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Polarisation-dependent studies of exclusive J/ψ production in hadron-hadron and lepton-hadron interactions

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We studied polarisation-dependent exclusive J/ψ production in ultraperipheral heavy-ion collisions at RHIC and LHC energies and in eA collisions at EIC energies, in the framework of color glass condensate effective theory. The azimuthal averaged J/ψ production cross section measured by STAR and ALICE is accurately described by our calculation. We further predict significant $\cos 2\phi$ azimuthal asymmetries both in UPCs and in eA collisions, which are attributed to the linearly polarized photon, the double-slit interference effect in photonuclear reactions, and the final state soft photon radiation effect. This study may provide further information on limiting gluon transverse spatial distribution inside large nuclei.

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1. Introduction

As we know, relativistically moving ions will introduce electromagnetic field. This electromagnetic field can be described by equivalent photon approximation (EPA), which was developed by Weizäscker and Williams in 1930s [1, 2], but the idea could be traced back to 1924 by Fermi [3]. In the equivalent photon approximation, the photon probability distribution is proportional to the square of the nuclear charge. For a hadron collider with a high nuclear charge, the luminosity will be very high, but strong interaction dominant in central collisions. Utilizing ultra-peripheral collisions (UPC) to avoid the huge QCD background while maintaining high luminosity is a good choice. In UPC two nucleus physically miss each other, but they still sit in the electromagnetic field induced by the other nucleus. In this way, the only interaction is electromagnetic interaction, so the background is very clean. We predicted that the EPA photons is linearly polarized [4, 5], which can be measured through azimuthal asymmetries in processes such as photon induced dilepton production process. This effect was soon verified by RHIC STAR Collaboration [6], with the measured $|2\langle\cos 4\phi\rangle|$ to be $16.8\% \pm 2.5\%$ and our predicted result to be -16.5% for $2\langle\cos 4\phi\rangle$. This linearly polarized characteristic makes the UPC process an ideal platform for studying the nuclear structure, because in photon-nuclear collision mode of UPC, a photon produced by a nucleus can be used as a probe to detect the 3D structure of the other nucleus. Compared to the traditional nucleon structure study which is in the center of the collision area, UPC has the advantages of clean background and high luminosity as described above, and linearly polarized photons will provide brand-new experimental observable.

In fact, the STAR collaboration has previously reported significant $\cos 2\phi$ and $\cos 4\phi$ asymmetries for ρ^0 meson production in UPCs [7, 8]. These asymmetries result from the linear polarization of the incident photon as well as the unique diffractive pattern of the meson production which depends on the double-slit-like quantum interference effect and the gluon transverse distribution in the nucleus [9, 10].

The research on J/ψ has always been one of the focuses in experiments, not only because of its high cross section, which makes it easily detected, but also due to its appropriate mass. The mass is heavy enough to make perturbative computations reliable, but not so heavy that it prevents access to the saturation regime. The J/ψ production process in UPC has also attracted a lot of experimental interest at the RHIC and LHC. With the coherent photons being linearly polarized and the double-slit-like quantum interference effect mechanism clarified, we studied the polarization dependent diffractive J/ψ production in hadron-hadron and lepton-hadron interactions [11].

2. Linearly polarized photons

Similar to the gluons, the EPA photons can also be formulated in the context of TMD factorization [12]:

$$\int \frac{2dy^- d^2y_\perp}{xP^+(2\pi)^3} e^{ik\cdot y} \langle P|F_+^\mu(0)F_+^\nu(y)|P\rangle\big|_{y^+=0} = \delta_\perp^{\mu\nu} f_1(x,k_\perp^2) + \left(\frac{2k_\perp^\mu k_\perp^\nu}{k_\perp^2} - \delta_\perp^{\mu\nu}\right) h_1^\perp(x,k_\perp^2), \quad (1)$$

Suppose that the nucleus moves along P^+ direction, the dominant component of the gauge potential is A^+ since the other component of A will be suppressed by the Lorentz contraction, so $F_+^\mu \propto k_\perp^\mu A^+$.

