Published for SISSA by Springer

Received: April 11, 2025
Accepted: June 9, 2025
Published: July 9, 2025

Search for jet quenching with dijets from high-multiplicity pPb collisions at $\sqrt{s_{_\mathrm{NN}}} = 8.16$ TeV

JHEP07(2025)118

The CMS collaboration

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

Abstract: The first measurement of the dijet transverse momentum balance x_j in proton-lead (pPb) collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{_\mathrm{NN}}} = 8.16\,\mathrm{TeV}$ is presented. The x_j observable, defined as the ratio of the subleading over leading jet transverse momentum in a dijet pair, is used to search for jet quenching effects. The data, corresponding to an integrated luminosity of $174.6\,\mathrm{nb}^{-1}$, were collected with the CMS detector in 2016. The x_j distributions and their average values are studied as functions of the charged-particle multiplicity of the events and for various dijet rapidity selections. The latter enables probing hard scattering of partons carrying distinct nucleon momentum fractions x in the proton- and lead-going directions. The former, aided by the high-multiplicity triggers, allows probing for potential jet quenching effects in high-multiplicity events (with up to 400 charged particles), for which collective phenomena consistent with quark-gluon plasma (QGP) droplet formation were previously observed. The ratios of x_j distributions for high- to low-multiplicity events are used to quantify the possible medium effects. These ratios are consistent with simulations of the hard-scattering process that do not include QGP production. These measurements set an upper limit on medium-induced energy loss of the subleading jet of 1.26% of its transverse momentum at the 90% confidence level in high multiplicity pPb events.

Keywords: Heavy Ion Experiments, Jets

ArXiv ePrint: 2504.08507

https://doi.org/10.1007/JHEP07(2025)118

Contents

1 Introduction **1**

2 The CMS detector and event reconstruction **2**

3 Event selection **3**

4 Analysis procedure **4**

5 Systematic uncertainties **6**

6 Results **7**

7 Summary **8**

A The x_j distributions for various event multiplicities and jet rapidity selections **15**

The CMS collaboration **37**

1 Introduction

High-energy jets consist of particles produced by the fragmentation and hadronization of partons (quarks and gluons) that have undergone hard scattering in the early stages of a collision. Jets have been successfully employed to probe the properties of the quark-gluon plasma (QGP), a unique form of hot and dense matter formed in high-energy heavy ion collisions [1]. One of the most recognized signatures of the QGP is the jet quenching phenomenon, which refers to the suppression or modification of the energy and shape of jets caused by partonic interaction in the hot QGP medium. The presence of jet quenching has been demonstrated using a wide range of measurements in lead-lead (PbPb) and gold-gold (AuAu) collisions [2–7]. A recent review of CMS jet quenching measurements is presented in ref. [7].

More recently, possible indications of QGP production have been observed in small colliding systems. For example, particle collectivity attributed to hydrodynamic flow within a QGP has been measured in high-multiplicity proton-proton (pp) and proton-lead (pPb) collisions at the CERN LHC [8–10], as well as in pAu, deuteron-Au, and helium-Au collisions at the BNL RHIC [11]. In addition, strangeness enhancement, another QGP signature, has been observed by ALICE in pp and pPb collisions [12]. However, the observations of jet quenching, which is expected in a hot and dense medium, remain elusive in such small systems [13–18].

Motivated by the measurements of dijet transverse momentum (p_{T}) balance in PbPb collisions [2, 6], this analysis aims to study the same quantity in different multiplicity classes of the pPb data sample. The study utilizes CMS high-multiplicity events to probe different pseudorapidity regions in the center-of-mass frame (η_{CM}) of the collision, allowing investigations of possible jet quenching effects for the hard scattering processes initiated by partons carrying different nucleon momentum fraction x in the p- and Pb-going directions. The data, collected in 2016 during LHC Run2 at a center-of-mass energy of 8.16 TeV, correspond to a total integrated luminosity of 174.6 nb^{-1} [19–21]. During part of the data-taking period, the directions of the proton and lead beams were reversed. For consistency, positive η_{lab} is defined to always point in the direction of the proton beam. Because the two beams have different energy per nucleon, a massless particle emitted at $\eta_{\mathrm{CM}} = 0$ in the nucleon-nucleon center-of-mass frame will be detected at $\eta_{\mathrm{lab}} = +0.465$ in the laboratory frame.

This work presents searches for jet quenching signals using dijets, which are composed of the two highest energy, back-to-back jets in the event. The observable under study, dijet p_{T} balance (x_j), is defined as a ratio of transverse momenta of subleading (less energetic) to leading (more energetic) jets in a dijet. The analysis is performed by selecting leading and subleading jets with transverse momenta of at least 100 GeV and 50 GeV, respectively, and in different kinematic regions (detailed below) to isolate mid-, forward, and backward rapidities. The measured x_j distributions for events with different charged-particle multiplicities are compared with Monte Carlo (MC) simulations of the hard scattering process without quenching effects. Tabulated results are provided in the HEPData record for this analysis [22].

