Collision energy and system size dependence of longitudinal flow decorrelation in heavy-ion collisions at RHIC energies

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Abstract

In relativistic heavy-ion collisions, the initial collision geometry and its event-by-event fluctuations govern the collective expansion of final-state hadrons in the transverse plane. Longitudinal fluctuations, however, induce event-plane twist and flow-magnitude asymmetries, collectively referred to as longitudinal flow decorrelation. Using a multi-phase transport (AMPT) model, we systematically investigate the dependence of this phenomenon on collision energy and system size for Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 19.6$, 27, 54.4, 200 GeV and isobar collisions (Zr+Zr and Ru+Ru) at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV. The results reveal two distinct decorrelation components: $r_n(\eta)$, which encompasses both flow-magnitude asymmetry and event-plane twist, and $R_n(\eta)$, which arises purely from event-plane twist. Both $r_n(\eta)$ and $R_n(\eta)$ decrease linearly with η and exhibit a pronounced dependence on collision energy and system size. The strength of decorrelation is quantified via the slope parameters F_n in the linear parametrization $r_n(\eta) = 1 - 2F_n\eta$. Furthermore, we find that both F_2 and F_3 display a clear power-law scaling with collision energy, following the relation $F_n \propto log\sqrt{s_{NN}}$. These findings provide valuable constraints for three-dimensional modeling of the initial state and subsequent evolution of relativistic heavy-ion collisions.

Full Text

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In heavy-ion collisions, the initial collision geometry and its fluctuations drive the collective expansion of final-state hadrons in the transverse plane. However, longitudinal fluctuations induce event-plane twist and flow magnitude asymmetries, collectively known as longitudinal flow decorrelation. Using a multi-phase transport (AMPT) model, we systematically investigate the dependence √ of collision energy and system size of this phenomenon with Au+Au collisions at sNN = 19.6, 27, √ 54.4, 200 GeV and isobar collisions (Zr+Zr and Ru+Ru) at sNN = 200 GeV. The results reveal two distinct decorrelation components: rn (η), which includes flow magnitude asymmetry and event-plane twist, and Rn (η) which arises purely from event-plane twist. Both rn (η) and Rn (η) decrease linearly with η and exhibit a significant dependence on collision energy and the size of

the system. Through the slope parameters Fn in the linear parametrization rn

$(\eta) = 1 - 2$Fn η, we can quantify the strength of decorrelation. We further observe that both F2 and F3 demonstrate a √ pronounced power-law scaling behavior with collision energy, following the relation Fn log sN N . These results provide valuable insights into the three-dimensional modeling of the initial stage and the evolution of relativistic heavy-ion collisions.

I. INTRODUCTION known that the higher order harmonics can better constrain viscosity and fluctuating initial conditions, and the Anisotropic flow [1], which describes the azimuthal temperature dependence of η/s can be well handled by angle distribution of final-state charged hadrons, pro- the rapidity differential anisotropic flow in heavy-ion colvides critical constraints on the initial state and trans- lisions [15]. These measurements are essential for extractport properties of the Quark-Gluon Plasma (QGP) cre- ing QGP properties through comparisons with hydrodyated in high-energy heavy-ion collisions at the Relativis- namic and transport models. However, recent theoretitic Heavy Ion Collider (RHIC) and the Large Hadron cal [16–20] and experimental progresses [21] suggest that Collider (LHC). The flow can be characterized through the boost invariant approximation scenario is not accu- Fourier expansion of hadron yield distribution in az- rate enough, as the two-particle correlations as a function imuthal angle ϕ [2–4]: of pseudorapidity revealed strong event-by-event fluctuations, i.e. Vn∆ (\$ \$1 , \$ 2) = $vn(\ 1)vn(\ 2).dN/d$ \$ 1 + 2 X vn cos n($\phi - \psi$n) (1) Many previous studies have shown that this non-boost n invariant can lead to longitudinal flow decorrelation. For example, torqued fireball model [22], 3DMCG model [23], where vn and ψn represent the magnitude and phase 3DGlasma [24] and the AMPT model [25, 26]. The differof the nth -order of flow vector, respectively. Here, ent geometry of wounded nucleons between the forward v2 denotes the elliptic flow and v3 is the triangular and backward rapidity directions leads to a twist in the fiflow. The absence of sine terms in this expansion arises nal state event-plane angles or an asymmetry in the flow from symmetry constraints with respect to the event magnitudes due to random fluctuation of participating plane. Extensive measurements of the magnitudes of vn nucleons. The signature of longitudinal flow decorrelaand event-by-event fluctuations have been performed at tion has been measured by experiments at RHIC [27, 28] RHIC [5-9] and LHC [10–13]. With a boost invariant and LHC [29–31]. based space-time evolution of heavy ion collisions sce- Flow decorrelation can be quantified with a flow decornario, the (2+1)D event-by-event viscous hydrodynamrelation observable, factorization ratio rn , ical model has achieved great success in understanding these anisotropic flow parameters [14]. It is now well Vn∆ ($-\eta$, ηref) rn (η, ηref) = (2) Vn∆ (η, ηref)

