Probing the linear polarization of photons in ultraperipheral heavy ion collisions

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We propose to measure the linear polarization of the external electromagnetic fields of a relativistic heavy ion through azimuthal asymmetries in dilepton production in ultraperipheral collisions. The asymmetries estimated with the equivalent photon approximation are shown to be sizable.

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I. INTRODUCTION

Transverse momentum dependent(TMD) parton distribution function [1] is one of the most powerful theoretical tools that are utilized to explore the three-dimensional imaging of nucleon/nuclei. Among many TMD parton distributions, the linearly polarized gluon distribution [2] has received growing attentions in recent years. It describes the correlation of gluon transverse momentum and its polarization vector inside an unpolarized nucleon or nucleus. It is of particular interest to study linearly polarized gluon distribution at small $x$ [3, 4], as it is predicated to grow equally rapidly towards small $x$ as compared to the unpolarized gluon distribution in the dilute limit. In the saturation limit, the dipole type linearly polarized gluon distribution and the dipole type unpolarized gluon distribution remain identical, whereas the linearly polarization of Weizsäcker-Williams gluons is suppressed. Though it has been found promising to probe the linearly polarized gluon distribution by measuring $\cos 2\phi$ azimuthal asymmetry for two particle production in various high energy scattering processes at RHIC, LHC, or a future Electron-Ion Collider (EIC) [3–13], this gluon distribution so far has not yet been studied experimentally.

In analogy to the QCD case, one also can define a linearly polarized photon distribution for an unpolarized nucleon or nuclei target, which can be accessed by measuring the azimuthal asymmetries in di-lepton production in hadron-hadron collisions [8]. However, it is not very practical to extract the polarized photon distribution in hadronic reactions due to the di-lepton Drell-Yan production background. Instead, the cleaner and more promising way to probe the linearly polarization of photons would be the purely electromagnetic two photon reaction $\gamma\gamma \rightarrow l^+l^-$ in heavy-ion ultraperipheral collisions (UPCs) where the hadronic background is absent. Though photon-photon collisions in the UPC case has been extensively studied [14–27], to the best of our knowledge, the polarization dependent effects have not yet been addressed so far. Both the unpolarized photon distribution and the polarized one in the UPC case can be determined using the external classical field approximation [14, 15]. It is not surprising to find that they are identical to each other in this approximation, just like the relation established between the dipole amplitude and the polarized gluon distributions [3, 28–30]. In the present paper, we propose to test this theoretical predication by measuring $\cos 2\phi$ and $\cos 4\phi$ asymmetries in di-lepton production induced by the linearly polarized photon distribution.

Recently, the STAR collaboration at RHIC [27] and the ATLAS collaboration [26] at LHC have carried out the measurements of transverse momentum ($q_\perp$) spectra of lepton pairs for various invariant mass regions with high precision. The significant $q_\perp$ broadening effect found in hadronic heavy-ion collisions in comparison to those in UPCs has stimulated a lot of theoretical progress [20–24], as the transverse momentum broadening effect plays a crucial role in understanding the properties of the hot medium created in heavy-ion collisions. Moreover, a small tail of events at high transverse momentum observed by the ATLAS offers a clean way to test the resummation formalism for the QED case [22]. Here we would like to point out that it is doable to extract linearly polarized photon distribution by analyzing the angular modulations of di-lepton production cross section from the existed experimental data collected by the STAR collaboration and the ATLAS collaboration. This analysis can be considered as a new way to test how reliable the equivalent photon approximation widely used for computing UPCs observables is. Furthermore, it sets a baseline for studying the electromagnetic properties of QGP, since this contribution yields the asymmetries in hadronic heavy-ion collisions as well.

