Published for SISSA by Springer

Received: July 20, 2023
Revised: June 5, 2024
Accepted: July 12, 2024
Published: August 20, 2024

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

The CMS collaboration

E-mail: cms-publication-committee-chair@cern.ch

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.

Keywords: Heavy Ion Experiments, Particle Correlations and Fluctuations, Relativistic Heavy Ion Physics

ArXiv ePrint: 2307.11185

https://doi.org/10.1007/JHEP08(2024)148

JHEP08(2024)148

Contents

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 $-q$

JHEP08(2024)148

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 $\Delta\eta \sqrt{m_0^2 + p_T^2}$, 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 $\sqrt{s_{NN}} = 200\,\text{GeV}$, 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 $\sqrt{s_{NN}} = 8.16\,\text{TeV}$ and $5.02\,\text{TeV}$, 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 $\sqrt{s_{NN}}$ 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 $1 < p_T < 10$ 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 $\sqrt{s_{NN}} = 5.02$ TeV collected by the CMS experiment in 2018. Approximately 4.27×10^9 PbPb events were used, corresponding to an integrated luminosity $0.607\,\text{nb}^{-1}$ [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, ≥ 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}, $\sigma_{p_{\mathrm{T}}}/p_{\mathrm{T}}$, 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

JHEP08(2024)148

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].

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

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

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.

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],

$$S(\Delta\eta, \Delta\phi) = \frac{1}{N_{trig}} \frac{d^2 N^{same}}{d\Delta\eta\, d\Delta\phi}, \tag{4.1}$$

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:

$$M(\Delta\eta, \Delta\phi) = \frac{1}{N_{trig}} \frac{d^2 N^{mix}}{d\Delta\eta\, d\Delta\phi}, \tag{4.2}$$

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:

$$C_2(\Delta\eta, \Delta\phi) = M(0,0) \frac{S(\Delta\eta, \Delta\phi)}{M(\Delta\eta, \Delta\phi)}, \tag{4.3}$$

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

JHEP08(2024)148

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

$$B(\Delta\eta,\Delta\phi) = \frac{1}{2}[C_2(+,-) + C_2(-,+) - C_2(+,+) - C_2(-,-)]. \tag{4.4}$$

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: $|v_z| < 3\,\mathrm{cm}$, $-15 < v_z < -3\,\mathrm{cm}$; and $3 < v_z < 15\,\mathrm{cm}$. Similarly, the track quality requirements are varied, by changing $|d_z|/\sigma_z$ and $|d_{xy}|/\sigma_{xy}$ from 2 to 5, $\sigma_{p_{\mathrm{T}}}/p_{\mathrm{T}}$ 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} ($<2\,\mathrm{GeV}$) 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 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

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. Summary of systematic uncertainties calculated in $\langle|\Delta\eta|\rangle$ and $\langle|\Delta\phi|\rangle$ for PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ 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	0.8	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

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

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.

This measurement is also extended to higher values of p_{T} ($2 < p_{\mathrm{T,asso}} < 3 < p_{\mathrm{T,trig}} < 4\,\mathrm{GeV}$, $3 < p_{\mathrm{T,asso}} < 8 < p_{\mathrm{T,trig}} < 15\,\mathrm{GeV}$). The p_{T} of the trigger particle is denoted by $p_{\mathrm{T,\ trig}}$, whereas that of the associated particle is denoted by $p_{\mathrm{T,\ asso}}$. The systematic uncertainty values from each source, in all multiplicity classes and $p_{\mathrm{T}} < 2\,\mathrm{GeV}$, 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, $2 < p_{\mathrm{T,asso}} < 3 < p_{\mathrm{T,trig}} < 4\,\mathrm{GeV}$. 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 ($2 < p_{\mathrm{T,asso}} < 3 < p_{\mathrm{T,trig}} < 4\,\mathrm{GeV}$) and the higher ($3 < p_{\mathrm{T,asso}} < 8 < p_{\mathrm{T,trig}} < 15\,\mathrm{GeV}$) 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 figure 1.

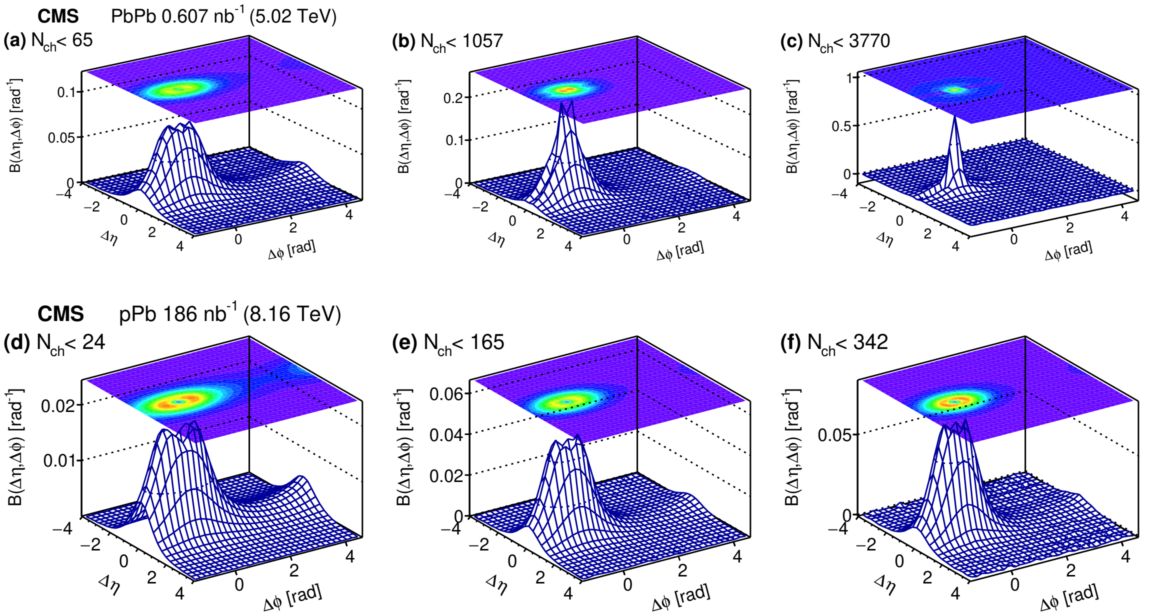

Figure 1. The balance function is shown in terms of $\Delta\eta$ and $\Delta\phi$ in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ (upper panels) and for pPb collisions at 8.16 TeV (lower panels). From left to right, the results are shown for the lowest to highest multiplicity classes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

The upper panels in figure 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 figure 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 figure 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 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

JHEP08(2024)148

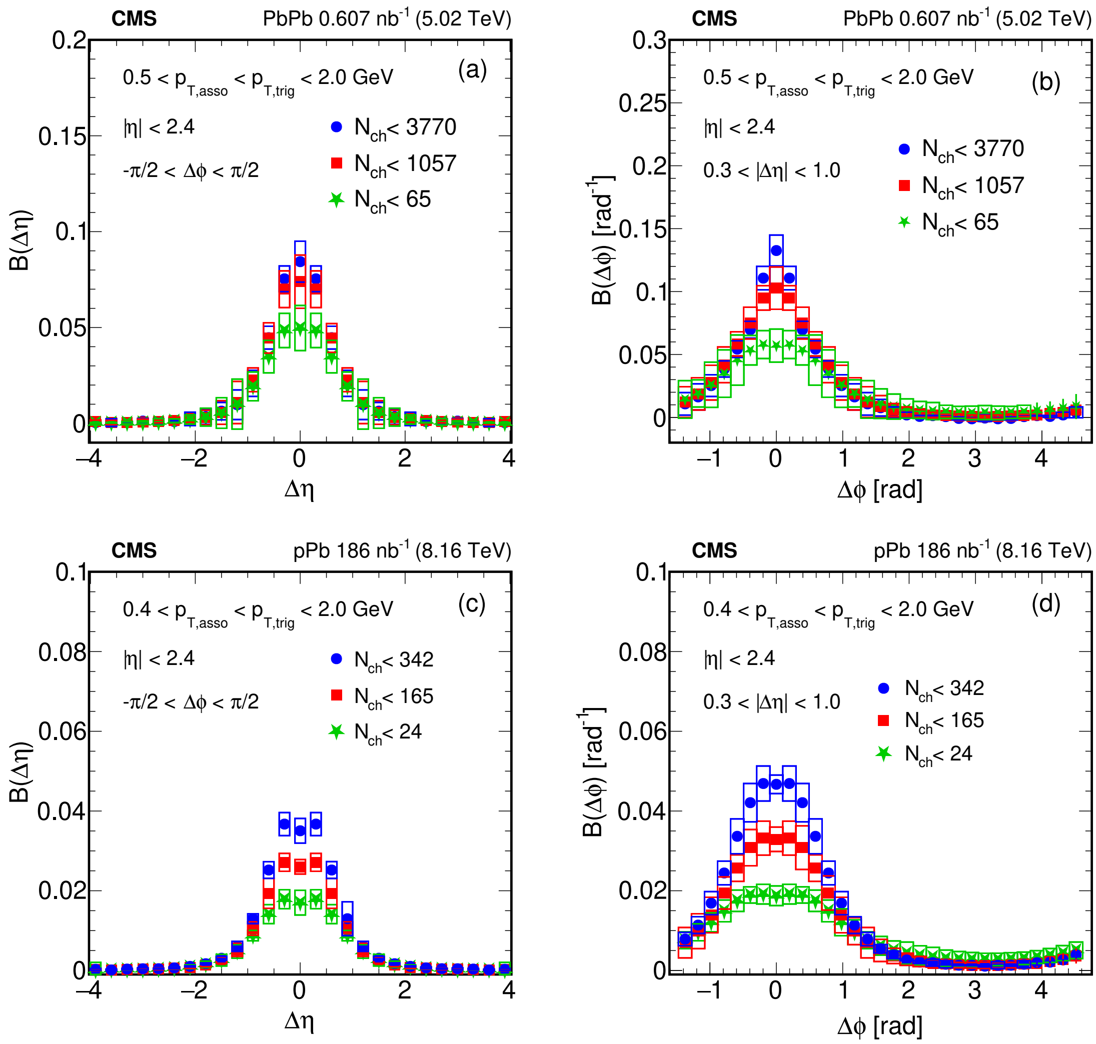

Figure 2. The projection of the balance function is presented in the upper panel for PbPb (lower panel for pPb) collisions as a function of $\Delta\eta$ (left column) and in $\Delta\phi$ (right column). The statistical uncertainties of the data points are smaller than the marker size and rectangular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

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.

