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Longitudinal fluctuations in the partonic and hadronic initial state

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Collective flow in collisions between lead nuclei at the CERN Large Hadron Collider (LHC) are influenced by random initial state fluctuations, especially for odd harmonics. Here we extend fluctuation studies to longitudinal fluctuations, which may have significant effect on the rapidity distribution of odd harmonics. Furthermore center-of-mass rapidity fluctuations are measurable, but not yet analyzed. Here in the PACIAE parton and hadron molecular dynamics model we make an analysis of initial state fluctuations. As previous analyses have discussed mainly the effects of fluctuations on eccentricity and the elliptic flow we pay particular attention to the fluctuations of the center-of-mass rapidity of the system, which is conservatively estimated in our model as $\Delta y_{\mathrm{c.m.}} = 0.1$, by neglecting all pre-equilibrium emission effects that increase the $y_{\mathrm{c.m.}}$ fluctuations.

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I. INTRODUCTION

Global collective observables are becoming the most essential observables in ultrarelativistic heavy-ion reactions [1]. When we want to extract precise knowledge from experiments, both on the equation of state (EoS) and the transport properties of matter [2,3], we have to invoke a most realistic description with fully $3 + 1$-dimensional dynamical evolution at all stages of the reaction, including the initial state. This most adequate description of all stages can only be achieved by the multimodule, hybrid models. (See, e.g., Ref. [4].)

The initial state, where we have very little direct experimental information, is of paramount importance in the theoretical description. This leads to a wide variety of initial state models, which behave differently. Theoretical models and experimental results indicate that the initial state fluctuations are essential in understanding the data, although in the global continuum (fluid dynamical or field theoretical) models these fluctuation effects may inherently not be present and even may not survive to the hadronic final state. Nevertheless, we need to analyze the behavior of these initial state models from the point of view of fluctuations. (See, e.g., Ref. [5].)

However, one has to take into account that the center-of-mass rapidity (CMR) is not exactly the same for all events because of random fluctuations in the initial state caused by the difference of participant nucleon numbers from the projectile and the target. This leads to considerable fluctuations at large impact parameters, where the flow asymmetry is the strongest but the number of participant nucleons is the smallest.

Just as all initial state fluctuations, we have two sources of CMR fluctuations: First, the number of nucleons are randomly located in the configuration space and, due to their fluctuating location, the number of participants from the target nucleus and the projectile nucleus must not be the same event-by-event, even in the symmetric, $A + A$, collisions. Second, those nucleons, which are in the geometrical participant zone, may actually not collide with any single nucleon from the opposite nucleus; consequently these will not become participants. Some recent results on the subject concerning the v_2 and v_3 fluctuations are discussed in Refs. [6–8].

Up to now less attention is paid to the fluctuations in the beam direction. The expected momentum and/or rapidity fluctuations in this direction may be bigger due to the large beam momentum in recent experiments. In the case of CMR fluctuations there is an additional problem: It is not obvious if the tightly bound system is the initial state. The number of participant nucleons may not come from the projectile and the target nuclei equally; there can be one or a few more nucleons from one side. The momentum carried by the extra nucleons may be shared (i) by all participants equally in a tightly bound system (a single large confined quark-gluon-plasma (QGP) bag may be considered as such a system) or (ii) by a loosely connected cloud of nucleons (where the extra nucleons have little direct effect on the participant matter). In the later case, although the total momentum is conserved, the internal energy of the participant matter is increased considerably by the energy of the extra nucleons but the momentum of the participant matter is not correlated with the momenta of the extra nucleons. So, the collective rapidity change is much less.

It is important to mention that the phase transitions and the consequent fluctuations both in and out of QGP may enhance the collective behavior of the system [9]. However, it is rather difficult to estimate the consequences of such transitions and fluctuations to the CMR fluctuations. From the point of view of initial state fluctuations we have to arrive at a system that is close to local equilibrium; thus, at high energies the transition to QGP has to happen earlier than the formation of the initial state. Thus, it is important to study the CMR fluctuation as an observable on its own to learn about energy deposition, and also due to its strong effect on flow observables. (See, e.g., Ref. [10]).

