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Recent results on event-by-event fluctuations in ALICE at the LHC

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Abstract. Non-statistical event-by-event fluctuations in relativistic heavy-ion collisions have been proposed as a probe of phase instabilities near the QCD phase transition. In a thermodynamical picture of the strongly interacting system formed in heavy-ion collisions, the fluctuations of the mean transverse momentum, mean multiplicity fluctuations, the balance function, higher moments of net-particle multiplicity distributions, etc., are related to the fundamental properties of the system, hence they may reveal information about the QCD phase transition. We present and discuss recent results on event-by-event measurements at LHC energies.

1. Introduction
Quantum chromodynamics (QCD) [1] predicts that at a sufficiently high energy density, on the order of 0.5 GeV/fm$^3$, a deconfined state of quarks and gluons is produced, the so-called quark gluon plasma (QGP). Heavy-ion collisions at ultra-relativistic energies can produce this state of matter, which is characterized by high temperatures and energy densities, where the degrees of freedom are no longer determined by hadrons, but by their constituents, the quarks and gluons [2]. Many different observables are used to verify the existence of and subsequently study the properties of the QGP. In this article, we will discuss on the net-charge fluctuations, the balance functions and the mean $\langle p_T \rangle$ fluctuation results obtained with the ALICE [3] detector at the Large Hadron Collider (LHC) at CERN. The central detectors at ALICE cover a large pseudorapidity region with good momentum resolution as well as good particle identification capabilities. This gives us an excellent opportunity to study the fluctuations and correlations of physical observables on an event-by-event basis. In these analyses, the Time Projection Chamber (TPC) [3] is used for selecting tracks, the Inner Tracking System (ITS) [3] is used for vertexing and triggering and the VZERO [3] scintillator hodoscopes are used for estimating centrality as well as for triggering.

2. Net-charge fluctuations
The net–charge fluctuations are sensitive to the number of charges in the system, thus the fluctuations in the QGP, with fractionally charged partons, are significantly different from those of a hadron gas with unit charged particles. The net–charge fluctuations can be expressed by the quantity $D$ [4], defined as:

$$D = 4 \frac{\langle \delta Q^2 \rangle}{N_{\text{ch}}} \approx \nu_{(+,-,\text{dyn})} \times \langle N_{\text{ch}} \rangle + 4$$

(1)
where \( \langle \delta Q^2 \rangle \) is the variance of the net–charge \( Q \) with \( Q = N_+ - N_- \) and \( N_{\text{ch}} = N_+ + N_- \). Here \( N_+ \) and \( N_- \) are the numbers of positive and negative particles. In the experiment, the net–charge fluctuations are best studied by calculating the quantity \( \nu_{+-,\text{dyn}} \):

\[
\nu_{+-,\text{dyn}} = \frac{\langle N_+ (N_+ - 1) \rangle}{\langle N_+ \rangle^2} + \frac{\langle N_- (N_- - 1) \rangle}{\langle N_- \rangle^2} - 2\frac{\langle N_- N_+ \rangle}{\langle N_- \rangle \langle N_+ \rangle}.
\] (2)

Taking into account global charge conservation and finite acceptance, one obtains the corrected value of \( \nu_{+-,\text{dyn}}^{\text{corr}} = \nu_{+-,\text{dyn}} + \frac{1}{\langle N_{\text{total}} \rangle} \) where \( \langle N_{\text{total}} \rangle \) is the average total number of charged particles produced over the full phase space. In the figure 1 (a), the variation of \( \nu_{+-,\text{dyn}} \times N_{\text{ch}} \) with respect to \( \Delta \eta \) is studied. The relative value of \( \nu_{+-,\text{dyn}} \times N_{\text{ch}} \) reduces smoothly with increasing \( \Delta \eta \) window. This behavior was predicted earlier in Ref. [7] and was attributed to the dissipation of the primordial signal arising from hadronic diffusion during the evolution from quark gluon plasma stage to the freeze-out stage. The data points are fitted with an error function of the form \( \text{erf}(\Delta \eta/\sqrt{8\sigma_f}) \), representing the diffusion process. In figure 1(b), the energy dependence of the net–charge fluctuations is shown in terms of \( \nu_{+-,\text{dyn}} \times N_{\text{ch}} \) and \( D \) (left– and right–axis, respectively). By confronting the measured value with the theoretically predicted fluctuations [4, 7], it is observed that the ALICE results are within the limits of the QGP and the HG scenarios.

**Figure 1.** (a): \( \Delta \eta \) dependence of net–charge fluctuation, expressed in term \( \langle N_{\text{ch}} \rangle \nu_{+-,\text{dyn}} \) (left axis) and \( D \) (right axis) for three different centrality percentiles. (b): The energy dependence of the net–charge fluctuations, expressed in term \( \langle N_{\text{ch}} \rangle \nu_{+-,\text{dyn}} \) (left axis) and \( D \) (right axis) of ALICE at \( \Delta \eta = 1 \) and \( \Delta \eta = 1.6 \) along with RHIC [5] results. The expectations for a hadron resonance gas and the QGP are shown as shaded bands [4]. Figures are taken from [6].