∗ maowu.nie@sdu.edu.cn where ηref is the reference pseudorapidity common to † zhenyuchen@sdu.edu.cn the numerator and the denominator, thus rn is sensitive ‡ li.yi@sdu.edu.cn to the correlation between η and $-\eta$. If the value of rn § jiangyong.jia@stonybrook.edu is lower than unity which means the presence of longitu-

dinal flow decorrelation due to the factorization breaks slope: down between $-\eta$

and η. rn (η) $1 - 2$Fn η, Fn = Fnasy + Fntwi (3)

The longitudinal decorrelation mainly includes contribution from asymmetry in the magnitude of vn , Fnasy , and the twist of the event plane, Fntwi , between η and -η. Based on Ref.[32], the observable rn (η) can be approxi- To estimate the separate contribution of the asymmetry mately described by a linear function of η with a negative and twist effect, a new observable is used:

qn ($-\eta$ref)qn∗ (η)qn ($-\eta$)qn∗ (ηref) Rn (η) = qn ($-\eta$ref)qn∗ ($-\eta$)qn (η)qn∗ (ηref) (4) vn ($-\eta$ref)vn ($-\eta$)vn (η)vn (ηref) cos {n[ψn ($-\eta$ref) $-$ ψn (ηref) + (ψn ($-\eta$) $-$ ψn (η))]} = vn ($-\eta$ref)vn ($-\eta$)vn (η)vn (ηref) cos {n[ψn ($-\eta$ref) $-$ ψn (ηref) $-$ (ψn ($-\eta$) $-$ ψn (η))]}

The choice of the range of ηref is fully motivated by that will follow elastic parton cascade, simulating by ZPC physical considerations. A smaller gap between η and ηref model [38], eventually, hadronization and hadron rescatcan lead to sizable nonflow contributions, mainly from terings are described by the quark coalescence model and