In this work, after some simple considerations, we present an analysis of these fluctuations in the PACIAE model, where the major sources of fluctuations are taken into account.

II. ANALYTICAL ESTIMATES FOR THE CMR FLUCTUATIONS

As mentioned above, the initial state fluctuation is stemming from the participant nucleon number ($Na + Nb = N_{\text{part}}$) fluctuation. Here Na and Nb are the numbers of participant nucleons from the projectile and target nuclei, respectively. The participant matter forms and then the initial state system. In the following examples we present three situations where different fractions of the beam energy are contributing to the total transverse mass of the locally equilibrated participant matter.

Let us first estimate the effect of fluctuations of the participant matter for an impact parameter of $b = 0.7b_{\max}$ collision in Pb + Pb reactions at the CERN Large Hadron Collider (LHC) energy of $1.38 + 1.38$ A TeV for a tightly bound and unexcited system. We assume that one extra nucleon from the projectile nucleus will be absorbed into the participant matter, which otherwise would contain $N_{\text{part}} = Na + Nb = 32.5 + 32.5 = 65$ nucleons. Then this extra projectile nucleon, $\delta N \equiv Na - Nb = 1$, carries $m_t * \sinh(y_0)$ momentum, where $y_0 = 8$ is the beam rapidity at the above LHC energy and $m_t = m_N$ is the transverse mass of a nucleon in the beam. If this extra momentum is absorbed in the participant matter, then according to the momentum conservations,

$$P_z = M_t^{\text{c.m.}} \sinh(\triangle y_{\text{c.m.}}) = \delta N\, m_t \sinh(y_0), \tag{1}$$

$$E = M_t^{\text{c.m.}} \cosh(\triangle y_{\text{c.m.}}) = N_{\text{part}}\, m_t \cosh(y_0), \tag{2}$$

this extra nucleon will lead to a change of the CMR, $\triangle y_{\text{c.m.}}$ (which is zero if the participant nucleons are coming in equal numbers from the projectile and the target). In the above equations the $M_t^{\text{c.m.}}$ is the transverse mass of the participant matter.

In the initial state model based on expanding flux tubes or streaks [11] used in fluid dynamical calculations [10,12], the initial state system is tightly bound and stopped within each "streak." Thus, this model is applicable streak by streak and its momentum change is more pronounced for the peripheral streaks where the asymmetry between the projectile and target involvements is the biggest. In this initial state model the transverse mass, $M_t^{\text{c.m.}}$, is more than what would arise from the nucleon masses, $N_{\text{part}} m_N$, due to the field strength in the string. So $M_t^{\text{c.m.}} = N_{\text{part}}(m_t + L\sigma)$, where L is the length of the streak and σ is the effective string tension. If the participant matter is weakly excited, $M_t^{\text{c.m.}} \approx N_{\text{part}}(m_t + 1\ \text{GeV})$. The resulting shift of the CMR can be derived from Eq. (1):

$$\triangle y_{\text{c.m.}} \approx \text{arsinh}\left[\frac{\delta N\, m_t}{N_{\text{part}}(m_t + 1\,\text{GeV})} \sinh(y_0)\right] = 3.1.$$

Thus, CMR fluctuations may be quite substantial. In this case a large fraction of beam energy should be carried away through other channels, like pre-equilibrium emission.

For the initial state in hadronic transport models the momentum of extra nucleons hardly influences the momenta of the other participant nucleons. The extra nucleons are not stopped in this picture, the transverse mass ($M_t^{\text{c.m.}}$) in the above expression includes large prethermal momenta, but $M_t^{\text{c.m.}}$ can still be proportional to $m_t * \sinh(y_0)$. In such a model the CMR fluctuation will be significantly smaller. For example, in the above $b = 0.7b_{\max}$ Pb+Pb reaction at $(1.38 + 1.38)$ A TeV if we assume $65 + \delta N$, (where $\delta N = 1$) participant nucleons, and full equilibration, so that two-thirds of the beam kinetic energy is converted into the transverse mass of the participant matter, and $M_t^{\text{c.m.}}$ can be approximated as $M_t^{\text{c.m.}} = N_{\text{part}}(m_t + \epsilon_0 * 2/3)$, where $\epsilon_0 = 1.38$ TeV per nucleon in the Lab/c.m. frame, then the CMR fluctuation can be approximated as

$$\triangle y_{\text{c.m.}} \approx \text{arsinh}\left[\frac{\delta N\, m_t}{N_{\text{part}}(m_t + 2\epsilon_0/3)} \sinh(y_0)\right] = 0.025. \tag{3}$$

Although here we discuss the hadronic initial state in a hadronic transport model, it is suitable for the partonic initial state in hadron and parton transport models also.