Compare both sides of this formula, we can conclude that $f_1(x, k_\perp^2) = h_1^\perp(x, k_\perp^2)$, which means that the photons are highly linearly polarized, just as the gluons in a large nucleus are, which was predicted in Ref.[13]

3. Photoproduction of J/ψ

Besides the linearly polarized photon, the key ingredients for studying the spin effect in the diffractive photo-nuclear production of a vector meson include the following aspects: 1). the color dipole model, 2). the color glass condensate (CGC) theory, which is needed to calculate gluon distribution, 3). joint impact parameter and transverse-momentum dependent cross section, 4). double-slit-like quantum interference effect, and 5). final-state soft photon radiation effect. We will explain these ingredients in detail in this section.

In Fig. 1 we show the illustration Feynman diagram of the J/ψ production in UPC. A photon from nucleus A splits into a quark pair, which can be treated as a color dipole. And this color dipole will interact with the other nucleus through the CGC gluons and finally form a vector meson. Usually, the vector meson will decay, so the production amplitude (boxed with a yellow dashed line in Fig.1) can be written as the convolution of the dipole scattering amplitude and the overlap between the wave function of the photon and vector meson,

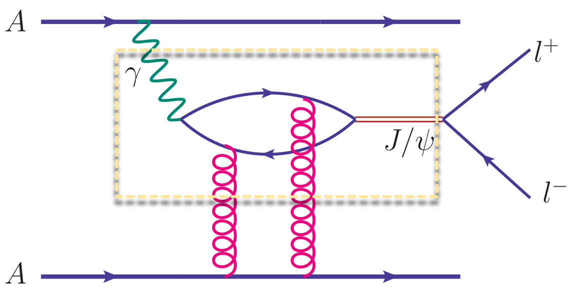


Figure 1: Illustration Feynman diagram for the diffractive J/ψ production in UPC process.

$$\mathcal{A}(\Delta_\perp) = i\int d^2b_\perp e^{i\Delta_\perp\cdot b_\perp}\int \frac{d^2r_\perp}{4\pi}\int_0^1 dz\, \Psi^{\gamma\to q\bar{q}}(r_\perp, z, \epsilon_\perp^\gamma)N(r_\perp, b_\perp)\Psi^{V\to q\bar{q}*}(r_\perp, z, \epsilon_\perp^V), \quad (2)$$

where the variables $-\Delta_\perp$, $\epsilon_\perp^\gamma$, and $\epsilon_\perp^V$ represent the nucleus recoil transverse momentum, and

the magnitudes of transverse polarization vectors for the incident quasi-real photon and final outgoing vector meson, respectively. The dipole-nucleus scattering amplitude $N(r_\perp, b_\perp)$, which represents the amplitude for the scattering of a $q\bar{q}$ dipole of size $r_\perp$ on a target nucleus at the impact parameter $b_\perp$ of the γA collision, is usually expressed in terms of dipole-nucleon scattering amplitude $\mathcal{N}(r_\perp)$ [14–18],

$$N(b_\perp, r_\perp) \approx 1 - \left[1 - 2\pi B_p T_A(b_\perp)\mathcal{N}(r_\perp)\right]^A \quad (3)$$

where $B_p = 4\,\mathrm{GeV}^{-1}$. The dipole-nucleon scattering amplitude is parametrized as [16–20],

$$\mathcal{N}(r_\perp) = \left\{1 - \exp\left[-r_\perp^2 G(x_g, r_\perp)\right]\right\} \quad (4)$$

Here G is proportional to the DGLAP evolved gluon distribution in the Bartels, Golec-Biernat and Kowalski (BGBK) parametrization [19],

$$G(x_g, r_\perp) = \frac{1}{2\pi B_p} \frac{\pi^2}{2N_c} \alpha_s \left(\mu_0^2 + \frac{C}{r_\perp^2}\right) x f_g \left(x_g, \mu_0^2 + \frac{C}{r_\perp^2}\right) \tag{5}$$

with C chosen as 4 and $\mu_0^2 = 1.17\,\mathrm{GeV}^2$ resulting from the fit [15] that describes the HERA data quite well.

