Collectivity in ultra-peripheral heavy-ion collisions

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Abstract. We present full (3+1)D dynamical simulations to study collective behavior in ultra-peripheral nucleus-nucleus collisions (UPC) at the Large Hadron Collider (LHC) with the 3DGlauber+MUSIC+UrQMD framework [1, 2]. By extrapolating from asymmetric p+Pb collisions, we simulate a quasi-real photon γ∗ interacting with the Pb nucleus in an ultra-peripheral collision at the LHC, assuming strong final-state effects. We study the elliptic flow hierarchy between p+Pb and γ∗+Pb collisions, which is dominated by the difference in longitudinal flow decorrelations. Our theoretical framework provides a quantitative tool to study collectivity in small asymmetric collision systems at current and future collider experiments.

1 Introduction

Collective features of strongly-coupled systems have been observed in relativistic nuclear collisions with light and heavy nuclei, such as p+Au, d+Au, 3He+Au at the Relativistic Heavy-Ion Collider (RHIC) [3, 4], and p+p and p+Pb collisions at the Large Hadron Collider (LHC) [5–7]. The theoretical interpretation of these flow-like signals has been a hot topic, driving our field to unravel how the collective behavior emerges depending on the collision system size [8, 9]. Recently, the ATLAS Collaboration measured the two-particle azimuthal correlations in ultra-peripheral Pb+Pb collisions (UPCs) at the LHC [10]. The high multiplicity UPC events created from the photo-nuclear interactions showed the persistence of collective phenomena with correlations comparable to those observed in p+p and p+Pb collisions at similar multiplicity [10].

Quantitative understanding of the many-body dynamics in these small collision systems requires the development and application of full (3+1)D simulations beyond Bjorken’s boost-invariance paradigm in the high energy limit [11–18]. In photon-nucleus collisions, the quasi-real photon γ∗’s energy fluctuates event-by-event, and is much smaller than the energy of the incoming Pb nucleus. Such unbalanced and fluctuating kinematics leads to a highly asymmetric collision system, strongly violating the longitudinal boost invariance. In these asymmetric systems, the rapidity decorrelation of the collision geometry plays a crucial role when computing and measuring the anisotropic flow coefficients.

In this proceeding, we study the flow rapidity decorrelation in detail for γ∗+Pb and p+Pb collisions, providing complementary information to Ref. [1].

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2 Fluctuations in collision kinematics of $\gamma^*+$A collisions in UPCs

The fast-moving Pb spectators in the UPC events generate strong fluxes of quasi-real photons. The emitted photons have the following energy spectrum [19, 20],

$$\frac{dN^\gamma}{dk^\gamma} = \frac{2\alpha^2}{\pi k^\gamma} \left[ w^A_R K_0(w^A_R) K_1(w^A_R) - \frac{(w^A_R)^2}{2} (K_1^2(w^A_R) - K_0^2(w^A_R)) \right],$$  \hspace{1cm} (1)

where $\alpha = 1/137$ and $w^A_R = 2k_y R_A/\gamma_L$, with the longitudinal Lorentz contraction factor $\gamma_L = \sqrt{s_{NN}}/(2m_N)$. The functions $K_0(x)$ and $K_1(x)$ are the modified Bessel functions of the second kind. For the Pb nucleus, $R_A = 6.62$ fm and $Z = 82$. The kinematics for incoming photon projectile and nucleon target in the Pb nucleus are $P^\mu = (k_y, 0, 0, k_y)$ and $P^\nu_N = (\sqrt{s_{NN}}/2, 0, 0, -\sqrt{s_{NN}}/2)$, where we neglect the photon’s virtuality and nucleon’s rest mass. The center of mass collision energy for the $\gamma^*+$A system is

$$\sqrt{s^\gamma/N} = \sqrt{2k^\gamma \sqrt{s_{NN}}}.$$

(2)

From Eqs. (1) and (2), we can compute the probability distribution for the center of mass energy in $\gamma^*+$A collisions,

$$P(\sqrt{s^\gamma/N}) \propto \frac{\sqrt{s^\gamma/N}}{k^\gamma} \left[ w^A_R K_0(w^A_R) K_1(w^A_R) - \frac{(w^A_R)^2}{2} (K_1^2(w^A_R) - K_0^2(w^A_R)) \right],$$  \hspace{1cm} (3)

with the photon momentum $k^\gamma = s^\gamma/N/(2 \sqrt{s_{NN}})$. Because of the unequal incoming longitudinal momentum between the quasi-real photons and the target nucleon, the center of mass rapidity of the $\gamma^*+$Pb system differs from the lab frame rapidity by

$$\Delta y = y_{\text{beam}}(\sqrt{s^\gamma/N}) - y_{\text{beam}}(\sqrt{s_{NN}}),$$

(4)

where the beam rapidity for a given center-of-mass collision energy can be computed as $y_{\text{beam}}(\sqrt{s}) = \text{arccosh}(\sqrt{s)/(2m_N))$.