6.1 Balance function integral

The left and right plots in figure 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

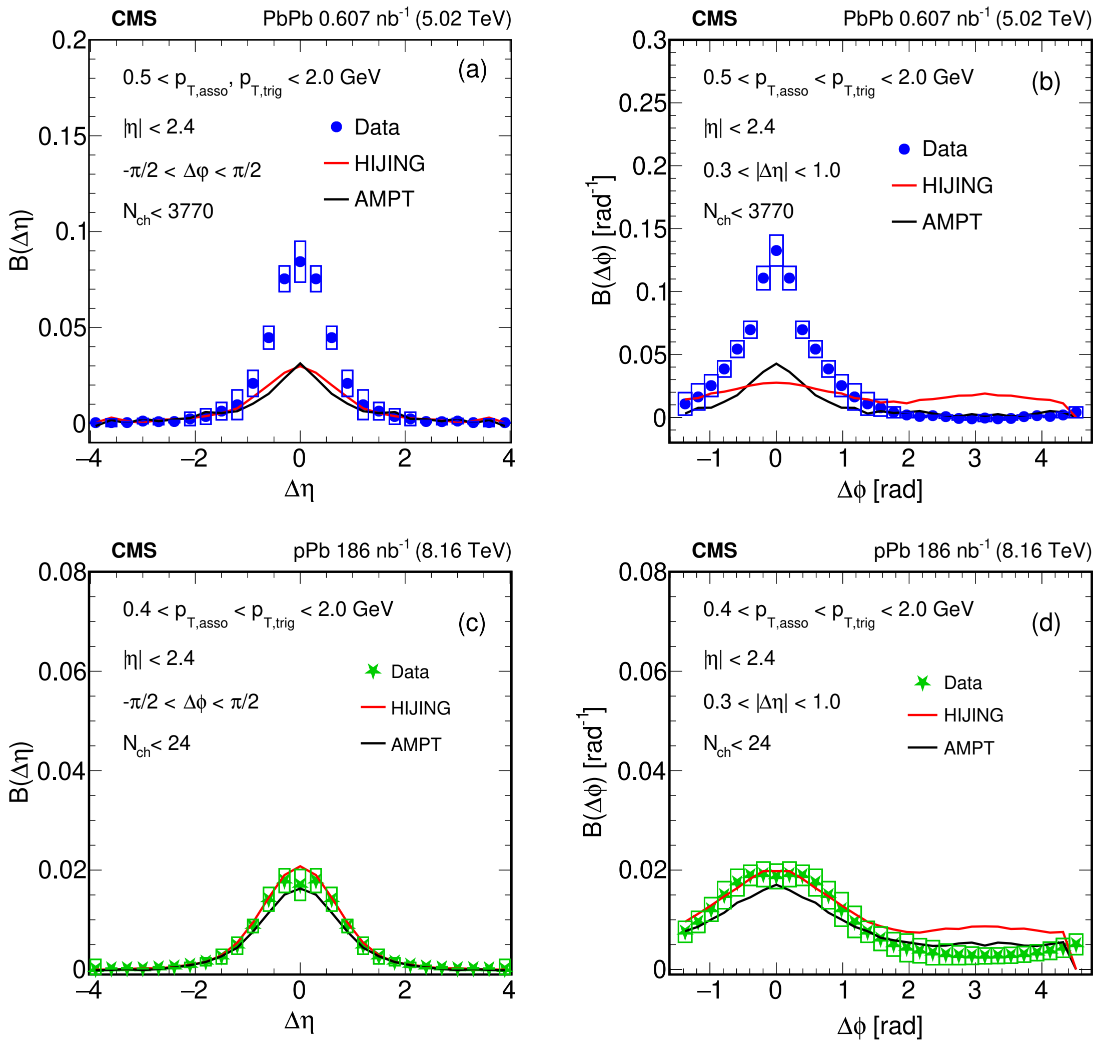

Figure 3. The comparison of the balance function with AMPT and HIJING event generators is presented in the upper panel ((a) and (b)) for PbPb collisions and the lower panel ((c) and (d)) for pPb collisions as a function of $\Delta\eta$ (left column) and in $\Delta\phi$ (right column). For PbPb collisions,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

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 $p_{\mathrm{T}} < 2.0\,\mathrm{GeV}$, 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

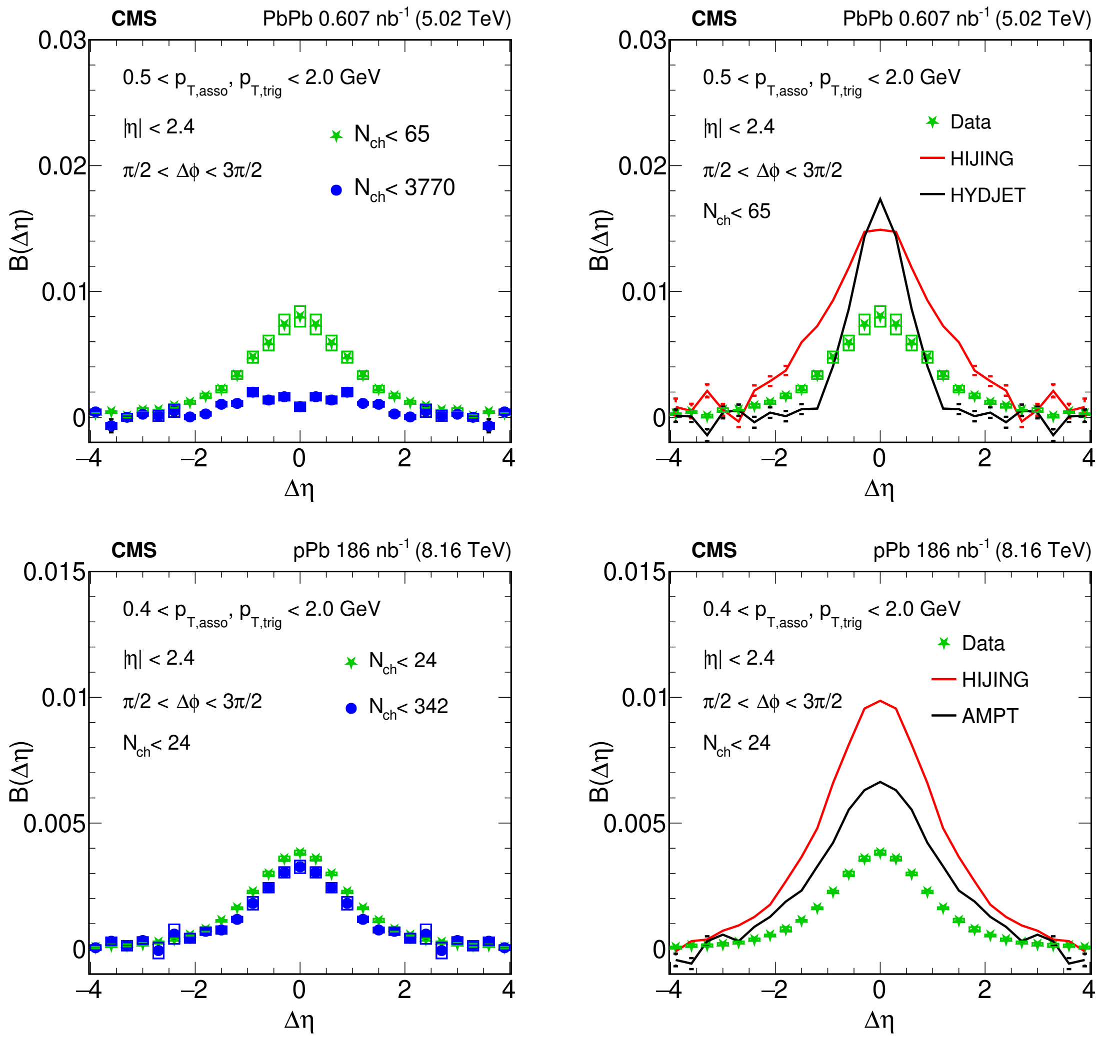

Figure 4. The away-side projection of the balance function for the charged-particles with $p_{\mathrm{T}} < 2\,\mathrm{GeV}$ is shown for the PbPb upper panel ((a) and (b)) and pPb ((a) and (b)) collisions. The data results are compared with the different event generators with the lowest multiplicity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

with $|\eta| < 0.8$ and $0.2 < p_{\mathrm{T}} < 2.0\,\mathrm{GeV}$ [61]. Comparison with the model calculations from HIJING, HYDJET, and AMPT are also shown in figure 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

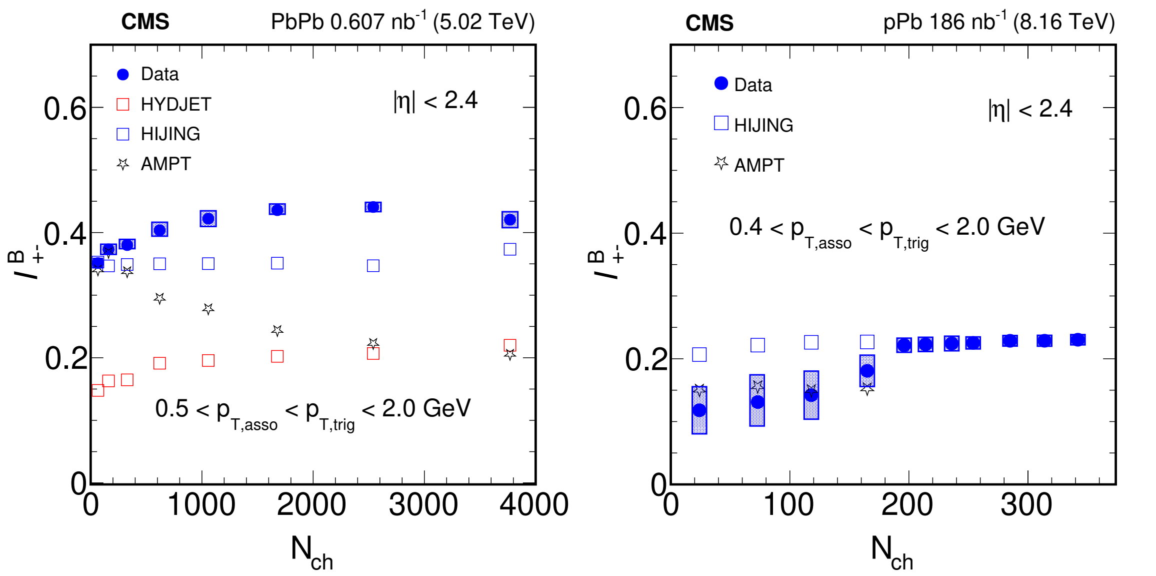

Figure 5. The integral of the balance functions (I^B_{+-}) in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ (left) and in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$ (right). The balancing partners fall within the specified pseudorapidity range ($|\eta| < 2.4$)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

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. (6.1),

$$\langle|\Delta\eta|\rangle = \frac{\sum_i B(\Delta\eta_i)|\Delta\eta_i|}{\sum_i B(\Delta\eta_i)}, \tag{6.1}$$

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. (6.2),

$$B_{+-}(\Delta\eta|\eta_{\mathrm{max}}) = B_{+-}(\Delta\eta|\infty)\left(1 - \frac{\Delta\eta}{\eta_{\mathrm{max}}}\right). \tag{6.2}$$

