ASYMMETRIC FIREBALLS IN SYMMETRIC COLLISIONS*

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This contribution reports on the results obtained in the two recently published papers [A. Bialas, A. Bzdak, K. Zalewski, *Phys. Lett.* **B710**, 332 (2012); A. Bialas, K. Zalewski, *Acta Phys. Pol. B* **43**, 1357 (2012)] demonstrating that data of the STAR Collaboration show a substantial asymmetric component in the rapidity distribution of the system created in central Au–Au collisions, implying that boost invariance is violated on the event-by-event basis even at the mid c.m. rapidity.

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1. It is now widely recognized that long-range correlations (LRC) in rapidity originate at the early stages of the collision, before the longitudinal expansion separates the particles by large distances. Such correlations can thus be used as a probe of the initial conditions of the evolution. This is particularly interesting for hydrodynamic descriptions of particle production, as the initial conditions strongly influence the evolution of the system (called henceforth "a fireball") expanding according to the rules of hydrodynamics [1]. The event-by-event fluctuations of the initial conditions in the transverse plane were already shown to induce several interesting features in the transverse momentum correlations observed in the final state [2, 3].

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Fluctuations in rapidity distributions were mostly investigated in the special case of forward–backward correlations, where one compares particle distributions in two intervals located symmetrically in the forward and backward hemispheres. They have been extensively studied since the early times of high-energy physics [4]. In most of these studies, only the global density fluctuations were considered [5–8] and data were interpreted as evidence for strong event-by-event fluctuations of the multiplicity of the produced particles. With increasing precision of data and larger observed particle densities, however, it was possible to consider the more general scenario, with the event-by-event fluctuations of both *multiplicity* and *shape* of the created system [9–11]. Let us add that, as shown in [9, 11], such measurements allow also to discriminate between various models of the multiparticle production and thus to understand better the mechanism of such processes.

In the present contribution, we report on the results obtained using a rather general method of studying these phenomena, proposed recently in [12, 13]. In particular, we demonstrate how, using the relevant data of STAR Collaboration [14, 15], it was possible to uncover some asymmetric component of the rapidity distribution in the symmetric Au–Au collisions.

2. Consider a fireball created in a single collision and a narrow rapidity bin Δ_i. Let us denote the average number of particles from this fireball falling into Δ_i by $\bar{n}_i$. It is related to the corresponding particle density of the fireball by

$$\bar{n}_i = \int_{\Delta_i} \rho(y)dy \approx \rho(y_i)\Delta_i \,. \tag{1}$$

Since the fireballs created in various events are not identical, $\rho(y)$ changes from event to event. We call these fluctuations *dynamic* and our purpose is to estimate them from data[1].

Even for a given $\rho(y)$, however, the actual number of particles in Δ_i fluctuates around $\bar{n}_i$. These fluctuations represent the noise we want to correct for. To this end, we assume that they are simply random, *i.e.* approximately Poissonian [16]. Under this assumption, for B bins the probability distribution for the occupation numbers $n_1, \ldots, n_B$ produced by one fireball is

$$P(n_1,...,n_B;\bar{n}_1,...,\bar{n}_B) = p(n_1;\bar{n}_1)...p(n_B;\bar{n}_B)\,; \quad p(n;\bar{n}) = e^{-\bar{n}}\frac{\bar{n}^n}{n!}\,. \tag{2}$$

[1] For a more detailed description, see [12].

The observed distribution is the average over all events, or equivalently over the averages $\bar{n}_i$[2]

$$P(n_1,...,n_B) = \int d\bar{n}_1...d\bar{n}_B W(\bar{n}_1,...,\bar{n}_B) p(n_1;\bar{n}_1)...p(n_B;\bar{n}_B)\,, \qquad (3)$$

where $W(\bar{n}_1,...,\bar{n}_B)$ is the probability distribution of the set $[\bar{n}_1,...\bar{n}_B]$, characterizing the distribution of the densities of the produced fireballs, *i.e.* the basic quantity of interest.

From the well-known property of the Poisson distribution

$$F_k \equiv \sum_n \frac{n!}{(n-k)!} p(n;\bar{n}) = \bar{n}^k\,, \qquad (4)$$

one easily derives

$$F_{i_1,..,i_B} = \int d\bar{n}_1...d\bar{n}_B W(\bar{n}_1,...,\bar{n}_B) \bar{n}_1^{i_1},...,\bar{n}_B^{i_B} = \left\langle \bar{n}_1^{i_1},...,\bar{n}_B^{i_B} \right\rangle_W, \qquad (5)$$

where $F_{i_1,..,i_B}$ are the factorial moments of the distribution (3). Equation (5) shows that measurement of factorial moments of the observed multiplicity distribution gives directly the moments of the fluctuating fireball densities [16].

3. Using (5) we have shown in [12] that the published data of the STAR Collaboration [14] give evidence for a substantial asymmetric component in the fireballs created in Au–Au collisions.

In this experiment, the second moments of multiplicity observed in two rapidity bins, symmetric with respect to $y_{\rm cm} = 0$ [at $0.8 \leq |y| \leq 1.0$], were measured for various centralities, selected according to the number of particles observed in the central bin, located also symmetrically around $y_{\rm cm} = 0$. In particular, at the highest centrality, the data [14, 15] give

$$\begin{aligned} D^2_{\rm ff} &\equiv \left\langle n_{\rm f}^2 \right\rangle - \left\langle n_{\rm f} \right\rangle^2 = 350 \pm 17\,; \\ D^2_{\rm fb} &\equiv \left\langle n_{\rm f} n_{\rm b} \right\rangle - \left\langle n_{\rm f} \right\rangle^2 = 202 \pm 17; \quad \left\langle n_{\rm f} \right\rangle = 96 \pm 5\,, \end{aligned} \qquad (6)$$

where the indices f and b refer to the forward and backward bins, respectively, and $n_{\rm f}$ and $n_{\rm b}$ denote the actually observed numbers of particles in these bins.

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[2] To illustrate the idea, consider a Monte Carlo simulation in which the probability density of finding a number of particles at some momentum is not fixed but depends on some (random) parameters Q. The probability density at a given Q is our $\rho(y)$. Fluctuations resulting from fluctuations of Q are the dynamical fluctuations. The remaining random event by event fluctuations are our purely statistical fluctuations.

From (6), one can evaluate the factorial moments

$$
\begin{aligned}
F_{20} &\equiv \langle n_{\rm f}(n_{\rm f}-1)\rangle = \left\langle \bar{n}_{\rm f}^2\right\rangle_W = D_{\rm ff}^2 + \langle n_{\rm f}\rangle^2 - \langle n_{\rm f}\rangle \;; \\
F_{11} &\equiv \langle n_{\rm f} n_{\rm b}\rangle = \langle \bar{n}_{\rm f}\bar{n}_{\rm b}\rangle_W = D_{\rm fb}^2 + \langle n_{\rm f}\rangle^2 \;.
\end{aligned}
\tag{7}
$$

Noting that $(\bar{n}_{\rm f} \pm \bar{n}_{\rm b})^2 = \bar{n}_{\rm f}^2 + \bar{n}_{\rm b}^2 \pm 2\bar{n}_{\rm f}\bar{n}_{\rm b}$ we thus obtain for the asymmetric and symmetric fluctuations

$$
\begin{aligned}
D_-^2 &\equiv \tfrac{1}{4}\left\langle (\bar{n}_{\rm f}-\bar{n}_{\rm b})^2\right\rangle_W = \tfrac{1}{2}\left[F_{20}-F_{11}\right] = 26 \pm 12\,; \\
D_+^2 &\equiv \tfrac{1}{4}\left\langle (\bar{n}_{\rm f}+\bar{n}_{\rm b})^2\right\rangle_W - \langle n_{\rm f}\rangle^2 = \tfrac{1}{2}\left[F_{20}+F_{11}\right] - \langle n_{\rm f}\rangle^2 = 228 \pm 12\,.
\end{aligned}
\tag{8}
$$

Using (6), we have

$$
D_- = 5.1 \pm 1.2\,; \qquad D_+ = 15.1 \pm 0.4\,. \tag{9}
$$

One sees that, although the symmetric fluctuations dominate, there is also a substantial asymmetric component. Indeed, the ratio $D_-/D_+ \approx 1/3$. Thus, one has to conclude that the created fireballs are, generally, not symmetric (obviously, for a symmetric fireball $D_- = 0$). This observation implies that the standard assumption of boost invariance is violated on the event-by-event level *even* at $y \approx 0$. As the effect is expected to be stronger at the early times (because the expansion has a natural tendency to smooth out the original inhomogeneities), this observation may have important consequences for the theoretical description of the process (*e.g.* for the hydro calculations).

Similar effect is also present in pp collisions. Data [14, 15, 17], when interpreted according to Eqs. (7) and (8), give $D_- = 0.21 \pm 0.05$ and $D_+ = 0.26 \pm 0.04$. Thus, in this case, *(i)* the relative fluctuations are stronger ($[D/\langle n\rangle]_{pp} > [D/\langle n\rangle]_{\rm AuAu}$), and *(ii)* the asymmetry of the fireballs is even more important. This confirms the earlier observation [6] that the UA5 pp data [18] are consistent with the presence of two asymmetric contributions (most likely representing remnants of the forward and backward moving projectiles).

4. Let us end with several comments.

(i) As discussed in detail in [19], the measurement of D_+ is strongly affected by the procedure used in [14] for determination of the centrality of the collision. Fortunately, the value of D_-, which is our main interest, is unaffected by this problem. For further discussion, see [20].

(ii) The observed asymmetries find a natural explanation if, at RHIC energies, some remnants of the projectiles are still present even in the central rapidity region [21, 22]. Indeed, the contributions from the forward and backward moving projectiles are naturally asymmetric [21]. Since they are expected to fluctuate quasi-independently, they produce — generally — an asymmetric fireball.

(iii) Since the STAR data give only moments of the second order, it is clear that introducing such two components gives enough freedom to obtain a correct value for D_-. Moments of higher order are needed, however, to determine if they are sufficient as claimed in [22, 23], or if more components are necessary, as suggested *e.g.* by the dual-parton model [24] (suggesting also that the observed asymmetry should have a tendency to decrease with increasing energy of the collision). Therefore, the relevant measurements at LHC and at lower energies may be of special interest[3].

(iv) It should be emphasized that the density $\rho(y)$, whose fluctuations we proposed to study, summarizes effects of all processes leading to the observed final state. It thus includes, at least partly, the effects of hadronization. Indeed, during hadronization the density of plasma is replaced by the densities of particles and resonances, thus introducing some additional randomness. Our Poissonian Ansatz (2), (3) removes the purely statistical fluctuations, but does not remove the possible dynamical fluctuations which may be induced during hadronization, for example, by the resonance production. These fluctuations are much more difficult to control, as they are model-dependent. We would like to point out, however, that these are genuine dynamical effects which provide relevant physical information about the process of particle production. Therefore, they should be included in the analysis.

(v) An estimate of these hadronization effects is of clear interest, however, since otherwise it is not possible to make definite statements about the initial conditions of the collision. We have, therefore, worked out [13] how resonance production can modify the results of [12], presented in Section 3. We have considered an extreme situation in which all observed pions are decay products of resonances. For ρ production, the correction to D_- does not exceed 8–10%, for the transverse momentum of the ρ up to 1 GeV. Similar results are obtained for ω production and for production of heavy (1.5 GeV) clusters decaying into 3 particles. The corrections can reach up to 20% in pp collisions, still within the quoted errors. We, therefore, conclude that neither resonance production nor clustering effects can explain the asymmetry observed in data.

[3] A systematic method to study the general fluctuations of the fireball density in rapidity was recently proposed in [25].

5. In conclusion, it is argued that the systematic study of the factorial moments of the multiplicity distribution in several rapidity intervals represents a powerful tool allowing to investigate, on event-by-event basis, the longitudinal structure of systems ("fireballs") produced in high-energy collisions. The proposed procedure allows to remove the random statistical fluctuations and thus to obtain information on the true, dynamical, event-by-event fluctuations of the system.

It was shown that, when applied to the data of STAR Collaboration [14], this method allows to uncover the importance of *asymmetric* fireballs produced dynamically in the *symmetric* Au–Au collisions. This result seems interesting, since it implies that the hypothesis of boost invariance is violated on the event-by-event level *even in the central rapidity region*. It is also interesting to note that the effect seems more significant for *pp* collisions, thus indicating a violation of boost-invariance also in "elementary" collisions. We feel that these observations should be seriously taken into account in modeling the particle production processes.

The method proposed in [12] is very general and flexible. It can be applied to any specific sample of events, *e.g.*, those associated with a large transverse momentum jet and/or selected according to overall multiplicity, transverse momentum and many others. Hopefully, the coming measurements at LHC will be able to exploit its full capacity.

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