The diffraction process of photo-nuclear reactions is divided into two cases depending on whether the target is broken. If it is not broken, the target nucleus interacts with the color dipole as a whole, and the nucleus remains in the ground state after the interaction. In this case, the amplitude of all nucleons in the nucleus needs to be averaged over the position and then squared. This is called coherent production. Usually, when the recoil transverse momentum of the nuclear target is small, the Compton wavelength corresponding to the exchanged gluon is large, so it is coupled with the color nuclear matter in the entire nuclear target, and the main production is coherent production. For gold nuclei, the typical coherent transverse momentum is $\Delta_\perp \sim 1/R \approx 30$ MeV. On the other hand, if the nucleus is broken but still undergoes quasi-elastic scattering, the nucleus is in an excited state after the interaction, which is called incoherent production. In this case the amplitude of all nucleons in the nucleus needs to be squared first and then averaged over the position when calculating the cross section. The coherent and incoherent amplitude can be expressed as

$$\begin{aligned}
\mathcal{A}_{co}(x_g, \Delta_\perp) &= \int d^2 b_\perp e^{-i\Delta_\perp \cdot b_\perp} \int \frac{d^2 r_\perp}{4\pi} N(r_\perp, b_\perp)[\Phi^* K](r_\perp), \\
\mathcal{A}_{in}(x_g, \Delta_\perp) &= \sqrt{A} 2\pi B_p e^{-B_p \Delta_\perp^2/2} \left[\int \frac{d^2 r_\perp}{4\pi} \mathcal{N}(r_\perp) e^{-2\pi(A-1)B_p T_A(b_\perp)\mathcal{N}(r_\perp)} [\Phi^* K](r_\perp)\right],
\end{aligned} \tag{6}$$

where $[\Phi^* K]$ denotes the overlap of the virtual photon wave function and the vector meson wave function,

$$[\Phi^* K](r_\perp) = \frac{N_c e e_q}{\pi} \int_0^1 dz \left\{ m_q^2 \Phi^*(|r_\perp|, z) K_0(|r_\perp| e_f) + \left[z^2 + (1-z)^2\right] \frac{\partial \Phi^*(|r_\perp|, z)}{\partial |r_\perp|} \frac{\partial K_0(|r_\perp| e_f)}{\partial |r_\perp|} \right\}. \tag{7}$$

where $\Phi^*(|r_\perp|, z)$ is the scalar part of the vector meson wave function, and in the numerical calculation we use the "Gaus-LC" wave function which taken from Ref. [14, 15],

$$\Phi^*(|r_\perp|, z) = \beta z(1-z) \exp\left[-\frac{r_\perp^2}{2R_\perp^2}\right], \tag{8}$$

with $\beta = 1.23$, $R_\perp^2 = 6.5\,\mathrm{GeV}^{-2}$ for J/ψ meson.

A unique aspect of the diffractive vector meson production in heavy ion collisions is the double-slit interference effect. When the mass of the vector meson is much larger than the reciprocal of the nuclear target radius, the vector meson can be approximately regarded as locally produced in the transverse plane of the nuclear target. This is easy to satisfy because the mass of the vector meson (e.g., $M_\rho \sim 770$ MeV, $M_{J/\psi} \sim 3.1$ GeV) is much greater than $1/R$. At a given transverse position $b_\perp$, which corresponds to the transverse momentum of J/ψ being $q_\perp$ through Fourier transform, the production amplitude of the vector meson is proportional to the electromagnetic potential excited by one of the colliding nucleons and the gluon matter density produced by the other colliding nucleus at this transverse position. The two nuclei take turns playing the role of the nucleus target and the electromagnetic source, and we cannot distinguish these two different situations by measuring the final-state distribution. Therefore, we should first add these two amplitudes together and then take the square, which will result in interference terms. This interference effect is very similar to the Young's double-slit interference effect and is crucial for correctly describing the experimental phenomenon [10]. The illustration diagram is shown in Fig. 2. The final cross section will depend simultaneously on the impact parameters and the transverse momentum of J/ψ, which is the joint $\tilde{b}_\perp$ and $q_\perp$ dependent picture as we mentioned at the beginning of this section.