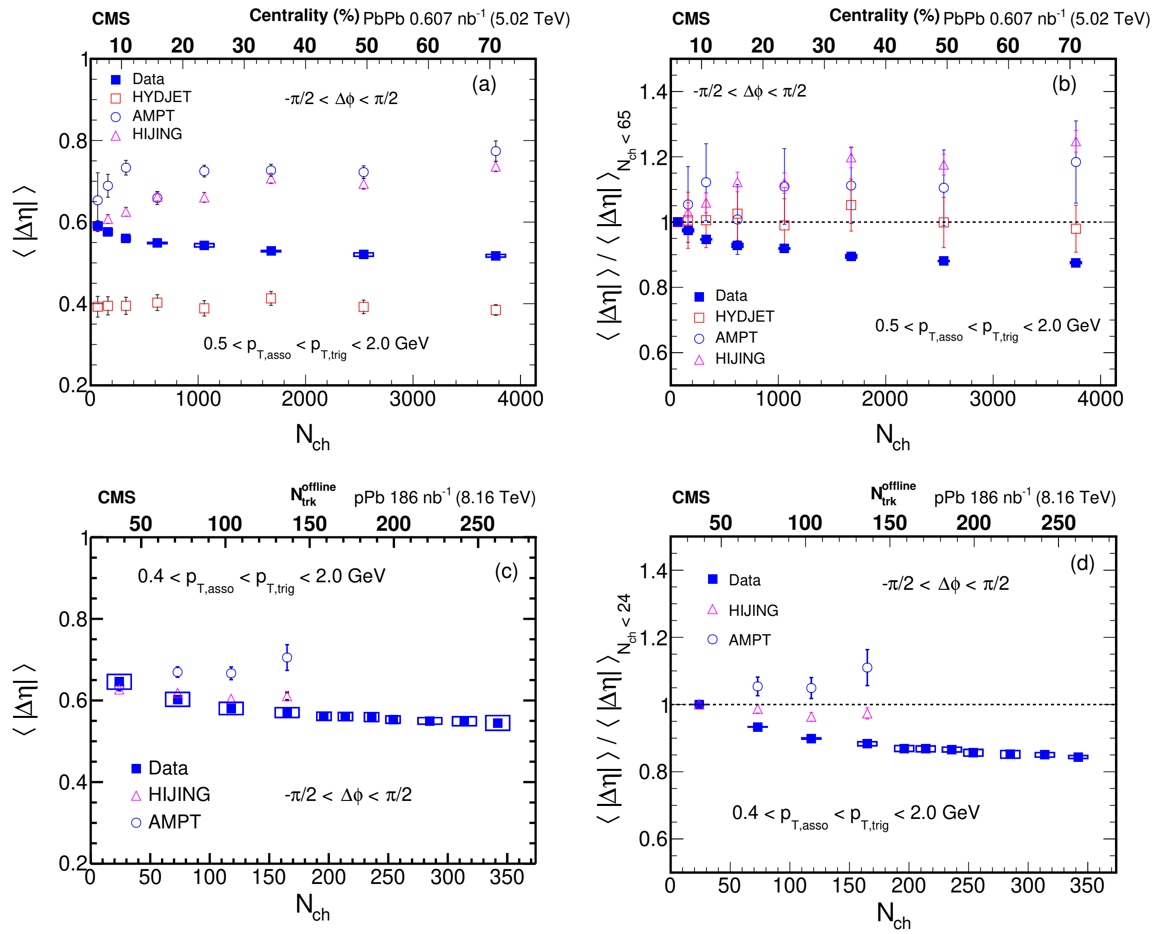

Figure 6. The width of the balance function in $\langle|\Delta\eta|\rangle$ and the ratio of $\langle|\Delta\eta|\rangle/\langle|\Delta\eta|\rangle_{N_{\rm ch}<65}$ and $\langle|\Delta\eta|\rangle/\langle|\Delta\eta|\rangle_{N_{\rm ch}<24}$ are shown as functions of $N_{\rm ch}$ for PbPb collisions in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

The factor $\left(1 - \frac{\Delta\eta}{\eta_{\rm max}}\right)$ 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 $N_{\rm ch}$, 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 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., $\langle|\Delta\eta|\rangle_{N_{\mathrm{ch}}<65}$ (for PbPb) and $\langle|\Delta\eta|\rangle_{N_{\mathrm{ch}}<24}$ (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 figure 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 balancing partners by preserving their initial-state correlations in $\Delta\phi$, in both systems. This trend is also reflected in figures 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 figure 7d.

6.3 Transverse momentum dependence of balance functions

This measurement is extended to higher values of the p_{T} ($> 2\,\mathrm{GeV}$) to study if the narrowing or the widening of the balance function is constrained to the bulk particle production at low p_{T} ($p_{\mathrm{T}} < 2\,\mathrm{GeV}$) 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} ($2 < p_{\mathrm{T,asso}} < 3 < p_{\mathrm{T,trig}} < 4\,\mathrm{GeV}$) and high-$p_{\mathrm{T}}$ ($3 < p_{\mathrm{T,asso}} < 8 < p_{\mathrm{T,trig}} < 15\,\mathrm{GeV}$) ranges. The upper panels show the plots for PbPb collisions, and the lower panel is for pPb collisions. It can be seen that they become narrower for increasing p_{T}, as compared

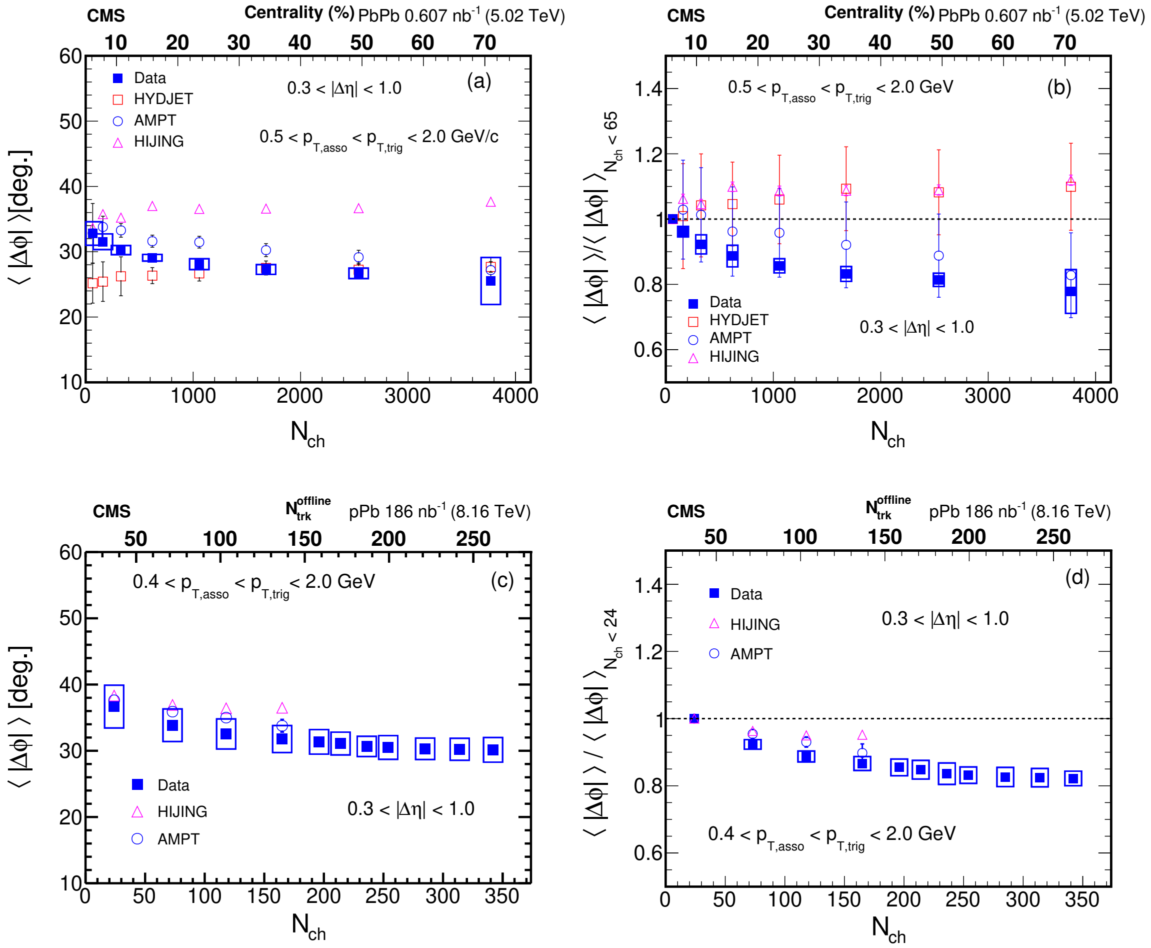

Figure 7. The width of the balance function in $\langle|\Delta\phi|\rangle$ and the ratios of $\langle|\Delta\phi|\rangle/\langle|\Delta\phi|\rangle_{N_{\mathrm{ch}}<65}$ and $\langle|\Delta\phi|\rangle/\langle|\Delta\phi|\rangle_{N_{\mathrm{ch}}<24}$ are shown as functions of N_{ch} for PbPb collisions 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), respectively. The statistical uncertainties of the data points are smaller than the marker size and rectangular boxes indicate the systematic uncertainties.

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 figure 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 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