The paper is structured as follows. In the next section, we compute the azimuthal dependent cross section for the purely electromagnetic di-lepton production in terms of the linearly polarized photon distributions and the unpolarized photon distribution. We then present numerical results incorporating the Sudakov suppression effect for the asymmetries in the kinematical regions where the corresponding measurements have been carried out at RHIC and LHC. A summary of our findings and conclusions is presented in Sec.III.
II. AZIMUTHAL ASYMMETRIES IN DI-LEPTON PRODUCTION IN UPCs

Di-lepton production in UPCs is well described by two photons reaction at the lowest order QED,

$$\gamma(x_1P + k_{1\perp}) + \gamma(x_2\bar{P} + k_{2\perp}) \rightarrow l^{+}(p_1) + l^{-}(p_2)$$  \hspace{1cm} (1)

The leptons are produced nearly back-to-back in azimuthal with total transverse momentum \(q_\perp \equiv p_{1\perp} + p_{2\perp} = k_{1\perp} + k_{2\perp}\) being much smaller than the individual lepton transverse momenta \(p_{1\perp}\) or \(p_{2\perp}\). Since there are two well separated scales in this process, the application of TMD factorization is justified. If the calculation is formulated in TMD factorization, the two leading power photon TMDs: the normal unpolarized photon TMD and the linearly polarized photon TMD contribute to the differential cross section. They are formally defined as the following,

$$\int \frac{dy^-d^2y_\perp}{xP^+(2\pi)^3} e^{ik\cdot y} \langle P| F^\mu_\perp(x) F^\nu_\perp(y) |P \rangle |_{y^-=0} = \delta \overline{\gamma}_1 f_1(x, k_{1\perp}^2) - \left( \frac{2k_{1\perp}^\mu k_{1\perp}^\nu}{k_{1\perp}^2} + \delta \overline{\gamma}_1 \right) h_{1\gamma}^{\perp}(x, k_{1\perp}^2),$$  \hspace{1cm} (2)

where two photon TMDs, \(f_1^\gamma\) and \(h_{1\gamma}^{\perp}\), are the unpolarized and linearly polarized photon distribution, respectively. This matrix element definition for photon TMDs bears much resemblance to those for the gluon ones [2]. However, one should note that there is no need to add gauge link for ensuring gauge invariance since photon does not carry charge. As such, the light cone singularity is absent for the photon TMD case.

One can easily recover the azimuthal dependent cross section for lepton pair production from the results for heavy quark pair production existed in the literatures [3, 4]. It is of course also straightforward to compute the cross section at the lowest order QED, which reads,

$$\frac{d\sigma}{dp_{1\perp}^2 dp_{2\perp}^2 dy_1 dy_2} = \frac{2\alpha^2}{Q^4} [A \cos 2\phi + B \cos 4\phi]$$  \hspace{1cm} (3)

where \(\phi\) is the angle between transverse momenta \(q_{\perp}\) and \(P_{\perp} = (p_{1\perp} - p_{2\perp})/2\). \(y_1\) and \(y_2\) are leptons rapidities, respectively. \(Q\) is the invariant mass of the lepton pair. The coefficients \(A\), \(B\) and \(C\) contain convolutions of photon TMDs,

$$A = \frac{(Q^2 - 2m^2)m^2 + (Q^2 - 2P_{\perp}^2)P_{\perp}^2}{(m^2 + P_{\perp}^2)^2} x_1 x_2 \int d^2k_{1\perp} d^2k_{2\perp} \delta^2(q_{\perp} - k_{1\perp} - k_{2\perp}) f_1^\perp(x_1, k_{1\perp}^2) f_1^\perp(x_2, k_{2\perp}^2)$$

$$+ \frac{m^4}{(m^2 + P_{\perp}^2)^2} x_1 x_2 \int d^2k_{1\perp} d^2k_{2\perp} \delta^2(q_{\perp} - k_{1\perp} - k_{2\perp}) \left[ 2(\hat{k}_{1\perp} \cdot \hat{k}_{2\perp})^2 - 1 \right] h_{1\gamma}^{\perp}(x_1, k_{1\perp}^2) h_{1\gamma}^{\perp}(x_2, k_{2\perp}^2)$$  \hspace{1cm} (4)

and

$$B = \frac{4m^2P_{\perp}^2}{(m^2 + P_{\perp}^2)^2} x_1 x_2 \int d^2k_{1\perp} d^2k_{2\perp} \delta^2(q_{\perp} - k_{1\perp} - k_{2\perp})$$

$$\times \left\{ 2(\hat{k}_{2\perp} \cdot \hat{q}_{\perp})^2 - 1 \right\} f_1^\perp(x_1, k_{1\perp}^2) h_{1\gamma}^{\perp}(x_2, k_{2\perp}^2) + \left[ 2(\hat{k}_{1\perp} \cdot \hat{q}_{\perp})^2 - 1 \right] h_{1\gamma}^{\perp}(x_1, k_{1\perp}^2) f_1^\perp(x_2, k_{2\perp}^2)$$  \hspace{1cm} (5)

