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Multiplicity and transverse momentum dependence of charge-balance functions in pPb and PbPb collisions at LHC energies

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Abstract

Measurements of the charge-dependent two-particle angular correlation function in proton-lead (pPb) collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{_{\mathrm{NN}}}} = 8.16\,\mathrm{TeV}$ and lead-lead (PbPb) collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$ are reported. The pPb and PbPb data sets correspond to integrated luminosities of $186\,\mathrm{nb}^{-1}$ and $0.607\,\mathrm{nb}^{-1}$, respectively, and were collected using the CMS detector at the CERN LHC. The charge-dependent correlations are characterized by balance functions of same- and opposite-sign particle pairs. The balance functions, which contain information about the creation time of charged particle pairs and the development of collectivity, are studied as functions of relative pseudorapidity ($\Delta\eta$) and relative azimuthal angle ($\Delta\phi$), for various multiplicity and transverse momentum (p_{T}) intervals. A multiplicity dependence of the balance function is observed in $\Delta\eta$ and $\Delta\phi$ for both systems. The width of the balance functions decreases towards high-multiplicity collisions in the momentum region $<2\,\mathrm{GeV}$, for pPb and PbPb results. Integrals of the balance functions are presented in both systems, and a mild dependence of the charge-balancing fractions on multiplicity is observed. No multiplicity dependence is observed at higher transverse momentum. The data are compared with HYDJET, HIJING, and AMPT generator predictions, none of which capture completely the multiplicity dependence seen in the data. The comparison of results with different center-of-mass energies suggests that the balance functions become narrower at higher energies, which is consistent with the idea of delayed hadronization and the effect of radial flow.

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*See Appendix A for the list of collaboration members

1 Introduction

Ultrarelativistic heavy-ion collisions provide a means to investigate the properties of the quark-gluon plasma (QGP) [1–6]. This state of matter is formed in the first few moments ($\sim$3 $\times 10^{-24}$ seconds) of such collisions, and is characterized by large energy density compressed into a small volume. Two-particle angular correlations are used as a tool to study the properties of the system created in high-energy collisions [7–12]. These correlations are usually measured as functions of $\Delta\eta$ and $\Delta\phi$, which denote the relative angle in pseudorapidity (η) and azimuthal angle (ϕ), respectively. Many physical phenomena manifest themselves in these correlations: the collective behavior of the medium can be apparent in the long-range longitudinal structure at small $\Delta\phi$ angles [11–14], the jet-related correlations can be observed as a peak at small relative $\Delta\eta, \Delta\phi$ angles together with a broad $\Delta\eta$ structure at $\Delta\phi \sim \pi$, while correlations in relative momentum caused by resonance decays or quantum statistics, such as Bose–Einstein correlations, will appear at small relative angles only.

Recent theoretical studies suggest that the QGP evolves during a high-energy heavy ion collision, producing quarks in two waves [15]. The first wave occurs during the first 5–10 fm $/c$ of the collision, when gluons thermalize into the QGP, followed by a isentropic expansion and hadronization, where most quark production occurs. The motivation behind the study in PbPb collisions stems from the expectation to differentiate between the early and late production of charges within the collision dynamics [16].

Charged-particle production is subject to local charge conservation, which ensures that for each created charge there is always an opposite balancing partner [15, 17]. The electric charge balance function represents the probability that a charge $+q$ will see its balancing charge $-q$ within a limited range of $\Delta\phi$ and $\Delta\eta$ [17]. The width of the balance function represents a powerful tool to study the dynamics of particle production [7–9, 18]. Specifically, the width of the balance function is expected to be narrower when the particles are produced at a later stage of the system evolution. Conversely, a wider distribution would correspond to charge creation earlier in the evolution. Additionally, collective medium expansion, specifically the radial flow, may also affect the observed width of the correlated distributions. The azimuthal width of the balance function depends on the strength of the radial flow, while its longitudinal spread is related to the longitudinal momentum as $\Delta\eta\ \sqrt{m_0^2 + p_{\mathrm{T}}^2}$, where p_{T} is the transverse momentum and m_0 is the particle mass [19]. Therefore, radial flow can contribute to the narrowing of the balance functions for more central collisions.

Additionally, balance functions may provide a sensitive probe to study the hadronization of jets in proton-proton (pp) collisions [20]. They can be used as a tool for studying the chemistry of the quark-gluon plasma [15, 16], the collision dynamics [21, 22], the hydrochemistry of particle formation [23, 24], and the balancing particle production [25, 26]. Moreover, the balance functions binned in the relative azimuthal angle, $\Delta\phi$, can effectively determine the diffusivity of light quarks [23, 24]. Thus, charge balance functions provide some of the most compelling evidence for forming a state of matter at chemical equilibrium with sufficient number of light quarks produced in the early stages of the collision [27]. Balance function integrals relate to net-charge fluctuations, which are crucial to understanding the transition from hadronic matter to the deconfined state and estimating QGP susceptibilities [23, 25, 28, 29]. Finally, the balance functions are also valuable for confirming the chiral magnetic effect. The latter predicts an electric charge separation along the direction of the magnetic field, which can be experimentally observed as a charge-dependent correlation in the momentum space [30].

The STAR Collaboration has performed measurements of the balance function in various collision systems, including AuAu, dAu, and pp collisions [31]. In AuAu collisions at $\sqrt{s_{_{\mathrm{NN}}}}$ =

200 GeV, for particles of $|\eta| < 1.0$, the balance function was found to have a strong centrality dependence in both $\Delta\eta$ and $\Delta\phi$. A similar measurement covering the range $|\eta| < 0.8$ was reported by the ALICE Collaboration at the CERN LHC [32]. These measurements demonstrate that charge separation at kinetic freeze-out is sensitive to the details of the hadronization dynamics. However, more quantitative comparisons are required between experimental measurements and theoretical predictions in balance function studies to fully understand the underlying physics. Extending the acceptance to cover more of the produced particle pairs could reveal additional details of the mechanism(s) driving the particle correlations.

In this paper the charge-balance function is measured over a wide coverage of $|\eta| < 2.4$ by exploiting the large acceptance of the CMS detector [33]. Results are presented as a function of charged-particle multiplicity and p_{T} in proton-lead (pPb) and lead-lead (PbPb) collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 8.16$ TeV and 5.02 TeV, respectively. A comparison of the PbPb and pPb collisions can provide insight into the origin of long-range correlations observed in high-multiplicity pPb collisions [8]. This paper is organized as follows. The CMS detector is briefly discussed in Section 2. Section 3 describes the data samples and selection criteria. Section 4 specifies the analysis procedure. Section 5 reports on the various sources of systematic uncertainty. Section 6 discusses the balance function results in both pPb and PbPb collisions, and comparison with models. Section 7 presents the energy dependence of charge balance functions and comparisons with the previous lower $\sqrt{s_{_{\mathrm{NN}}}}$ measurements. Finally, Section 8 summarizes the findings. Tabulated results are provided in the HEPData record for this analysis [34].

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume there is a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. The silicon tracker consists of 1440 silicon pixel and 15,148 silicon strip detector modules (Phase-0). In 2017, an additional layer was added in both the barrel and endcap regions of the pixel detector and the number of silicon pixel modules increased to 1856 (Phase-1). The tracker detector measured the charged particles within the range $|\eta| < 3.0$, and provides track resolutions of typically 1.5% in p_{T} and 25–90 (20–75) μm in the transverse impact parameter [35, 36] in Phase-0 (-1) of pixel detector for nonisolated particles of $1 < p_{\mathrm{T}} < 10$ GeV [37]. The forward hadron (HF) calorimeter uses steel as an absorber and quartz fibers as the sensitive material. The two halves of the HF are located 11.2 m from the interaction region, one on each end, and together they provide coverage in the range $3.0 < |\eta| < 5.2$. The HF calorimeters are subdivided into "towers" with $\Delta\eta \times \Delta\phi = 0.175 \times 0.175$, and energy deposited in a tower is treated as a detected hadron in this analysis. They also serve as luminosity monitors. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables can be found in Ref. [33].

3 Data samples and event selections

The analysis presented in this paper is based on PbPb collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02$ TeV collected by the CMS experiment in 2018. Approximately 4.27×10^9 PbPb events were used, corresponding to an integrated luminosity 0.607 nb^{-1} [38, 39]. The data samples were collected by the CMS experiment with a two-tiered trigger system. The first level trigger (L1) consists of custom hardware processors and, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 μs [40]. The second level or high-level trigger (HLT) consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [41]. The MB events are triggered by requiring signals above the readout threshold of 3 GeV in each of the HF calorimeters[41]. Further selections are applied offline to reject events from background processes (beam-gas interactions and nonhadronic collisions), as discussed in Ref. [42]. In the offline analysis, events are required to have at least one interaction vertex, based on two or more reconstructed tracks, with a distance of less than 15 cm from the center of the nominal interaction point along the beam axis, z_{vtx}. The primary vertex is taken to be the vertex corresponding to the highest track multiplicity in the event, evaluated using tracking information alone, as described in Section 9.4.1 of Ref. [43]. In the final analysis, the PbPb collision events are required to have at least two calorimeter towers in each HF detector with energy deposits of more than 4 GeV per tower. These criteria select $(99 \pm 2)\%$ of inelastic hadronic PbPb collisions. Finding values higher than 100% reflects the possible presence of ultra-peripheral (nonhadronic) collisions in the selected event sample.

The pPb data were recorded in 2016 and approximately 1.37×10^9 events were used, corresponding to an integrated luminosity of $186\,\mathrm{nb}^{-1}$ [39, 44]. The beam energies were 6.5 TeV for protons and 2.56 TeV per nucleon for lead nuclei, resulting in $\sqrt{s_{_{\mathrm{NN}}}} = 8.16$ TeV. The nucleon-nucleon center of mass in the pPb collisions is not at rest with respect to the laboratory frame because of the energy difference between the colliding particles. Massless particles emitted at $\eta_{\mathrm{cm}} = 0$ in the nucleon-nucleon center-of-mass frame will be detected at $\eta = -0.465$ (clockwise proton beam) or 0.465 (counterclockwise proton beam) in the laboratory frame. To select high-multiplicity pPb collisions, a dedicated high-multiplicity trigger was implemented [42]. At L1, the pPb events were triggered by requiring at least one track with $p_{\mathrm{T}} > 0.4$ GeV in the pixel tracker during a pPb bunch crossing and at least one tower in one of the two HF detectors having an energy above 1 GeV. In addition, the total number of ECAL+HCAL towers with the transverse energies above a threshold of 0.5 GeV is required to exceed 120 (ECAL) and 150 (HCAL). The events that pass the L1 trigger are subsequently processed at the HLT.

