IL NUOVO CIMENTO **48 C** (2025) 16
DOI 10.1393/ncc/i2025-25016-3

Colloquia: WPCF-Resonance 2023

Probing the dynamical evolution of QGP using charge-dependent correlations and fluctuations at CMS

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received 23 July 2024

Summary. — We present the first studies of net-charge fluctuations and charge-balance functions using the broad rapidity coverage of the CMS experiment. These types of event-by-event fluctuations are a powerful tool to characterize the thermodynamic properties of the quark-gluon plasma (QGP). The net-charge of the system is a conserved quantity, meaning its fluctuations are sensitive to the QGP formation and phase transition. It therefore provides an understanding of strong interactions complementary to that from the charge balance function. Relative to past measurements which probed a limited phase space region, we extract fluctuations up to a pseudorapidity separation of $\Delta\eta = 4.8$, and as such, significantly improving the sensitivity to test what has been theoretically predicted for the QGP formation. In turn, the width of the balance function, both in relative $|\eta|$ and relative azimuthal angle, is found to decrease with multiplicity for low particle transverse momentum ($p_{\mathrm{T}} < 2$ GeV/c). The effect is observed for both PbPb and pPb collisions, and it is consistent with a late hadronization scenario, where particles are produced at a later stage during the system evolution. The multiplicity dependence is weaker for higher p_{T}, which signifies that the balancing charge partners are strongly correlated compared to the low-p_{T} region. Model comparisons cannot reproduce the multiplicity dependence of the width in $\Delta\eta$. However, a model which incorporates collective effects can reproduce the narrowing of the width.

1. – Introduction

Ultra-relativistic heavy-ion collisions are used to study the deconfined state of matter. In the initial stages of these collisions, the system has highest energy density and minimal volume. During the early stages of the collision, the system reaches a local equilibrium state characterized by frequent collisions among the constituents. The time taken to establish this local equilibrium is called the thermalization time. As the system expands, the energy density decreases, leading to a decrease in temperature. Two-particle angular correlations are used as a powerful tool to study the properties of the system created in high-energy collisions. The correlation can exhibit different characteristic features, such as, (i) a near-side ridge associated to the collective behavior, (ii) a peak at $(\Delta\eta, \Delta\phi) = (0, 0)$ due to intra-jet correlations, (iii) a correlation due to a decay resonance or quantum statistics correlation, and (iv) a broad structure in $\Delta\eta$ at $\Delta\phi = \pi$, due to the contribution from back-to-back jets. The mechanism driving particle production is primarily governed by local charge conservation principles, ensuring that for every positive charge generated, there exists a corresponding opposite balancing partner. This correlation between space and time manifests in momentum space as a result of radial expansion and subsequent hadronization. Specifically, the breadth of this balance is anticipated to be narrower when particles are produced during later stages influenced by radial flow. Conversely, a broader distribution may indicate the creation of charges during the early evolution stages. In our analysis, we present findings utilizing the extensive pseudorapidity coverage provided by the CMS detector, allowing us to observe developments in the medium's evolution as we can reach up to $|\eta| < 2.4$, a crucial capability for understanding the dynamics at play.

The balance function is defined as the difference of the associated yields per trigger particle for unlike- and like-sign combinations, according to B($\Delta\eta$, $\Delta\phi$) = $\frac{1}{2}$ [$C_2(+,-)$ + $C_2(-,+)$ - $C_2(+,+)$ - $C_2(-,-)$] [1].

The measurement of event-by-event fluctuations in the conserved quantities, such as the net-charge or net-baryon, or the net-strangenes numbers are frequently useful tools for characterizing the thermodynamic properties of the QGP medium produced in the heavy-ion collisions, as they fluctuate when measured in a limited rapidity space or based on the collision impact parameter. Such fluctuations in the conserved quantities are given by, $\Delta O^2 = \langle O^2 \rangle - \langle O \rangle^2 = \mathrm{T}\, \frac{\delta \langle O \rangle}{\delta \mu}$ where T is the temperature and μ is the chemical potential of the system. The net-charge fluctuations are proportional to the square of the charges in the system. The particles in hadron gas phase have unit charge (± 1). But quarks are the charge carriers in the QGP phase, and have fractional charge ($\pm\frac{2}{3}$, $\pm\frac{1}{3}$). So the net-charge fluctuations in QGP phase are thus much smaller than that in the hadron gas or resonance gas phase.