The other limiting case is when all reaction energy is absorbed in the participant matter. Then both Eqs. (1) and (2) are satisfied, and for the same example of Pb + Pb collision as above the resulting CMR is

$$\triangle y_{\text{c.m.}} = \text{artanh}\left[\frac{\delta N}{N_{\text{part}}} \tanh(y_0)\right] = 0.015. \tag{4}$$

The above considerations show that the question of initial state fluctuations is a rather complex and model-dependent question. After all, the collectivity or looseness of the initial state must be estimated experimentally. The CMR fluctuations may provide a very good tool for this research.

III. LONGITUDINAL FLUCTUATIONS IN PARTONIC INITIAL STATE IN THE PACIAE MODEL

We discussed above the hadronic initial state, now we turn to the partonic initial state. In the parton and hadron cascade model, PACIAE [13], the initial partonic state is generated as follows.

(i) The overlap zone and the number of participant nucleons from the projectile and the target are first calculated geometrically [14] for an $A + A$ (or $A + B$) collision, at a given impact parameter.

(ii) The participant nucleons are distributed randomly inside the overlap zone, starting from nucleons inside the corresponding nuclear sphere having an isotropic Woods-Saxon distribution. Nucleons are given beam momentum, and a particle-list of initial nucleons is constructed.

(iii) An $A + A$ ($A + B$) collision is decomposed into nucleon-nucleon (NN) collision pairs, and each with a collision time calculated by assuming that the nucleons propagate along straight line trajectories and interact with the NN inelastic (total) cross sections. Then the initial NN collision list is constructed by these NN collision pairs.

The PACIAE model assumes that if a NN collision happens both colliding nucleons become participants, and eventual occupations of final particle states are disregarded. These approximations would decrease the longitudinal fluctuations and angular asymmetries [15].

(iv) A NN collision pair with the earliest collision time is selected from the collision list, and the final state of the collision is obtained by the PYTHIA model with string fragmentation switched off. Afterward the diquarks (anti-diquarks) are broken randomly into quark pairs (antiquark pairs), and one obtains a configuration of quarks, antiquarks, and gluons, besides a few hadronic remnants for a NN collision.
Although gluons are treated as pointlike particles, this treatment is not accurate, as gluons are mediating the interaction among the color charges and they have a significant role in the formation and hadronization of QGP. In these transitions, the energy of gluons is connected to the masses of the hadrons and to the energy of the emitted high-energy photons. We neglect photons in the initial state and so we neglect pre-equilibrium photon emission also. The detailed treatment of the gluons, hadron-parton transition, and pre-equilibrium emission would increase the $y_{\rm c.m.}$ fluctuations. To include these effects would be overly complicated and not realized in models similar to PACIAE. Thus, instead we chose to neglect the gluon contribution to $y_{\rm c.m.}$. In the present highly approximate treatment, where gluons are treated as pointlike classical particles, the inclusion of the gluons would reduce $y_{\rm c.m.}$ fluctuations contrary to the physical expectations.

(v) Each of the particles (nucleons) travels along straight-line trajectories between two consecutive NN collisions. After the collision, the particle list and collision time list are updated; the last step and this process are repeated until the NN collision list becomes empty (the NN collision pairs are exhausted).

The hadron and parton cascade model, PACIAE, includes the most important geometrical effect of the fluctuation of center-of-mass momentum in heavy-ion collisions, as the positions of the initial nucleons are random following the original Woods-Saxon profiles of the projectile and the target nuclei. Then in the overlap region nucleons may collide with each other according to NN cross section, and those which do not will become spectators. This construction provides the participant nucleons, their positions and momenta, and the number of spectators from the projectile and the target separately. All other effects that would influence the $y_{\rm c.m.}$ fluctuations are neglected. In this way the model gives a lower limit for the fluctuations of the initial state CMR.