Track reconstruction is performed online as part of the HLT with the same reconstruction algorithm used offline [41]. The number of tracks with $|\eta| < 2.4$ and $p_{\mathrm{T}} > 0.4$ GeV (denoted as the primary tracks, i.e. originated at the primary vertex and satisfying the high-purity criteria [35]), and a distance of closest approach of less than 0.12 cm to the primary vertex, is determined for each event [45]. The primary tracks are used to perform the analysis, and to define event categories based on the charged-particle multiplicity ($N_{\mathrm{trk}}^{\mathrm{offline}}$). The multiplicity classification (120–150, 150–185, 185–250, $\geq$250) in this analysis is identical to that used in Ref. [46], where more details are provided, including a table relating $N_{\mathrm{trk}}^{\mathrm{offline}}$ to the fraction of minimum bias triggered events. When measuring the charge-balance function in pPb collisions, the same event may contain multiple independent interactions (pileup), which constitutes a background for the analysis of high-multiplicity events. The average number of collisions per event in pPb data varied between 0.10–0.25, and is negligible in PbPb collisions. A similar procedure to that described in [45] is used for identifying and rejecting events with pileup, which is based on the number of tracks associated with each reconstructed vertex and the distance between the vertices.

4 Analysis methods

Charged particle tracks are selected if the significance of the longitudinal (d_z) and transverse (d_{xy}) distance from the beam axis satisfies $|d_z|/\sigma_z < 3$ and $|d_{xy}|/\sigma_{xy} < 3$, where σ_z and σ_{xy} are the measurement uncertainties. The relative uncertainty in p_T, σ_{p_T}/p_T, must be less than 10%. To ensure high tracking efficiency and to reduce the rate of misreconstructed tracks, particles are selected within $|\eta| < 2.4$. For this analysis, we have applied a minimum p_T cutoff value of 0.4 (0.5) GeV for pPb (PbPb) collisions. Simulation studies based on HYDJET (version 1.8) [47], AMPT (version 1.1) [48] in PbPb and HIJING (version 1.3) [49, 50] in pPb are used to estimate the geometrical acceptance and efficiency for the primary track reconstruction as well as the rate of misreconstructed tracks. Each reconstructed track is weighted by the inverse of the correction factor, $f_c = AE/(1-F)$, as a function of pseudorapidity and transverse momentum. The weight factor accounts for the detector acceptance $A(\eta, p_T)$, reconstruction efficiency $E(\eta, p_T)$, and the fraction of misreconstructed tracks $F(\eta, p_T)$. The acceptance is defined as the probability that a charged particle generates enough hits in the tracker to be reconstructed by the track-finding algorithm, while the efficiency is defined as the likelihood that these hits will be used to reconstruct a track with parameters representative of the original particle. A detailed analysis of tracking performance based on Monte Carlo (MC) simulations and collision data can be found in Ref [51]. Simulated MC events show that the combined geometrical acceptance and reconstruction efficiency for the primary tracks is about 60% for the 0–5% most central PbPb collisions over the full acceptance of $|\eta| < 2.4$ and 65% for $|\eta| < 1.0$. The fraction of misreconstructed tracks is within 1–2% for $|\eta| < 1.0$ and 14% for $|\eta| < 2.4$. The contribution due to the secondary tracks coming from the beampipe and the detector material is also considered in this analysis and this found to be less than 0.01% or negligible. We note that the requirements on the distance from the primary vertex imposed on the selected tracks, as described above, are effective in removing the e^+e^- contamination in the opposite-sign particle correlations. This contamination stems from photon conversions in the detector material and is suppressed effectively, thanks to the high resolution of inner pixel detector layers and their proximity to the beam pipe responsible for the majority of this type of background. Track splitting and merging can impact pairs of tracks in close spatial and momentum proximity, affecting two-particle correlations. We studied the potential impact of these effects on the physics quantities of interest by comparing the nominal results with those constructed by removing all charged-particle pairs with momentum separation below a given threshold (minimal allowed separation of 0.1, 0.15, and 0.2 GeV were considered) along with the $\cos(\theta) < 0.9999$ requirement, which yielded negligible difference in the final measurements. In PbPb collisions, additional selections are applied to reject the misreconstructed tracks: the number of hits in the silicon tracker is required to be larger than 11 and the χ^2 per degree of freedom per layer of the silicon detector must be less than 0.18. Systematic uncertainty calculations related to the track selection variations are discussed in the next Section. The MC simulations of the CMS detector response are based on GEANT4 [52]. The PbPb collision centrality is defined as a fraction of the inelastic hadronic cross section, with 0% corresponding to the full overlap of the two colliding nuclei. The event centrality is determined offline and is based on the total transverse energy measured in the HF calorimeters, using the methodology described in Ref. [53]. The value of N_{ch} (charged-particle multiplicity) is corrected for the tracking efficiency and misidentification rate in both systems. For the N_{ch} calculation, a minimum p_T threshold of 0.5 (0.4) GeV is applied for PbPb (pPb) collisions. The centrality binning for PbPb and multiplicity binning for pPb collisions used for this measurement are listed in Table 1. Table 1 also presents values of the corrected average charged-particle multiplicity $\langle N_{ch} \rangle$ within $|\eta| < 2.4$ for different centrality bins, and multiplicities in PbPb and pPb collisions [46].

Table 1: Corrected average N_{ch} ($\langle N_{ch} \rangle$) values, calculated for different multiplicities in PbPb collisions at $\sqrt{s_{_{NN}}} = 5.02$ TeV and in pPb collisions at 8.16 TeV.

PbPb		pPb	
Centrality (%)	$\langle N_{ch} \rangle$	$N_{trk}^{offline}$	$\langle N_{ch} \rangle$
0–10	3770 ±189	0–40	24 ±1
10–20	2540 ±127	40–80	73 ±3
20–30	1678 ±84	80–120	118 ±5
30–40	1057 ±53	120–150	165 ±7
40–50	620 ±31	150–165	196 ±8
50–60	328 ±16	165–185	214 ±9
60–70	160 ±8	185–200	236 ±9
70–80	65 ±3	200–225	254 ±10
		225–250	285 ±11
		250–270	314 ±13
		270–300	342 ±14

The differential correlation function is constructed using the standard CMS method [7, 8, 11–13, 42, 46]. In each event, every "trigger" particle within a specified p_T interval is matched with other "associated" particles within a corresponding p_T interval. The trigger and associated particles may be selected from the same or different p_T intervals [54–56]. The trigger particles are defined, for each track multiplicity class, as charged particles originating from the primary vertex (PV) within a given p_T ranges and $|\eta| < 2.4$. There can be more than one trigger particle in the event, the total number of trigger particles is denoted as N_{trig}. The signal distribution $S(\Delta\eta, \Delta\phi)$ is constructed by using pairs of particles within the same event per trigger particle [7],

$$S(\Delta\eta, \Delta\phi) = \frac{1}{N_{trig}} \frac{d^2 N^{same}}{d\Delta\eta \, d\Delta\phi}, \tag{1}$$

where N^{same} is the number of pairs in ($\Delta\eta$, $\Delta\phi$) bin where $\Delta\eta$ and $\Delta\phi$ are the relative angular variables between the particles of the pairs. The so-called mixed event distribution $M(\Delta\eta, \Delta\phi)$ is constructed using the mixed event technique [45] by pairing the trigger particles in each event with the associated particles from 10 different random events within the same 2 cm wide z_{vtx} range and from the same track multiplicity class, as shown in Table 1:

$$M(\Delta\eta, \Delta\phi) = \frac{1}{N_{trig}} \frac{d^2 N^{mix}}{d\Delta\eta \, d\Delta\phi}, \tag{2}$$

where N^{mix} is the number of mixed event pairs in a given ($\Delta\eta, \Delta\phi$) bin. The correlation function is constructed using the normalized signal and mixed event distributions:

$$C_2(\Delta\eta, \Delta\phi) = M(0,0) \frac{S(\Delta\eta, \Delta\phi)}{M(\Delta\eta, \Delta\phi)}, \tag{3}$$

where $M(0,0)$ represents the mixed-event associated yield for both particles of the pair going in approximately the same direction (with a bin width of 0.3 in $\Delta\eta$ and $\pi/6$ in $\Delta\phi$). The $M(0,0)$ bin has the highest pair-acceptance, as for a given particle passing the analysis selection criteria, the conditional probability for the second particle to be accepted as well is highest in the closest spatial proximity to the first one. Therefore, the ratio $M(0,0)/M(\Delta\eta, \Delta\phi)$ is the pair-acceptance correction factor used to derive the corrected per-trigger-particle associated yield distribution [57]. The signal and mixed-event distributions are first calculated for each event, and then averaged over all the events within the same track multiplicity class, for each p_T bin. The correlation function is denoted by $C_2(\Delta\eta, \Delta\phi)$ in terms of the relative $\Delta\eta$ and $\Delta\phi$ variables. Using the positively and negatively charged particles, we construct four different charge combinations, which can be written as $C_2(+,-), C_2(+,+), C_2(-,+), C_2(-,-)$. The functions $C_2(+,+)$ and $C_2(-,-)$ are called SS correlations, and the other two are called OS correlations. The SS correlations are affected by the Hanbury–Brown–Twiss effect [58, 59], by Coulomb repulsion, and by a contribution from minijet production [60]. The OS correlations contain a minijet component [60], an attractive Coulomb contribution [58], and correlations due to the decay of resonances. The OS and SS correlations exhibit long-range rapidity correlations, called "ridge-like" correlations. The balance function combines same-sign subtractions to isolate the opposing charge statistically [15, 17, 56]. The balance function $B(\Delta\eta, \Delta\phi)$ is defined as

$$B(\Delta\eta, \Delta\phi) = \frac{1}{2}[C_2(+,-) + C_2(-,+) - C_2(+,+) - C_2(-,-)]. \tag{4}$$

5 Systematic uncertainties

Systematic uncertainties are calculated by varying the event and track selections for both PbPb and pPb collisions events. The balance function is calculated for three ranges of z-vertex of PV: $|v_z| < 3$ cm, $-15 < v_z < -3$ cm; and $3 < v_z < 15$ cm. Similarly, the track quality requirements are varied, by changing $|\mathrm{d}_z|/\sigma_z$ and $|\mathrm{d}_{xy}|/\sigma_{xy}$ from 2 to 5, σ_{p_T}/p_T from 0.05–0.10, and the χ^2 per layer from 0.15–0.18. Moreover, the centrality calibration is varied to estimate the related systematic uncertainties in the width of the balance function for PbPb collisions. Finally, the impact of pileup in pPb collisions is estimated by varying the pileup selection of events in the analysis by changing the required separation between reconstructed vertices and their numbers of associated tracks. The systematic uncertainties for each source are estimated from the difference between the nominal and varied results. The maximum variation is taken as the final systematic uncertainty for each source, and the total systematic uncertainty is evaluated by adding all the sources in quadrature. In PbPb simulations a discrepancy between $\Delta\phi$ balance functions obtained for particle level information and from reconstructed particle tracks was observed. This discrepancy is related to a reduced track finding efficiency for close-by low-p_T ($<$2 GeV) tracks in central PbPb collisions. A residual correction is a ratio of generated with reconstructed tracks, was obtained from MC simulations, where three models (HYDJET, HIJING and AMPT) provided consistent correction functions for the range $0.3 < |\Delta\eta| < 1.0$. The difference between corrected and uncorrected data was used as an conservative estimate of the corresponding systematic uncertainty. The maximum uncertainty was found to be 13.5% in the $\langle|\Delta\phi|\rangle$ comparison of the balance function discussed in Table 3.