The net-charge fluctuations are reduced in the system where there is rapid hadronization of the medium. Furthermore, the fluctuations per entropy in QGP medium may be less than the hadron gas. Hence, net-charge fluctuations measurement can reveal its origin of phase. These fluctuations are regarded as a sensitive observable to study the phase transition of hadronic matter to QGP. However fluctuations in the net charge are plagued by the errors and uncertainties arising from the volume fluctuations. Hence it is recommended to measure them via the ratio fluctuations (where ratio R = $\frac{N+}{N-}$) of R_{+-}, R_{--}, and R_{++}. Where the dynamic charge observable, ν_{dyn} is given by $\nu_{\mathrm{dyn}} = R_{++} + R_{--} - R_{+-} - R_{-+}$. The entropy produced in the medium is proportional to the number of charged particles. The measure of charge fluctuations per unit entropy is provided by D parameter. Nu-dynamics (ν_{dyn}) is directly related to the D-measure by $D = 4\, \frac{\langle \delta Q^2 \rangle}{\langle N_{\mathrm{ch}} \rangle} = \langle N_{\mathrm{ch}} \rangle \nu_{+-\mathrm{dyn}} + 4$. Although the correlations between N+ and N- can be reduced by neutral resonances, and the existence of resonance is anticipated to increase this value up to roughly $D = 3$. In the QGP phase D measure is equal to 0.75. While for the case of lattice QCD along with the entropy density included, the value of D can lie between 1–1.5 [2].

2. – Analysis method

The differential 2D correlation function is constructed using the standard CMS approach [3,4]. In two-particle correlations, the first particle is always the "trigger" particle, and the second particle is the associated particle. The number of trigger particles for each event is denoted by N_{trig}, the signal distribution S($\Delta\eta$, $\Delta\phi$) is constructed from the pairs of particles within the same event pair particles S($\Delta\eta$, $\Delta\phi$) = $\frac{1}{N_{\text{trig}}}\frac{d^2N^{\text{same}}}{d\Delta\eta\Delta\phi}$, where N^{same} is the number of pairs in ($\Delta\eta$, $\Delta\phi$) bin, where $\Delta\eta$ and $\Delta\phi$ are the relative pseudorapidity and the relative azimuthal angle between the two-particle which forms the pairs. The mixed event distribution M($\Delta\eta$, $\Delta\phi$) is constructed using mixed event technique by pairing the trigger particles in each event with the particles from other 10 random events. Events are mixed only if they are within the same centrality (in PbPb), or track multiplicity (in pPb) range and the relative difference of the primary vertex along the z-axis is less than 2cm. So the mixed event distribution is defined as M($\Delta\eta$, $\Delta\phi$) = $\frac{1}{N_{\text{trig}}}\frac{d^2N^{\text{mix}}}{d\Delta\eta\Delta\phi}$, where N^{mix} is the number of mixed event pairs in a given ($\Delta\eta$, $\Delta\phi$) bin. The per-trigger-particle associated yield is defined as $\frac{1}{N_{\text{trig}}}\ \frac{d^2N^{\text{pair}}}{d\Delta\eta\Delta\phi} = C_2\ (\Delta\eta,\ \Delta\phi)$ $= M(0,\ 0)\ \frac{S(\Delta\eta,\Delta\phi)}{M(\Delta\eta,\Delta\phi)}$ [1].

3. – Results

3˙1. *Balance Function.* – The balance function for non-identified charged particles is presented as a function of $\Delta\eta$ and $\Delta\phi$ in different multiplicity classes, and p_{T} ranges for both collision systems.

Figure 1 shows the 2D balance function in PbPb 5.02 TeV. Left to right addresses from central to peripheral collisions, and it is showing a broadening trend. Similarly, fig. 2 shows a broadening trend from high to low multiplicity in pPb 8.16 TeV. We can see the 1D projections from the 2D balance function in fig. 3 for both longitudinal and transverse directions in PbPb and pPb collisions in CMS, where central (0–10%) and high multiplicity have narrow peaks, implying late hadronization and peripheral or low