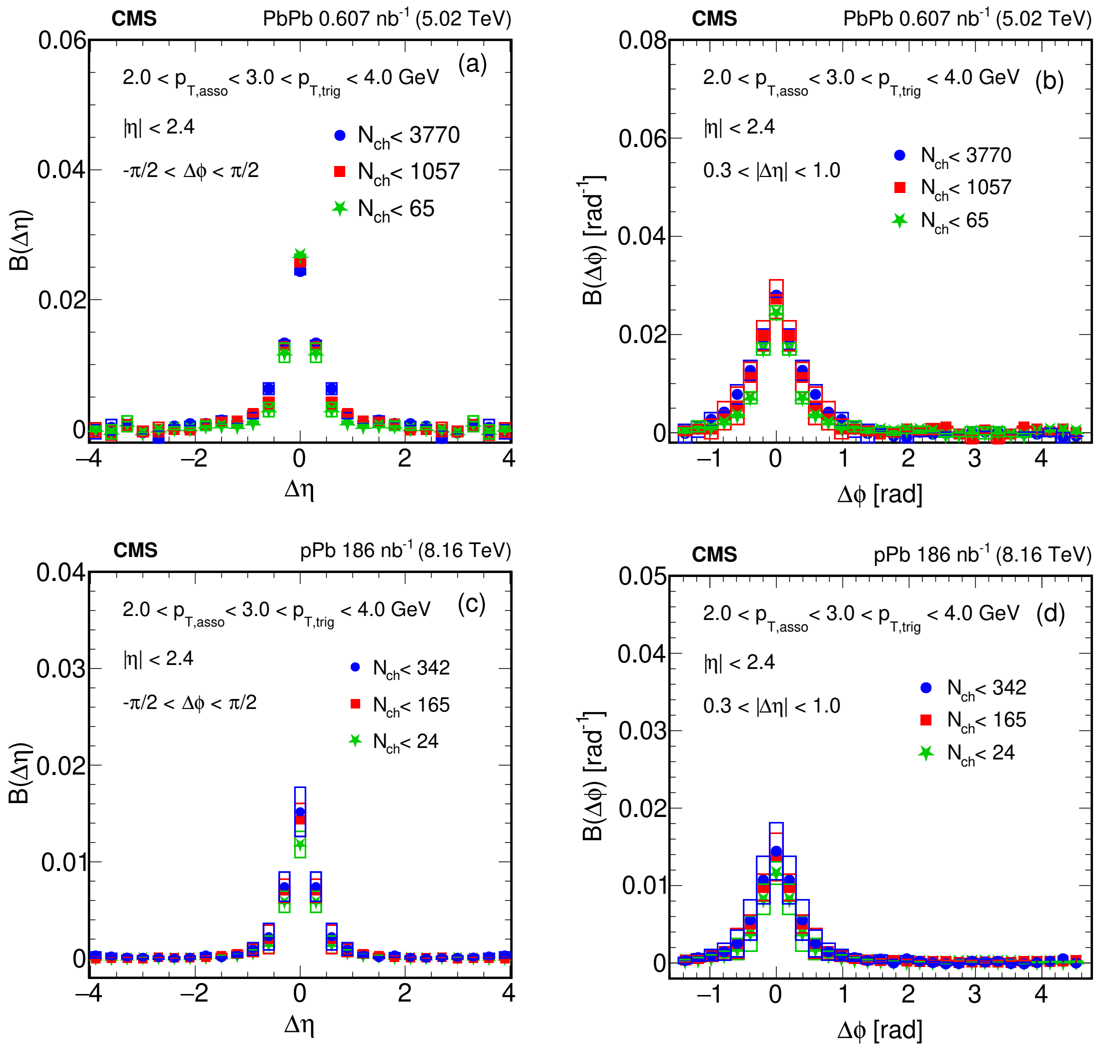

Figure 8. The projection of the balance function is presented for PbPb in $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ (upper panels) and pPb in $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$ (lower panels) collisions as a function of $\Delta\eta$ (left column) and $\Delta\phi$ (right column), for $2.0 < p_{\mathrm{T,asso}} < 3.0 < p_{\mathrm{T,trig}} < 4.0\,\mathrm{GeV}$ 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.

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 figure 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 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,

JHEP08(2024)148

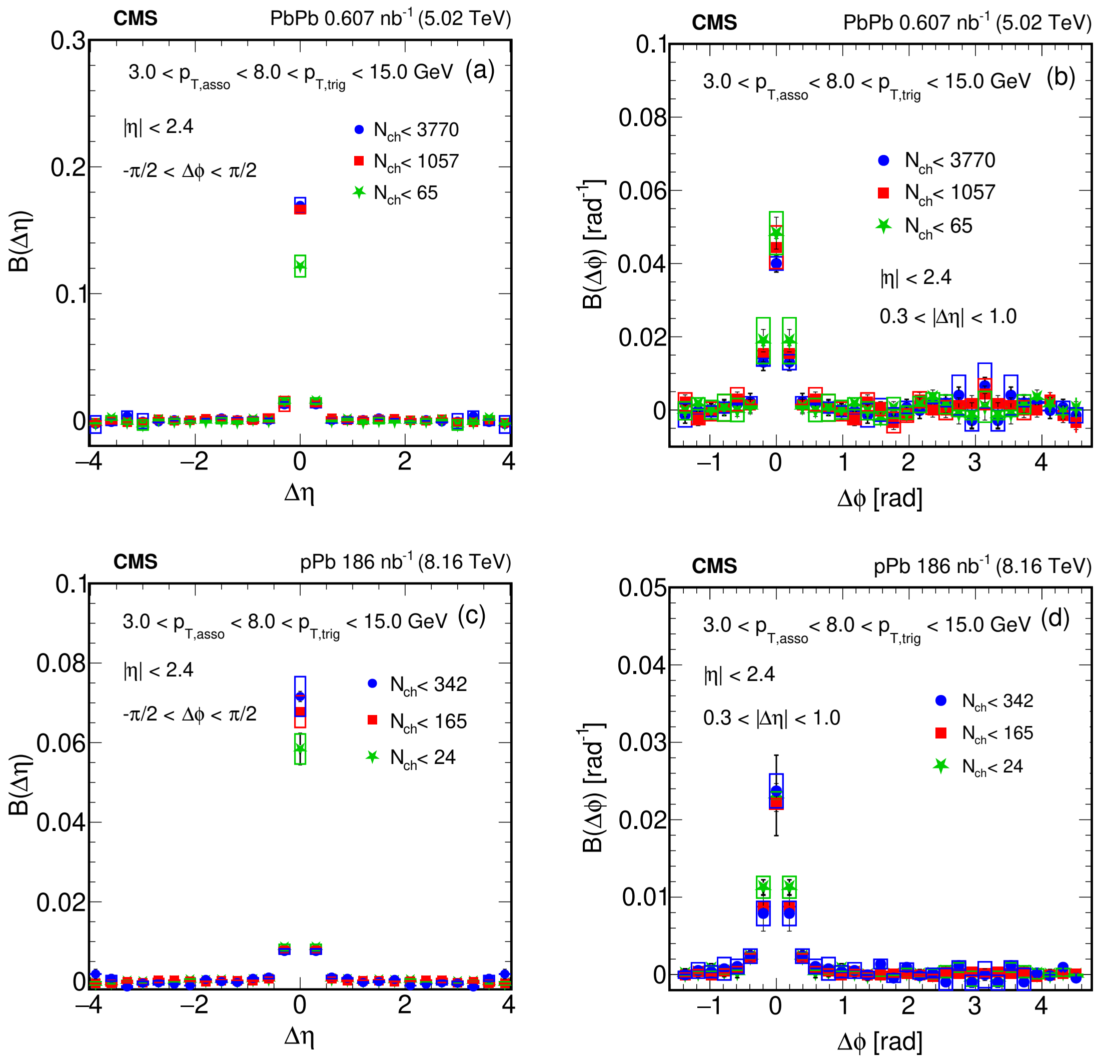

Figure 9. The projection of the balance function is presented for PbPb in $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ (upper panels) and pPb in $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$ (lower panels) collisions as a function of $\Delta\eta$ (left column) and $\Delta\phi$ (right column), for $3.0 < p_{\mathrm{T,asso}} < 8.0 < p_{\mathrm{T,trig}} < 15.0\,\mathrm{GeV}$ 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.

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 figure 11 shows the relative decrease of the width in $\langle\Delta\eta\rangle$ and $\langle\Delta\phi\rangle$ from peripheral to central collisions.

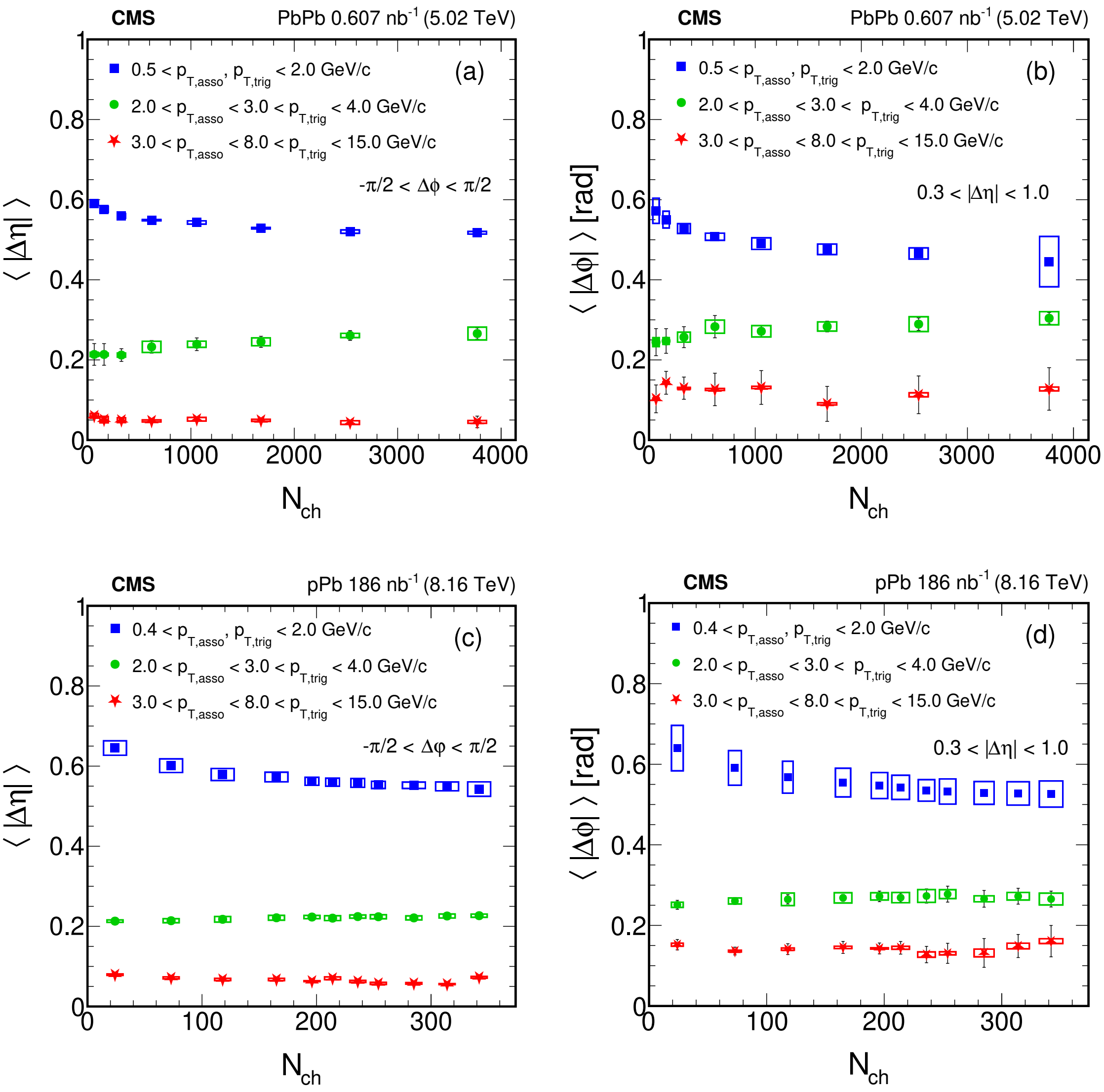

Figure 10. The width of the balance function in $\Delta\eta$ (left column) and $\Delta\phi$ (right column) is calculated for different p_{T} interval in PbPb in $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ (upper panels) and pPb collisions in $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$ (lower panels).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

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.