Table 2: Summary of systematic uncertainties calculated in $\langle|\Delta\eta|\rangle$ and $\langle|\Delta\phi|\rangle$ for PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and pPb collisions at 8.16 TeV.

Uncertainty source	PbPb		pPb	
	$\langle\lvert\Delta\eta\rvert\rangle$	$\langle\lvert\Delta\phi\rvert\rangle$	$\langle\lvert\Delta\eta\rvert\rangle$	$\langle\lvert\Delta\phi\rvert\rangle$
Vertex selection	0.005	0.009	0.016	0.012
Centrality calibration	0.005	0.005	—	—
Pileup selection	—	—	0.002	0.001
Track quality requirements	0.004	0.012	0.017	0.004
Tracking efficiency	0.001	0.005	0.001	0.003
MC closure test	0.002	0.062	0.001	0.001

Table 2 lists the maximum absolute systematic uncertainties calculated for both collision systems in terms of $\langle|\Delta\eta|\rangle$ and $\langle|\Delta\phi|\rangle$. The systematic uncertainties in the amplitudes, widths, and integrals of the balance functions, due to the track and vertex selections, are estimated by varying these selections. For this analysis, we applied a minimum p_T requirement (0.4 GeV for pPb and 0.5 GeV for PbPb collisions) because of the inefficiency in the low-p_T tracking.

Table 3: Summary of percentage systematic uncertainties calculated in $\langle|\Delta\eta|\rangle$ and $\langle|\Delta\phi|\rangle$ for PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and pPb collisions at 8.16 TeV.

Uncertainty source	PbPb (%)		pPb (%)	
	$\langle|\Delta\eta|\rangle$	$\langle|\Delta\phi|\rangle$	$\langle|\Delta\eta|\rangle$	$\langle|\Delta\phi|\rangle$
Vertex selection	0.8	1.3	3.2	0.7
Centrality calibration	0.8	0.8	—	—
Pileup selection	—	—	0.4	0.1
Track quality requirements	0.7	3.5	2.7	2.8
Tracking efficiency	1.2	1.0	1.0	3.0
MC closure test	0.5	13.5	1.0	2.0

This measurement is also extended to higher values of p_T ($2 < p_{T,asso} < 3 < p_{T,trig} < 4$ GeV, $3 < p_{T,asso} < 8 < p_{T,trig} < 15$ GeV). The p_T of the trigger particle is denoted by $p_{T,\,trig}$, whereas that of the associated particle is denoted by $p_{T,\,asso}$. The systematic uncertainty values from each source, in all multiplicity classes and $p_T < 2$ GeV, are summarized in Table 3 for the two systems. The maximum systematic uncertainties in the width of the $\langle|\Delta\eta|\rangle$ and $\langle|\Delta\phi|\rangle$ are measured to be 6.0% for PbPb collisions and 3.0% for pPb collisions for intermediate values of transverse momentum, $2 < p_{T,asso} < 3 < p_{T,trig} < 4$ GeV. The maximum systematic uncertainties in $\langle|\Delta\eta|\rangle$ and $\langle|\Delta\phi|\rangle$ are found to be 4% in PbPb collisions; for pPb collisions, 4% and 6% are found for the lower ($2 < p_{T,asso} < 3 < p_{T,trig} < 4$ GeV) and the higher ($3 < p_{T,asso} < 8 < p_{T,trig} < 15$ GeV) values of p_T, respectively. In addition, the systematic uncertainties are calculated for the integral of the balance function. The highest variation for PbPb collisions is 3%, whereas the maximum difference for pPb collisions is 5%.

6 Results

The balance functions for nonidentified charged particles are presented as a function of $\Delta\eta$ and $\Delta\phi$ in different multiplicity classes and p_T ranges for both collision systems in Fig. 1.

The upper panels in Fig. 1 show the centrality dependence of the charge-balance function in PbPb collisions. The magnitude of the balance function changes with multiplicity, with higher values corresponding to collisions with higher multiplicity. A narrower balance function distribution is observed in central PbPb collisions. This is consistent with particle production at later times in the collision process for the larger system created in more central collisions, leading to a smaller separation in $\Delta\eta$ and $\Delta\phi$ [31].

The lower panels in Fig. 1 represent the multiplicity dependence of the balance function in pPb collisions. The balance function is observed to also become narrower in $\Delta\eta$ and $\Delta\phi$ with increasing multiplicity. A similar depletion structure around $(\Delta\eta, \Delta\phi) = (0, 0)$ is also seen in mid-central to peripheral PbPb events, as shown in upper panels of Fig. 1 and previously in Ref. [61]. This type of structure is more pronounced in pPb collisions in the smaller range of multiplicities. One possible mechanism that could create such a structure in both collision systems is the charge-dependent short-range correlations, such as Coulomb attraction or repulsion, or quantum statistical correlations [62].

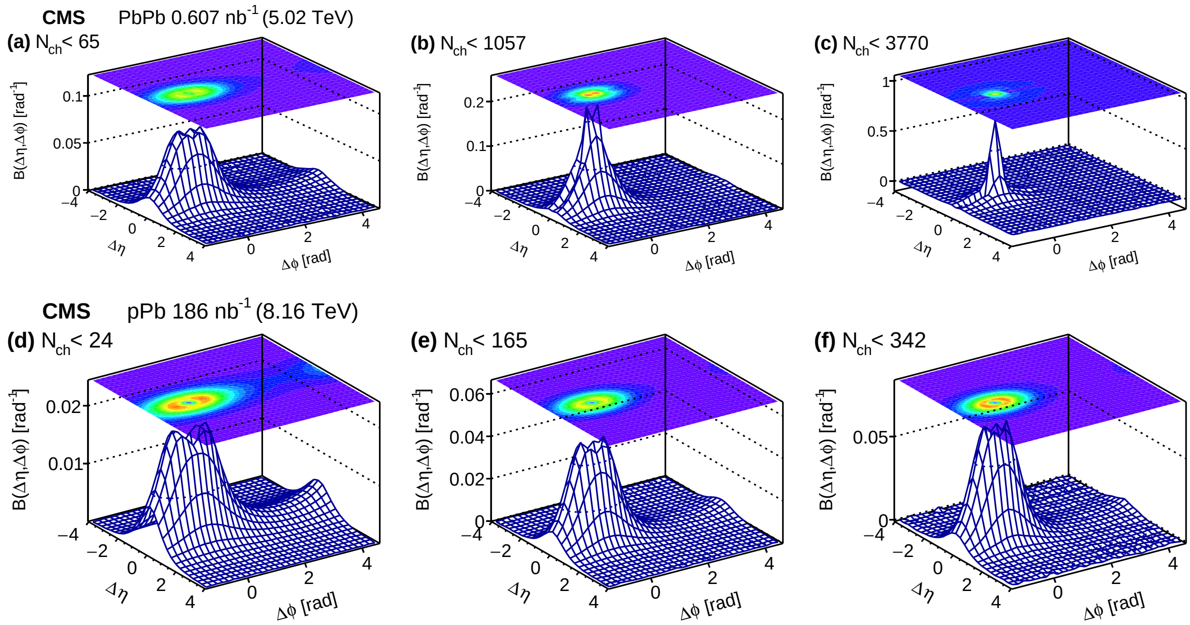

Figure 1: The balance function is shown in terms of $\Delta\eta$ and $\Delta\phi$ in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ (upper panels) and for pPb collisions at 8.16 TeV (lower panels). From left to right, the results are shown for the lowest to highest multiplicity classes in PbPb and pPb collisions. The trigger and associated particles in PbPb (pPb) collisions satisfy the condition $0.5(0.4) < p_{\mathrm{T,asso}} < p_{\mathrm{T,trig}} < 2.0\,\mathrm{GeV}$.

Figure 2 shows 1D projections, derived for $\Delta\eta$ ($|\Delta\phi| < \pi/2$ range) and $\Delta\phi$ ($0.3 < |\Delta\eta| < 1.0$ range). The balance function distributions show a strong multiplicity dependence in $\Delta\eta$ and $\Delta\phi$ on the near-side $|\Delta\phi| < \pi/2$, for both collision systems. As before, a narrower peak is observed in high-multiplicity pPb collisions as compared to low-multiplicity ones.

Figure 3 presents the near-side projection of the balance functions in PbPb and pPb collisions, and its comparisons with different MC model calculations. Neither AMPT nor HIJING can fully explain the balance function projections in $\Delta\eta$ and $\Delta\phi$ in PbPb collisions, as they both underestimate the balance function's magnitude, and anticipate far broader distributions. However, the one-dimensional projection is quantitatively in agreement with both the models in $\Delta\eta$, while AMPT slightly underestimates the pPb data in $\Delta\phi$ comparisons.

Figure 4 presents the away-side ($-\pi/2 < \Delta\phi < 3\pi/2$) projection of the charge balance functions for $p_{\mathrm{T}} < 2\,\mathrm{GeV}$ in both pPb and PbPb collisions. The away-side of the balance function demonstrates a distinct pattern, a larger magnitude of $B(\Delta\eta)$ is observed in the low-multiplicity events compared to their counterparts in high-multiplicity events. It is seen that none of these models from AMPT, HIJING, and HYDJET are in quantitative agreement with the data point and exhibit a correlation peak on the away-side of a significantly higher magnitude.

