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, ^{3}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 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 γ^*+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],

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

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

$$\sqrt{s_{\gamma^* N}} = \sqrt{2k_\gamma\sqrt{s_{\rm NN}}}. \tag{2}$$

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

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

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

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

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

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

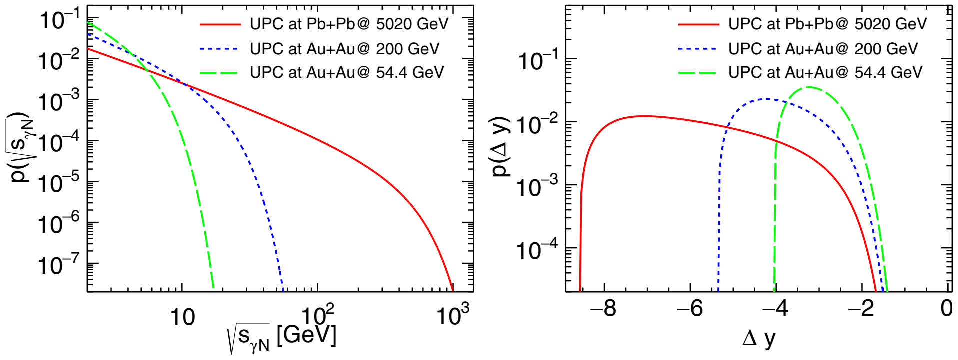

Figure 1. *Left Panel:* The probability distributions of the center-of-mass collision energies for photon-nucleus collisions in Au+Au and Pb+Pb UPC events at three collision energies. *Right Panel:* The probability distributions of the global rapidity shifts in γ^*+A collisions from the center-of-mass frame to the lab frame. Negative Δy represents the shift towards the nucleus-going direction.

collision energies in γ^*+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 γ^*+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 γ^*+A collisions with large $\sqrt{s_{\gamma^* N}}$.

3 Flow rapidity decorrelation in γ^*+Pb and p+Pb collisions

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

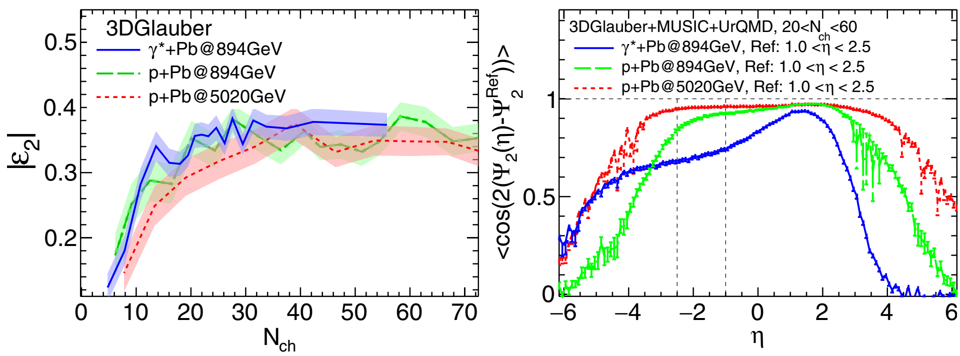

Figure 2. *Left Panel:* Initial-state ellipticities of the fireballs in $1 < |\eta_s| < 2.5$ at $\tau = 0.6$ fm/c for γ^*+Pb and p+Pb collisions at $\sqrt{s} = 894$ GeV and $\sqrt{s} = 5020$ GeV. *Right Panel:* Final-state elliptic flow event-plane correlation with respect to a reference flow angle $\psi_2^{\rm ref}$ at $1 < \eta < 2.5$ for γ^*+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 γ^*+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 γ^*+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 γ^*+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 η 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 ~ 0.9. The extra global rapidity shift in γ^*+Pb collisions further reduces the correlation strength to ~ 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 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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References

[1] W. Zhao, C. Shen, B. Schenke (2022), 2203.06094
[2] C. Shen, B. Schenke, Phys. Rev. C **105**, 064905 (2022), 2203.04685
[3] C. Aidala et al. (PHENIX), Phys. Rev. Lett. **120**, 062302 (2018), 1707.06108
[4] C. Aidala et al. (PHENIX), Nature Phys. **15**, 214 (2019), 1805.02973
[5] W. Li, Mod. Phys. Lett. A **27**, 1230018 (2012), 1206.0148
[6] K. Dusling, W. Li, B. Schenke, Int. J. Mod. Phys. E **25**, 1630002 (2016), 1509.07939
[7] J.L. Nagle, W.A. Zajc, Ann. Rev. Nucl. Part. Sci. **68**, 211 (2018), 1801.03477
[8] C. Shen, L. Yan, Nucl. Sci. Tech. **31**, 122 (2020), 2010.12377
[9] B. Schenke, Rept. Prog. Phys. **84**, 082301 (2021), 2102.11189
[10] G. Aad et al. (ATLAS), Phys. Rev. C **104**, 014903 (2021), 2101.10771
[11] P. Bozek, A. Bzdak, G.L. Ma, Phys. Lett. B **748**, 301 (2015), 1503.03655
[12] W. Ke, J.S. Moreland, J.E. Bernhard, S.A. Bass, Phys. Rev. C **96**, 044912 (2017), 1610.08490
[13] B. Schenke, S. Schlichting, Phys. Rev. C **94**, 044907 (2016), 1605.07158
[14] C. Shen, B. Schenke, Phys. Rev. C **97**, 024907 (2018), 1710.00881
[15] C. Shen, S. Alzhrani, Phys. Rev. C **102**, 014909 (2020), 2003.05852
[16] X.Y. Wu, G.Y. Qin (2021), 2109.03512
[17] A. Schäfer, I. Karpenko, X.Y. Wu, J. Hammelmann, H. Elfner (2021), 2112.08724
[18] M.A. Lisa, J.a.G.P. Barbon, D.D. Chinellato, W.M. Serenone, C. Shen, J. Takahashi, G. Torrieri, Phys. Rev. C **104**, 011901 (2021), 2101.10872
[19] C.A. Bertulani, S.R. Klein, J. Nystrand, Ann. Rev. Nucl. Part. Sci. **55**, 271 (2005), nucl-ex/0502005
[20] A.J. Baltz, Phys. Rept. **458**, 1 (2008), 0706.3356
[21] R. Pordes et al., J. Phys. Conf. Ser. **78**, 012057 (2007)
[22] I. Sfiligoi, D.C. Bradley, B. Holzman, P. Mhashilkar, S. Padhi, F. Wurthwrin, WRI World Congress **2**, 428 (2009)