From the point of view of global collective flow phenomena, we would have to consider an initial system of particles in local thermal equilibrium. This system does not contain nonthermalized, pre-equilibrium emitted particles, jets, high-energy direct γ's, etc. In the present estimate we neglect all these effects, because the quantitative theoretical estimate of all these effects is exceedingly difficult, and even the definition of which particles could be considered belonging to the collective initial state is not settled. These channels take away considerable energy and momentum from the collective initial state, so the CMR of the collective initial state will be bigger than the "lower limit" estimate provided by the model PACIAE.

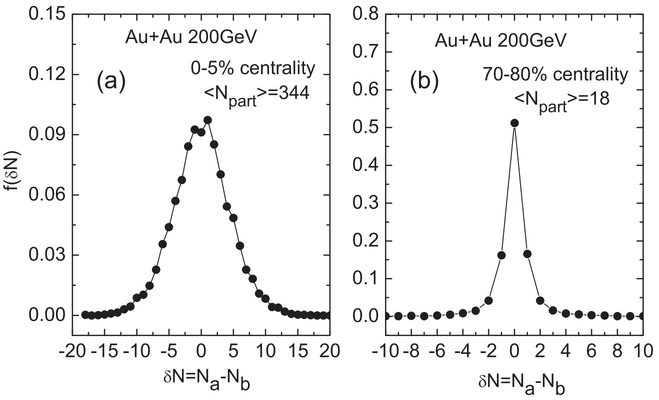

FIG. 1. Initial state fluctuation of the number of extra nucleons, δN, in $100 + 100$ A GeV, 0–5% central and 70–80% peripheral Au + Au collisions in the PACIAE model.

A. Particle number asymmetries in the PACIAE model

First, we estimate the probability distribution of the participant nucleons that have suffered at least one NN collision. Let us have Na participant nucleons from the projectile and Nb from the target. When $Na = Nb$ the participant matter is symmetric, so the center-of-mass momentum and the CMR vanish.

At a given impact parameter we have a possibility for symmetric fluctuations when $Na = Nb$ changes by an equal number of nucleons. This will not effect the center of mass. If we have an asymmetry, $\delta N = Na - Nb$, this leads to a change of the CMR.

Taking into account the effect of overlap geometry and of the NN cross section, the PACIAE model [13] estimates the δN distribution from $N_{\rm part}$ fluctuations as presented in Figs. 1 and 2.

In our model calculations the centrality bins are defined in terms of the geometrical cross section, $b^2_{\rm max}\pi = (2R_A)^2\pi$, and, for example, a centrality bin of 60–70% corresponds to an impact parameter range $[b_i, b_j]$, such that $(b_i^2\pi)/(b^2_{\rm max}\pi) = 0.6$ and $(b_j^2\pi)/(b^2_{\rm max}\pi) = 0.7$.

As shown in Fig. 1 for the central BNL Relativistic Heavy Ion Collider (RHIC) collisions $|\delta N|/\langle N_{\rm part}\rangle \approx 1.5\%$, while

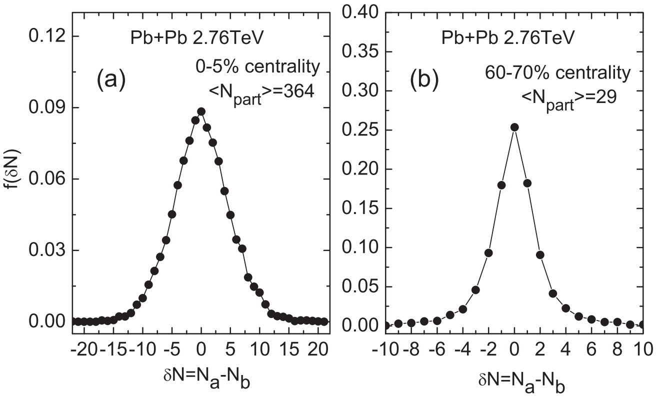

FIG. 2. Initial state fluctuation of the number of extra nucleons, δN, in $1.38 + 1.38$ A TeV, 0–5% central and 60–70% peripheral Pb + Pb collisions in the PACIAE model.

for peripheral collisions it is 5%. In peripheral collisions the longitudinally moving uppermost and lowermost layers have relatively more particles than in central collisions, and so the random fluctuations include relatively more particles, although the absolute number of particle asymmetry is less.