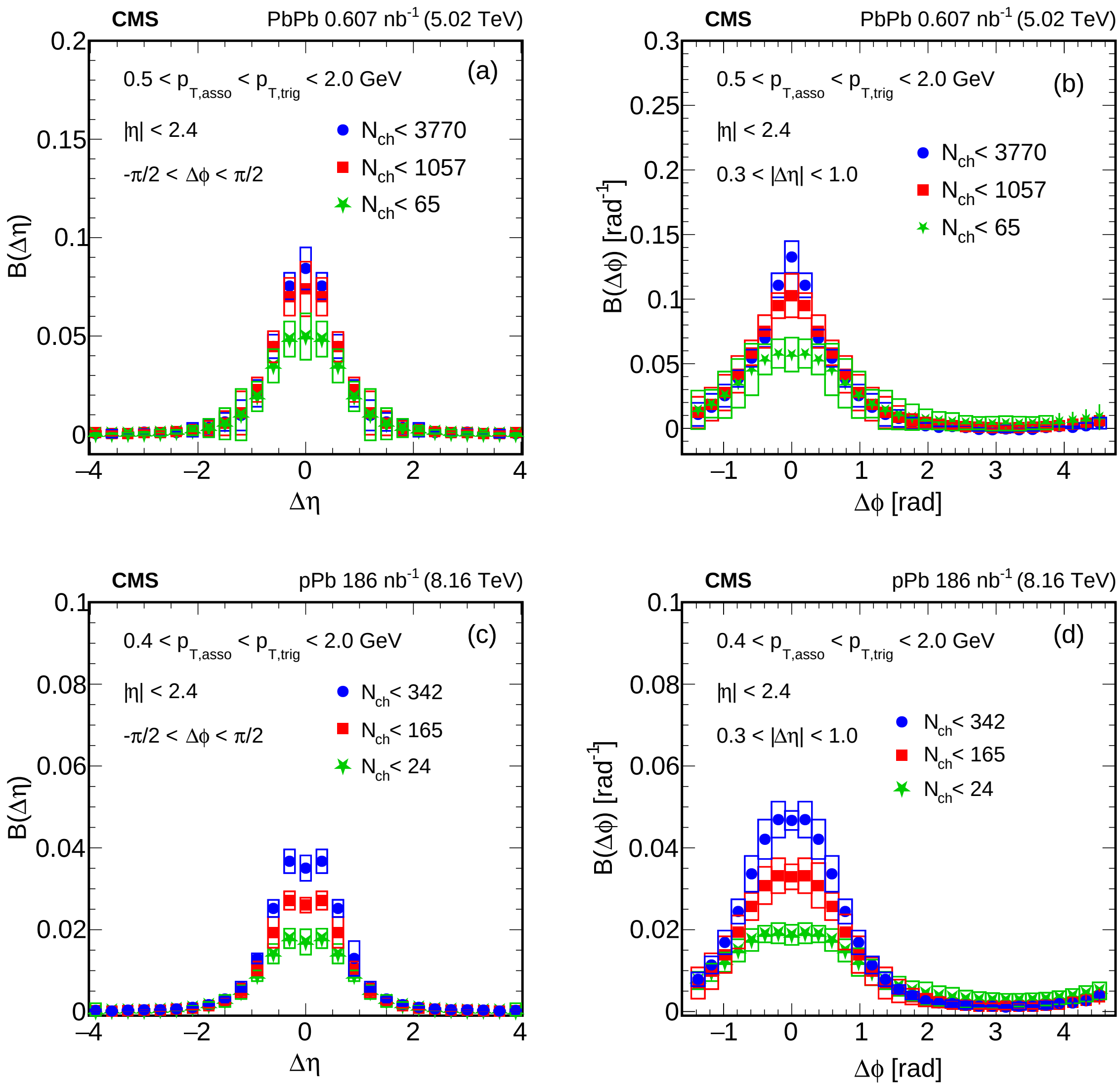

Figure 2: The projection of the balance function is presented in the upper panel for PbPb (lower panel for pPb) collisions as a function of $\Delta\eta$ (left column) and in $\Delta\phi$ (right column). The statistical uncertainties of the data points are smaller than the marker size and rectangular boxes indicate the systematic uncertainties.

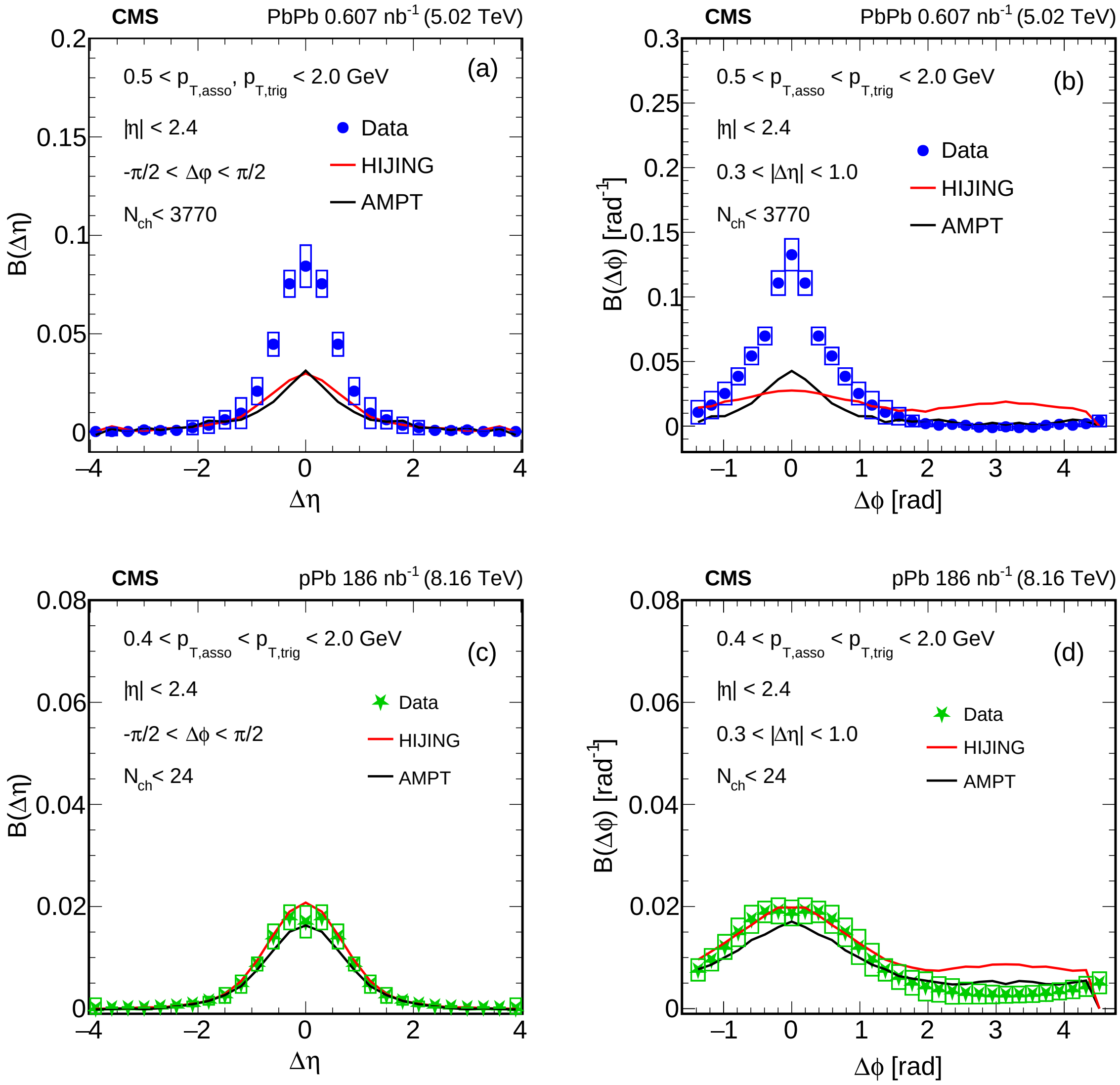

Figure 3: The comparison of the balance function with AMPT and HIJING event generators is presented in the upper panel ((a) and (b)) for PbPb collisions and the lower panel ((c) and (d)) for pPb collisions as a function of $\Delta\eta$ (left column) and in $\Delta\phi$ (right column). For PbPb collisions, only the highest multiplicity ($N_{ch} < 3770$) and for pPb collisions, only the lowest multiplicity ($N_{ch} < 24$) are shown.

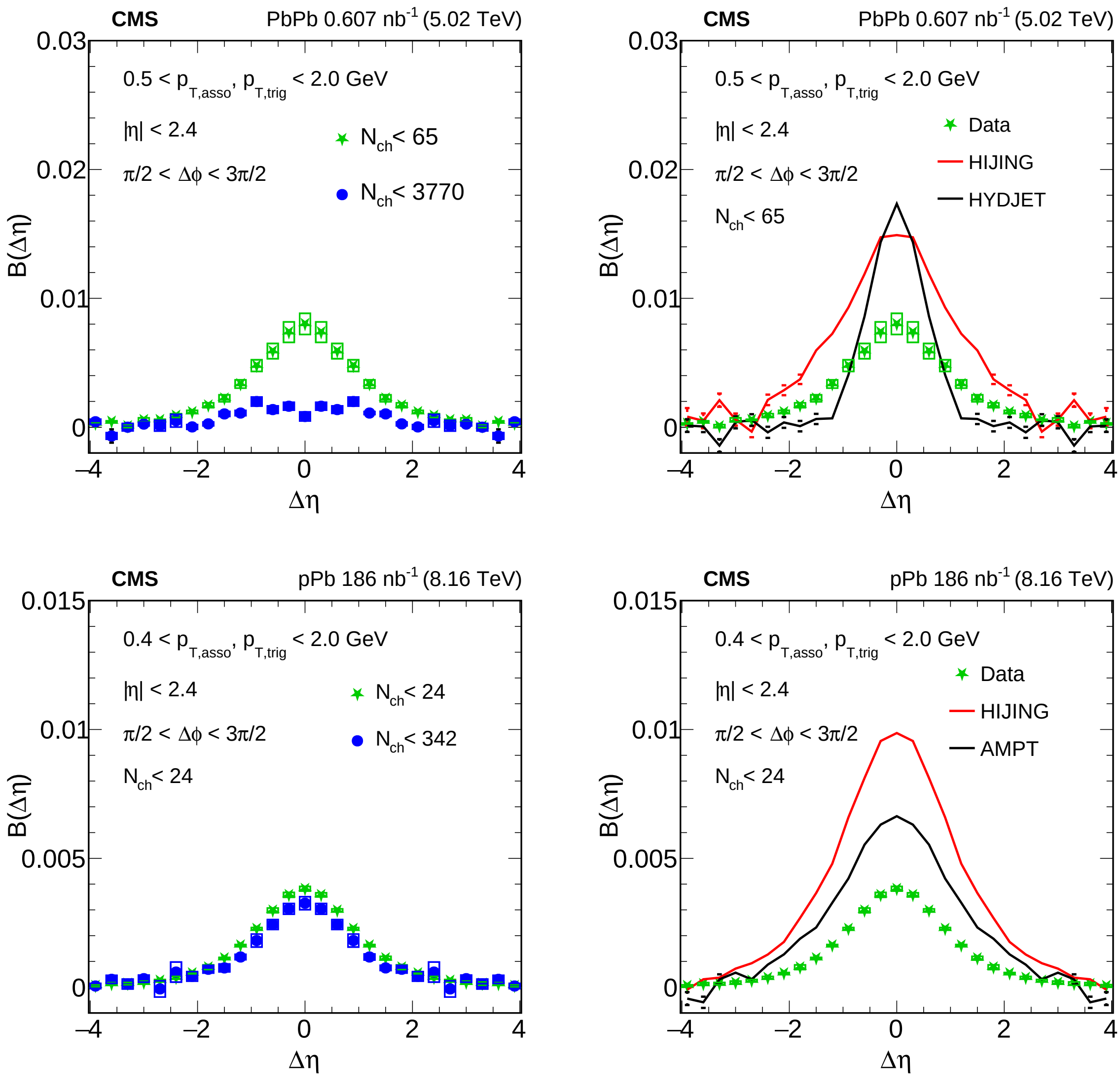

Figure 4: The away-side projection of the balance function for the charged-particles with $p_T <$ 2 GeV is shown for the PbPb upper panel ((a) and (b)) and pPb ((a) and (b)) collisions. The data results are compared with the different event generators with the lowest multiplicity in both the systems.

