EF07: Ultra-Peripheral Collisions in Heavy-Ion Physics

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ABSTRACT

Ultraperipheral collisions (UPCs) of heavy ions at RHIC and LHC offer great opportunities to study strong field QED, EM/color charge fluctuations, collective phenomenon, electromagnetic properties of QGP, search BSM physics, and explore 3D nuclear structure with high luminosity beams of linearly polarized photons from Lorentz-boosted Coulomb field. Among these exciting directions of UPC studies, we select a few important new developments and emphasize on the polarization dependent effects in photon-photon processes and photon-nuclear interactions, and the processes as an electromagnetic probe of QGP properties.

1 Photon-nucleus/nucleon interactions

1.1 Linearly polarized photon-gluon collisions

The diffractive photoproduction of vector mesons at RHIC and LHC can probe the gluon momentum and space distribution inside nuclei and is the closest to the gluon imagining an electron-ion collider will perform in the near future. The diffractive vector meson production in UPCs[1–12] is the dominant channel of photon-nuclear interactions. Recent experimental studies have probed nuclear effects such as gluon shadowing in an unprecedented way, but more systematic studies are needed to address several open questions[13–23]. For example, there are still uncertainties hindering the extraction of the gluon distribution at a quantative level due to the uncertainty of the photon source generated by the heavy-ion Coulomb field, the separation of coherent diffractive production from the incoherent process, and a model with matching precision on the data. One alternative is to address these aspects from a new angle with the polarization dependent observables in UPCs. The significant $\cos 2\phi$ and $\cos 4\phi$ modulations in diffractive ρ^0 production have been reported by STAR collaboration[24]. A recent analysis[25] shows that the $\cos 2\phi$ asymmetry essentially results from the linearly polarization of incident coherent photons. The obtained transverse momentum dependent $\cos 2\phi$ asymmetry has a distinctive diffractive pattern which is sensitive to the nuclear geometry, the quantum interference effect[26–28], and the production mechanism (coherent/incoherent). To reproduce such a diffractive pattern, it is crucial to derive a joint impact parameter and transverse momentum dependent cross sections, which is also important for reliably extracting the transverse spatial distribution of gluons inside a nucleus. Similar measurements of azimuthal harmonic distributions of J/ψ at RHIC and LHC are feasible and will allow more reliable comparison to the QCD calculations. In addition, more experimental measurements and theoretical developments on the Fourier transformation of the gluon distribution with multiple azimuthal harmonics with the linearly polarized photon as a probe are required.

1.2 Ultraperipheral pA collisions

The 3D gluonic tomography of a nucleon can be studied before the operation of EIC in ultraperipheral pA collisions, where the photons generated from the Lorentz-boosted field from a nucleus interact with the gluons inside the nucleon. It has been proposed to constrain the gluon Wigner distribution in a nucleon by measuring the exclusive diffractive dijet production process in UPCs at RHIC, LHC[29] as well as at EIC[30–33]. In particular, the elliptical gluon Wigner distribution[30] describing the correlation between $b_\perp$ and the gluon transverse momentum can be accessed via a $\cos 2\phi$ azimuthal asymmetry. An unexpectedly large $\cos 2\phi$ asymmetry in diffractive dijet production has been observed in a recent measurement by the CMS collaboration[34] in AA collisions, whose quantitative connection to the elliptic gluon Wigner distribution requires further exploration. In addition to the nucleon 3D imaging, the proton mass decomposition also can be addressed in ultraperipheral pA collisions[35] similar to that in ep collisions[36]. One of the most interesting contributions to the intrinsic proton mass is the trace anomaly, or the gluon condensate contribution which can be probed via diffractive J/ψ production in ultraperipheral pA collisions where the nucleus merely acts as a source of quasi-real photons. The challenge is that one has to detect J/ψ in the very forward, low transverse momentum region. This may be possible after the forward upgrades at RHIC and LHC. A unique capability to probe the generalized gluon distribution function (GPD E_g) with the collider mode at RHIC and the fixed-target mode at the LHC is to use the polarized proton source in ultra-peripheral pA collisions[37–39].

1.3 Photoproduction in non-UPC heavy-ion collisions

The ALICE Collaboration at the LHC has pioneered the experimental measurements of the photoproduction of J/ψ at low transverse momentum in non-UPC heavy-ion collisions[40], accompanying the more violent hadronic collisions. More detailed study of the diffractive $|t|$ distribution by the STAR Collaboration at RHIC[41] has shown that the $|t|$ distribution is more consistent with the coherent process than the incoherent process. Although models[42,43] incorporating different partial coherent photon and nuclear interactions could explain the yields, it remains unclear how the coherent process happens and whether final-state effects play any role[44]. Resolving this puzzle with high statistics data and detailed $|t|$ distributions at different centralities at RHIC and the LHC may be important for understanding what defines the coherence of the photoproduction and how vector mesons are formed in the process.