JHEP08(2024)148

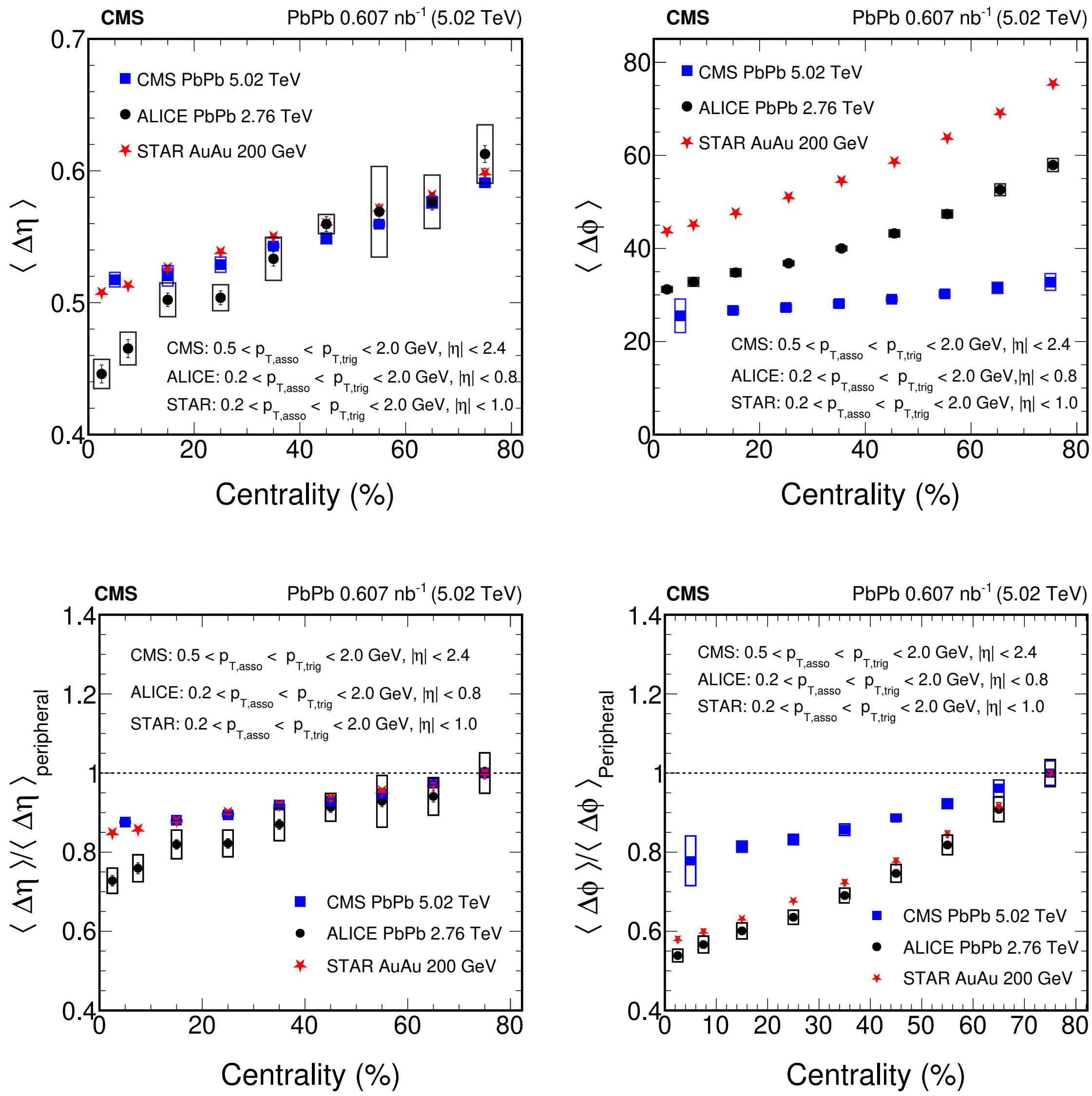

Figure 11. The centrality dependence of the balance function width (upper panels) and relative change in the width (lower panels) in $\Delta\eta$ and $\Delta\phi$. The CMS results are compared to the STAR results at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$ in AuAu collisions and ALICE at $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$ 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.

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

JHEP08(2024)148

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.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (U.S.A.).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 884104, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee,

JHEP08(2024)148

project no. 22rl-037 (Armenia); the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science — EOS" — be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, grant FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy — EXC 2121 "Quantum Universe" — 390833306, and under project number 400140256 — GRK2497; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Hungarian Academy of Sciences, the New National Excellence Program — ÚNKP, the NKFIH research grants K 124845, K 124850, K 128713, K 128786, K 129058, K 131991, K 133046, K 138136, K 143460, K 143477, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF "a way of making Europe", and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B05F650021 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (U.S.A.).

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JHEP08(2024)148

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JHEP08(2024)148

The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. Tumasyan[1]

Institut für Hochenergiephysik, Vienna, Austria
W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, A. Escalante Del Valle, P.S. Hussain, M. Jeitler[2], N. Krammer, L. Lechner, D. Liko, I. Mikulec, J. Schieck[2], R. Schöfbeck, D. Schwarz, M. Sonawane, S. Templ, W. Waltenberger, C.-E. Wulz[2]

Universiteit Antwerpen, Antwerpen, Belgium
M.R. Darwish[3], T. Janssen, T. Kello[4], P. Van Mechelen

Vrije Universiteit Brussel, Brussel, Belgium
E.S. Bols, J. D'Hondt, A. De Moor, M. Delcourt, H. El Faham, S. Lowette, A. Morton, D. Müller, A.R. Sahasransu, S. Tavernier, W. Van Doninck, S. Van Putte, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium
B. Clerbaux, S. Dansana, G. De Lentdecker, L. Favart, D. Hohov, J. Jaramillo, K. Lee, M. Mahdavikhorrami, I. Makarenko, A. Malara, S. Paredes, L. Pétré, N. Postiau, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

Ghent University, Ghent, Belgium
D. Dobur, J. Knolle, L. Lambrecht, G. Mestdach, C. Rendón, A. Samalan, K. Skovpen, M. Tytgat, N. Van Den Bossche, B. Vermassen, L. Wezenbeek

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
A. Benecke, G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, I.S. Donertas, A. Giammanco, K. Jaffel, Sa. Jain, V. Lemaitre, J. Lidrych, K. Mondal, T.T. Tran, P. Vischia, S. Wertz

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, E. Coelho, C. Hensel, A. Moraes, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[5], E.M. Da Costa, G.G. Da Silveira[6], D. De Jesus Damiao, V. Dos Santos Sousa, S. Fonseca De Souza, J. Martins[7], C. Mora Herrera, K. Mota Amarilo, L. Mundim, H. Nogima, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, A. Vilela Pereira

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
C.A. Bernardes[6], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, P.G. Mercadante, S.F. Novaes, B. Orzari, Sandra S. Padula

JHEP08(2024)148

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria
A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov, E. Shumka

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile
S. Keshri, S. Thakur

Beihang University, Beijing, China
T. Cheng, Q. Guo, T. Javaid[8], M. Mittal, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
G. Bauer[9], Z. Hu, S. Lezki, K. Yi[9,10]

Institute of High Energy Physics, Beijing, China
G.M. Chen[8], H.S. Chen[8], M. Chen[8], F. Iemmi, C.H. Jiang, A. Kapoor, H. Liao, Z.-A. Liu[11], V. Milosevic, F. Monti, R. Sharma, J. Tao, J. Wang, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ban, A. Carvalho Antunes De Oliveira, A. Levin, C. Li, Q. Li, X. Lyu, Y. Mao, S.J. Qian, X. Sun, D. Wang, J. Xiao, H. Yang

Sun Yat-Sen University, Guangzhou, China
M. Lu, Z. You

University of Science and Technology of China, Hefei, China
N. Lu

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
X. Gao[4], D. Leggat, H. Okawa, Y. Zhang

Zhejiang University, Hangzhou, Zhejiang, China
Z. Lin, C. Lu, M. Xiao

Universidad de Los Andes, Bogota, Colombia
C. Avila, D.A. Barbosa Trujillo, A. Cabrera, C. Florez, J. Fraga, J.A. Reyes Vega

Universidad de Antioquia, Medellin, Colombia
J. Mejia Guisao, F. Ramirez, M. Rodriguez, J.D. Ruiz Alvarez

JHEP08(2024)148

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
D. Giljanovic, N. Godinovic, D. Lelas, I. Puljak, A. Sculac

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac, T. Sculac

Institute Rudjer Boskovic, Zagreb, Croatia
P. Bargassa, V. Brigljevic, B.K. Chitroda, D. Ferencek, S. Mishra, M. Roguljic, A. Starodumov[12], T. Susa

University of Cyprus, Nicosia, Cyprus
A. Attikis, K. Christoforou, S. Konstantinou, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, A. Stepennov

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr., A. Kveton

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
A.A. Abdelalim[13,14], E. Salama[15,16]

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
A. Lotfy, M.A. Mahmoud

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, R.K. Dewanjee, K. Ehataht, M. Kadastik, T. Lange, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
S. Bharthuar, E. Brücken, F. Garcia, J. Havukainen, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, M. Lotti, L. Martikainen, M. Myllymäki, M.m. Rantanen, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
P. Luukka, H. Petrow, T. Tuuva[†]

JHEP08(2024)148

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, V. Lohezic, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[17], P. Simkina, M. Titov

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
C. Baldenegro Barrera, F. Beaudette, A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, F. Damas, O. Davignon, B. Diab, G. Falmagne, B.A. Fontana Santos Alves, S. Ghosh, R. Granier de Cassagnac, A. Hakimi, B. Harikrishnan, G. Liu, J. Motta, M. Nguyen, C. Ochando, L. Portales, R. Salerno, U. Sarkar, J.B. Sauvan, Y. Sirois, A. Tarabini, E. Vernazza, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[18], J. Andrea, D. Apparu, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, J. Choi, D. Contardo, P. Depasse, C. Dozen[19], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, M. Vander Donckt, P. Verdier, S. Viret

Georgian Technical University, Tbilisi, Georgia
G. Adamov, I. Lomidze, Z. Tsamalaidze[12]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Botta, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, N. Röwert, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, M. Erdmann, P. Fackeldey, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, M.y. Lee, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, S. Mondal, S. Mukherjee, D. Noll, A. Novak, F. Nowotny, A. Pozdnyakov, Y. Rath, W. Redjeb, F. Rehm, H. Reithler, A. Schmidt, S.C. Schuler, A. Sharma, A. Stein, F. Torres Da Silva De Araujo[20], L. Vigilante, S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
C. Dziwok, G. Flügge, W. Haj Ahmad[21], O. Hlushchenko, T. Kress, A. Nowack, O. Pooth, A. Stahl, T. Ziemons, A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, Germany
H. Aarup Petersen, M. Aldaya Martin, J. Alimena, Y. An, S. Baxter, M. Bayatmakou, H. Becerril Gonzalez, O. Behnke, S. Bhattacharya, F. Blekman[22], K. Borras[23], D. Brunner, A. Campbell, A. Cardini, C. Cheng, F. Colombina, S. Consuegra Rodríguez, G. Correia Silva, M. De Silva, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov,