In Fig. 2 the same results for LHC collisions are 1.4% for central and 6% for peripheral collisions. Thus, the relative number fluctuation for central collisions decreased slightly due to the difference in the number of participants, while for peripheral collisions the small increase was primarily caused by the difference in the centrality bin. The small difference indicates that the relative number fluctuation in peripheral collisions is less sensitive to centrality bin selection than the absolute numbers.

At higher energy the cross sections are bigger, so both the number of realized primary-primary collisions and the number of primary-secondary collisions are bigger. This results in an increase in the participant number in the same overlap domain. This leads to the observed fact that while the absolute numbers are increasing the relative number fluctuations show a smaller increase.

B. Rapidity fluctuations in the PACIAE model

Let us make a simple estimate: what is the resulting CMR fluctuation. The extra nucleons, δN, carry a longitudinal momentum of $\delta p_z = \delta N\, m_N \sinh(y_0)$. The total momentum of the symmetric part, $(Na + Nb - |\delta N|)$, of the participant matter vanishes. We assume a fixed impact parameter, b, and neglect mass number fluctuations of the symmetric part of the participant matter. Then we can assume the mass number of the symmetric part to be $\langle N_{\text{part}}\rangle - \langle|\delta N|\rangle$. If we assume further that all of the reaction energy is absorbed in the participant matter and $\langle N_{\text{part}}\rangle \gg \delta N$, then we get

$$\Delta y_{\text{c.m.}}(\delta N) \approx \operatorname{artanh}\left[\frac{\delta N}{\langle N_{\text{part}}\rangle}\tanh(y_0)\right].$$

Thus, the CMR distribution becomes a series of δ functions according to the δN distribution. If we allow for the fluctuation of the symmetric mass number for a range of impact parameters or a range of multiplicities, or we allow other channels mentioned above, leaking energy from the initial state the peaks of the CMR distribution will be smoothed out.

Figure 3 shows this δ function structure in the resulting partonic initial state generated by the PACIAE model for 1.38 + 1.38 A TeV 0–5% central Pb + Pb collisions.

The sharp peak structure indicates that all other channels (pre-equilibrium emissions, etc.) are neglected in our estimate; so the source of rapidity fluctuations is the momentum of those extra nucleons, which are not matched in originating from the projectile and the target.

C. Center-of-mass fluctuations of different matter components

In the partonic initial state generated by the PACIAE model a large part of reaction energy is invested into gluons. The gluons are treated as classical pointlike particles just like the quarks and antiquarks. If these gluons were regarded as a distinct gluon field, then this gluon field might keep the partonic initial state system more bound and uniform. Then the remaining part (quarks and antiquarks) of the partonic initial state fluctuates stronger.

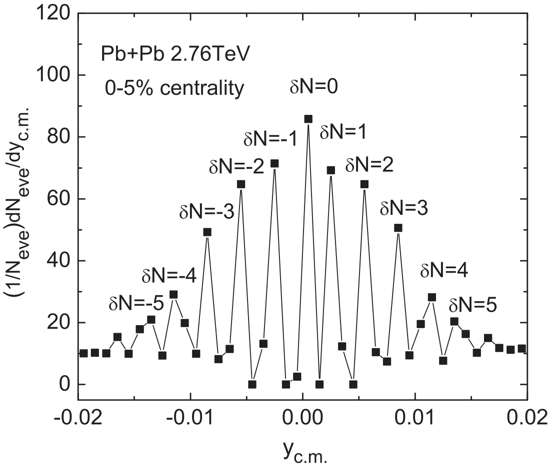

FIG. 3. Initial state CMR fluctuation in 1.38 + 1.38 A TeV, 0–5% central Pb + Pb collisions in the PACIAE model. The figure shows that the rapidity change caused by $\delta N = 1, 2, 3, \ldots$ extra nucleons leads to a very sharp peak in the CMR distribution, each peak corresponding to a given δN value. This is because there is no tightly bound system to absorb energy and momentum in the model. If this is not so, the bound system will allow for rapidity fluctuations at given δN, making each sharp peak much wider and increasing the width of the overall $y_{\text{c.m.}}$ distribution.

