Longitudinal Fluctuations in Partonic and Hadronic Initial State

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Substantial collective flow is observed in collisions between Lead nuclei at LHC as evidenced by the azimuthal correlations in the transverse momentum distributions of the produced particles. Initial state fluctuations turned out to be important in analysing the flow data, especially for odd harmonics. In the PACIAE parton and hadron molecular dynamics model we made an analysis of initial state fluctuations. As previous analyses discussed mainly the effects of fluctuations on eccentricity and the elliptic and triangular flow we paid particular attention to the fluctuations of the Center of Mass rapidity of the system.

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I. INTRODUCTION

Global collective observables are becoming the most essential observables in ultra-relativistic 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 multi-module, hybrid models.

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.

Theoretical simulations have to be compared to averaged experimental collision data in the corresponding impact parameter range. However, one has to take into account that the Center of Mass (CM) rapidity 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 projectile and 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.

There are numerous models to estimate the initial state rapidity or longitudinal momentum fluctuations, with quite different assumptions and suppling different results for the initial CM-rapidity fluctuations. Just as all initial state fluctuations we have two sources of CM-rapidity 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 and projectile nucleus must not be the same event-by-event, even in the symmetric, A+A, collisions. Second, those nucleons, which are in the 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. [4–6].

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 case of CM-rapidity fluctuations there is an additional problem: It is not obvious how 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 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 [7]. However, it is rather difficult to estimate the consequences of such transitions and fluctuations to the CM-rapidity fluctuations. From the point of view of initial state fluctuations we have to arrive at system, which is close to local equilibrium, thus, at high energies the transition to QGP has to happen earlier than the formation of the initial state.

II. ANALYTICAL ESTIMATES FOR THE CM-RAPIDITY FLUCTUATIONS

As mentioned above, the initial state fluctuation is stemming from the participant nucleon number ($Na + Nb = N_{part}$) fluctuation. Here Na and Nb are the numbers of participant nucleons from the projectile and target nuclei, respectively. The participant matter forms then the initial state system. The study of initial state fluctuations is bound to the study of participant matter fluctuations.

Let us first estimate the effect of fluctuations of the participant matter for a impact parameter of $b = 0.7b_{max}$ collision in Pb+Pb reactions at the 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 $N_{part} = Na+Nb = 32.5+32.5 = 65$ 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, $\epsilon_0 = 1.38$TeV per nucleon in the Lab/CM frame 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:

$$P_z = M_t^{CM} \sinh(\triangle y_{CM}) \ = \ \delta N \ m_t \sinh(y_0) \qquad (1)$$
$$E = M_t^{CM} \cosh(\triangle y_{CM}) \ = \ N_{part} \ m_t \cosh(y_0) \qquad (2)$$

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

In the initial state model based on expanding flux tubes or streaks [8] used in fluid dynamical calculations [9, 10], 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^{CM} is more than what would arise from the nucleon masses, $N_{part}m_N$, due to the field strength in the string. So $M_t^{CM} = N_{part}(m_t + L\sigma)$, where L is the length of the streak and σ is the effective string tension. If the participant matter is weakly excited, $M_t^{CM} \approx N_{part}(m_t + 1\text{GeV})$. The resulting shift of CM-rapidity can be derived from Eq. (1):

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

Thus, CM-rapidity 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 are hardly influencing the momenta of the other participant nucleons. The extra nucleons are not stopped in this picture, the transverse mass (M_t^{CM}) in the above expression includes large pre-thermal momenta, but M_t^{CM} can still be proportional to $m_t * sinh(y_0)$. In such a model the CM-rapidity 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 $2/3^{rd}$ of the beam kinetic energy is converted into the transverse mass of the participant matter, and M_t^{CM} can be approximated as $M_t^{CM} = N_{part}(m_t + \epsilon_0 * 2/3)$. Then the CM-rapidity fluctuation can be approximated as

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

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. (1,2) are satisfied, and for the same example of Pb+Pb collision as above the resulting CM-rapidity is

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

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 CM-rapidity fluctuations may provide a very good tool to this research.

III. LONGITUDINAL FLUCTUATIONS IN PARTONIC INITIAL STATE IN 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 [11] the initial partonic state is generated as follows:

1. The overlap zone and the number of participant nucleons from the projectile and target are first calculated geometrically [12] for an A+A (or A+B) collision, at a given impact parameter.

2. 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 set (list) of initial particles (nucleons) is constructed.

3. An A+A (A+B) collision is decomposed into nucleon-nucleon (NN) collision pairs and every one

with a calculated collision time, assuming that nucleons propagate along straight line trajectories, and NN inelastic (total) cross sections are taken into account. Then the initial NN collision list is constructed by these NN collision pairs.