The left panel of Figure 1 shows the probability distributions of the center-of-mass collision energies in Au+Au and Pb+Pb UPC events at RHIC and LHC. The center-of-mass

![Figure 1](https://doi.org/10.1051/epjconf/202327601002)

**Figure 1. Left Panel:** The probability distributions of the center-of-mass collision energies for photon-nucleus collisions in Au+Au and Pb+Pb UPC events at three collision energies. **Right Panel:** The probability distributions of the global rapidity shifts in $\gamma^*+$A collisions from the center-of-mass frame to the lab frame. Negative $\Delta y$ represents the shift towards the nucleus-going direction.
collision energies in $\gamma^*+A$ collisions are much smaller than in their corresponding heavy-ion collisions. The values of $\sqrt{s_{NN}}$ fluctuate over wide ranges, which results in broad intervals for rapidity shifts between the center-of-mass frame and lab frame, as shown in the right panel of Figure 1. For UPC events in Pb+Pb collisions at 5020 GeV, the rapidity shifts fluctuate from $-2$ to $-8.5$. Therefore, it is important to include these kinematics fluctuations in $\gamma^*+A$ collisions, which result in non-trivial effects in the rapidity direction. We note that small collision energy and large global rapidity shift result in little particle production at mid-rapidity in the lab frame. Therefore, triggering high multiplicity events at mid-rapidity effectively selects the $\gamma^*+A$ collisions with large $\sqrt{s_{NN}}$.

3 Flow rapidity decorrelation in $\gamma^*+$Pb and p+Pb collisions

In the work [1], we found the different amounts of longitudinal flow decorrelations in $\gamma^*+$Pb and p+Pb collisions led to the elliptic flow hierarchy observed by the ATLAS Collaboration [10]. The different flow rapidity decorrelations in $\gamma^*+$Pb and p+Pb collisions come from the difference in center-of-mass collision energy and the global rapidity shift in $\gamma^*+$Pb collisions [1].

![Figure 2](image_url)

**Figure 2.** Left Panel: Initial-state ellipticities of the fireballs in $1 < |\eta_f| < 2.5$ at $\tau = 0.6$ fm/c for $\gamma^*+$Pb and p+Pb collisions at $\sqrt{s} = 894$ GeV and $\sqrt{s} = 5020$ GeV. Right Panel: Final-state elliptic flow event-plane correlation with respect to a reference flow angle $\psi_2^{ref}$ at $1 < \eta < 2.5$ for $\gamma^*+$Pb and p+Pb collisions at two collision energies.

To investigate the flow rapidity correlations at a charged hadron multiplicity of 40 – 50, we focus on the following analysis with $\gamma^*+$Pb collisions at their highest energy, 894 GeV. The left panel of Figure 2 shows that the values of initial-state ellipticity are almost the same between $\gamma^*+$Pb and p+Pb collisions as a function of the particle multiplicity, which means that the shape fluctuations in the transverse plane are at the same level for the two collision systems. The right panel of Figure 2 shows the evolution of event-plane correlations in steps from p+Pb collisions at 5020 GeV to $\gamma^*+$Pb at 894 GeV collisions. The ATLAS Collaboration measured the two-particle correlation with a rapidity gap of $|\Delta\eta| > 2$. This analysis method computes the flow angular correlation between the two pseudorapidity intervals, namely $\eta_1 \in [-2.5, -1]$ and $\eta_2 \in [1, 2.5]$. The right panel of Figure 2 shows that the angular correlations of the elliptic flow vectors are strong in p+Pb collisions at 5020 GeV, very close to unity between these two $\eta$ intervals. Reducing the collision energy to 894 GeV shortens the length of the produced strings in the rapidity space, weakening the event-plane correlation to $\sim 0.9$. The extra global rapidity shift in $\gamma^*+$Pb collisions further reduces the correlation strength to $\sim 0.7$. 

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4 Conclusion

We applied a newly developed (3+1)D dynamical framework to study the collectivity in highly asymmetric relativistic nuclear collisions, such as p+A collisions and γ∗+A in the ultra-peripheral A+A collisions at RHIC and LHC energies [1, 2]. In this proceeding, we present a detailed analysis of the flow rapidity decorrelation in γ∗+Pb and p+Pb collisions. We discuss how to include fluctuating collision energies in simulating the 3D dynamics of γ∗+A collisions in the UPC events. At LHC energies, the elliptic flow hierarchy between the γ∗+Pb and p+Pb collisions can be explained by the different amounts of flow rapidity decorrelations in these systems, demonstrating the necessity of full (3+1)D simulations for these asymmetric collision systems.

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