There are other possibilities which may increase the CMR fluctuation, e.g., pre-equilibrium emission of high-energy particles reducing the energy or mass of the initial state system, considerable kinetic energy in rotation of the initial state system, etc.

Gluons have an important role in developing collective flow still in the QGP phase (indicated by the constituent quark number scaling observed at RHIC). This collective flow at high energies may lead to a collective rotation [5,10] where a significant part of the collision energy remains in longitudinal flow, and so it does not contribute to the transverse mass of the system. This would lead to a form of collective energy

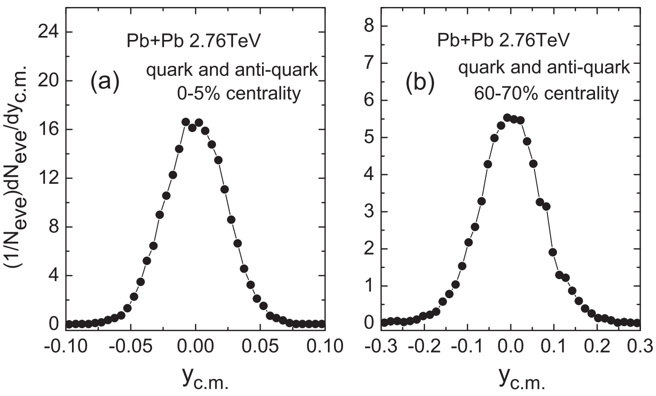

FIG. 4. The CMR fluctuation of quarks and antiquarks in the initial state calculated for 1.38 + 1.38 A TeV, 0–5% central and 60–70% peripheral Pb + Pb collisions by PACIAE model.

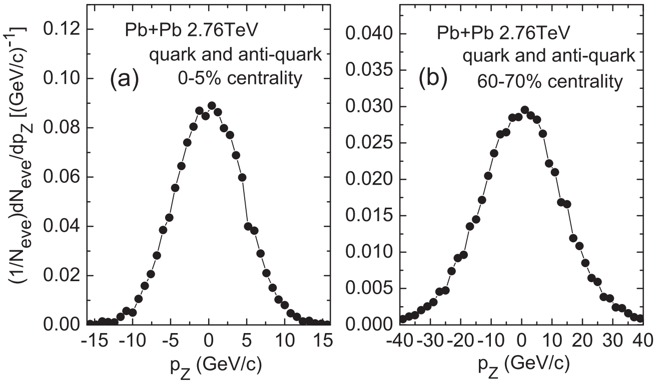

FIG. 5. The fluctuation of the center-of-mass longitudinal momentum per participant nucleon of the quarks and antiquarks in the partonic initial state, i.e., p_z fluctuation calculated for $1.38 + 1.38$ *A* TeV, 0–5% central and 60–70% peripheral Pb + Pb collisions by the PACIAE model.

from the gluons, which leads to increased $y_{\text{c.m.}}$ fluctuations because this energy reduces the transverse mass of the system. Such collective effects are not included in the PACIAE model, because gluons are treated as classical pointlike particles.

The initial state fluctuations of the energetic partonic matter may be important because the developments of these components may not be identical, especially at the final freeze out and hadronization stages of the reaction. The gluon fields may contribute to forming the final rest masses of the hadrons, and they may contribute different amounts of thermal and collective kinetic energy to different hadrons [16]. All effects mentioned above would increase the CMR fluctuation of the initial state, but these are not included in the PACIAE model we used.