E. Gallo[22], A. Geiser, A. Giraldi, G. Greau, A. Grohsjean, V. Guglielmi, M. Guthoff, A. Jafari[24], N.Z. Jomhari, B. Kaech, M. Kasemann, H. Kaveh, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka[25], W. Lohmann[26], R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, J. Metwally, A.B. Meyer, G. Milella, M. Mormile, A. Mussgiller, A. Nürnberg, Y. Otarid, D. Pérez Adán, E. Ranken, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio, M. Savitskyi, M. Scham[27,23], V. Scheurer, S. Schnake[23], P. Schütze, C. Schwanenberger[22], M. Shchedrolosiev, R.E. Sosa Ricardo, L.P. Sreelatha Pramod, D. Stafford, F. Vazzoler, A. Ventura Barroso, R. Walsh, Q. Wang, Y. Wen, K. Wichmann, L. Wiens[23], C. Wissing, S. Wuchterl, Y. Yang, A. Zimermmane Castro Santos

University of Hamburg, Hamburg, Germany
A. Albrecht, S. Albrecht, M. Antonello, S. Bein, L. Benato, M. Bonanomi, P. Connor, K. De Leo, M. Eich, K. El Morabit, A. Fröhlich, C. Garbers, E. Garutti, M. Hajheidari, J. Haller, A. Hinzmann, H.R. Jabusch, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, V. Kutzner, F. Labe, J. Lange, A. Lobanov, C. Matthies, A. Mehta, L. Moureaux, M. Mrowietz, A. Nigamova, Y. Nissan, A. Paasch, K.J. Pena Rodriguez, T. Quadfasel, M. Rieger, D. Savoiu, J. Schindler, P. Schleper, M. Schröder, J. Schwandt, M. Sommerhalder, H. Stadie, G. Steinbrück, A. Tews, M. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
S. Brommer, M. Burkart, E. Butz, T. Chwalek, A. Dierlamm, A. Droll, N. Faltermann, M. Giffels, J.O. Gosewisch, A. Gottmann, F. Hartmann[28], M. Horzela, U. Husemann, M. Klute, R. Koppenhöfer, M. Link, A. Lintuluoto, S. Maier, S. Mitra, Th. Müller, M. Neukum, M. Oh, G. Quast, K. Rabbertz, I. Shvetsov, H.J. Simonis, N. Trevisani, R. Ulrich, J. van der Linden, R.F. Von Cube, M. Wassmer, S. Wieland, R. Wolf, S. Wunsch, X. Zuo

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, P. Assiouras, G. Daskalakis, A. Kyriakis, A. Stakia

National and Kapodistrian University of Athens, Athens, Greece
M. Diamantopoulou, D. Karasavvas, P. Kontaxakis, A. Manousakis-Katsikakis, G. Melachroinos, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, I. Zisopoulos

National Technical University of Athens, Athens, Greece
G. Bakas, T. Chatzistavrou, G. Karapostoli, K. Kousouris, I. Papakrivopoulos, E. Siamarkou, G. Tsipolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece
K. Adamidis, I. Bestintzanos, I. Evangelou, C. Foudas, P. Gianneios, C. Kamtsikis, P. Katsoulis, P. Kokkas, P.G. Kosmoglou Kioseoglou, N. Manthos, I. Papadopoulos, J. Strologas

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanád, K. Farkas, M.M.A. Gadallah[29], P. Major, K. Mandal, G. Pásztor, A.J. Rádl[30], O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
M. Bartók[31], C. Hajdu, D. Horvath[32,33], F. Sikler, V. Veszpremi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
G. Bencze, N. Beni, S. Czellar, J. Karancsi[31], J. Molnar, Z. Szillasi, D. Teyssier

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, B. Ujvari[34], G. Zilizi

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
T. Csorgo[30], F. Nemes[30], T. Novak

Panjab University, Chandigarh, India
J. Babbar, S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[35], R. Gupta, A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, P. Kumari, M. Meena, K. Sandeep, T. Sheokand, J.B. Singh[36], A. Singla

University of Delhi, Delhi, India
A. Ahmed, A. Bhardwaj, A. Chhetri, B.C. Choudhary, A. Kumar, M. Naimuddin, K. Ranjan, S. Saumya

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
S. Baradia, S. Barman[37], S. Bhattacharya, D. Bhowmik, S. Dutta, S. Dutta, B. Gomber[38], M. Maity[37], P. Palit, G. Saha, B. Sahu[38], S. Sarkar

Indian Institute of Technology Madras, Madras, India
P.K. Behera, S.C. Behera, S. Chatterjee, P. Kalbhor, J.R. Komaragiri[39], D. Kumar[39], A. Muhammad, L. Panwar[39], R. Pradhan, P.R. Pujahari, N.R. Saha, A. Sharma, A.K. Sikdar, S. Verma

Bhabha Atomic Research Centre, Mumbai, India
K. Naskar[40]

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, I. Das, S. Dugad, M. Kumar, G.B. Mohanty, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India
A. Bala, S. Banerjee, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, A. Thachayath

JHEP08(2024)148

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
S. Bahinipati[41], A.K. Das, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu[42], A. Nayak[42], P. Saha, S.K. Swain, S. Varghese, D. Vats[42]

Indian Institute of Science Education and Research (IISER), Pune, India
A. Alpana, S. Dube, B. Kansal, A. Laha, S. Pandey, A. Rastogi, S. Sharma

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[43,44], E. Khazaie[44], M. Zeinali[45]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[46], S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

University College Dublin, Dublin, Ireland
M. Grunewald

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], R. Aly[a,b,13], C. Aruta[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], B. D' Anzi[a,b], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], W. Elmetenawee[a,b], F. Errico[a,b], L. Fiore[a], G. Iaselli[a,c], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a,b], V. Mastrapasqua[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a], D. Ramos[a], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a], F.M. Simone[a,b], Ü. Sözbilir[a], A. Stamerra[a], R. Venditti[a], P. Verwilligen[a]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a], L. Brigliadori[a], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a,b], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,47], L. Lunerti[a,b], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b]

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy
S. Costa[a,b,48], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,48], C. Tuve[a,b]

INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy
G. Barbagli[a], G. Bardelli[a,b], B. Camaiani[a,b], A. Cassese[a], R. Ceccarelli[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a,b], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], L. Viliani[a]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, S. Meola[49], D. Piccolo

INFN Sezione di Genova[a], Università di Genova[b], Genova, Italy
M. Bozzo[a,b], P. Chatagnon[a], F. Ferro[a], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milano, Italy
A. Benaglia[a], G. Boldrini[a], F. Brivio[a,b], F. Cetorelli[a,b], F. De Guio[a,b], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a,b], M.T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], B.S. Pinolini[a], S. Ragazzi[a,b], N. Redaelli[a], T. Tabarelli de Fatis[a,b], D. Zuolo[a,b]

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy; Università della Basilicata[c], Potenza, Italy; Università G. Marconi[d], Roma, Italy
S. Buontempo[a], A. Cagnotta[a,b], F. Carnevali[a,b], N. Cavallo[a,c], A. De Iorio[a,b], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a,b,50], P. Paolucci[a,28], B. Rossi[a], C. Sciacca[a,b]

INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy; Università di Trento[c], Trento, Italy
R. Ardino[a], P. Azzi[a], N. Bacchetta[a,51], D. Bisello[a,b], P. Bortignon[a], A. Bragagnolo[a,b], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], F. Fanzago[a], F. Gasparini[a,b], U. Gasparini[a,b], G. Grosso[a], L. Layer[a,52], E. Lusiani[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], J. Pazzini[a,b], P. Ronchese[a,b], F. Simonetto[a,b], G. Strong[a], M. Tosi[a,b], H. Yarar[a,b], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy
S. Abu Zeid[a,16], C. Aimè[a,b], A. Braghieri[a], S. Calzaferri[a,b], D. Fiorina[a,b], P. Montagna[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy
P. Asenov[a,53], G.M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], M. Magherini[a,b], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,53], A. Piccinelli[a,b], M. Presilla[a,b], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

INFN Sezione di Pisa[a], Università di Pisa[b], Scuola Normale Superiore di Pisa[c], Pisa, Italy; Università di Siena[d], Siena, Italy
P. Azzurri[a], G. Bagliesi[a], V. Bertacchi[a,c], R. Bhattacharya[a], L. Bianchini[a,b], T. Boccali[a], E. Bossini[a,b], D. Bruschini[a,c], R. Castaldi[a], M.A. Ciocci[a,b], V. D'Amante[a,d], R. Dell'Orso[a], S. Donato[a], A. Giassi[a], F. Ligabue[a,c], D. Matos Figueiredo[a], A. Messineo[a,b], M. Musich[a,b], F. Palla[a], S. Parolia[a], G. Ramirez-Sanchez[a,c], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a], T. Sarkar[a], A. Scribano[a], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma[a], Sapienza Università di Roma[b], Roma, Italy
P. Barria[a], M. Campana[a,b], F. Cavallari[a], L. Cunqueiro Mendez[a,b], D. Del Re[a,b], E. Di Marco[a], M. Diemoz[a], E. Longo[a,b], P. Meridiani[a], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a], R. Tramontano[a,b]

INFN Sezione di Torino[a], Università di Torino[b], Torino, Italy; Università del Piemonte Orientale[c], Novara, Italy

N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], A. Bellora[a,b], C. Biino[a], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], L. Finco[a], M. Grippo[a,b], B. Kiani[a,b], F. Legger[a], F. Luongo[a,b], C. Mariotti[a], S. Maselli[a], A. Mecca[a,b], E. Migliore[a,b], M. Monteno[a], R. Mulargia[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], M. Ruspa[a,c], K. Shchelina[a], F. Siviero[a,b], V. Sola[a,b], A. Solano[a,b], D. Soldi[a,b], A. Staiano[a], C. Tarricone[a,b], M. Tornago[a,b], D. Trocino[a], G. Umoret[a,b], A. Vagnerini[a,b], E. Vlasov[a,b]

INFN Sezione di Trieste[a], Università di Trieste[b], Trieste, Italy

S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], G. Della Ricca[a,b], G. Sorrentino[a,b]

Kyungpook National University, Daegu, Korea

S. Dogra, C. Huh, B. Kim, D.H. Kim, G.N. Kim, J. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, M.S. Ryu, S. Sekmen, Y.C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

H. Kim, D.H. Moon

Hanyang University, Seoul, Korea

E. Asilar, T.J. Kim, J. Park

Korea University, Seoul, Korea

S. Choi, S. Han, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh

Sejong University, Seoul, Korea

H. S. Kim, Y. Kim, S. Lee

Seoul National University, Seoul, Korea

J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, S. Ko, H. Kwon, H. Lee, S. Lee, B.H. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

University of Seoul, Seoul, Korea

W. Jang, D.Y. Kang, Y. Kang, D. Kim, S. Kim, B. Ko, J.S.H. Lee, Y. Lee, J.A. Merlin, I.C. Park, Y. Roh, D. Song, I.J. Watson, S. Yang

Yonsei University, Department of Physics, Seoul, Korea

S. Ha, H.D. Yoo

Sungkyunkwan University, Suwon, Korea

M. Choi, M.R. Kim, H. Lee, Y. Lee, I. Yu

JHEP08(2024)148

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
T. Beyrouthy, Y. Maghrbi

Riga Technical University, Riga, Latvia
K. Dreimanis, G. Pikurs, A. Potrebko, M. Seidel, V. Veckalns[54]