4. 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. Afterwards the diquarks (anti-diquarks) are broken randomly into quark pairs (anti-quark pairs), and one obtains a configuration of quarks, anti-quarks, and gluons, beside a few hadronic remnants for a NN collision.

5. 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 is becomes empty (the NN collision pairs are exhausted). Thus, one obtains a partonic initial state consisting of quarks, anti-quarks, and gluons, for an A+A (A+B) collision.

The PACIAE model assumes that if a collision happens both colliding particles become participants, and eventual occupations of final particle states are disregarded. These approximations decrease the longitudinal fluctuations and angular asymmetries [13].

A. Particle number asymmetries in PACIAE model

We first estimate the probability distribution of the participant nucleons suffered at least one nucleon-nucleon 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 CM momentum and the CM-rapidity vanish.

At a given impact parameter we have a possibility for symmetric fluctuations when $Na = Nb$ change by 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 CM-rapidity.

Taking into account the effect of overlap geometry and of the nucleon-nucleon cross section, the PACIAE model [11], estimates the δN distribution from N_{part} fluctuations as presented in Figures 1 and 2.

B. Rapidity fluctuations in PACIAE model

Let us make a simple estimate: what is the resulting CM-rapidity 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 fix impact parameter, b and neglect mass number fluctuations

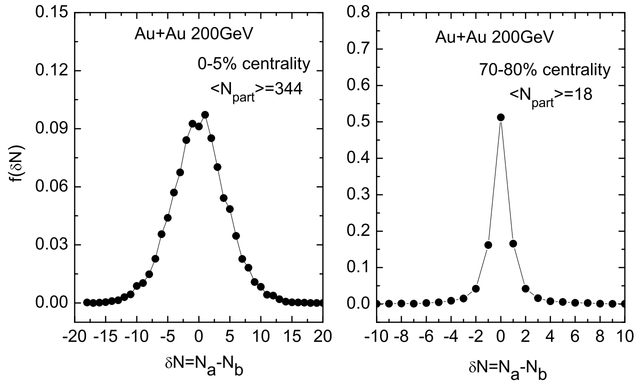

FIG. 1: Initial state fluctuation of the number of extra nucleons, δN, in 100+100 A·GeV 0-5% central and 70-80% peripheral Au+Au collisions in PACIAE model.

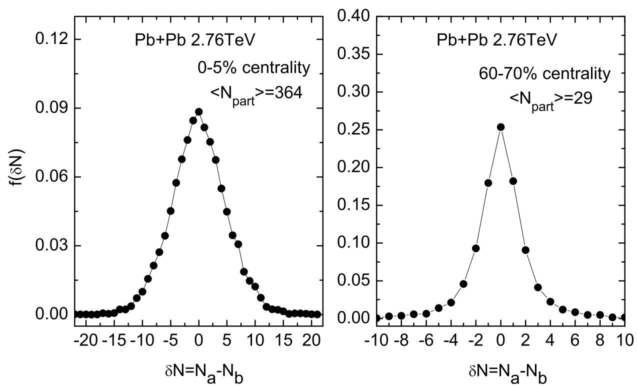

FIG. 2: Initial state fluctuation of the number of extra nucleons, δN, in 1.38+1.38 A·TeV 0-5% central and 60-70% peripheral Pb+Pb collisions in PACIAE model.

of the symmetric part of participant matter. Then we can assume the mass number of the symmetric part to be $< N_{part} > - < |\delta N| >$. If we assume further that all of the reaction energy is absorbed in the participant matter and $< N_{part} > \gg \delta N$ then we get

$$\Delta y_{CM}(\delta N) \approx \text{artanh}\left[\frac{\delta N}{< N_{part} >}\tanh(y_0)\right] .$$

Thus, the CM-rapidity distribution becomes a series of delta 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 CM-rapidity distribution will be smoothed out.

Figure 3 is the simulated results from partonic initial state generated by PACIAE model for 1.38+1.38 A·TeV 0-5% central Pb+Pb collisions.

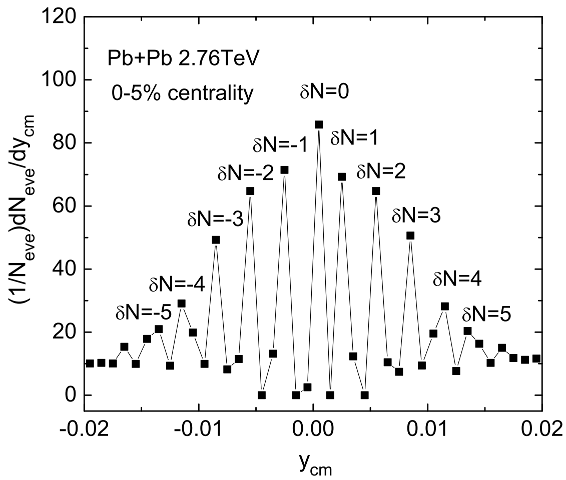

FIG. 3: Initial state CM-rapidity fluctuation in 1380+1380 A·GeV 0-5% central Pb+Pb collisions in PACIAE model. The figure shows that the rapidity change caused by δN=1, 2, 3, ..., extra nucleons is a very sharp peak in the CM-rapidity. This is because there is no tightly bound system to absorb energy and momentum in the model. If not so, the bound system will allow for rapidity fluctuations at given δN, making each sharp peak much wider, and increases the width of the overall y_{CM} distribution.