Figure 4 gives CMR fluctuation of the quarks and antiquarks in the partonic initial state calculated for $1.38 + 1.38$ *A* TeV, 0–5% central and 60–70% peripheral Pb + Pb collisions by PACIAE model. The fact that the massive gluon field may carry energy and momentum makes it possible to incorporate part of the fluctuations. This enables the model to achieve around a few times larger CMR fluctuations than without a flexibly moving massive gluon field as one can see in comparing Fig. 3 with Fig. 4. Figure 5 gives the fluctuation of the center-of-mass longitudinal momentum per participant nucleon of the quarks and antiquarks in the partonic initial state, i.e., p_z fluctuation.

In the PACIAE model calculations above, nearly 57.6% of the total collision energy is shared by the quarks and antiquarks and 42.4% by the gluons in the 60–70% centrality Pb + Pb collisions. These values are 57.9% and 42.1% for quarks and antiquarks and gluons, respectively, in the 0–5% central Pb + Pb collisions. Therefore, how gluons are treated is an important issue.

IV. CONCLUSIONS

Initial state fluctuations were analyzed in the PACIAE model, with particular attention to the CMR fluctuations. It was found that in central collisions the longitudinal asymmetry, arising from different numbers of projectile and target participants, in longitudinal momentum is around 1.5% only, while for peripheral reactions it can reach –6% (see Figs. 1 and 2). In central collisions the CMR fluctuations that arise from this longitudinal asymmetry are not large in the PACIAE model as indicated by Fig. 3.

We can see in Fig. 4 that the arising CMR fluctuation is around ±0.03 units for central collisions and around ±0.1 units for peripheral ones. These are about 5–10 times smaller than the assumptions used in Ref. [10], and this would result in less reduction of the original $v_1(y)$ calculations. On the other hand, the PACIAE estimates can be considered as conservative lower limits of the $y_{\text{c.m.}}$ fluctuations; therefore, the measured $y_{\text{c.m.}}$ fluctuations may exceed these values. In the present formulation of the PACIAE model, with pointlike gluons, the gluon contribution would decrease the CMR fluctuations (cf. Fig. 3).

In the PACIAE partonic initial state study above, we do not include the pre-equilibrium emission; the collective effects such as, e.g., rotation; and the formation of excited intermediate states. These could lead to the increase of CMR fluctuations. The developing collective flow may increase and decrease fluctuations, depending on the quantitative details of the developing flow pattern. The structure of the collective flow will be detected at the end of the reaction, but this pattern develops from the initial state in the QGP phase where the gluon component is essential. The collective flow has both transverse and longitudinal components. The precollision initial state has exclusively longitudinal collective motion. At the time point of strongest stopping, this longitudinal flow energy is reduced to about 30% of the initial value, while on average at the end of the reaction the longitudinal energy and the transverse energy have about 50–50% share [17]. Soft EoS (like QGP) and collective rotation may increase the share of longitudinal flow energy. The increased longitudinal energy (especially from rotation) and the projectile/target participant asymmetry may in themselves contribute to direct increased longitudinal fluctuation.

The share of longitudinal and transverse flow energies also influences the transverse mass of the system, which indirectly contributes to longitudinal fluctuations. The transverse part of the flow energy increases the transverse mass, while the longitudinal part reduces it. Larger transverse mass reduces the $y_{\text{c.m.}}$ fluctuations. We know that with increasing beam energy the collective flow becomes more energetic and it is the most dominant phenomenon at the LHC energies. This arises from the initial energy and momentum distribution, including the gluon components, as these are necessary for the development of the large collective flow processes.

The PACIAE model with pointlike gluons has less ability to incorporate these collective flow effects, and about two-thirds of the available energy will contribute to the transverse mass, while no direct longitudinal flow fluctuation will develop from the initial state asymmetries. Thus, PACIAE with pointlike gluons underestimates the $y_{\text{c.m.}}$ fluctuations.

The initial state longitudinal fluctuations are essential for the analysis of the directed flow, as these fluctuations have significant effect on the measurable v_1 flow [10]. The present situation regarding the directed flow is rather complex because at the RHIC and LHC energies the observed collective v_1

flow is rather weak, $|v_1| \leqslant 0.001$ at $\eta = 0.8$; therefore, the v_1 flow from the initial state fluctuations may exceed the global collective v_1 flow. Thus, the evaluation of $v_1(p_t)$ at low momenta and low rapidities is a complex problem, where the two processes are interacting [18]. The event-by-event longitudinal fluctuations may be important in the assessment and separation of the global directed flow and the directed flow arising from the initial state random fluctuations.