3. Balance Function
The system that is produced in a heavy-ion collision undergoes an expansion, during which it exhibits collective behavior and can be described in terms of hydrodynamics. It was proposed to measure the creation time of particles via the correlations between positively and negatively charged pairs as a function of rapidity by the balance function [8]. The definition of the balance function for the pseudorapidity difference \( \Delta \eta \) (similar equation for \( B(\Delta \varphi) \)) reads:

\[
B_{+-}(\Delta \eta) = \frac{1}{2} \left( C_{+-}(\Delta \eta) + C_{-+}(\Delta \eta) - C_{--}(\Delta \eta) - C_{++}(\Delta \eta) \right).
\] (3)

Each term of Eq. 3, is corrected for detector and tracking inefficiencies as well as for acceptance effects and can be written as \( C_{ab} = (N_{ab}/N_{b})/f_{ab} \). The factors \( f_{ab} \) where in the case of charged
particles, $a$ and $b$ correspond to the charge i.e. $f_{++}$, $f_{--}$, $f_{+-}$ and $f_{-+}$) represent the probability given that a particle $a$ is reconstructed, a second particle emitted at a relative pseudorapidity or azimuthal angle ($\Delta \eta$ or $\Delta \phi$, respectively), would also be detected.

![Figure 2. Balance function as a function of $\Delta \eta$ for different centrality classes: 0-5% (a), 30-40% (b) and 70-80% (c). Mixed events results, not corrected for the detector effects, are shown by open squares. See text for details. Figures are taken from [9].](image)

First balance functions from the ALICE were obtained from Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and can be found at [9]. Figure 2 presents the balance function as a function of the relative pseudorapidity $\Delta \eta$ for three different centrality classes: the (a) 0-5% (most central), the (b) 30-40% (midcentral) and the (c) 70-80% (most peripheral) centrality bins. It is seen that the width of the balance function gets smaller for more central collisions.

4. Mean $p_T$ fluctuations

Event-by-event fluctuations of the mean transverse momentum, i.e. $\langle p_T \rangle$, contain information about the dynamics and correlations in heavy-ion collisions. It has been suggested that the fluctuations in $\langle p_T \rangle$ may be related to the occurrence of thermalization and collectivity [10]. In general, there may be a variation in the fluctuations (increase or decrease) in heavy-ion collisions with respect to those that occur in pp collisions, which serve as the baseline for comparison. The two-particle correlator $C_m = \langle \Delta p_{T,i} \Delta p_{T,j} \rangle$ [11] is a measure of the dynamical component of the variance of $\langle p_T \rangle$ and is defined by

$$C_m = \frac{1}{\sum_{k=1}^{n_{ev}} N_k^{\text{pairs}} \sum_{k=1}^{n_{ev}} \sum_{i=1}^{N_k} \sum_{j=i+1}^{N_k} (p_{T,i} - \langle p_T \rangle_m) \cdot (p_{T,j} - \langle p_T \rangle_m)}, \quad (4)$$

where $n_{ev}$ is the number of events in a given multiplicity class $m$, $N_k^{\text{pairs}}$ is the number of pairs constructed out of $N_k$ number of particles in an event and equal to $0.5 \cdot N_k \cdot (N_k - 1)$ and $\langle p_T \rangle$ is the average $p_T$ of all tracks of all events in class $m$. $C_m$ vanishes in the presence of only statistical fluctuations.

In figure 3 (a), the relative dynamical fluctuation $\sqrt{C_m/M(p_T)_m}$ ($M(p_T)$ is the average $p_T$ of all tracks in all events of class $m$) is shown as a function of the average charged-particle multiplicity ($dN_{ch}/d\eta$) in pp collisions at $\sqrt{s} = 0.9$, 2.76 and 7 TeV. The non-zero values of $\sqrt{C_m/M(p_T)_m}$ indicate significant dynamical event-by-event $M(p_T)$ fluctuations which decrease with the increase of multiplicity. No beam energy dependence is observed in the relative fluctuation $\sqrt{C_m/M(p_T)_m}$. Figure 3 compares the ALICE results for $\sqrt{C_m/M(p_T)_m}$ to measurements in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR experiment at RHIC [12].
as a function of (b) \(\langle dN_{ch}/d\eta \rangle\) and (c) \(\langle N_{\text{part}} \rangle\). The agreement between LHC and the RHIC energies, albeit within the large experimental uncertainties, points to a relation between the observed fluctuation patterns and the collision geometry.

![Figure 3](image)

**Figure 3.** (a): Relative fluctuations \(\sqrt{C_{\text{m}}/M(p_T)_m}\) as a function of \(\langle dN_{ch}/d\eta \rangle\), for pp collisions at \(\sqrt{s} = 0.9, 2.76\) and 7 TeV. The relative dynamic fluctuations in Pb–Pb collisions measured by ALICE and Au–Au collisions measured by STAR as a function of \(\langle dN_{ch}/d\eta \rangle\) (b) and \(\langle N_{\text{part}} \rangle\) (c) along with power-law fits to the data as shown in dashed lines. The lower panels of (b) & (c) show ratios to power law fits. For the STAR data points, statistical and systematic uncertainties are combined. Figures are taken from [13].

5. Summary and outlook

In summary, dynamical net-charge fluctuations were presented as a function of centrality and pseudorapidity. Their value is below the expectation for a hadron resonance gas and above that of the QGP. The widths of the balance functions are found to decrease when moving from peripheral to central collisions. The fluctuations of mean transverse momentum get diluted for higher multiplicities. An additional reduction of the fluctuations is observed for central Pb–Pb collisions. Future studies will extend the analysis of net-charges to higher moments net-particle multiplicity distributions and will add moment analyses of identified quark flavors. In addition, the balance functions and mean transverse momentum fluctuations will be studied in pp and p–Pb collisions as well as for identified particles with respect to their transverse momentum and event–plane dependence.

References