and

$$C = \frac{-2P_{\perp}^4}{(m^2 + P_{\perp}^2)^2} x_1 x_2 \int d^2k_{1\perp} d^2k_{2\perp} \delta^2(q_{\perp} - k_{1\perp} - k_{2\perp})$$

$$\times \left[ 2 \left( 2(\hat{k}_{2\perp} \cdot \hat{q}_{\perp})(\hat{k}_{1\perp} \cdot \hat{q}_{\perp}) - \hat{k}_{1\perp} \cdot \hat{k}_{2\perp} \right)^2 - 1 \right] h_{1\gamma}^{\perp}(x_1, k_{1\perp}^2) h_{1\gamma}^{\perp}(x_2, k_{2\perp}^2)$$  \hspace{1cm} (6)

where \(\hat{k}_{1\perp}\) and \(\hat{q}_{\perp}\) are unit vectors defined as \(\hat{k}_{1\perp} = k_{1\perp}/|k_{1\perp}|\) and \(\hat{q}_{\perp} = q_{\perp}/|q_{\perp}|\) respectively. The incoming photons longitudinal momenta fraction are fixed by the external kinematics according to \(x_1 = \sqrt{\frac{p_{\perp}^2 + m^2}{s}} (e^{y_1} + e^{-y_1})\) and \(x_2 = \sqrt{\frac{p_{\perp}^2 + m^2}{s}} (e^{-y_1} + e^{-y_2})\) with \(m\) being lepton mass.

When going beyond the lowest order QED, the Sudakov type logarithm terms \(\frac{\alpha^2}{2\pi} \ln^2 \frac{Q^2}{Q_T^2}\) will arise from the final state soft photon radiation in higher order calculation. In particular, at LHC energy, the logarithm terms are sizeable and need to be resummed to all orders to improve the convergence of the perturbation series. This can be achieved by applying the Collins-Soper-Sterman(CSS) [7] formalism. The CSS formalism is formulated in the impact parameter
space in which the large logarithms are resummed into an exponentiation known as the Sudakov factor. By taking into account the Sudakov factor, the coefficients $\mathcal{A}$ and $\mathcal{C}$ after the Fourier transform can be rewritten as,

$$\mathcal{A} = \frac{(Q^2 - 2P_0^2)}{P_0^2} \times \int d^2 b e^{i q_\perp \cdot b_\perp} e^{-S(\mu_b^2, Q^2)} \right.$$  
$$\left. \times \int |k_{1\perp}| J_0(|k_{1\perp}| |b_1|) f_1^\gamma(x_1, k_{1\perp}^2) d|k_{1\perp}| \int |k_{2\perp}| J_0(|k_{2\perp}| |b_2|) f_1^\gamma(x_2, k_{2\perp}^2) d|k_{2\perp}| \right.$$  

$$\mathcal{C} = -2x_1x_2 \int d^2 b e^{i q_\perp \cdot b_\perp} \cos(4\theta) e^{-S(\mu_b^2, Q^2)} \right.$$  
$$\left. \times \int |k_{1\perp}| J_2(|k_{1\perp}| |b_1|) h_1^\perp(\gamma(x_1, k_{1\perp}^2) d|k_{1\perp}| \int |k_{2\perp}| J_2(|k_{2\perp}| |b_2|) h_1^\perp(\gamma(x_2, k_{2\perp}^2) d|k_{2\perp}| \right.$$  

where $\theta$ is the angle between $q_\perp$ and $b_\perp$, and $\mu_b = 2e^{-\gamma e} / |b_1|$. At LHC energy, one can neglect the contributions suppressed by the power of $m_\mu^2$ in the hard part as shown in the above formulas. Note that cos $2\phi$ asymmetry vanishes at LHC energy under this approximation because it is proportional to $dQ/Q^2$. However, muon mass can not be neglected when computing both cos $2\phi$ and cos $4\phi$ asymmetries at RHIC energy. At one loop order, the Sudakov factor is given by $[22]$, 

$$S(\mu_b^2, Q^2) = \left\{ \begin{array}{ll}
\frac{\alpha_e}{2\pi} \ln^2 \frac{Q^2}{\mu_b^2}, & \mu_b > m_\mu \\
\frac{\alpha_e}{2\pi} \ln \frac{Q^2}{m_\mu^2} \left[ \ln \frac{Q^2}{\mu_b^2} + \ln \frac{m_\mu}{\mu_b} \right], & \mu_b < m_\mu
\end{array} \right.$$  

It has been shown that this Sudakov factor plays a crucial role in correctly reproducing the high $q_\perp$ tail observed by the ATLAS collaboration $[22]$. 