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[1] K. Aamodt *et al.* (ALICE Collaboration), Phys. Rev. Lett. **105**, 252302 (2010).

[2] P. K. Kovtun, D. T. Son, and A. O. Starinets, Phys. Rev. Lett. **94**, 111601 (2005).

[3] L. P. Csernai, J. I. Kapusta, and L. D. McLerran. Phys. Rev. Lett. **97**, 152303 (2006).

[4] S. A. Bass, A. Dumitru, M. Bleicher, L. Bravina, E. Zabrodin, H. Stocker, and W. Greiner, Phys. Rev. C **60**, 021902 (1999); T. Hirano, P. Huovinen, and Y. Nara, *ibid.* **84**, 011901(R) (2011). H. Petersen, G. Y. Qin, S. A. Bass, and B. Muller, *ibid.* **82**, 041901 (2010); B. Bauchle and M. Bleicher, *ibid.* **81**, 044904 (2010).

[5] H. Petersen, Ch. Coleman-Smith, S. A. Bass, and R. Wolpert, J. Phys. G **38**, 045102 (2011); F. G. Gardim, F. Grassi, Y. Hama, M. Luzum, and J. Y. Ollitrault, Phys. Rev. C **83**, 064901 (2011); P. Bozek, W. Broniowski, and J. Moreira, *ibid.* **83**, 034911 (2011); P. Bozek and I. Wyskiel, *ibid.* **81**, 054902 (2010).

[6] G. Y. Qin, H. Petersen, S. A. Bass, and B. Muller, Phys. Rev. C **82**, 064903 (2010).

[7] H. Petersen, V. Bhattacharya, S. A. Bass, and C. Greiner, arXiv:1105.0340.

[8] F. G. Gardim, F. Grassi, Y. Hama, M. Luzum, and J. Y. Ollitrault, Phys. Rev. C **83**, 064901 (2011).

[9] L. P. Csernai and J. I. Kapusta, Phys. Rev. Lett. **69**, 737 (1992); Phys. Rev. D **46**, 1379 (1992).

[10] L. P. Csernai, V. K. Magas, H. Stöcker, and D. D. Strottman, Phys. Rev. C **84**, 024914 (2011).

[11] V. K. Magas, L. P. Csernai, and D. D. Strottman, Phys. Rev. C **64**, 014901 (2001); V. K. Magas, L. P. Csernai, and D. Strottman, Nucl. Phys. A **712**, 167 (2002).

[12] L. P. Csernai, Y. Cheng, V. K. Magas, I. N. Mishustin, and D. Strottman, Nucl. Phys. A **834**, 261c (2010).

[13] B.-H. Sa, X.-M. Li, S.-Y. Hu, S.-P. Li, J. Feng, and D.-M. Zhou, Phys. Rev. C **75**, 054912 (2007); B.-H. Sa, D.-M. Zhou, Y.-L. Yan, X.-M. Li, S.-Q. Feng, B.-G. Dong, and X. Cai, arXiv:1104.1238.

[14] B.-H. Sa, A. Bonasera, A. Tai, and D.-M. Zhou, Phys. Lett. B **537**, 268 (2002).

[15] C. B. Chiu, R. C. Hwa, and C. B. Yang, Phys. Rev. C **78**, 044903 (2008).

[16] S. Zschocke, S. Horvat, I. N. Mishustin, and L. P. Csernai, Phys. Rev. C **83**, 044903 (2011).

[17] L. Bravina, L. P. Csernai, P. Levai, and D. Strottman, Phys. Rev. C **50**, 2161 (1994).

[18] Contributions of R. Snellings, I. Selyuzhenkov, and G. Eyyubova *et al.* (all for the ALICE collaboration) at the Quark Matter 2011 Conference, Annecy, France, May 22–28, 2011 (to be published in the proceedings).