dijets. The reference pseudorapidity dependence ηref has ART model [39], respectively. The effect of longitudinal already studied experimentally [28], 3.1 < |ηref | < 5.1 flow decorrelation arise from generating varying string reduces the effect of dijets and provides good statisti- lengths of initial partons of the interaction resulting in cal precision at RHIC energies. A recent study also fluctuations in the initial geometry along the longitudisuggests the ηref dependence has been attributed to lo- nal direction [25, 26, 40]. The elastic parton-parton cross cal fluctuations in rapidity [33]. In a previous AMPT section is chosen as the standard value of 3 mb at the top study [34], the energy dependence of r2 and r3 at RHIC RHIC energy to maintain parameter consistency across energies was investigated using a pseudorapidity range different collision energies. 2.1 < |ηref | < 5.1. However, the results—especially for The observable, rn (η), for flow decorrelations in Eq.(2) r2 —may have been significantly affected by nonflow con- is constructed using final state hadrons with transverse tributions. To achieve a more robust energy dependence, momentum 0.4 < pT < 4 GeV and pseudorapidity it is crucial to effectively subtract the contributions of |η| < 1.5 in centrality bins, where centralities are denonflow effects. Moreover, the system size dependence of termined by the multiplicity distribution of charged parflow decorrelation is less explored at RHIC energies. Ad- ticles within |η| < 0.5 that is chosen for correspondditionally, a comprehensive study on Rn is still needed ing to the acceptance of the Time Projection Chamber to probe initial state geometry fluctuations. (TPC) detector in the STAR experiment. In experimen- In this paper, we present a systematic study on lon- tal measurements, a rapidity gap is often required begitudinal flow decorrelation using the AMPT (A Multi- tween η and ηref to suppress non-flow correlations asso- Phase Transport) model, analyzing Au+Au collisions at ciated with jet fragmentation and resonance decays. For √ sNN = 19.6, 27, 54.4 and 200 GeV, along with iso- this analysis, we choose the reference pseudorapidity to √ bar (Zr+Zr and Ru+Ru) collisions at sNN = 200 GeV. be 3.1 < |ηref | < 5.1 for r2 and 2.1

$< |\eta$ref $| < 5.1$ for r3 . The collision energy dependence can be systematically As the isobar collisions have certain nuclear deformation, investigated through comparisons of Au+Au collisions the Wood-Saxon parameters for Zr+Zr and Ru+Ru are across different energies, while the system size depen- set with R0 = 5.09 and a = 0.52 fm, the deformation padence is quantified by comparing Au+Au and isobar col- rameter is set with \$ \$2 = 0.162 and \$ \$3 = 0 for Ru, \$ \$2 = lisions. This multi-dimensional approach enables simul- 0.06 and \$ \$3 = 0.2 for Zr, same as the previous study [41]. taneous characterization of both energy- and system sizedependent of flow decorrelation. III. RESULTS AND DISCUSSIONS

- II. MODEL SETUP Figure 1 depicts r2 and r3 as a function of η for Au+Au collisions in 0-10% and 10-40% centrality intervals at four The AMPT model with string melting scenario [35] is collision energies. Both r2 and r3 decrease linearly with √ utilized to simulate Au+Au collision at sNN = 19.6, increasing η. The decreasing trend can be described by 27, 54.4 and 200 GeV, isobar (Zr+Zr and Ru+Ru) col- a linear fit (dash line). The values of r2 and r3 both √ lisions at sNN = 200 GeV. In string melting version decrease from 200 GeV to 19.6 GeV, which indicates that of AMPT, Monte Carlo Glauber model [36] is used to lower energy leads to larger flow decorrelation due to a provide the initial conditions, HIJING model [37] gen- less boost invariant. erates the initial partons by strings and mini-jet melting To account for the beam-rapidity dependence, a ra-

pidity normalization procedure is further applied for the r2(η) comparison. Figure 2 shows r2 and r3 as a function of normalized pseudorapidity η/ybeam , where ybeam = 5.36 0.9 for 200 GeV, ybeam = 4.06 for 54.4 GeV, ybeam = 3.36 for 27 GeV and ybeam = 3.04 for 19.6 GeV. After nor- 0.8 malizing to the beam rapidity, both second- and third- 0-10% AMPT Au+Au 10-40% AMPT Au+Au order flow decorrelations exhibit a clear dependence on 0.7 200 GeV 54.4 GeV 3.1 $< |\eta | < 5.1$ ref