6.1 Balance function integral

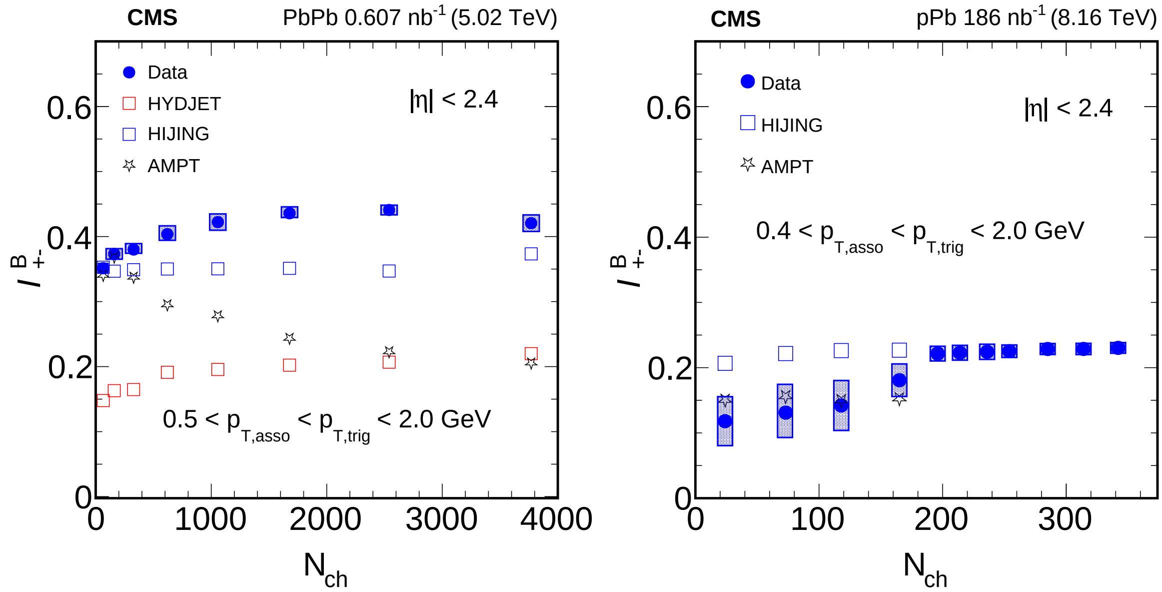

Figure 5: The integral of the balance functions (I^B_{+-}) in PbPb collisions at $\sqrt{s_{_{NN}}} = 5.02$ TeV (left) and in pPb collisions at $\sqrt{s_{_{NN}}} = 8.16$ TeV (right). The balancing partners fall within the specified pseudorapidity range ($|\eta| < 2.4$) and have transverse momenta within the range of $0.5 < p_T < 2.0$ GeV (for PbPb) and $0.4 < p_T < 2.0$ GeV (for pPb). The statistical uncertainties in the data points are smaller than the marker size and rectangular boxes indicate the systematic uncertainties.

The left and right plots in Fig. 5 present the integral of the balance functions in terms of N_{ch}, in PbPb and pPb collisions, respectively. By definition, the balance function is a conditional density. It is the likelihood that one event will occur under certain conditions while another possibility has occurred. In the ideal case [15, 25], the integral of the balance function over the full phase space (i.e., all possible values of η, p_T, and ϕ) is unity by construction, which means that the total charge in the collision is conserved. However, experimentally, because of the finite detector acceptance, the integral does not capture all the balancing partners due to the p_T selection made. The integral values of the balance function in PbPb and pPb collisions are determined to be 0.35–0.42 and 0.11–0.23, for $p_T < 2.0$ GeV, respectively. The integrals of the balance functions in the two systems show a notable difference. This may be due to the radial flow focusing pairs of both positive and negative particles into the same p_T range. In both these collisions, a minimal change in the integral with multiplicity classes is observed. Recently, ALICE reported the integral for nonidentified charged hadrons with $|\eta| < 0.8$ and $0.2 < p_T < 2.0$ GeV [61]. Comparison with the model calculations from HIJING, HYDJET, and AMPT are also shown in Fig. 5. The HIJING predictions show a weak dependence of the balance function integrals on the event multiplicity for both PbPb and pPb collision systems. The HYDJET calculations, available only for PbPb interactions, show an increasing trend toward higher-multiplicity events, similar to that seen in the data but significantly underestimating the magnitude of the measured integral values. Calculations from the AMPT model predict a decreasing trend towards the high multiplicity for PbPb collisions but little to no dependence on N_{ch} for pPb collisions. However, the multiplicity range for the latter predictions is limited. We note that within the N_{ch} overlap range, the AMPT calculations agree with the measured balance function integrals from pPb data within the uncertainties. A mild dependence of the integral of the balance function with collision centrality is observed, which could suggest the increase of multiplicity fluctuations for central events compared to peripheral events [63]. The integral of the balance function over the full acceptance is related to the charge fluctuations [25]. Additionally, the integral of balance functions is sensitive to the hydrochemistry of the collisions [26], which is necessary to infer contributions to single-particle spectra from hadronic resonance decays based on models.

6.2 Balance function width

The balance function distribution width can be used to quantify how tightly the balancing partners are correlated and can be characterized by the averages $\langle|\Delta\eta|\rangle$ and $\langle|\Delta\phi|\rangle$, with $\langle|\Delta\eta|\rangle$ given in Eq. (5),

$$\langle|\Delta\eta|\rangle = \frac{\sum_i B(\Delta\eta_i)|\Delta\eta_i|}{\sum_i B(\Delta\eta_i)}, \tag{5}$$

where $\sum_i B(\Delta\eta_i)$ is the balance function value for each $\Delta\eta_i$ bin, with the sum running over all bins i. The absolute average value of the balance function distribution is estimated in $\Delta\eta$ and $\Delta\phi$. The width of the balance function in $\Delta\eta$ and $\Delta\phi$ decreases with increasing N_{ch}, more significantly in the smaller N_{ch} range. For this analysis, we have used the range $|\Delta\eta| < 3$ for the $\langle|\Delta\eta|\rangle$ calculations, and $|\Delta\phi| < 1.5$ for the $\langle|\Delta\phi|\rangle$ calculations because of the probability of detecting both balancing charge-partners decreases with the increase of $\Delta\eta$ and $\Delta\phi$ windows. The balance function determined in a specific pseudorapidity window $B_{+-}(\Delta\eta|\eta_{\mathrm{max}})$ can be connected to the balance function over an infinite interval under the assumption of a boost-invariant system (independent of rapidity) [64] according to the Eq. (6),

$$B_{+-}(\Delta\eta|\eta_{\mathrm{max}}) = B_{+-}(\Delta\eta|\infty)\,(1 - \frac{\Delta\eta}{\eta_{\mathrm{max}}}). \tag{6}$$

The factor $(1 - \frac{\Delta\eta}{\eta_{\mathrm{max}}})$ represents the probability that a particle's partner, separated by $\Delta\eta$, will fall within the finite rapidity window [25].

6.2.1 Balance function in low transverse momentum and comparison with models

The results are compared with predictions from the HYDJET (PbPb collisions only) [65], AMPT, and HIJING MC event generators, by means of p-values [66] from a χ^2 test accounting for statistical uncertainties only. The HYDJET is composed by a combination of the soft, hydro-type state, and the hard multi-jets. In case of AMPT simulations, the string melting option is employed, with the generator parameters tuned to the available LHC experimental results. The HIJING model includes multiple minijet production, nuclear shadowing of parton distribution functions, and mechanisms of jet interactions in dense matter.

Figure 6 presents the experimental results of width values with N_{ch}, showing a strong multiplicity dependence of the $\langle|\Delta\eta|\rangle$ for both collision systems. In HYDJET, $\langle|\Delta\eta|\rangle$ does not show any significant dependence on N_{ch}. In this model, local charge conservation for more peripheral events (smaller multiplicities) has more influence on the charge-balance function than for large multiplicities. Comparing HIJING predictions with the PbPb and pPb data, no clear multiplicity dependence is seen in the model calculations. HIJING does not explain the experimental data properly as the p-value is smaller than 0.01. In addition, the magnitude of the balance function widths is larger in HIJING than in the data because the collective flow effect is not present in the HIJING model.

The data results are also compared with the AMPT model, which includes the quark coalescence and the decay of resonances. When comparing the $\langle|\Delta\eta|\rangle$ in both collision systems, AMPT predicts larger $\langle|\Delta\eta|\rangle$ than data (p-value of 0.01 in pPb), and overall shows worse agreement

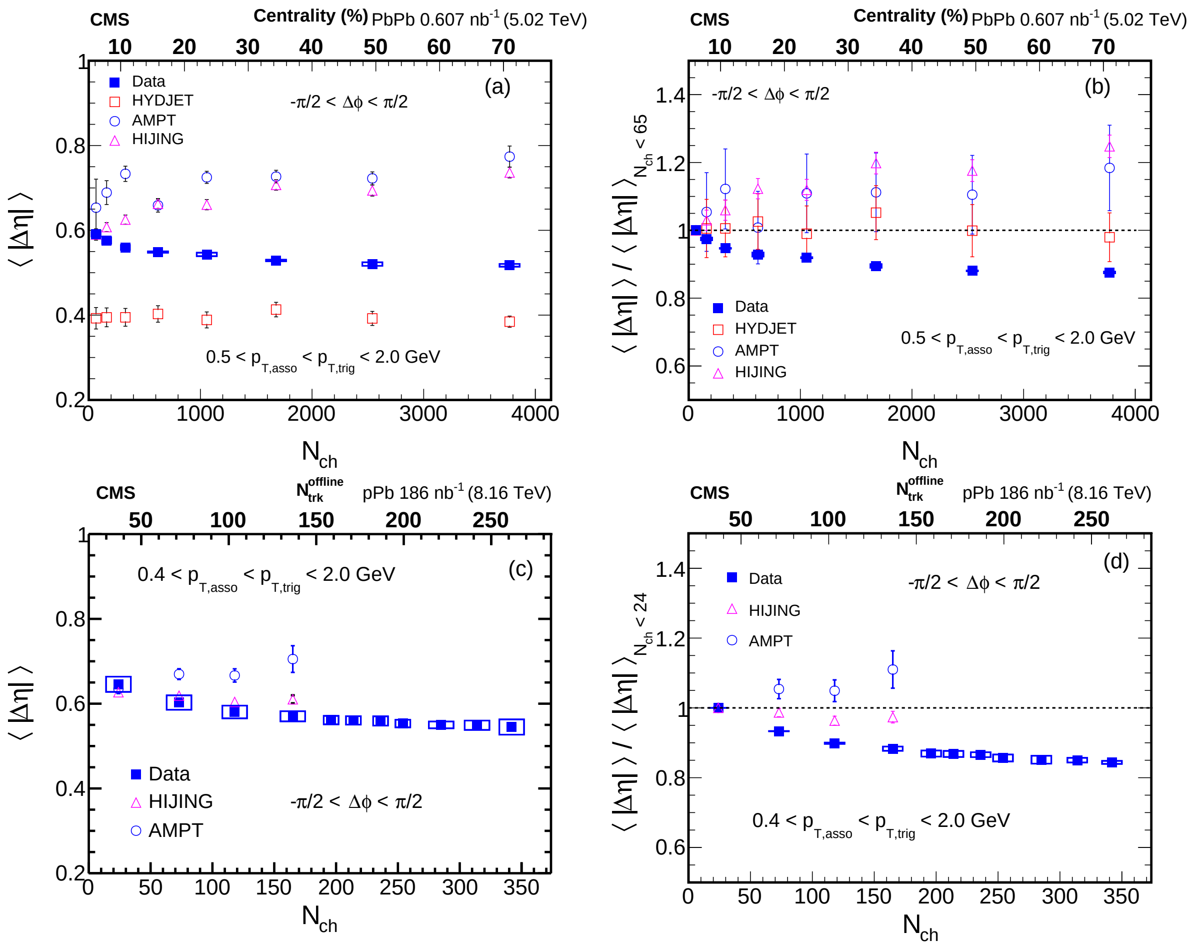

Figure 6: The width of the balance function in $\langle|\Delta\eta|\rangle$ and the ratio of $\langle|\Delta\eta|\rangle / \langle|\Delta\eta|\rangle_{N_{ch}<65}$ and $\langle|\Delta\eta|\rangle / \langle|\Delta\eta|\rangle_{N_{ch}<24}$ are shown as functions of N_{ch} for PbPb collisions in $\sqrt{s_{NN}} = 5.02$ TeV (upper panels) and pPb collisions in $\sqrt{s_{NN}} = 8.16$ TeV (lower panels), respectively. The statistical uncertainties of the data points are smaller than the marker size and rectangular boxes indicate the systematic uncertainties.

than HIJING (p-value of 0.01 in pPb). We estimate the relative decrease of the width, which is expressed by the ratio of $\langle|\Delta\eta|\rangle$ for each multiplicity class to the lowest multiplicity value, i.e., $\langle|\Delta\eta|\rangle_{N_{ch}<65}$ (for PbPb) and $\langle|\Delta\eta|\rangle_{N_{ch}<24}$ (for pPb) in order to compare the width in both collision systems within the same multiplicity range. However, due to the limitations in the model calculations, we are constrained within a specific range of multiplicity compared to the pPb data.