2 Photon-photon to dilepton process

2.1 Extreme QED field

It was perceived that photons participating in UPC events are quasi-real with transverse-momentum $k_t = 1/R$ (30 MeV/c) reflecting the virtuality and uncertainty principle of their origin. This led to the assumptions in models employing the equivalent photon approximation (EPA)[45–47] that the dilepton initial transverse momentum does not depend on impact parameter and the transverse space coordinates where the pair are created are randomly distributed based on the same principles. The new measurements of centrality dependence and azimuthal distributions at RHIC[1,48–50] and LHC[3,51–54] have shown that the photons behave like real photons in all observables. The models and theories have demonstrated that the correction to the real photon approximation is suppressed at the order of $1/\gamma^2$ even in the transverse momentum distribution of the pairs. The discovery of the Breit-Wheeler process and the utilization of linearly polarized photons in UPCs are conceptually and experimentally highly nontrivial[50]. With future high statistics data with larger acceptance in UPC at RHIC and LHC, we can explore the phase space of photon collisions in transverse momentum, rapidity and momentum-space-spin correlations in extreme QED fields[55,56]. More importantly, these measurements provide a precision calibration necessary for the photons as sources for the photonuclear processes discussed in the previous section.

The lowest order QED calculation[45–47] of lepton pair production via photon-photon fusion process with the EPA as the input for photon flux can describe the unpolarized cross section measured by RHIC and LHC[49,51,53,54] quite well. It was recently realized that the coherent photons are highly linearly polarized with the polarization vector being parallel to its transverse momentum direction. A sizable $\cos 4\phi$ azimuthal asymmetry induced by linearly polarized coherent photons was observed in a STAR measurement[50]. A remarkable agreement between the computed asymmetry(16.5%)[55,57] and the measured asymmetry(16.8%±2.5%) in UPCs has been reached. With it being experimentally confirmed, the linearly polarized photon beam in UPCs provides us a new tool to estimate the off-shellness of the coherent photons participating in the Breit-Wheeler process and explore novel QCD phenomenology.

The extreme EM field in UPCs also facilitates searches for the elusive Coulomb correction[58–66]. The total cross section of lepton pair production in UPCs is predicted to be reduced by the Coulomb correction. However, there is no clear evidence of the Coulomb correction found in heavy ion collisions so far[65,66]. The multiple coherent Coulomb rescattering is suppressed by the powers of $q_\perp^2/m_{ee}^2$. To maximally enhance the Coulomb correction, pushing the measurement to the lower invariant mass region is required, which should be feasible at RHIC and LHC with forward instrumentation. It would be even more optimal to study Coulomb correction via a polarization dependent observable, for instance $\cos 4\phi$ asymmetry discussed above, which does not depend on the uncertainty of the heavy ion beam luminosity.

2.2 Dileptons as a probe in heavy ion collisions:

The comprehensive understanding of pure electromagnetic lepton pair production is not only important for probing extreme electromagnetic fields, but also interesting for studying the EM properties of QGP. For example, the significant pair transverse momentum $q_\perp$ broadening effect at different impact parameters found by the STAR[49,50], ATLAS[54] and CMS[52] collaborations has triggered quite an amount of theoretical efforts aimed at understanding if this effect results from the initial QED field strength, or is caused by the final state medium effect. The detailed comparison between theory/model calculations and experimental data appears to be in favor of the initial state effect[46,47,56,67,68], though there is some room left for the final state effect, such as the trapped magnetic field[69] and multiple EM scattering in QGP. Since such an impact-parameter sensitive observable is implicitly dependent on the photon Wigner distribution, it can serve as a clean testing ground for developing the QCD factorization formalism in terms of quark and gluon Wigner functions, which play a central role in exploring the 3D structure of nucleons/nuclei in the forthcoming EIC era. Another interesting development along this line is the prediction of a sizable v_4 anisotropic distribution with respect to the reaction plane [70] in lepton pair production in non-central heavy ion collisions. This EM v_4 anisotropy is purely generated by the initial EM field configuration, while the EM v_2 anisotropy is absent. This unique prediction, if confirmed from the experiments, shall provide a crucial handle on the production mechanism for dileptons in two photon processes in non-UPC collisions.

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