collision energy, which indicates the nontrivial dynamical 27 GeV 19.6 GeV 0.4 < p < 4.0 GeV T 0.6 behavior cannot be fully explained by simple scaling with 0 0.1 0.2 0.3 0.4 0 0.1 0.2 0.3 0.4 η/y η/y beam beam the beam rapidity. At 200 GeV, the flow decorrelation is weaker compared to other collision energies. For the r3(η) remaining energies, the results are generally consistent, 0.8 except for the second-order decorrelation in the 0-10% centrality range. Notably, the decorrelation strengths at 0.6 27 GeV and 19.6 GeV tend to align within uncertainties, 0.4 0-10% AMPT Au+Au 10-40% AMPT Au+Au suggesting a possible hint of non-linear dependence on 0.2 200 GeV 54.4 GeV 2.1 $< |\eta | < 5.1$ collision energy. ref 27 GeV 19.6 GeV 0.4 < p < 4.0 GeV T 0 0.1 0.2 0.3 0.4 0 0.1 0.2 0.3 0.4 η/y η/y r2(η)

beam beam

0.9 FIG. 2. The rn (η/ybeam) (n=2, 3) compared between the √ Au+Au collisions at sNN = 19.6 (black), 27 (red), 54.4 0.8 (blue) and 200 (orange) GeV in centrality bins: 0-10% and 0-10% AMPT Au+Au 10-40% AMPT Au+Au 10-40% by simulating AMPT model. The dashed line repre- 0.7 200 GeV 54.4 GeV 3.1 < $|\eta|$ < 5.1 sents a linear fit to the data. ref 27 GeV 19.6 GeV 0.4 < p < 4.0 GeV T 0.6 0 0.5 η 1 0 0.5 η 1 r2(η) r3(η) 0.8 0.9

0.6 0.8 0-10% sNN = 200 GeV 10-40% sNN = 200 GeV 0.4 0-10% AMPT Au+Au Au+Au Zr+Zr 3.1 < $|\eta|$ < 5.1 10-40% AMPT Au+Au ref

200 GeV 54.4 GeV 2.1 < $|\eta|$ < 5.1 0.7 Ru+Ru 0.4 < p < 4.0 GeV 0.2 ref T 0 0.5 1 0 0.5 1 27 GeV 19.6 GeV 0.4 < p < 4.0 GeV T η η 0 0.5 η 1 0 0.5 η 1 r3(η) FIG. 1. The rn (η) (n=2, 3) compared between the Au+Au √ collisions at sNN = 19.6 (black), 27 (red), 54.4 (blue) and 0.8 200 (orange) GeV in centrality bins: 0-10% and 10-40% by simulating AMPT model. The dashed line represents a linear 0.6 0-10% s = 200 GeV NN 10-40% sNN = 200 GeV fit to the data. Au+Au Zr+Zr 2.1 < $|\eta|$ < 5.1 ref 0.4 Ru+Ru 0.4 < p < 4.0 GeV T Figure 3 compares the decorrelation observables r2 and 0 0.5 1 0 0.5 1 η η r3 in Au+Au and isobar collisions (Zr+Zr and Ru+Ru) √ at sNN = 200 GeV. Au has a larger system size (in terms of nucleon number) than Zr and Ru. The overall FIG. 3. The rn (η) (n=2, 3) compared between the Zr+Zr √ (red), Ru+Ru (blue), Au+Au (Orange) collisions at sNN = level of v2 decorrelation in Au+Au collisions is consider- 200 GeV in centrality bins: 0-10% and 10-40% by simulating ably larger than in isobar collisions, where r2 values in AMPT model. The vertical line on the data points represent Au+Au are approximately 4% larger than in isobar colli- the statistical uncertainty. sions in 0-10% centrality and 5% larger in 10-40% centrality. Meanwhile, the difference in r3 between Au+Au and isobar collisions is relatively small, with a difference of with the picture where smaller initial system size is asaround 1% in 0-10% centrality and a 2% difference in the sociated with more fluctuations due to fewer participant 10-40% centrality. The results indicate a stronger decor- nucleons, leading to a larger difference between forward relation in smaller collision systems (Zr+Zr and Ru+Ru) and backward pseudorapidity directions. The tiny differcompared to larger systems (Au+Au). This is consistent ence between Zr+Zr and Ru+Ru is attributed to differ-