Vilnius University, Vilnius, Lithuania
M. Ambrozas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
N. Bin Norjoharuddeen, S.Y. Hoh[55], I. Yusuff[55], Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello, J.A. Murillo Quijada, A. Sehrawat, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, I. Heredia-De La Cruz[56], R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sánchez Hernández

Universidad Iberoamericana, Mexico City, Mexico
C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

University of Montenegro, Podgorica, Montenegro
I. Bubanja, J. Mijuskovic[57], N. Raicevic

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, M. Gul, H.R. Hoorani, W.A. Khan

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

JHEP08(2024)148

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, D. Bastos, A. Boletti, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, M. Pisano, J. Seixas, J. Varela

Faculty of Physics, University of Belgrade, Belgrade, Serbia
P. Adzic, P. Milenovic

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
M. Dordevic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, M. Barrio Luna, Cristina F. Bedoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. León Holgado, D. Moran, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, D.D. Redondo Ferrero, L. Romero, S. Sánchez Navas, J. Sastre, L. Urda Gómez, J. Vazquez Escobar, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain
J.F. de Trocóniz

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, C. Vico Villalba

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, C. Fernandez Madrazo, G. Gomez, C. Lasaosa García, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, J. Piedra Gomez, C. Prieels, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
M.K. Jayananda, B. Kailasapathy[58], D.U.J. Sonnadara, D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna, K. Liyanage, N. Perera, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Auffray, G. Auzinger, J. Baechler, D. Barney, A. Bermúdez Martínez, M. Bianco, B. Bilin, A.A. Bin Anuar, A. Bocci, E. Brondolin, C. Caillol, T. Camporesi, G. Cerminara, N. Chernyavskaya, S.S. Chhibra, S. Choudhury,

JHEP08(2024)148

M. Cipriani, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, M. Dünser, N. Dupont, F. Fallavollita[59], A. Florent, L. Forthomme, G. Franzoni, W. Funk, S. Ghosh[60], S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, E. Govorkova, M. Haranko, J. Hegeman, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, N. Kratochwil, S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, B. Maier, L. Malgeri, M. Mannelli, A.C. Marini, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, S. Orfanelli, L. Orsini, F. Pantaleo, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, M. Pitt, H. Qu, T. Quast, D. Rabady, A. Racz, G. Reales Gutiérrez, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas[61], A.G. Stahl Leiton, A. Steen, S. Summers, K. Tatar, D. Treille, P. Tropea, A. Tsirou, D. Walter, J. Wanczyk[62], K.A. Wozniak, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

T. Bevilacqua[63], L. Caminada[63], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[63], L. Noehte[63], T. Rohe

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

T.K. Aarrestad, K. Androsov[62], M. Backhaus, A. Calandri, K. Datta, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, L. Marchese, C. Martin Perez, A. Mascellani[62], F. Nessi-Tedaldi, J. Niedziela, F. Pauss, V. Perovic, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, F. Riti, D. Ruini, D.A. Sanz Becerra, R. Seidita, J. Steggemann[62], D. Valsecchi, R. Wallny

Universität Zürich, Zurich, Switzerland

C. Amsler[64], P. Bärtschi, C. Botta, D. Brzhechko, M.F. Canelli, K. Cormier, A. De Wit, R. Del Burgo, J.K. Heikkilä, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger, M. Senger, Y. Takahashi

National Central University, Chung-Li, Taiwan

C. Adloff[65], C.M. Kuo, W. Lin, P.K. Rout, P.C. Tiwari[39], S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

L. Ceard, Y. Chao, K.F. Chen, P.s. Chen, H. Cheng, W.-S. Hou, R. Khurana, G. Kole, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, J. Thomas-Wilsker, H.y. Wu, E. Yazgan

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

C. Asawatangtrakuldee, N. Srimanobhas, V. Wachirapusitanand

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

D. Agyel, F. Boran, Z.S. Demiroglu, F. Dolek, I. Dumanoglu[66], E. Eskut, Y. Guler[67], E. Gurpinar Guler[67], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[68], A. Polatoz, B. Tali[69], U.G. Tok, S. Turkcapar, E. Uslan, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey

G. Karapinar[70], K. Ocalan[71], M. Yalvac[72]

Bogazici University, Istanbul, Turkey

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[73], O. Kaya[74], S. Tekten[75]

Istanbul Technical University, Istanbul, Turkey

A. Cakir, K. Cankocak[66], Y. Komurcu, S. Sen[76]

Istanbul University, Istanbul, Turkey

O. Aydilek, S. Cerci[69], V. Epshteyn, B. Hacisahinoglu, I. Hos[77], B. Isildak[78], B. Kaynak, S. Ozkorucuklu, C. Simsek, D. Sunar Cerci[69]

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine

B. Grynyov

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine

L. Levchuk

University of Bristol, Bristol, United Kingdom

D. Anthony, J.J. Brooke, A. Bundock, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou[79], K. Walkingshaw Pass, R. White

Rutherford Appleton Laboratory, Didcot, United Kingdom

A.H. Ball, K.W. Bell, A. Belyaev[80], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, K.V. Ellis, K. Harder, S. Harper, M.-L. Holmberg[81], Sh. Jain, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom

R. Bainbridge, P. Bloch, J. Borg, C.E. Brown, O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya, V. Cepaitis, G.S. Chahal[82], D. Colling, J.S. Dancu, P. Dauncey, G. Davies, J. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, A. Howard, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, M. Mieskolainen, J. Nash[83], M. Pesaresi, B.C. Radburn-Smith, A. Richards, A. Rose, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, L.H. Vage, T. Virdee[28], M. Vojinovic, N. Wardle, S.N. Webb, D. Winterbottom

JHEP08(2024)148

Brunel University, Uxbridge, United Kingdom
K. Coldham, J.E. Cole, A. Khan, P. Kyberd, I.D. Reid

Baylor University, Waco, Texas, USA
S. Abdullin, A. Brinkerhoff, B. Caraway, J. Dittmann, K. Hatakeyama, J. Hiltbrand, A.R. Kanuganti, B. McMaster, M. Saunders, S. Sawant, C. Sutantawibul, M. Toms, J. Wilson

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, C. Huerta Escamilla, A.E. Simsek, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, Alabama, USA
R. Chudasama, S.I. Cooper, D. Di Croce, S.V. Gleyzer, C.U. Perez, P. Rumerio[84], E. Usai, C. West

Boston University, Boston, Massachusetts, USA
A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, C. Erice, E. Fontanesi, D. Gastler, S. May, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, S. Yuan

Brown University, Providence, Rhode Island, USA
G. Benelli, X. Coubez[23], D. Cutts, M. Hadley, U. Heintz, J.M. Hogan[85], T. Kwon, G. Landsberg, K.T. Lau, D. Li, J. Luo, M. Narain, N. Pervan, S. Sagir[86], F. Simpson, W.Y. Wong, X. Yan, D. Yu, W. Zhang

University of California, Davis, Davis, California, USA
S. Abbott, J. Bonilla, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, P.T. Cox, R. Erbacher, G. Haza, F. Jensen, O. Kukral, G. Mocellin, M. Mulhearn, D. Pellett, B. Regnery, W. Wei, Y. Yao, F. Zhang

University of California, Los Angeles, California, USA
M. Bachtis, R. Cousins, A. Datta, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, E. Manca, W.A. Nash, D. Saltzberg, B. Stone, V. Valuev

University of California, Riverside, Riverside, California, USA
R. Clare, J.W. Gary, M. Gordon, G. Hanson, O.R. Long, W. Si, S. Wimpenny

University of California, San Diego, La Jolla, California, USA
J.G. Branson, S. Cittolin, S. Cooperstein, D. Diaz, J. Duarte, R. Gerosa, L. Giannini, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, F. Mokhtar, M. Pieri, M. Quinnan, B.V. Sathia Narayanan, V. Sharma, M. Tadel, E. Vourliotis, F. Würthwein, Y. Xiang, A. Yagil

JHEP08(2024)148

University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
L. Brennan, C. Campagnari, M. Citron, G. Collura, A. Dorsett, J. Incandela, M. Kilpatrick, J. Kim, A.J. Li, P. Masterson, H. Mei, M. Oshiro, J. Richman, U. Sarica, R. Schmitz, F. Setti, J. Sheplock, P. Siddireddy, D. Stuart, S. Wang

California Institute of Technology, Pasadena, California, USA
A. Bornheim, O. Cerri, A. Latorre, J.M. Lawhorn, J. Mao, H.B. Newman, T. Q. Nguyen, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
J. Alison, S. An, M.B. Andrews, P. Bryant, V. Dutta, T. Ferguson, A. Harilal, C. Liu, T. Mudholkar, S. Murthy, M. Paulini, A. Roberts, A. Sanchez, W. Terrill

University of Colorado Boulder, Boulder, Colorado, USA
J.P. Cumalat, W.T. Ford, A. Hassani, G. Karathanasis, E. MacDonald, N. Manganelli, F. Marini, A. Perloff, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper

Cornell University, Ithaca, New York, USA
J. Alexander, S. Bright-Thonney, X. Chen, D.J. Cranshaw, J. Fan, X. Fan, D. Gadkari, S. Hogan, J. Monroy, J.R. Patterson, J. Reichert, M. Reid, A. Ryd, J. Thom, P. Wittich, R. Zou

Fermi National Accelerator Laboratory, Batavia, Illinois, USA
M. Albrow, M. Alyari, O. Amram, G. Apollinari, A. Apresyan, L.A.T. Bauerdick, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, K.F. Di Petrillo, J. Dickinson, I. Dutta, V.D. Elvira, Y. Feng, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, L. Horyn, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, S. Norberg, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[87], F. Ravera, A. Reinsvold Hall[88], L. Ristori, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, I. Zoi

University of Florida, Gainesville, Florida, USA
P. Avery, D. Bourilkov, L. Cadamuro, P. Chang, V. Cherepanov, R.D. Field, E. Koenig, M. Kolosova, J. Konigsberg, A. Korytov, E. Kuznetsova[89], K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, K. Shi, J. Wang, Z. Wu

JHEP08(2024)148

Florida State University, Tallahassee, Florida, USA
T. Adams, A. Askew, N. Bower, R. Habibullah, V. Hagopian, T. Kolberg, G. Martinez, H. Prosper, O. Viazlo, M. Wulansatiti, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, Florida, USA
M.M. Baarmand, S. Butalla, T. Elkafrawy[16], M. Hohlmann, R. Kumar Verma, M. Rahmani, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, Illinois, USA
M.R. Adams, R. Cavanaugh, S. Dittmer, O. Evdokimov, C.E. Gerber, D.J. Hofman, D. S. Lemos, A.H. Merrit, C. Mills, G. Oh, T. Roy, S. Rudrabhatla, M.B. Tonjes, N. Varelas, X. Wang, Z. Ye, J. Yoo

The University of Iowa, Iowa City, Iowa, USA
M. Alhusseini, K. Dilsiz[90], L. Emediato, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[91], J. Nachtman, O. Neogi, H. Ogul[92], Y. Onel, A. Penzo, C. Snyder, E. Tiras[93]