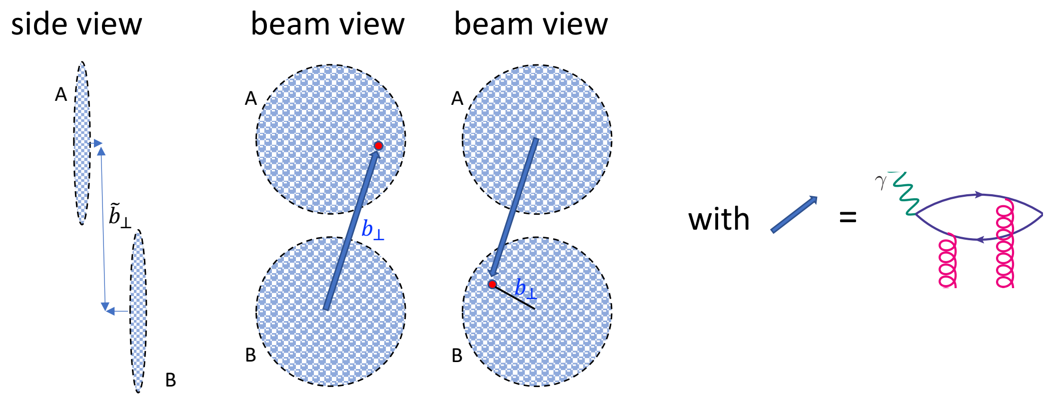


Figure 2: Two nuclei A and B take turns being the source of photons and targets, which results in the Fermi-scale double-slit-like interference. $\tilde{b}_\perp$ is the transverse distance between the center of the two colliding nuclei, and $b_\perp$ is the position of the produced vector meson with respect to the center of B.

According to the analysis above we can write down the joint $\tilde{b}_\perp$ and $q_\perp$ dependent cross section,

$$
\begin{aligned}
\frac{d\sigma}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2d^2\tilde{b}_\perp} &= \frac{C}{2(2\pi)^7}\frac{24e^4e_q^2}{(Q^2-M^2)^2+M^2\Gamma^2}\frac{|\phi(0)|^2}{M} \\
&\times\int d^2\Delta_\perp d^2k_\perp d^2k'_\perp \delta^2(k_\perp+\Delta_\perp-q_\perp)\left[\hat{k}'_\perp\cdot\hat{k}_\perp-\frac{4(P_\perp\cdot\hat{k}_\perp)(P_\perp\cdot\hat{k}'_\perp)}{M^2}\right] \\
&\times\Bigg\{\int d^2b_\perp e^{i\tilde{b}_\perp\cdot(k'_\perp-k_\perp)}\left[T_A(b_\perp)\mathcal{A}_{in}(x_2,\Delta_\perp)\mathcal{A}^*_{in}(x_2,\Delta'_\perp)\mathcal{F}(x_1,k_\perp)\mathcal{F}(x_1,k'_\perp)+(A\leftrightarrow B)\right] \\
&\quad+\left[e^{i\tilde{b}_\perp\cdot(k'_\perp-k_\perp)}\mathcal{A}_{co}(x_2,\Delta_\perp)\mathcal{A}^*_{co}(x_2,\Delta'_\perp)\mathcal{F}(x_1,k_\perp)\mathcal{F}(x_1,k'_\perp)\right] \\
&\quad+\left[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp-\Delta_\perp)}\mathcal{A}_{co}(x_1,\Delta_\perp)\mathcal{A}^*_{co}(x_1,\Delta'_\perp)\mathcal{F}(x_2,k_\perp)\mathcal{F}(x_2,k'_\perp)\right] \\
&\quad+\left[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp-k_\perp)}\mathcal{A}_{co}(x_2,\Delta_\perp)\mathcal{A}^*_{co}(x_1,\Delta'_\perp)\mathcal{F}(x_1,k_\perp)\mathcal{F}(x_2,k'_\perp)\right] \\
&\quad+\left[e^{i\tilde{b}_\perp\cdot(k'_\perp-\Delta_\perp)}\mathcal{A}_{co}(x_1,\Delta_\perp)\mathcal{A}^*_{co}(x_2,\Delta'_\perp)\mathcal{F}(x_2,k_\perp)\mathcal{F}(x_1,k'_\perp)\right]\Bigg\}. \qquad (9)
\end{aligned}
$$