ences in nuclear structure [41]. gitudinal structure of the initial state in heavy-ion colli- To directly quantify the strength of flow decorrelation, sions, and can be verified by RHIC-STAR experimental the slope parameters F2 and F3 were extracted from the data. parameterization described in Eq. (3) within 10-40% centrality interval. These parameters are plotted as func- F2 F3 Zr+Zr 200 GeV Zr+Zr 200 GeV tions of collision energy, as shown in Fig. 4. A clear 0.3 Ru+Ru 200 GeV Ru+Ru 200 GeV hierarchy is observed, where 19.6 GeV has the largest F2 Au+Au 200 GeV 0.3 Au+Au 200 GeV 3.1 < $|\eta|$ < 5.1 2.1 < $|\eta|$ < 5.1 and F3 . The energy dependence of flow decorrelation is 0.2 ref 0.4 < pT < 4.0 GeV ref 0.4 < pT < 4.0 GeV consistent with the scenario where lower collision energies 0.2 result in a smaller number of initial partons and shorter 0.1 string lengths, leading to stronger decorrelation [25]. We 0.1 also find that both F2 and F3 exhibit a clear power-law √ dependence on collision energy, where Fn log sN

N . 0 0 100 200 300 400 0 100 200 300 400 This observation should be further validated with exper- Npart Npart imental data. FIG. 5. The slope parameter F2 and F3 are plotted as function F2 F3 √ Centrality: 10-40% Centrality: 10-40% of participant at sNN = 200 GeV in Au+Au (orange), Zr+Zr 0.4 3.1 < |η | < 5.1 2.1 < |η | < 5.1 (red) and Ru+Ru (blue) collisions. The vertical line on the ref ref 0.4 < p < 4.0 GeV 0.4 < p < 4.0 GeV T T data points represent the statistical uncertainty. 0.3 1

0.2 F2 F3 0.5 Zr+Zr 200 GeV Zr+Zr 200 GeV 0.1 0.3 Ru+Ru 200 GeV Ru+Ru 200 GeV Power Function Power Function Au+Au 200 GeV 0.3 Au+Au 200 GeV 0 0 3.1 < |η | < 5.1 2.1 < |η | < 5.1 0.2 ref 0.4 < pT < 4.0 GeV ref 0.4 < pT < 4.0 GeV 10 102 10 102 0.2 sNN sNN

0.1 0.1 FIG. 4. The slope parameter F2 and F3 are plotted as a function of collision energies. 0 0 0 0.2 0.4 0.6 0.8 1 0 0.2 0.4 0.6 0.8 1 Npart/2A Npart/2A Figure 5 shows F2 and F3 as a function of Npart for Au+Au and isobar collisions. F2 and F3 for Ru+Ru and Zr+Zr almost overlap with each other. The value of F2 FIG. 6. The slope parameter F2 and F3 are plotted as function √ in isobar collisions larger than in Au+Au collisions at of scaled participant at sNN = 200 GeV in Au+Au (orange), Zr+Zr (red) and Ru+Ru (blue) collisions. The vertical line same Npart . The results suggest clear system size depenon the data points represent the statistical uncertainty. dence. While for F3 , Au+Au results are slightly larger than isobar collisions at same Npart . The opposite trend of system size dependence between F2 and F3 is already To gain insight into collision energy and system size deobserved by ATLAS experiments [31], and the results are pendence of event plane twist effect of longitudinal flow also consistent with the Glauber model study. The Npart decorrelation. The R2 (η) is firstly compared in Au+Au √ and Npart /2A, where A is the atomic number, can be collisions at sNN = 19.6, 27, 54.4, 200 GeV and isobar √ considered as measured the absolute and scaled system (Zr+Zr and Ru+Ru) collisions at sNN = 200 GeV as size. shown in Figure 7 and Figure 8. Lower energy has larger Previous studies indicate that $ 2fordifferentsystemseventplanetwisteffectin10 − 40 $) shows ing observed when plotted against Npart /2A. In con- a significant system size dependence which is similar as trast, $ 3isdrivenbytherandomfluctuationsofquarkr2( ).Thestatisticalprecisionrequiredf R3($) analysis in this analysis is prohibitively high and versal scaling at small Npart (where fluctuations domi- precludes its calculation with the current dataset. nate), which transitions to a system-dependent deviation at large Npart [42]. We have further plotted F2 and F3 as a function of Npart /2A for Au+Au and isobar colli- IV. SUMMARY sions as shown in Figure 6. The opposite trend of system size dependence observed for F2 and F3 appears to van- We investigated the collision energy and the system ish in contrast to longitudinal eccentricity decorrelations. size dependence of longitudinal flow decorrelation using √ Thus the system size dependence serves as a powerful the AMPT model for Au+Au collisions at sNN = 19.6, constraint, enabling a clearer disentanglement of the lon- 27, 54.4, and 200 GeV, as well as for isobar (Zr+Zr and