Johns Hopkins University, Baltimore, Maryland, USA
B. Blumenfeld, L. Corcodilos, J. Davis, A.V. Gritsan, S. Kyriacou, P. Maksimovic, J. Roskes, S. Sekhar, M. Swartz, T.Á. Vámi

The University of Kansas, Lawrence, Kansas, USA
A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, P. Baringer, A. Bean, Z. Flowers, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, C. Lindsey, J. Marquez, N. Minafra, M. Murray, M. Nickel, C. Rogan, C. Royon, R. Salvatico, S. Sanders, C. Smith, Q. Wang, G. Wilson

Kansas State University, Manhattan, Kansas, USA
B. Allmond, S. Duric, A. Ivanov, K. Kaadze, A. Kalogeropoulos, D. Kim, Y. Maravin, T. Mitchell, A. Modak, K. Nam, J. Natoli, D. Roy

Lawrence Livermore National Laboratory, Livermore, California, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, Maryland, USA
E. Adams, A. Baden, O. Baron, A. Belloni, A. Bethani, Y.m. Chen, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, Y. Lai, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer, C. Papageorgakis, L. Wang, K. Wong

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
J. Bendavid, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, P. Harris, D. Hoang, D. Kovalskyi, J. Krupa, Y.-J. Lee, K. Long, C. Mironov, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, J. Wang, Z. Wang, B. Wyslouch, T. J. Yang

JHEP08(2024)148

University of Minnesota, Minneapolis, Minnesota, USA
R.M. Chatterjee, B. Crossman, B.M. Joshi, C. Kapsiak, M. Krohn, Y. Kubota, D. Mahon, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Mississippi, Oxford, Mississippi, USA
L.M. Cremaldi

University of Nebraska-Lincoln, Lincoln, Nebraska, USA
K. Bloom, M. Bryson, D.R. Claes, C. Fangmeier, F. Golf, C. Joo, I. Kravchenko, I. Reed, J.E. Siado, G.R. Snow[†], W. Tabb, A. Wightman, F. Yan, A.G. Zecchinelli

State University of New York at Buffalo, Buffalo, New York, USA
G. Agarwal, H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, M. Morris, D. Nguyen, J. Pekkanen, S. Rappoccio, H. Rejeb Sfar, A. Williams

Northeastern University, Boston, Massachusetts, USA
G. Alverson, E. Barberis, Y. Haddad, Y. Han, A. Krishna, J. Li, G. Madigan, B. Marzocchi, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, A. Tishelman-Charny, B. Wang, D. Wood

Northwestern University, Evanston, Illinois, USA
S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert, K.A. Hahn, Y. Liu, D.G. Monk, N. Odell, M.H. Schmitt, A. Taliercio, M. Velasco

University of Notre Dame, Notre Dame, Indiana, USA
R. Band, R. Bucci, M. Cremonesi, A. Das, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, K. Mohrman, C. Moore, Y. Musienko[12], R. Ruchti, A. Townsend, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

The Ohio State University, Columbus, Ohio, USA
B. Bylsma, M. Carrigan, L.S. Durkin, C. Hill, M. Joyce, A. Lesauvage, M. Nunez Ornelas, K. Wei, B.L. Winer, B. R. Yates

Princeton University, Princeton, New Jersey, USA
F.M. Addesa, H. Bouchamaoui, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, S. Higginbotham, G. Kopp, S. Kwan, D. Lange, A. Loeliger, D. Marlow, I. Ojalvo, J. Olsen, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, Puerto Rico, USA
S. Malik

Purdue University, West Lafayette, Indiana, USA
A.S. Bakshi, V.E. Barnes, S. Chandra, R. Chawla, S. Das, A. Gu, L. Gutay, M. Jones, A.W. Jung, D. Kondratyev, A.M. Koshy, M. Liu, G. Negro, N. Neumeister,

JHEP08(2024)148

G. Paspalaki, S. Piperov, A. Purohit, J.F. Schulte, M. Stojanovic[17], J. Thieman, A. K. Virdi, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, Indiana, USA
J. Dolen, N. Parashar

Rice University, Houston, Texas, USA
D. Acosta, A. Baty, T. Carnahan, S. Dildick, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, A. Kumar, W. Li, O. Miguel Colin, B.P. Padley, R. Redjimi, J. Rotter, S. Yang, E. Yigitbasi, Y. Zhang

University of Rochester, Rochester, New York, USA
A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, P. Parygin, E. Popova, R. Taus, G.P. Van Onsem

The Rockefeller University, New York, New York, USA
K. Goulianos

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
B. Chiarito, J.P. Chou, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, D. Jaroslawski, O. Karacheban[26], I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Routray, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora, H. Wang

University of Tennessee, Knoxville, Tennessee, USA
H. Acharya, A.G. Delannoy, S. Fiorendi, T. Holmes, E. Nibigira, S. Spanier

Texas A&M University, College Station, Texas, USA
M. Ahmad, O. Bouhali[94], M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[95], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, Texas, USA
N. Akchurin, J. Damgov, V. Hegde, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, I. Volobouev, A. Whitbeck

Vanderbilt University, Nashville, Tennessee, USA
E. Appelt, S. Greene, A. Gurrola, W. Johns, R. Kunnawalkam Elayavalli, A. Melo, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen

University of Virginia, Charlottesville, Virginia, USA
B. Cardwell, B. Cox, G. Cummings, J. Hakala, R. Hirosky, A. Ledovskoy, A. Li, C. Neu, C.E. Perez Lara

Wayne State University, Detroit, Michigan, USA
P.E. Karchin

JHEP08(2024)148

University of Wisconsin - Madison, Madison, Wisconsin, USA
A. Aravind, S. Banerjee, K. Black, T. Bose, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C.K. Koraka, A. Lanaro, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, S. Mondal, G. Parida, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, H.F. Tsoi, W. Vetens, A. Warden

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN
S. Afanasiev, V. Andreev, Yu. Andreev, T. Aushev, M. Azarkin, A. Babaev, A. Belyaev, V. Blinov[96], E. Boos, V. Borshch, D. Budkouski, M. Chadeeva[96], V. Chekhovsky, R. Chistov[96], A. Demiyanov, A. Dermenev, T. Dimova[96], I. Dremin, A. Ershov, G. Gavrilov, V. Gavrilov, S. Gninenko, V. Golovtcov, N. Golubev, I. Golutvin, I. Gorbunov, A. Gribushin, Y. Ivanov, V. Kachanov, L. Kardapoltsev[96], V. Karjavine, A. Karneyeu, L. Khein, V. Kim[96], M. Kirakosyan, D. Kirpichnikov, M. Kirsanov, O. Kodolova[97], D. Konstantinov, V. Korenkov, V. Korotkikh, A. Kozyrev[96], N. Krasnikov, A. Lanev, P. Levchenko[98], A. Litomin, N. Lychkovskaya, V. Makarenko, A. Malakhov, V. Matveev[96], V. Murzin, A. Nikitenko[99,97], S. Obraztsov, A. Oskin, I. Ovtin[96], V. Palichik, V. Perelygin, S. Petrushanko, S. Polikarpov[96], V. Popov, O. Radchenko[96], M. Savina, V. Savrin, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen[96], S. Slabospitskii, V. Smirnov, A. Snigirev, D. Sosnov, V. Sulimov, E. Tcherniaev, A. Terkulov, O. Teryaev, I. Tlisova, A. Toropin, L. Uvarov, A. Uzunian, I. Vardanyan, A. Vorobyev[†], N. Voytishin, B.S. Yuldashev[100], A. Zarubin, I. Zhizhin, A. Zhokin

[†] *Deceased*
[1] *Also at Yerevan State University, Yerevan, Armenia*
[2] *Also at TU Wien, Vienna, Austria*
[3] *Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt*
[4] *Also at Université Libre de Bruxelles, Bruxelles, Belgium*
[5] *Also at Universidade Estadual de Campinas, Campinas, Brazil*
[6] *Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil*
[7] *Also at UFMS, Nova Andradina, Brazil*
[8] *Also at University of Chinese Academy of Sciences, Beijing, China*
[9] *Also at Nanjing Normal University, Nanjing, China*
[10] *Now at The University of Iowa, Iowa City, Iowa, USA*
[11] *Also at University of Chinese Academy of Sciences, Beijing, China*
[12] *Also at an institute or an international laboratory covered by a cooperation agreement with CERN*
[13] *Also at Helwan University, Cairo, Egypt*
[14] *Now at Zewail City of Science and Technology, Zewail, Egypt*
[15] *Also at British University in Egypt, Cairo, Egypt*
[16] *Now at Ain Shams University, Cairo, Egypt*
[17] *Also at Purdue University, West Lafayette, Indiana, USA*
[18] *Also at Université de Haute Alsace, Mulhouse, France*
[19] *Also at Department of Physics, Tsinghua University, Beijing, China*
[20] *Also at The University of the State of Amazonas, Manaus, Brazil*
[21] *Also at Erzincan Binali Yildirim University, Erzincan, Turkey*

[22] *Also at University of Hamburg, Hamburg, Germany*
[23] *Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
[24] *Also at Isfahan University of Technology, Isfahan, Iran*
[25] *Also at Bergische University Wuppertal (BUW), Wuppertal, Germany*
[26] *Also at Brandenburg University of Technology, Cottbus, Germany*
[27] *Also at Forschungszentrum Jülich, Juelich, Germany*
[28] *Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland*
[29] *Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt*
[30] *Also at Wigner Research Centre for Physics, Budapest, Hungary*
[31] *Also at Institute of Physics, University of Debrecen, Debrecen, Hungary*
[32] *Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
[33] *Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania*
[34] *Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary*
[35] *Also at Punjab Agricultural University, Ludhiana, India*
[36] *Also at UPES - University of Petroleum and Energy Studies, Dehradun, India*
[37] *Also at University of Visva-Bharati, Santiniketan, India*
[38] *Also at University of Hyderabad, Hyderabad, India*
[39] *Also at Indian Institute of Science (IISc), Bangalore, India*
[40] *Also at Indian Institute of Technology (IIT), Mumbai, India*
[41] *Also at IIT Bhubaneswar, Bhubaneswar, India*
[42] *Also at Institute of Physics, Bhubaneswar, India*
[43] *Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany*
[44] *Now at Department of Physics, Isfahan University of Technology, Isfahan, Iran*
[45] *Also at Sharif University of Technology, Tehran, Iran*
[46] *Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran*
[47] *Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy*
[48] *Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy*
[49] *Also at Università degli Studi Guglielmo Marconi, Roma, Italy*
[50] *Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy*
[51] *Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
[52] *Also at Università di Napoli 'Federico II', Napoli, Italy*
[53] *Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy*
[54] *Also at Riga Technical University, Riga, Latvia*
[55] *Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia*
[56] *Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico*
[57] *Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
[58] *Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka*
[59] *Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy*
[60] *Also at Indian Institute of Technology Hyderabad, Hyderabad, India*
[61] *Also at National and Kapodistrian University of Athens, Athens, Greece*
[62] *Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland*
[63] *Also at Universität Zürich, Zurich, Switzerland*
[64] *Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria*
[65] *Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France*
[66] *Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey*
[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*

JHEP08(2024)148

[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*

JHEP08(2024)148