The distribution of photons coherently generated by the charge source inside relativistic nuclei is commonly computed with the Weizsäcker-Williams method. This quasi-classical method also can be used to determine the linearly polarized photon distribution following the similar derivation that relates the dipole amplitude to the various polarized gluon distributions $[3, 28, 30]$. Supposing that a nuclei moves along $P^+$ direction, the dominant component of the gauge potential is $A^+$ and other components are suppressed by the Lorentz contraction factor $\gamma$. Based on this observation, after taking partial integration the photon field strength tensor is approximated as $F^\mu_+ F^-_+ \propto k_{1\perp} k_{2\perp} A^+ A^+$, which implies the relation,

$$f_1^\gamma(x, k_{1\perp}^2) = h_1^\perp(\gamma(x, k_{1\perp}^2))$$

In the equivalent photon approximation, one then has $[14, 13]$,

$$\left. x f_1^\gamma(x, k_{1\perp}^2) = x h_1^\perp(x, k_{1\perp}^2) = \frac{Z^2 \alpha_e k_{1\perp}}{\pi^2} \left[ F\left(\frac{k_{1\perp}^2 + x^2 M_\mu^2}{k_{1\perp}^2 + x^2 M_\mu^2}\right) \right]^2 \right.$$  

where $Z$ is the nuclear charge number, and $F$ is the nucleon charge form factor. $M_\mu$ is proton mass. The form factor is often parameterized using the Woods-Saxon distribution,

$$F(\vec{k}^2) = \int d^3 r e^{i \vec{k} \cdot \vec{r}} \frac{\rho_0}{1 + \exp[(r - R_{WS})/d]}$$

where the radius $R_{WS}(\text{Au}: 6.38\text{fm}, \text{pb}: 6.62\text{fm})$ and the skin depth $d(\text{Au}: 0.535\text{fm}, \text{Pb}: 0.546\text{fm})$. $\rho_0$ is the normalization factor. Alternatively, one can use the form factor in momentum space from the STARlight MC generator $[13]$,

$$F(|\vec{k}|) = \frac{4\pi \rho_0}{|\vec{k}|^3 A} \left[ \sin(|\vec{k}| R_A) - |\vec{k}| R_A \cos(|\vec{k}| R_A) \right] \frac{1}{a^2 k^2 + 1}$$

where $R_A = 1.1 A^{1/3}\text{fm}$, and $a = 0.7\text{fm}$. This parametrization numerically is very close to the Woods-Saxon distribution, and will be used in our numerical evaluation. With all these ingredients, we are ready to perform numerical study of the azimuthal asymmetries in lepton pair production in UPCs.
The numerical results for the computed azimuthal asymmetries in the different kinematical regions are presented in Figs. [1-4]. Here the azimuthal asymmetries, i.e. the average value of $\cos(2\phi)$ and $\cos(4\phi)$ are defined as,

$$\langle \cos(2\phi) \rangle = \frac{\int \frac{d\sigma}{dP.S.} \cos(2\phi) dP.S.}{\int \frac{d\sigma}{dP.S.} dP.S.} \quad (13)$$

$$\langle \cos(4\phi) \rangle = \frac{\int \frac{d\sigma}{dP.S.} \cos(4\phi) dP.S.}{\int \frac{d\sigma}{dP.S.} dP.S.} \quad (14)$$

As the $\cos(2\phi)$ azimuthal asymmetry is suppressed by the power of $m^2/P^2_\perp$, it is only sizable for di-muon production at RHIC energy. We plot the $\cos(2\phi)$ asymmetry for muon pair production at mid-rapidity as the function of the total transverse momentum $q_\perp$ for three different invariant mass regions at the center mass energy $\sqrt{s} = 200\text{GeV}$. Obviously, the asymmetry decreases with increasing invariant mass as its power behavior indicates. In the lowest invariant mass region $M_{\mu\mu} \in [0.4, 0.76] \text{GeV}$, the asymmetry reaches a maximal value of 7% percent around $q_\perp = 110\text{MeV}$.