√ R2(η) Ru+Ru) collisions at sNN = 200 GeV. The longitudinal flow decorrelation is characterized by rn (η), which captures the combined effects of vn asymmetry and event 0.8 plane twist, whereas Rn (η) solely isolates the contribution of the event plane twist. The slope parameter Fn (n 0.6 = 2, 3) as a function of Npart and the scaled system size 0-10% AMPT Au+Au 10-40% AMPT Au+Au Npart /2A to quantify the decorrelation strength. The re- 200 GeV 54.4 GeV 2.1 < $|\eta|$ < 5.1 sults show that both rn (η) and Rn (η) exhibit a clear colref 0.4 0.4 < p < 4.0 GeV 27 GeV 19.6 GeV T lision energy and system size dependence. Specifically, 0 0.5 η 1 0 0.5 η 1 lower energies have stronger longitudinal decorrelation even after beam rapidity scaling, which is consistent with √ the less boost invariant picture at lower collision energies. FIG. 7. The R2 (η) compared at sNN = 19.6 (black), 27 Notably, An opposite trend of system size dependence (red), 54.4 (blue) and 200 (orange) GeV in Au+Au collisions between F2 and F3 as a function of Npart is observed, in centrality 0-10% and 10-40%. The vertical line on the data which is consistent with the previous studies. However, points represent the statistical uncertainty the opposite trend disappears when the scaled system size Npart /2A is considered, which needs to be verified by R2(η) 1 RHIC-STAR experimental data. These systematic studies of the collision energy and system size dependence

0.9 provide the most stringent constraints to date on the initial state geometry and subsequent dynamical evolution 0.8 in relativistic heavy ion collisions. 0-10% sNN = 200 GeV 10-40% sNN = 200 GeV V. ACKNOWLEDGMENTS 0.7 Au+Au Zr+Zr 2.1 < $|\eta|$ < 5.1 ref 0.4 < p < 4.0 GeV Ru+Ru T 0.6 We thank Jianing Dong for maintaining the high- 0 0.5 1 0 0.5 1 η η quality performance of the computer facility. M. Nie, L.Yi and Z. Chen are supported by the National Natural √ Science Foundation of China under Grant No. 12105156, FIG. 8. The R2 (η) compared at sNN = 200 GeV in Au+Au (orange), Zr+Zr (red) and Ru+Ru (blue) collisions in central- No. 11890710 and No. 11890713, National Key R&D ity 0-10% and 10-40%. The vertical line on the data points Program of China under Grant No. 2022YFA1604903 represent the statistical uncertainty and Shandong Provincial Natural Science Foundation under Grant No. ZR2021QA084. J. Jia is supported by DOE Award No. DEFG0287ER40331.

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