The right plots of Fig. 6 present the normalized width in $\Delta\eta$, where the data results are compared with different models and this indicates the model prediction does not show significant multiplicity dependence. Our experimental findings, based on considering only the statistical uncertainties from the limited sample size, suggest that the relative change in pPb collisions appears to similar to that in PbPb collisions.

Figure 7 presents the experimental findings for $\langle|\Delta\phi|\rangle$ in PbPb and pPb collisions. A significant change in the balance function width is observed with multiplicity. Similarly, the data results are compared with the various MC predictions. The HYDJET and HIJING generators are not able to reproduce the trend of data results in the case of PbPb collisions. A significant multiplicity dependence is shown in $\langle|\Delta\phi|\rangle$ because of the radial flow effect in AMPT, which acts over the

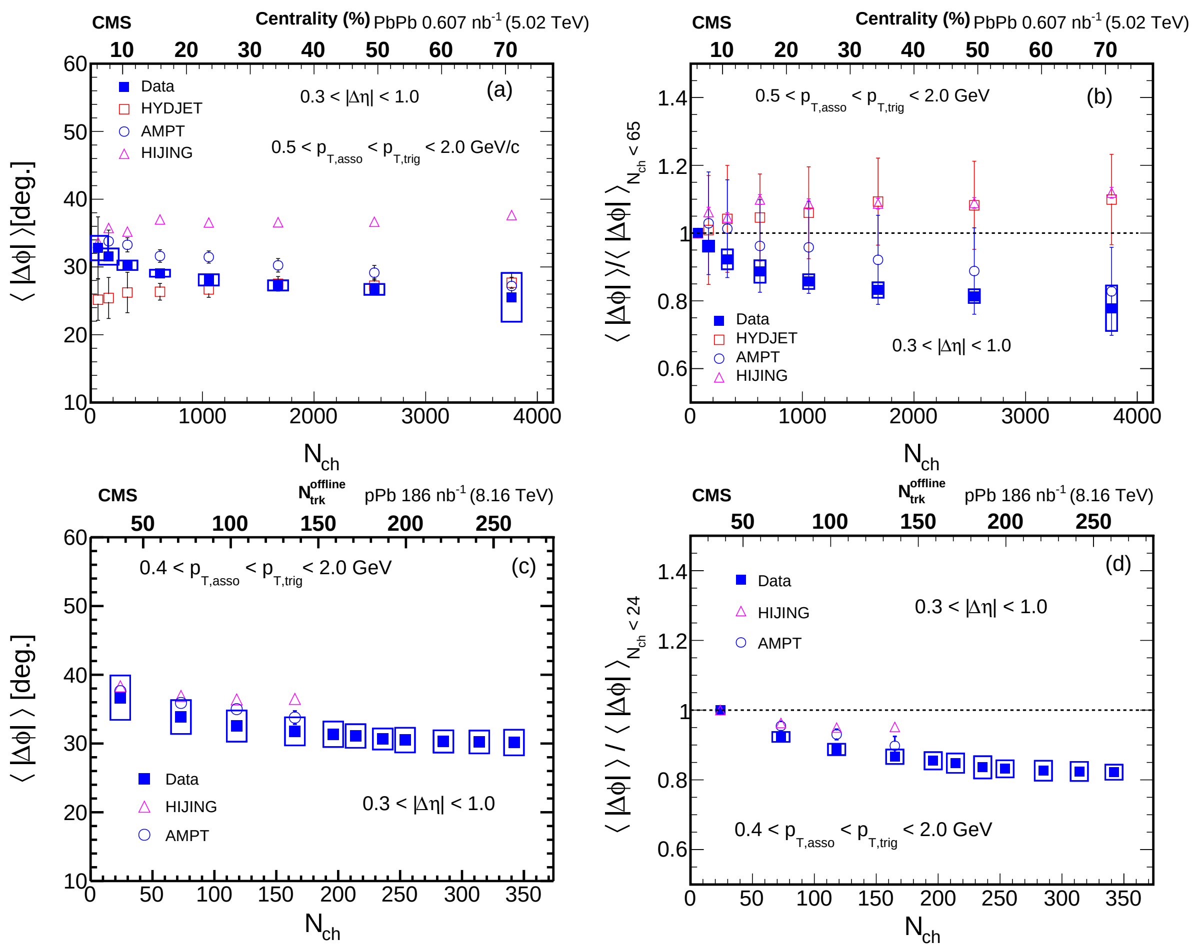

Figure 7: The width of the balance function in $\langle|\Delta\phi|\rangle$ and the ratios of $\langle|\Delta\phi|\rangle/\langle|\Delta\phi|\rangle_{N_{ch}<65}$ and $\langle|\Delta\phi|\rangle/\langle|\Delta\phi|\rangle_{N_{ch}<24}$ are shown as functions of N_{ch} for PbPb collisions in $\sqrt{s_{NN}} = 5.02$ TeV (upper panels) and pPb collisions in $\sqrt{s_{NN}} = 8.16$ TeV (lower panels), respectively. The statistical uncertainties of the data points are smaller than the marker size and rectangular boxes indicate the systematic uncertainties.

balancing partners by preserving their initial-state correlations in $\Delta\phi$, in both systems. This trend is also reflected in Figs. (7b) and (7d), where the relative decrease of the width in $\langle|\Delta\phi|\rangle$ has a strong contribution from collective final state effects. The normalized value of $\langle|\Delta\phi|\rangle$ in pPb collisions has a similar ratio to PbPb data. The HIJING and AMPT predictions (p-values of 0.01 and 0.02) are able to describe the decreasing trend of the pPb data with N_{ch} for small values of N_{ch}, where the correlations are dominated by resonance decays. On the other hand, the two generators show little dependence on N_{ch} for larger values of N_{ch} in pPb, whereas the data continues its decreasing trend, as demonstrated in Fig. (7d).

6.3 Transverse momentum dependence of balance functions

This measurement is extended to higher values of the p_T (>2 GeV) to study if the narrowing or the widening of the balance function is constrained to the bulk particle production at low p_T ($p_T < 2$ GeV) or is also connected to hard process. Figures 8 and 9 represent the 1D projections of the balance function in $\Delta\eta$ and $\Delta\phi$ for the trigger and associated particles in the intermediate-p_T ($2 < p_{T,asso} < 3 < p_{T,trig} < 4$ GeV) and high-p_T ($3 < p_{T,asso} < 8 < p_{T,trig} < 15$ GeV) ranges. The upper panels show the plots for PbPb collisions, and the lower panel is for pPb collisions. It

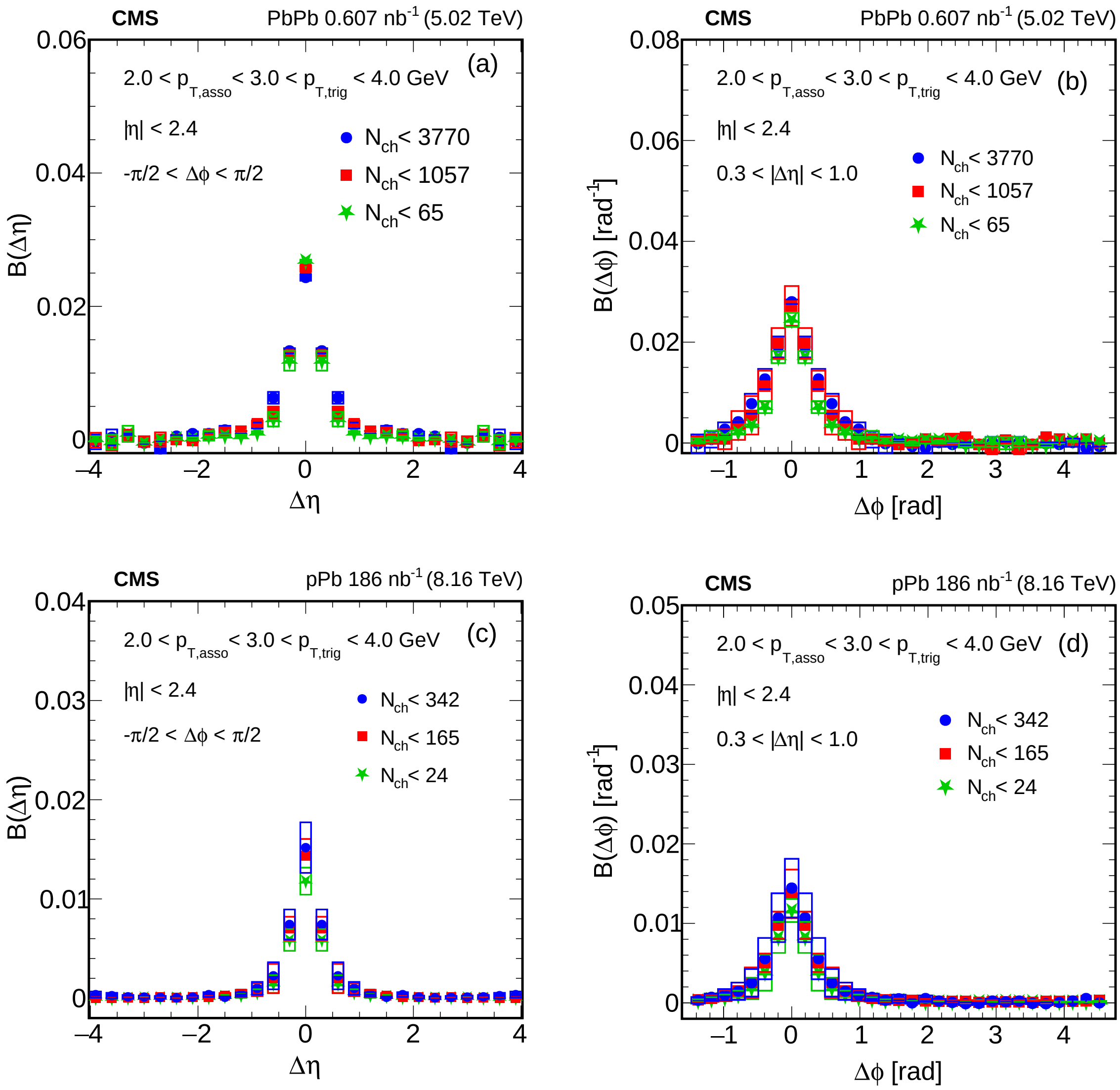

Figure 8: The projection of the balance function is presented for PbPb in $\sqrt{s_{_{NN}}} = 5.02$ TeV (upper panels) and pPb in $\sqrt{s_{_{NN}}} = 8.16$ TeV (lower panels) collisions as a function of $\Delta\eta$ (left column) and $\Delta\phi$ (right column), for $2.0 < p_{T,asso} < 3.0 < p_{T,trig} < 4.0$ GeV ranges. The 1D projection is derived for $\Delta\eta$ in near-side ($|\Delta\phi| < \pi/2$) and $\Delta\phi$ ($0.3 < |\Delta\eta| < 1.0$) regions.