where $p_{1\perp}$ and $p_{2\perp}$, y_1 and y_2 are the momenta and rapidities of the final state leptons, respectively, and $P_\perp$ is defined as $P_\perp=(p_{1\perp}-p_{2\perp})/2$. A prefactor C is introduced here to account for the real part of the amplitude as well as the skewness effect, which is fixed to be 1.5 for RHIC energy, 1.4 for LHC energy, and 1.2 for EIC energy, following the prescription described in Ref. [21]. Q is the invariant mass of the dilepton system, $\phi(0)$ is the wave function for the charm quark inside the J/ψ at the origin. M and Γ are the mass and decay width of the J/ψ, respectively. $k_\perp$, $\Delta_\perp$, $k'_\perp$ and $\Delta'_\perp$ are the incoming photon's transverse momenta and the nucleus recoil transverse momenta in the amplitude and the conjugate amplitude, respectively. The unit transverse vector $\hat{k}_\perp = k_\perp/|k_\perp|$ is parallel to the incident coherent photon's polarization vector $\epsilon^\gamma_\perp$. The longitudinal momentum fractions are constrained by $x_1 = \sqrt{\frac{P_\perp^2+m^2}{S}}(e^{y_1} + e^{y_2})$ and $x_2 = \sqrt{\frac{P_\perp^2+m^2}{S}}(e^{-y_1} + e^{-y_2})$ with m and S being the lepton mass and center of mass energy of the AA collider. $\mathcal{F}(x, k_\perp)$ describes the probability amplitude for finding a photon that carries a certain momentum, which in the equivalent photon approximation reads,

$$\mathcal{F}(x, k_\perp) = \frac{Z\sqrt{\alpha_e}}{\pi}|k_\perp|\frac{F(k_\perp^2 + x^2M_p^2)}{(k_\perp^2 + x^2M_p^2)}, \tag{10}$$

where M_p is the proton mass and F is the conventional Woods-Saxon distribution.

The term $\left[\hat{k}'_\perp \cdot \hat{k}_\perp - \frac{4(P_\perp\cdot\hat{k}_\perp)(P_\perp\cdot\hat{k}'_\perp)}{M^2}\right]$ in Eq.(9) includes the azimuthal asymmetry information of the decay products, which induced by the spin correlation between the polarization and transverse momentum of the J/ψ which transferred from the linearly polarized incident photon.

On the other hand, at relatively high transverse momentum , the contribution from final state photon radiation dominant. This effect will not only change the magnitude of the unpolarized cross section and the cross section corresponding to the $\cos 2\phi$ term, but will also cause $\cos n\phi$ ($n = 2, 4, 6...$) asymmetry by itself [22, 23]. The reason is that the soft photon tends to be aligned with the lepton which it emitted from, so the recoiled lepton will have an equivalent orbital angular momentum. This is another origin of the azimuthal asymmetries. This effect can be resummed to all orders when $P_\perp \gg m$ with the cross section takes the form [22–25],

$$\frac{d\sigma(q_\perp)}{d\mathcal{P.S.}} = \int \frac{d^2r_\perp}{(2\pi)^2}\left[1 - \frac{2\alpha_e c_2}{\pi}\cos 2\phi_r + \frac{\alpha_e c_4}{\pi}\cos 4\phi_r + ...\right]e^{ir_\perp\cdot q_\perp}e^{-Sud(r_\perp)}$$
$$\times \int d^2q'_\perp e^{ir_\perp\cdot q'_\perp}\frac{d\sigma(q'_\perp)}{d\mathcal{P.S.}}. \tag{11}$$

where ϕ_r is the angle between $r_\perp$ and $P_\perp$. The Sudakov factor at one loop is given by [22, 23],