![FIG. 1: Estimates of the $\cos 2\phi$ asymmetry as the function of $q_\perp$ for the different muon pair mass regions 0.4-0.76 GeV, 0.76-1.2 GeV and 1.2-2.6 GeV at $\sqrt{s} = 200 \text{GeV}$. The muon and anti-muon rapidities are integrated over the regions [-1,1].](image)

For the same kinematical regions at RHIC, we also plot the $\cos 4\phi$ asymmetry for electron pair and muon pair production. The asymmetry grows with increasing $q_\perp$ until it reaches a maximal value at total transverse momentum around $120\text{MeV}$. The maximal value of the asymmetry is about 20% for electron pair production. The $\cos 4\phi$ asymmetry for di-muon production is slightly smaller than that for electron pair production in the same kinematical region. One sees that the $\cos 4\phi$ asymmetry drops rather fast at relatively large transverse momentum($>120\text{MeV}$).

The curve for the $\cos 4\phi$ asymmetry for di-muon production at LHC is presented in Fig.4. The the $q_\perp$ dependence of the asymmetry is similar to these for RHIC energy. The maximal size of the asymmetry is about 9% for the invariant mass region [4-45]GeV. We further found that the Sudakov suppression effect due to final state soft photon radiation reduce the asymmetry significantly at relatively large $q_\perp$ as compared to the lowest order calculation. This may serve as a very clean test of the resummation formalism for the QED case.

### III. CONCLUSIONS

The unpolarized photon distribution used to compute physical observables in ultraperipheral heavy ion collisions is commonly determined using the classical external electromagnetic fields of a relativistic charged nuclei. Applying this quasi-classical method to the polarized case, one easily finds that the linearly polarized photon distribution is identical
FIG. 2: Estimates of the $\cos 4\phi$ asymmetry as the function of $q_\perp$ for the different di-electron invariant mass regions 0.4-0.76 GeV, 0.76-1.2 GeV and 1.2-2.6 GeV at $\sqrt{s} = 200$ GeV. The electron and positron rapidities are integrated over the regions [-1,1].

FIG. 3: Estimates of the $\cos 4\phi$ asymmetry as the function of $q_\perp$ for the different di-muon mass regions 0.4-0.76 GeV, 0.76-1.2 GeV and 1.2-2.6 GeV at $\sqrt{s} = 200$ GeV. The muon and anti-muon rapidities are integrated over the regions [-1,1].

to the normal unpolarized photon distribution. The linearly polarized photon distribution can be cleanly probed through the $\cos 2\phi$ and $\cos 4\phi$ azimuthal asymmetries in lepton pair production in ultraperipheral heavy ion collisions, where $\phi$ is the angle between lepton pair total transverse momentum and individual lepton transverse momentum. We present numerical results for the azimuthal asymmetries in the kinematical regions where the experimental data for di-lepton production has been taken at RHIC and LHC. In these kinematical regions, the magnitude of the $\cos 4\phi$ azimuthal asymmetry for both electron pair and muon pair production are rather large. And moreover, the $\cos 2\phi$ azimuthal asymmetry in di-muon production at RHIC energy is sizable. These findings are very promising concerning a future extraction of $h_{L\perp}^{\gamma}$ in UPCs at RHIC and LHC. In our numerical estimation, we also took into account the Sudakov suppression effect which reduces the asymmetries significantly at relatively large lepton pair transverse momentum. The Sudakov suppression of the azimuthal asymmetry in this process would provide a clean way to test the resummation formalism in the QED case. Furthermore, one may expect that this mechanism also plays a role in generating azimuthal asymmetries in hadronic heavy-ion collisions. The study of such initial state effect thus would set a baseline for investigating the electromagnetic properties of the quark-gluon plasma created in hadronic heavy-ion
FIG. 4: Estimates of the $\cos 4\phi$ asymmetry as the function of $q_\perp$ for the di-muon mass region 4-45 GeV at $\sqrt{s} = 5.02$ TeV with and without the resummation effect being incorporated. The muon and anti-muon rapidities are integrated over the regions $[-1,1]$.

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