can be seen that they become narrower for increasing p_T, as compared with low-p_T results, and exhibit a smaller multiplicity dependence. The width of the balance function in $\Delta\eta$ is narrower in the high-p_T range than in the low- and intermediate-p_T ranges, which is consistent with the findings in $\Delta\phi$. This implies that the effects of radial flow on the balance function is weaker at higher p_T, and the balance function at high p_T is more sensitive to other effects such as jet fragmentation and medium response [67, 68].

The width of the balance functions in $\langle|\Delta\eta|\rangle$ and $\langle|\Delta\phi|\rangle$, for the different values of p_T, are presented in Fig. 10 as a function of N_{ch}, for both PbPb and pPb collisions. The narrowing of the balance function width in the low-p_T region is understood in a delayed hadronization picture, where the particles are produced at later stages of the evolution of the long-lived medium formed in these collisions. Also in comparison with higher p_T, the multiplicity dependence in low-p_T PbPb collisions is attributed to the centrality dependence of the radial flow, which

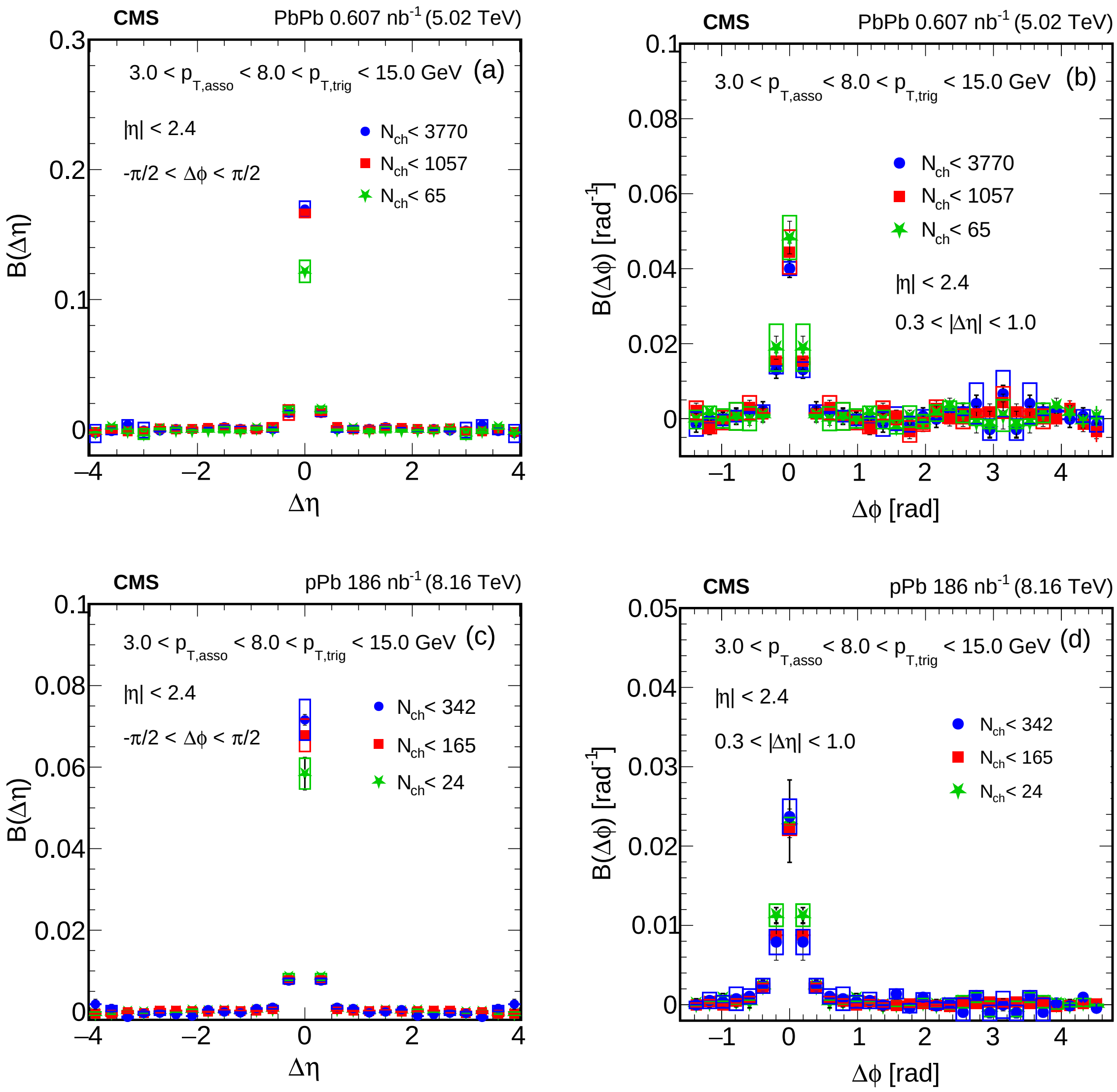

Figure 9: The projection of the balance function is presented for PbPb in $\sqrt{s_{NN}} = 5.02$ TeV (upper panels) and pPb in $\sqrt{s_{NN}} = 8.16$ TeV (lower panels) collisions as a function of $\Delta\eta$ (left column) and $\Delta\phi$ (right column), for $3.0 < p_{T,asso} < 8.0 < p_{T,trig} < 15.0$ GeV ranges. The 1D projection is derived for $\Delta\eta$ in near-side ($|\Delta\phi| < \pi/2$) and $\Delta\phi$ ($0.3 < |\Delta\eta| < 1.0$) regions.

retains part of the initial correlations of the balancing partners. These results suggest that the balance function is a useful tool to investigate the interplay between soft and hard processes in heavy-ion collisions at different p_T ranges. Similarly, the multiplicity dependence in low-p_T pPb collisions could be explained by collectivity. Collectivity in small collision systems is already suggested by the observation of long-range ridge correlations in pPb collisions [8, 69, 70]. The similarity of the balance functions in pPb and PbPb collisions suggests a similar origin of particle correlations in these two colliding systems.

7 Beam energy dependence

In the upper panel of the Fig. 11, a comparison is presented of the balance function widths in $\langle|\Delta\eta|\rangle$ and $\langle|\Delta\phi|\rangle$ as a function of centrality. The STAR and ALICE Collaborations reported

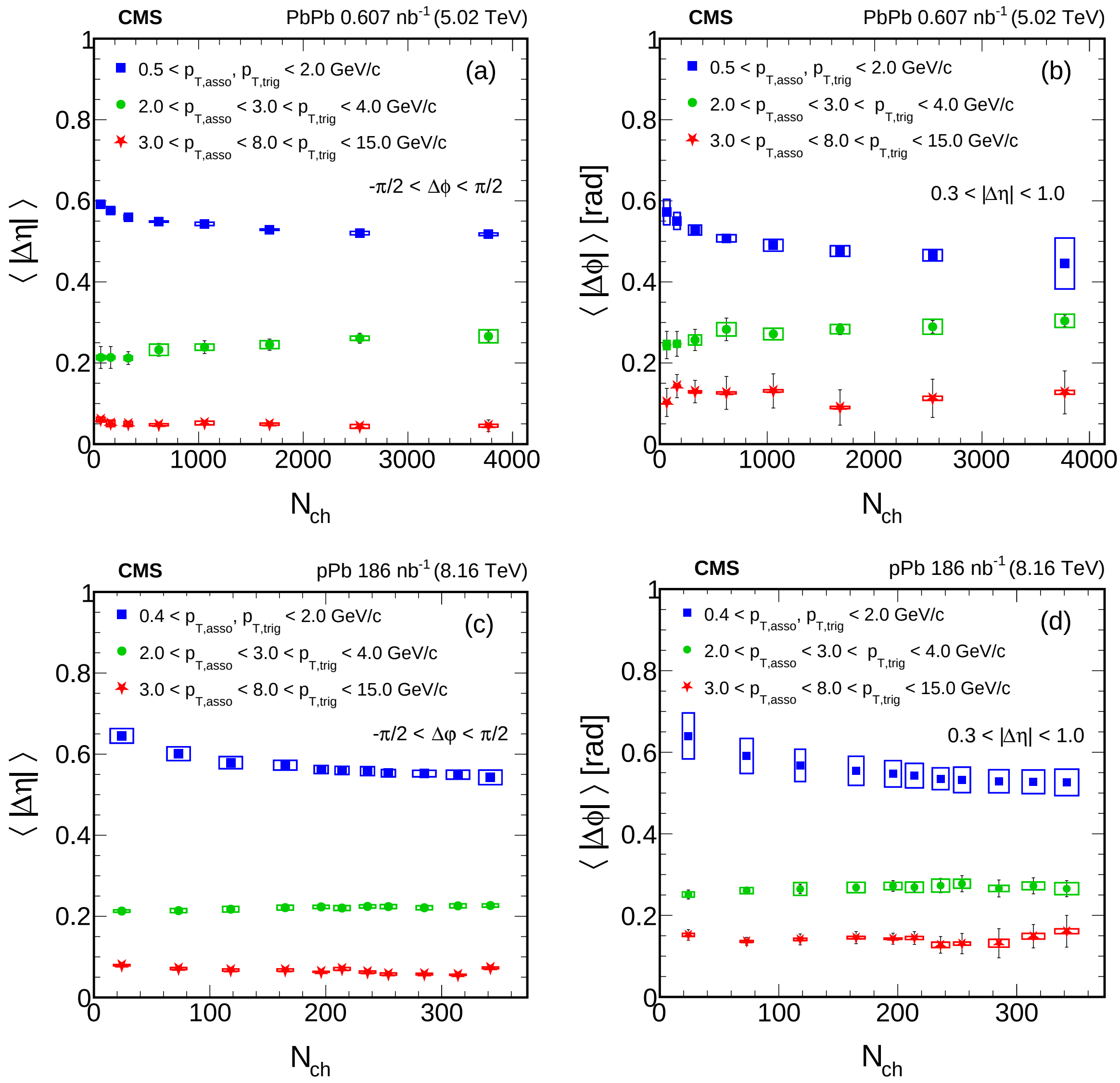

Figure 10: The width of the balance function in $\Delta\eta$ (left column) and $\Delta\phi$ (right column) is calculated for different p_{T} interval in PbPb in $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$ (upper panels) and pPb collisions in $\sqrt{s_{_{\mathrm{NN}}}} = 8.16\,\mathrm{TeV}$ (lower panels). The vertical lines indicate the statistical uncertainties of the data points, and the rectangular boxes indicate the systematic uncertainties.