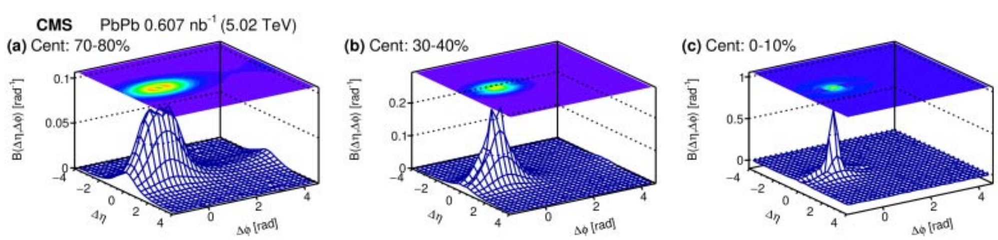

Fig. 1. – 2D balance function in PbPb collisions at 5.02 TeV [1]. Left is (70–80%) centrality, middle is (30–40%) centrality, and right is (0–10%) centrality.

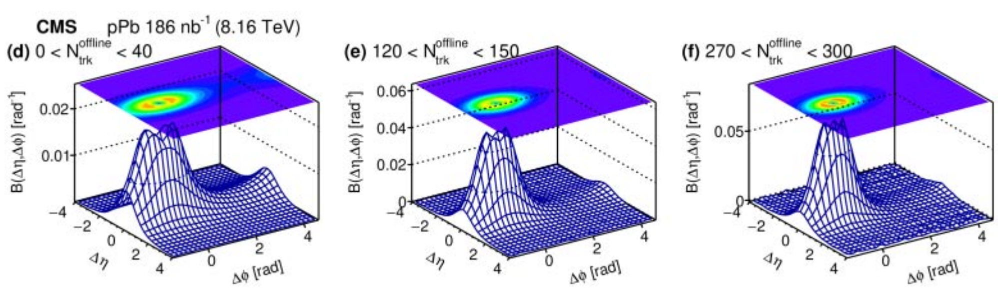

Fig. 2. – 2D balance functions in pPb collisions at 8.16 TeV [1]. $N_{\text{trk}}^{\text{offline}}$ ranges for the left is (0–40), for the middle is (120–150), and for the right is (270–300).

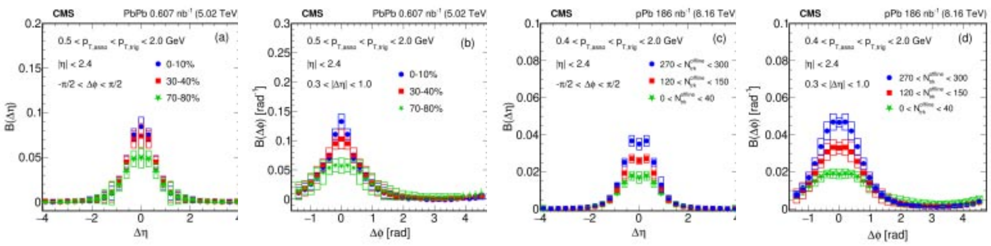

Fig. 3. – The above results are 1D $\Delta\eta$ and $\Delta\phi$ projections of the 2D balance functions [1] in PbPb and pPb collisions at 5.02 TeV and 8.16 TeV respectively. Trigger and associate $p_{\rm T}$ range is (0.5–2.0 GeV/c) for PbPb, and (0.4–2.0 GeV/c) for pPb. Three centrality bins and $N_{\rm trk}^{\rm offline}$ bins are considered for PbPb and pPb systems respectively.

multiplicity window have broader peak, referring early hadronization [1, 5].

$\Delta\eta$ and $\Delta\phi$ widths as a function of multiplicity are shown in fig. 4 for different $p_{\rm T}$ ranges in PbPb and pPb collisions. The balance function is getting narrower with increasing $p_{\rm T}$ range, whereas in high $p_{\rm T}$, multiplicity dependence is almost negligible.

3˙2. *Net-charge fluctuations.* – $\nu_{\rm dyn}$ as a function of centrality is presented in nine different bins ranging in between (0–80%). In general $\nu_{\rm dyn}$ is allowed to have positive or negative values. However, we observe the value of $\nu_{\rm dyn}$ is consistently negative, implying that the $R_{+-} + R_{-+}$ terms always dominate over the $R_{++} + R_{--}$ terms. We also see the absolute value of $\nu_{\rm dyn}$ increase from central to peripheral collisions. Implying an inverse dependence of $\nu_{\rm dyn}$ on multiplicity. As we move towards the most central collisions, with higher charge multiplicities, the absolute values of $\nu_{\rm dyn}$ monotonically approach zero.

The distribution of $\nu_{+-{\rm dyn}}$ against $\Delta\eta$ provides the information of the evolution of charge fluctuations through a purely hadronic medium, as these fluctuations diffuse with an increasing $\Delta\eta$ window. The distribution of $\nu_{\rm dyn}$ and D measure as a function of $\Delta\eta$ is plotted in fig. 5, rightmost plot. The lefthand side panel shows that absolute value of $\nu_{+-{\rm dyn}}$ decreases as we capture more particles with an increasing $\Delta\eta$ value in PbPb collisions at 5.02 TeV [2]. The value consistently approaches towards zero, but also consistently increases for the increasing values of centrality. Overall it shows a direct dependence on certain power of $\langle N_{\rm ch}\rangle$ until a certain limiting $\Delta\eta$ window, whereas almost less $\Delta\eta$ dependency observed in pp at 5.02 TeV. Our primary results lie on the

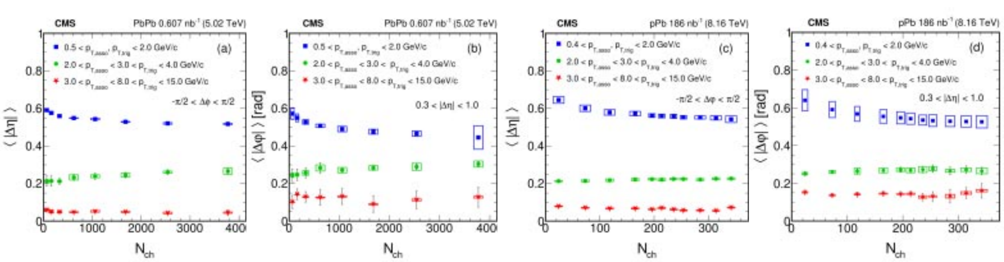

Fig. 4. – The above results are $\Delta\eta$ and $\Delta\phi$ width as observed over multiplicity for different $p_{\rm T}$ ranges in PbPb and pPb collisions at 5.02 TeV and 8.16 TeV respectively [1].

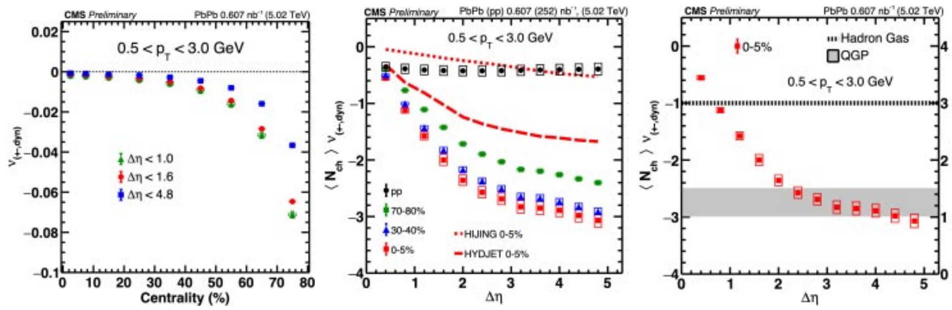

Fig. 5. – The above results are $\nu_{+-\mathrm{dyn}}$ *vs.* centrality (left), $\langle N_{\mathrm{ch}}\rangle\nu_{+-\mathrm{dyn}}$ *vs.* $\Delta\eta$ (center), and D value *vs.* $\Delta\eta$ (right) in PbPb and pp (center) collisions at 5.02 TeV [2].

right-hand side of fig. 5, which is the D measure as a function of $\Delta\eta$. With increasing $\Delta\eta$ that extends up to 4.8, the D measure steadily approaches values approximately equal to 1 [2, 6].

4. – Summary

Narrowing of width of the balance function with increasing multiplicities is consistent with the delayed hadronization. Narrowing in $\Delta\phi$ is also observed both in AMPT and Data. Width does not depend on multiplicity for higher p_{T}. Whereas a similar trend is observed in pPb collisions. ν_{dyn} value decreases with the increase of $\Delta\eta$ windows and saturating towards central collisions. Our experimental findings show that for $\Delta\eta = 4.8$, D measures close to 1 for central PbPb collisions, which indicates the formation of the QGP medium as predicted by the various theoretical models.

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