C. CM-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. If these gluons are regarded as a distinct gluon field, then this gluon field might keep the partonic initial state system more bound and uniform. The remaining part (quarks and anti-quarks) of the partonic initial state fluctuates stronger.

There are other possibilities, which may increase the CM-rapidity 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..

Figure 4 gives CM-rapidity fluctuation of the quarks and anti-quarks in the partonic initial state calculated for 1380+1380 A ·GeV, 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 CM-rapidity 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 CM-longitudinal momentum per participant nucleon of the quarks and anti-quarks 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

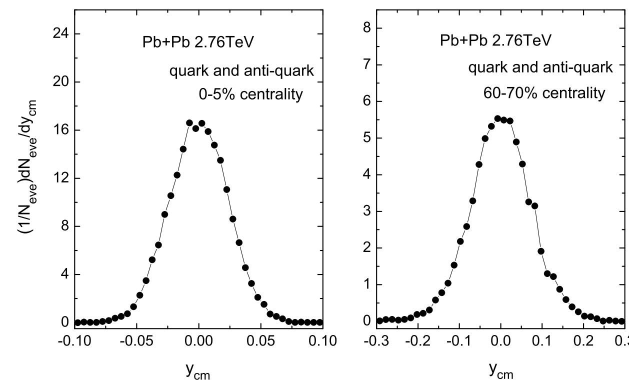

FIG. 4: The CM-rapidity fluctuation of quarks and anti-quarks in the initial state calculated for 1380+1380 A·GeV, 0-5% central and 60-70% peripheral Pb+Pb collisions by PACIAE model.

anti-quarks 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 anti-quarks and gluons, respectively, in the 0-5% central Pb+Pb collisions. So, how gluons are treated is an important issue.

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 FO 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 amount of thermal and collective kinetic energy to different hadrons [14].

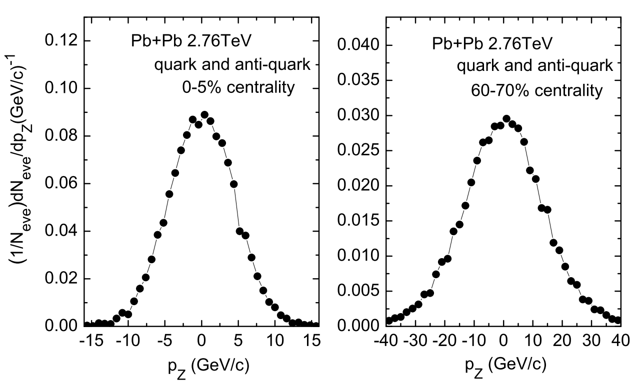

FIG. 5: The fluctuation of the CM-longitudinal momentum per participant nucleon of the quarks and anti-quarks in partonic initial state, i.e. p_z fluctuation calculated for 1380+1380 A·GeV 0-5% central and 60-70% peripheral Pb+Pb collisions by the PACIAE model.

IV. CONCLUSIONS

Initial state fluctuations were analyzed in the PACIAE model, with particular attention to the CM-rapidity fluctuations. It was found that in central collisions the longitudinal asymmetry, arising from different number of projectile and target participants, in longitudinal momentum is around 1.5% only, while for peripheral reactions it can reach $\pm 5.5 - 7\%$ (see Fig. 2). In central collisions the CM-rapidity fluctuations arise from this longitudinal asymmetry is not large in the PACIAE model as indicated by Figure 3.

We can see in Fig. 4 that the arising CM-rapidity fluctuation is around ± 0.03 units for central collisions and around ± 0.1 units in peripheral ones, they are quite small. In these estimates the contribution of gluons is not included, they would even decrease the CM-rapidity fluctuations further (cf. Fig. 3).

In the PACIAE partonic initial state study above, we do not include the pre-equilibrium emission, the collective effects as e.g. rotation, and the formation of excited intermediate states. These could lead to the increase of CM-rapidity 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 as at RHIC and LHC energies that, the observed collective v_1 flow is rather weak, $|v_1| \leq 0.001$ at $\eta = 0.8$, so 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 [15]. 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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