their results at $\sqrt{s_{_{\mathrm{NN}}}} = 200\,\mathrm{GeV}$ in AuAu collisions and $\sqrt{s_{_{\mathrm{NN}}}} = 2.76\,\mathrm{TeV}$ in PbPb collisions, respectively, with a transverse momentum interval of $0.2 < p_{\mathrm{T}} < 2.0\,\mathrm{GeV}$ [31, 32]. The balance function width calculated for STAR does not include any systematic uncertainties. The data points from both the ALICE and STAR experiments are corrected for acceptance and detector effects to make a proper comparisons with the CMS results. For all three experiments, a significant centrality dependence is observed in $\langle\Delta\eta\rangle$ and $\langle\Delta\phi\rangle$. The balance function width is found to be narrower at the LHC energies than at RHIC, which is consistent with the idea that the system produced during the collisions has a larger radial flow due to the increase of the center-of-mass energy [12, 71]. Additionally, the narrowing of the balance functions suggests that a longer duration of the QGP at the LHC can reduce the separation between charge pairs during their creation at hadronization. The lower panel of the Fig. 11 shows the relative decrease of the width in $\langle\Delta\eta\rangle$ and $\langle\Delta\phi\rangle$ from peripheral to central collisions.

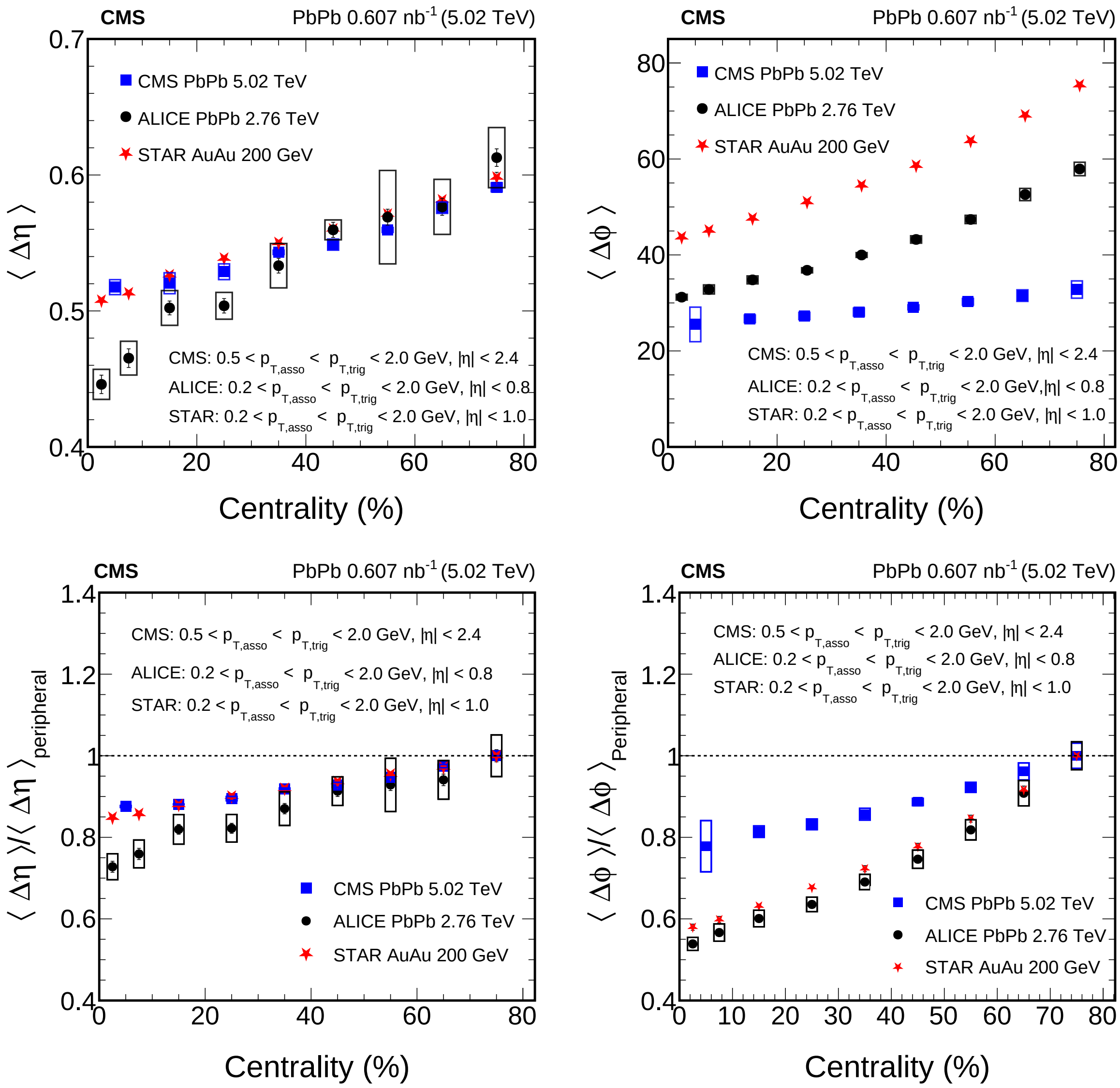

Figure 11: The centrality dependence of the balance function width (upper panels) and relative change in the width (lower panels) in $\Delta\eta$ and $\Delta\phi$. The CMS results are compared to the STAR results at $\sqrt{s_{_{\mathrm{NN}}}} = 200\,\mathrm{GeV}$ in AuAu collisions and ALICE at $\sqrt{s_{_{\mathrm{NN}}}} = 2.76\,\mathrm{TeV}$ in PbPb collisions. The STAR and ALICE measured their results in $0.2 < p_{\mathrm{T}} < 2.0\,\mathrm{GeV}$ ranges with a limited pseudorapidity coverage ($|\eta| < 1.0$ for STAR and $|\eta| < 0.8$ for ALICE). The vertical lines indicate the statistical uncertainties, and the rectangular boxes indicate the systematic uncertainties.

The relative change in the width in $\langle \Delta\eta \rangle$ is consistent in three different energies for RHIC and LHC within the uncertainties. This finding could shed light on the claim that the late-stage production of balancing partners was mainly responsible for narrowing the width in $\Delta\eta$. On the other hand, a significant difference is seen with respect to the STAR and ALICE results, when studying the relative width in $\Delta\phi$. This might be attributed to a stronger effect from radial flow on $\Delta\phi$ at higher energies and the different kinematic selections. Another factor to be considered at the LHC is a greater occurrence of more energetic jet-like structures resulting in particles emitted preferentially in cones with smaller $\Delta\eta$ and $\Delta\phi$ than at RHIC. Therefore, further theoretical and experimental studies are necessary to reconcile the late-stage creation of charges.

8 Summary

This paper presents a measurement of the charge-balance function for nonidentified charged particles in proton-lead (pPb) and lead-lead (PbPb) collisions using the broad pseudorapidity coverage of the CMS detector. For both systems, the dependence of the balance function on relative pseudorapidity ($\Delta\eta$) and relative azimuthal angle $\Delta\phi$ of particle pairs is studied for different multiplicity classes and transverse momentum (p_{T}) ranges. It is observed that the width in both $\Delta\eta$ and $\Delta\phi$ decreases with charged particle multiplicity (N_{ch}) in pPb and PbPb systems for $p_{\mathrm{T}} < 2\,\mathrm{GeV}$. These results are consistent with the system possessing a large radial flow, with particle creation at a later stage of the collision, or both. A mild dependence of the integral of the charge balance functions with collision multiplicity is observed in PbPb and pPb collisions. The multiplicity dependence is weaker for higher p_{T} as compared with the $p_{\mathrm{T}} < 2\,\mathrm{GeV}$ region, which implies that the balancing partners are strongly correlated. The data are compared with HYDJET, HIJING, and AMPT generator predictions, none of which capture completely the multiplicity dependence seen in the data. The comparisons of PbPb results with those at lower energies from STAR and ALICE show a similar dependence of the widths in $\Delta\eta$ and $\Delta\phi$ as a function of centrality. However, a significant difference is seen in the widths in $\Delta\phi$ as compared to both STAR and ALICE, suggesting a potential interplay from radial flow, different kinematic selection, and jet-like structures. By studying the charge-balance functions in both small and large systems, we have explored the evolution of particle production mechanisms and the transition from a small to a large system behavior. Further study of the balance function with identified particles can provide valuable insights into the hadronization process of the quark-gluon plasma (QGP) and a crucial benchmarks that constraints the theoretical models of hadron production and its transport in heavy-ion collisions.

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[61]Also at National and Kapodistrian University of Athens, Athens, Greece
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[63]Also at Universität Zürich, Zurich, Switzerland
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[67]Also at Konya Technical University, Konya, Turkey
[68]Also at Izmir Bakircay University, Izmir, Turkey

[69]Also at Adiyaman University, Adiyaman, Turkey
[70]Also at Istanbul Gedik University, Istanbul, Turkey
[71]Also at Necmettin Erbakan University, Konya, Turkey
[72]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
[73]Also at Marmara University, Istanbul, Turkey
[74]Also at Milli Savunma University, Istanbul, Turkey
[75]Also at Kafkas University, Kars, Turkey
[76]Also at Hacettepe University, Ankara, Turkey
[77]Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
[78]Also at Yildiz Technical University, Istanbul, Turkey
[79]Also at Vrije Universiteit Brussel, Brussel, Belgium
[80]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
[81]Also at University of Bristol, Bristol, United Kingdom
[82]Also at IPPP Durham University, Durham, United Kingdom
[83]Also at Monash University, Faculty of Science, Clayton, Australia
[84]Also at Università di Torino, Torino, Italy
[85]Also at Bethel University, St. Paul, Minnesota, USA
[86]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
[87]Also at California Institute of Technology, Pasadena, California, USA
[88]Also at United States Naval Academy, Annapolis, Maryland, USA
[89]Also at University of Florida, Gainesville, Florida, USA
[90]Also at Bingol University, Bingol, Turkey
[91]Also at Georgian Technical University, Tbilisi, Georgia
[92]Also at Sinop University, Sinop, Turkey
[93]Also at Erciyes University, Kayseri, Turkey
[94]Also at Texas A&M University at Qatar, Doha, Qatar
[95]Also at Kyungpook National University, Daegu, Korea
[96]Also at another institute or international laboratory covered by a cooperation agreement with CERN
[97]Also at Yerevan Physics Institute, Yerevan, Armenia
[98]Also at Northeastern University, Boston, Massachusetts, USA
[99]Also at Imperial College, London, United Kingdom
[100]Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan