $R_{pA}$.

However, normally the kinematic acceptance correction on determination of the invariant yields is based on the unpolarized $J/\psi$ assumption. Interestingly, the recent ALICE measurement on the $J/\psi$ polarization in the forward rapidity ($y$) region, $2.5 < y < 4.0$, in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV suggests that the $J/\psi$ meson is slightly transversely and longitudinally polarized in the helicity (HX) and Collins-Soper (CS) frames at low $p_T$, respectively [7]; while the measurement from the LHCb experiment shows that $J/\psi$ is slightly longitudinally polarized in both HX and CS frames in the similar $y$ range, $2.0 < y < 4.5$, in $p+p$ collisions at $\sqrt{s} = 7$ TeV [8]. The definitions of the HX and CS frames will be described in the next section. These results indicate that heavy quarkonium might have different production mechanisms or different ways to obtain their polarization in different collision systems. Therefore, it is important to
use the kinematic acceptance of $J/\psi$ implemented with the appropriate polarization in the invariant yield correction.

In this paper, we provide a systematic study of the polarization effect on kinematic acceptance of $J/\psi$ to the $R_{AA}$ measurements of $J/\psi$ using the available measurements on the $J/\psi$ polarization from the LHC and RHIC in both $A+A$ and $p+p$ collisions. The paper is organized as follows: Section 2 describes the analysis procedure. Section 3 shows the results in forward and central regions at the LHC and RHIC energies. Finally, the conclusions are given in Section 4.

2. Analysis Procedure

This analysis is conducted by using the Toy Monte Carlo (MC) samples implemented with the real kinematic (detector) configurations from the LHC and RHIC experiments. The quantitative study on the effect from the $J/\psi$ kinematic acceptance with certain polarization parameters can be achieved by comparing the input $p_T$ distribution (equivalent to the distribution obtained by using the correct kinematic acceptance) in Toy MC events to the $p_T$ distribution from the events which have applied kinematic selections and then corrected using unpolarized kinematic acceptance. The detailed procedure for this analysis is described in the following.

Firstly, the polarization parameters in both HX and CS frames for the $J/\psi$ meson, $\lambda_{\theta}$, $\lambda_{\phi}$, and $\lambda_{\theta\phi}$, are obtained from the measurements. Here, the HX frame is defined as the given polarization axis is along the $J/\psi$ momentum in the center-of-mass frame of colliding beams; while the CS frame is defined as the given polarization axis is the bisector between the directions of the first colliding parton and of the opposite of the second colliding parton in the $J/\psi$ rest frame. Secondly, the high statistics $J/\psi$ events ($10^8$) are generated using the single particle generator and forcing $J/\psi$ to decay to dilepton pair. The input $p_T$ and $y$ spectrum of $J/\psi$ are obtained from the real measurements and the global measurement [9], respectively. The polarization of the $J/\psi$ meson then is assigned by the $p_T$-dependent $\lambda_{\theta}$, $\lambda_{\phi}$, and $\lambda_{\theta\phi}$ parameters which are obtained from the parameterization of the measurements and the corresponding angular distributions of the decayed leptons are followed Eq. 3.

Next, the same kinematic selections used in the real measurements are applied on each event. As mentioned previously, to quantify the effect from the polarization of $J/\psi$ can be achieved by comparing the input $p_T$ spectrum and the corrected spectrum. Here, the candidate-by-candidate weighting method is used to correct the kinematic acceptance and the corrected yield ($N_{\text{corr.}}$) is defined as $N_{\text{corr.}} = \sum_{i=1}^{N_{J/\psi}} w_i$, where $w_i = 1/A$. This candidate-by-candidate weighting method is also used in several $J/\psi$ and $\Upsilon$ cross section analyses in $p+p$ collisions from the ATLAS and STAR collaboration [10, 11, 12]. Finally, the effect on the $J/\psi$ invariant yield in $A+A$ collisions originated from the kinematic acceptance with the wrong polarization parameters can be quantified by the ratio of the input $p_T$ spectrum to the acceptance-corrected one. Therefore, the $R_{AA}$ can be corrected by replacing the invariant yield under the
unpolarized assumption with the one using the appropriate acceptance correction. The corrected \( R_{AA}^{corr} \), can be expressed as

\[
R_{AA}^{corr} = R_{AA} \times \frac{C_{AA}^{pT,y}}{C_{pp}^{pT,y}}
\]

\[
= \frac{1}{\langle N_{coll} \rangle} \left( \frac{1}{2\pi p_T} \frac{d^2N_{J/\psi}}{dp_T dy} \right)_{A+A} \times \left( \frac{N_{input}}{N_{corr.}} \right)_{A+A} \times \left( \frac{N_{input}}{N_{corr.}} \right)_{p+p},
\]

(4)

where \( C_{AA(pp)}^{pT,y} \) is the corresponding correction on the invariant yield in \( A+A \) (\( p+p \)) collisions in a given \( p_T \) and \( y \) bin. It is defined as the ratio of \( N_{input} \) to \( N_{corr.}^{pT,y} \), where \( N_{input} \) is the number of events without any kinematic selections; while \( N_{corr.}^{pT,y} \) is the number of events with certain kinematic selections and applying acceptance correction which is based on the unpolarized assumption. The denominator in the \( C_{AA(pp)}^{pT,y} \) is to cancel the number of \( J/\psi \) using the wrong kinematic acceptance (unpolarized) in the measurements.

3. Results

3.1. Forward rapidity region

Figures 1(a) and 1(b) show the polarizations of \( J/\psi \) measured by ALICE in Pb+Pb collisions at 5.02 TeV [7] and LHCb in \( p+p \) collisions at 7 TeV [8], respectively. The rapidity range for these measurements is \( 2.5 < y < 4.0 \) (note that the LHCb measurement actually covered the rapidity range from 2.0 to 4.5, but only the mentioned range is used). As mentioned that the ALICE measurement suggests that the \( J/\psi \) meson is slightly transversely and longitudinally polarized in the HX and CS frames at low \( p_T \), respectively, and the LHCb measurement shows that \( J/\psi \) is slightly longitudinally polarized in both HX and CS frames. Since the non-zero polarizations will affect the \( J/\psi \) kinematic acceptance \( \mathcal{A} \) correction in the invariant yield, the \( p_T \)-dependent polarization parameters are obtained by the linear fit and they are used to build the kinematic acceptance with correct polarization of \( J/\psi \) in the forward region. Figure 2(a) and 2(b) show the 2-dimensional \( (J/\psi \ p_T \text{versus} \ y) \) kinematic acceptance ratio of polarized \( J/\psi \) with the parameters from the ALICE measurements to the unpolarized \( J/\psi \) in the HX and CS frames, respectively. It is obvious that the kinematic acceptance can vary by \(~15\% \ (\sim 12\%) \) in the low \( p_T \) region and \(~8\% \ (\sim 8\%) \) in the high \( p_T \) region in the HX (CS) frame.

Two key factors in the correction, \( N_{input}^{pT,y} \) and \( N_{corr.} \), in Eq. 4 can be obtained from the MC events with the \( p_T \) and \( y \) distributions obtained from the measurements [9]. However, the \( y \) distribution in \( A+A \) collisions is assumed to be the same as \( p+p \) collisions due to the lack of information in heavy-ion collisions. Figure 3(a) shows the \( p_T \) spectrum of \( J/\psi \) for 0-90\% centrality which can be parameterized by the function \( f(p_T) = \frac{N}{(1+(p_T/p_0)^2)^n} \), where \( p_0 \), \( N \), and \( n \) are free parameters. The Toy MC events are generated following this \( p_T \) distribution and, as mentioned in the previous section,
Figure 1. The polarization parameters $\lambda_\theta$, $\lambda_\phi$, and $\lambda_{\theta\phi}$ as a function of $p_T$ in [a] the HX and [b] CS frame measured from ALICE in Pb+Pb collisions at 5.02 TeV and LHCb in p+p collisions at 7 TeV. The rapidity range for these measurements is $2.5 < y < 4.0$. Black lines are a linear function fits to the data points and dashed lines are linear functions fit to the upper and lower bound of the date points. Note that the data points from LHCb are plotted only in the same $y$ region as ALICE.

Figure 2. The 2-dimensional ($J/\psi p_T$ versus $y$) kinematic acceptance ratio of polarized $J/\psi$ with the parameters from the ALICE measurements to the unpolarized $J/\psi$ in [a] HX and [b] CS frame.
each event is distributed in the phase space based on the Eq. 3. Then, the same kinematic selections used in the ALICE measurements are applied on the events, namely $2.5 < y < 4$ on $J/\psi$ and $2.5 < \eta < 4$ and $p_T > 1$ GeV/c on $\mu^+$ and $\mu^-$. The input $p_T$ spectrum of $J/\psi$ ($N^{\text{input}}$), the $p_T$ spectrum with aforementioned kinematic selections on $J/\psi$ and muons ($N^{\text{in Acc}}$), and the corrected $p_T$ spectrum using unpolarized kinematic acceptance ($N^{\text{corr.}}$) are shown in Fig. 3(b).

![Figure 3.](attachment:image.png)

**Figure 3.** (a) The $p_T$ spectrum of $J/\psi$ for 0-90% centrality fitted by the function (black line) and details are described in the text. (b) The $p_T$ spectra of the $J/\psi$ meson: the input spectrum ($N^{\text{input}}$, open boxes), the spectrum with kinematic selections on $J/\psi$ and muons ($N^{\text{in Acc}}$, solid black circles), and the corrected spectrum using unpolarized acceptance ($N^{\text{corr.}}$, solid triangles).

Figure 4 shows the $C_{AA(pp)}$ as a function of $p_T$ in the HX and CS frames. The corrections for Pb+Pb and $p+p$ have larger discrepancy in the HX frame than that of in the CS frame as expected since the $p_T$-dependency of the polarization parameters have different trends in the HX frame and similar ones in the CS frame, as shown in Fig. 1. The shaded area reflects the uncertainty from the polarization measurements which is determined, as mentioned in the previous section, by a conservative estimation using the linear functions to fit the upper or lower points and assuming that the uncertainty is 100% correlated between data points, as shown in the dashed lines in Fig. 1.

Finally, the original $R_{AA}$ measurements from ALICE (black points) [13] and the corrected $R_{AA}^{\text{corr.}}$ using Eq. 4 are shown in Fig. 5. The result shows that the correction in the low $p_T$ region is not negligible (up to $\sim 16\%$). On the other hand, the high $p_T$ region is not affected significantly as expected. These results show that considering the effect from the polarization of $J/\psi$, namely applying the correction or adding an extra systematic uncertainty, is needed to give a more accurate interpretation.
Figure 4. The $C_{AA(pp)}$ as a function of $p_T$ in the HX (left) and CS (right) frame in the forward rapidity range (2.5 < $y$ < 4.0) in Pb+Pb collisions at 5.02 TeV. The shaded area is due to the uncertainty of the polarization measurements.

Figure 5. The $R_{AA}$ measurements from ALICE (black points) and the corrected ones (shaded bands) in Pb+Pb collisions at 5.02 TeV in the HX and CS frame as a function of $p_T$.

3.2. Central rapidity region

To have a more clear picture of the $J/\psi$ production and more insights of the QGP in heavy-ion collisions, understanding the correction of polarization effects in the central rapidity region is also important. There are measurements of the $J/\psi$ polarization in the central rapidity region from the STAR [14] and CMS [15] Collaborations in $p+p$ collisions at $\sqrt{s} = 200$ GeV and 7 TeV, respectively. Figure 6(a) and 6(b) show the polarization measurements and their parametrizations from STAR and CMS, respectively; while
Figs. 7(a) and 7(b) show the $p_T$ spectra from STAR in Au+Au collisions at 200 GeV and CMS in Pb+Pb collisions at 5.02 TeV, respectively.

**Figure 6.** The polarization parameters $\lambda_\theta$, $\lambda_\phi$, and $\lambda_{\theta\phi}$ in $p+p$ collisions as a function of $p_T$ measured from the (a) STAR at 200 GeV and (b) CMS at 7 TeV [14, 15]. The rapidity ranges for these measurements are $|y| < 1.0$ and $|y| < 1.2$ for STAR and CMS, respectively. Black lines are a linear function fits to the data points and dashed lines are linear functions fit to the upper and lower bound of the data points.

However, there is no polarization of $J/\psi$ measured in heavy-ion collisions in this kinematic region. Therefore, to have a comprehensive study of this effect, five extreme configurations are considered to cover the possible polarization phase space: (1) unpolarized, $\lambda_\theta = \lambda_\phi = \lambda_{\theta\phi} = 0$; (2) longitudinally polarized, $\lambda_\theta = -1$, $\lambda_\phi = \lambda_{\theta\phi} = 0$; (3) zero transversely polarized, $\lambda_\theta = +1$, $\lambda_\phi = \lambda_{\theta\phi} = 0$; (4) positively transversely polarized, $\lambda_\theta = +1$, $\lambda_\phi = +1$, $\lambda_{\theta\phi} = 0$; and (5) negatively transversely polarized, $\lambda_\theta = +1$, $\lambda_\phi = -1$, $\lambda_{\theta\phi} = 0$. These choices of five extreme configurations are followed the ATLAS and STAR analyses of quarkonia production in $p+p$ collisions [10, 11, 12].

The same procedures are used as that of in the forward region and the systematic uncertainties from the polarization are assigned from the measurements in $p+p$ collisions and aforementioned five extreme polarization configurations in $A+A$ collisions. The correction factors, $C_{AA(pp)}$, as a function of $p_T$ in the HX and CS frame in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV ($p+p$ collisions at $\sqrt{s} = 200$ GeV) are shown in Fig. 8. It is important to notice that the correction in Au+Au collisions in this kinematic region is extremely large, up to a factor of 6, in low-$p_T$ region ($< 3$ GeV) and sizable, a factor
Figure 7. (a) and (b) are the $p_T$ spectra of $J/\psi$ from STAR in Au+Au collisions at 200 GeV and CMS in Pb+Pb collisions at 5.02 TeV.

Heavy quarkonium plays an important role in understanding the basic properties of the QGP which can be quantitatively studied via the experimental observable $R_{AA}$. In order to have correct interpretation to disentangle the contributions from HNM and CNM effects on the measured $R_{AA}$, all the ingredients in the $R_{AA}$ are needed to be determined carefully. In particular, the invariant yields are usually calculated under the assumption that quarkonium is unpolarized. However, the recent result on the polarization of the $J/\psi$ meson in Pb+Pb collisions from the ALICE Collaboration indicates that $J/\psi$ has
Figure 8. The \( C_{A\Lambda(pp)} \) as a function of \( p_T \) in the HX (left) and CS (right) frame in the central rapidity range (\(|y| < 1.0\)) in \( \text{Au+Au} \) collisions at 200 GeV. The shaded area is due to the uncertainty of the polarization measurements. Different lines depict different polarization assumptions: “flat” is unpolarized, “long” is longitudinally polarized, “trp0” is zero transversely polarized, “trpp” is positively transversely polarized, and “trpm” is negatively transversely polarized. Please see the detailed descriptions on the polarization definitions in the text.

Figure 9. The \( R_{AA} \) measurements from STAR (black points) and the corrected ones (shaded bands) in \( \text{Au+Au} \) collisions at 200 GeV in the HX and CS frame as a function of \( p_T \).
Figure 10. The $C_{AA(pp)}$ as a function of $p_T$ in the HX (left) and CS (right) frame in the central rapidity range ($|y| < 2.4$) in Pb+Pb collisions at 5.02 TeV. The shaded area is due to the uncertainty of the polarization measurements. Different lines depict different polarization assumptions: “flat” is unpolarized, “long” is longitudinally polarized, “trp0” is zero transversely polarized, “trpp” is positively transversely polarized, and “trpm” is negatively transversely polarized. Please see the detailed descriptions on the polarization definitions in the text.

Figure 11. The $R_{AA}$ measurements from CMS (black points) and the corrected ones (shaded bands) in Pb+Pb collisions at 5.02 TeV in the HX and CS frame as a function of $p_T$. 
slight but non-negligible transverse and longitudinal polarization in the HX and CS frames, respectively. This result warns us that the polarization effect on the kinematic acceptance correction might be important, particularly in the low $p_T$ region.

In this paper, we present a systematic study of the polarization effect on the $J/\psi$ $R_{AA}$ in the forward rapidity region based on the recent ALICE and LHCb results, for Pb+Pb and $p+p$ collisions, respectively. The result shows that the correction on the measured $R_{AA}$ with the unpolarized assumption can be up to $\sim 16\%$ in the HX frame in the low $p_T$ regions where the CNM contributes significantly [18]. Additionally, we provide the estimations of possible maximum effects in the central rapidity region at the RHIC and LHC energies. The polarizations of $J/\psi$ in $p+p$ collisions at the RHIC and LHC energies are obtained from the STAR and CMS experiments. Due to the lack of measurement on $J/\psi$ polarization in heavy-ion collisions at these kinematic regions, five extreme cases of the $J/\psi$ polarization are considered. The corrections on the measured $R_{AA}$ in the central rapidity region can be up to a factor of 6 in the low-$p_T$ region ($< 3$ GeV) and $\sim 10\% - 70\%$ in the high-$p_T$ region ($8 - 20$ GeV). Therefore, to provide better understanding on the QGP, using the appropriate polarization assumption in the kinematic acceptance correction is needed. Additionally, having more precise measurements of the quarkonium polarization in heavy-ion collisions is also very important to obtain the full picture of how quarkonium interacts with the QGP.

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