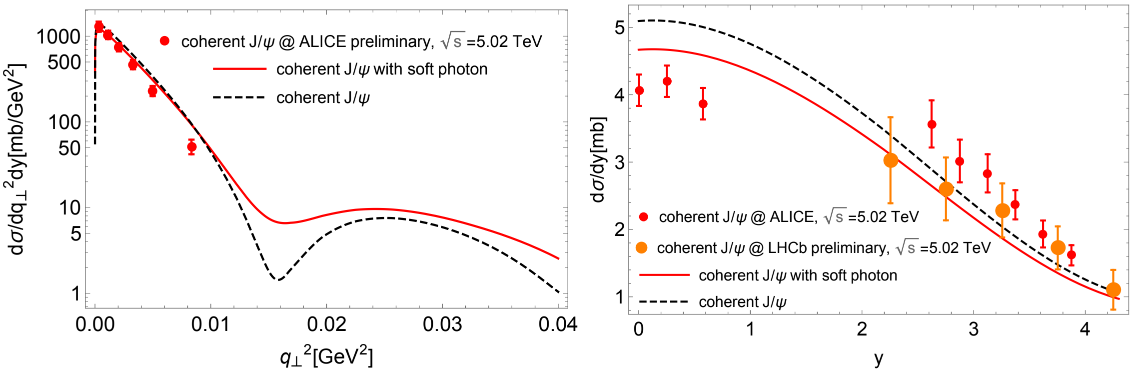
$$Sud(r_\perp) = \frac{\alpha_e}{\pi}\ln\frac{Q^2}{m^2}\ln\frac{P_\perp^2}{\mu_r^2} \tag{12}$$

with $\mu_r = 2e^{-\gamma_E}/|r_\perp|$, and $c_0 \approx \ln\frac{M^2}{m^2}$, $c_2 \approx \ln\frac{M^2}{m^2} - 4\ln 2$ and $c_4 \approx \ln\frac{M^2}{m^2} - 4$ when $y_1 = y_2$. The rapidity dependence of the c_i coefficient is quite mild for RHIC and LHC kinematics and is therefore ignored in our calculation.

4. Numerical calculation

With the theoretical setup we previously described, we present numerical results in this section. For the unrestricted UPC, the impact parameter $\tilde{b}_\perp$ is integrated from $2R_A$ to ∞. In Fig.3 we show the unpolarized differential cross section of diffractive J/ψ photoproduction. To compare with the LHC data, we integrate over the rapidity and then average over the region [-0.8, 0.8] in Fig.3(a).

The theoretical result at low transverse momentum fit the experimental data quite well. At larger transverse momentum, for example, larger than about 100 MeV, the soft photon radiation dominates the contribution. The azimuthally averaged differential cross section as a function of the J/ψ rapidity is shown in Fig.3(b). It is clear that the estimation is larger than the data at small rapidity, but if we take into account the soft photon radiation, the curve moves closer to the data.



(a) (b)

Figure 3: Azimuthal averaged cross section of coherent J/ψ production in unrestricted UPCs at LHC energies. (a). As a function of $q_\perp^2$ with the rapidity of the J/ψ being in the range [-0.8, 0.8], comparing with the ALICE data in Ref.[26]; (b). As a function of the rapidity of J/ψ with the transverse momentum of the J/ψ being integrated over the range [0, 0.2] GeV, comparing with the data of ALICE in Refs. [27, 28] and LHCb in Ref. [29]

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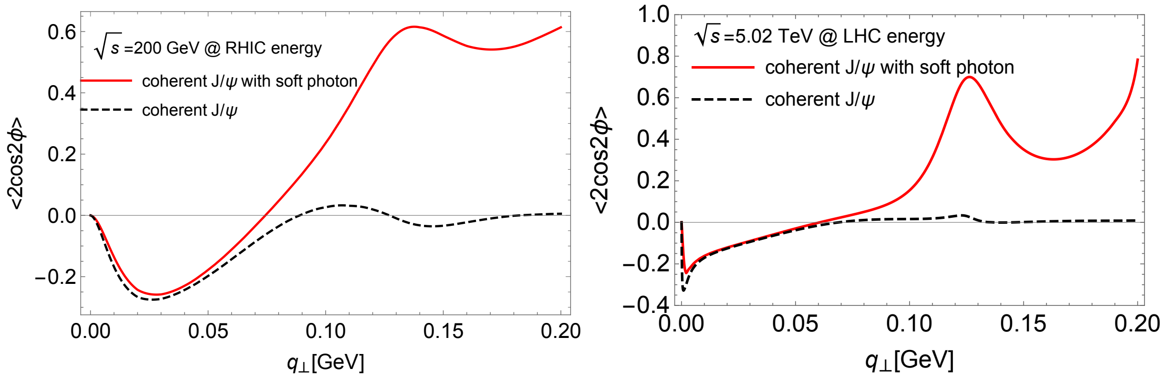
We give the $\cos 2\phi$ azimuthal asymmetry for J/ψ production in Fig.4 and 5, covering the RHIC, LHC and EIC energies. Notice that when performing calculation for EIC, the rapidities are defined in the lab frame and the longitudinal momentum fractions become $x_1 = \frac{\sqrt{P_\perp^2+m^2}}{2E_e}(e^{y_1}+e^{y_2})$, $x_2 = \frac{\sqrt{P_\perp^2+m^2}}{2E_A}(e^{-y_1}+e^{-y_2})$, with the electron beam and heavy-ion beam energies being 18 GeV and 100 GeV, respectively. Furthermore the impact parameter is integrated from 0 to infinity, and the last three terms in Eq.(9) do not contribute due to the absence of interference effect in lepton-hadron collisions. One can see that the basic difference among these three figures is that at small $q_\perp$, there are peaks for RHIC and LHC but no peak for EIC. That's because the interference effect is only remarkable at hadron colliders but absent at electron-hadron colliders. This unique characteristic would be interesting to be further tested in experiments. The peaks at large $q_\perp$ are induced by the linearly polarized photon. By taking into account the soft photon radiation contribution, the shape of the curves change a lot at large transverse momentum. This is consistent with the argument that soft photon radiation dominant at relatively large $q_\perp$.

5. Summary

We have studied the J/ψ exclusive production process in UPCs at RHIC and LHC, and at EIC. The results show that the cross section estimations are consistent with LHC measurements, and we predicted large $\cos 2\phi$ asymmetries in all these colliders. In the theoretical calculation, the three



(a) (b)

Figure 4: The $\cos 2\phi$ azimuthal asymmetry as a function of the transverse momentum in coherent J/ψ production in unrestricted UPCs at RHIC and LHC energies. (a). At RHIC energy, the J/ψ is reconstructed via the decay mode $J/\psi \to e^+e^-$, with the rapidity of e^+e^- being integrated over the range [-1, 1]; (b). At LHC energy, the J/ψ is reconstructed via the decay mode $J/\psi \to \mu^+\mu^-$, with the rapidity of $\mu^+\mu^-$ being integrated over the range [-0.8,0.8].

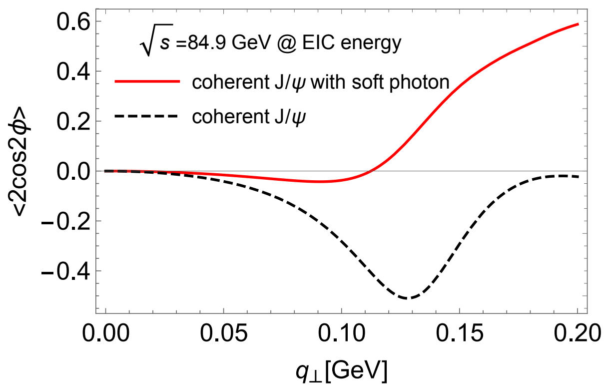


Figure 5: The $\cos 2\phi$ azimuthal asymmetry of the coherent J/ψ photoproduction in eA collisions at EIC energy. The rapidities of the J/ψ and its decay product di-electron pair are integrated over the range [2,3] in the Lab frame. The transverse momentum of the quasi-real photons emitted from the electron is required to be lower than 0.1 GeV.

ingredients, the linearly polarized photon, the double-slit-like quantum interference effect, and the final state soft photon radiation, all play important roles. Due to the interference effect, the shapes of the azimuthal asymmetry curves are different at AA and eA or pA collisions, which makes it very interesting to be tested in the future. And because the azimuthal asymmetries are sensitive to nuclear geometry, they may provide complementary method to extract spatial gluon distribution.

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