

# 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  $\gamma^*$  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  $\gamma^*$ +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, <sup>3</sup>He+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  $\gamma^*$ '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  $\gamma^*$ +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],

$$\frac{dN^\gamma}{dk_\gamma} = \frac{2Z^2\alpha}{\pi k_\gamma} \left[ w_R^{AA} K_0(w_R^{AA}) K_1(w_R^{AA}) - \frac{(w_R^{AA})^2}{2} (K_1^2(w_R^{AA}) - K_0^2(w_R^{AA})) \right], \quad (1)$$

where  $\alpha = 1/137$  and  $w_R^{AA} = 2k_\gamma R_A / \gamma_L$ , 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  $P_\gamma^\mu \simeq (k_\gamma, 0, 0, k_\gamma)$  and  $P_N^\mu \simeq (\sqrt{s_{NN}}/2, 0, 0, -\sqrt{s_{NN}}/2)$ , where we neglect the photon's virtuality and nucleon's rest mass. The center of mass collision energy for the  $\gamma^*$ +A system is

$$\sqrt{s_{\gamma^*N}} = \sqrt{2k_\gamma \sqrt{s_{NN}}}. \quad (2)$$

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

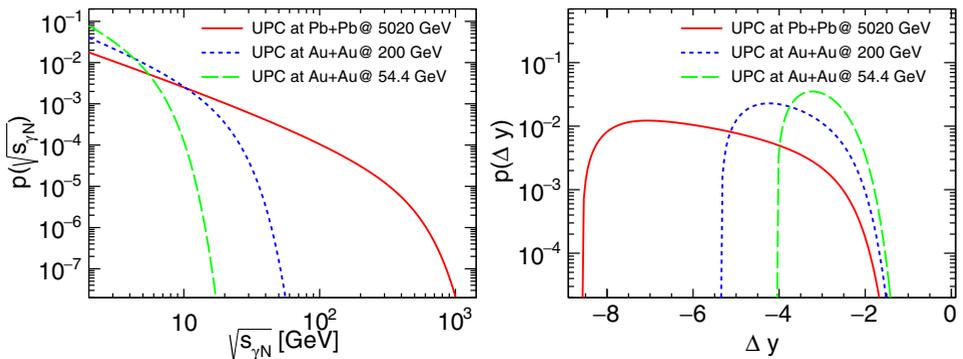
$$P(\sqrt{s_{\gamma^*N}}) \propto \frac{\sqrt{s_{\gamma^*N}}}{k_\gamma} \left[ w_R^{AA} K_0(w_R^{AA}) K_1(w_R^{AA}) - \frac{(w_R^{AA})^2}{2} (K_1^2(w_R^{AA}) - K_0^2(w_R^{AA})) \right], \quad (3)$$

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

$$\Delta y = y_{\text{beam}}(\sqrt{s_{\gamma^*N}}) - y_{\text{beam}}(\sqrt{s_{NN}}), \quad (4)$$

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

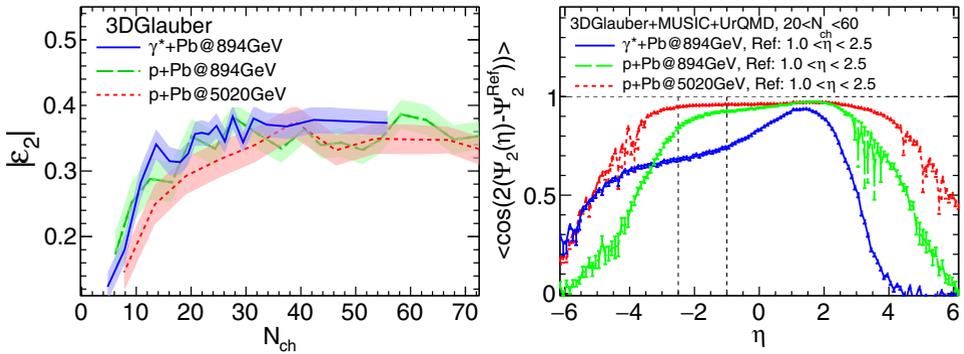


**Figure 1.** *Left Panel:* The probability distributions of the center-of-mass collision energies for photon-nucleus collisions in Au+Au and Pb+Pb UPC events at three collision energies. *Right Panel:* The probability distributions of the global rapidity shifts in  $\gamma^*$ +A collisions from the 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  $\sqrt{s_{\gamma^*N}}$  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  $\sqrt{s_{\gamma^*N}}$ .

### 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.** *Left Panel:* Initial-state ellipticities of the fireballs in  $1 < |\eta_s| < 2.5$  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  $\sim 0.7$ .

## 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  $\gamma^*+A$  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  $\gamma^*+Pb$  and p+Pb collisions. We discuss how to include fluctuating collision energies in simulating the 3D dynamics of  $\gamma^*+A$  collisions in the UPC events. At LHC energies, the elliptic flow hierarchy between the  $\gamma^*+Pb$  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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