2 The CMS detector and event reconstruction

The central feature of the CMS apparatus is a superconducting solenoid with a 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are the silicon pixel and strip trackers, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of barrel and two endcap sections. The CMS silicon tracker measures charged-particle tracks within $|\eta| < 2.5$. It consists of 1,856 silicon pixel and 15,148 silicon strip detector modules. Two hadron forward (HF) steel and quartz-fiber calorimeters complement the barrel and endcap detectors, extending the calorimeter coverage from the $|\eta| < 3.0$ range provided by the barrel and endcap out to $|\eta| < 5.2$. The HF calorimeters are subdivided in azimuth (ϕ) into 20° modular wedges and further segmented to form 0.175×0.175 radians ($\Delta\eta \times \Delta\phi$) "towers". Muons are measured in the range $|\eta| < 2.4$, with detection planes located outside the solenoid core. A detailed description of the CMS detector, along with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [23].

A particle-flow algorithm [24] aims to reconstruct and identify each individual particle in an event with an optimized combination of information from the various elements of the CMS detector. The energy of photons is obtained from the ECAL measurement. The energy of an electron is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of a muon is obtained from the curvature of the corresponding track. The energy of a charged hadron is determined from a combination of the momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies.

Events are selected using a two-tiered trigger system. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz [25]. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event

JHEP07(2025)118

reconstruction software optimized for fast processing, reducing the event rate to around 1 kHz in pp collisions [26] and up to 31 kHz and pPb collisions, before data storage.

3 Event selection

The triggers and event selections are similar to those described in refs. [27, 28]. Minimum bias (MB) events are triggered by requiring energy deposits in at least one of the two HF calorimeters above a threshold of approximately 1 GeV and the presence of at least one track with $p_T > 0.4\,\text{GeV}$ in the pixel tracker. Because of the high collision rate, the integrated luminosity collected by this trigger in 2016 data-taking was approximately $5.8\,\text{nb}^{-1}$.

To ensure the collection of a large sample of high-multiplicity (HM) pPb collisions, a dedicated trigger was implemented using both the CMS L1 and HLT systems. At L1, the total number of towers in the electromagnetic and hadronic calorimeters above a transverse energy threshold of 0.5 GeV is required to be greater than 120 and 150 towers, respectively. Track reconstruction is performed online as part of the HLT trigger with the identical reconstruction algorithm used offline [29]. For each event, the reconstructed vertex with the highest number of associated tracks is selected as the primary vertex. The number of tracks with $|\eta_{\text{lab}}| < 2.4$, $p_T > 0.4$ GeV, and a distance of closest approach less than 0.12 cm to the primary vertex is determined for each event and is required to exceed a certain threshold to enrich the sample with HM events. This analysis employs two distinct HM triggers designed to select events with charged-particle multiplicities exceeding 185 and 250 with approximate integrated luminosities of $96.2\,\text{nb}^{-1}$ and $174.6\,\text{nb}^{-1}$, respectively.

Events are required to have at least one interaction vertex, reconstructed from two or more tracks, within 15 cm of the nominal interaction point along the beam axis and 0.2 cm in the transverse direction. A requirement of at least one calorimeter tower with energy above 3 GeV on each side of the interaction point in an HF calorimeter is imposed, effectively removing ultraperipheral events and electromagnetic interactions. Events with exceptionally high occupancy in the tracker without a common vertex are removed. Additionally, selections are applied to remove events with more than one interaction per bunch crossing (pileup) [27, 28]. The average pileup probability, defining the chance to have more than one interaction recorded in a minimum bias event, in pPb collisions at 8.16 TeV varied between 10–25%, depending on the LHC operation conditions. Rejecting those events is essential to reduce possible contamination that can distort the jet energy, momentum, and shape, as well as introduce misidentified jets from random energy deposits.

For the charged-particle multiplicity ($N_{\text{trk}}^{\text{offline}}$), high-purity tracks [29] are utilized, where $N_{\text{trk}}^{\text{offline}}$ represents the number of offline-selected tracks [9, 29] with $|\eta| < 2.4$ and $p_T > 0.4\,\text{GeV}$. Additionally, a reconstructed track is considered a primary-track candidate if the impact parameter significance in the plane transverse to the beams ($d_{\text{xy}}/\sigma(d_{\text{xy}})$) and the significance of the separation in z between the track and the best reconstructed primary vertex ($d_{\text{z}}/\sigma(d_{\text{z}})$) are both less than 3. The primary vertex is defined as the vertex associated with the largest number of tracks. Tracks with poor momentum resolution are removed by requiring that the relative p_T uncertainty ($\sigma(p_T)/p_T$) is less than 10%. Primary tracks that fall within the kinematic range $|\eta| < 2.4$ and $p_T > 0.4\,\text{GeV}$ are selected in the analysis to ensure reasonable tracking efficiency ($\sim$90%) and a low misreconstruction rate (<2%).

Simulated events are employed in this analysis for cross-checks and to determine jet reconstruction performance, event selection, and other potential detector effects. Embedded PYTHIA8+EPOS LHC [30, 31] event generators are used, where PYTHIA8 (version 212) with the CUETP8M1 tune [32] is used to model the hard scattering, parton showering, and hadronization processes for the production of the dijets of interest, while EPOS LHC simulates the soft interactions and underlying event background. Additionally, GEANT4 [33] is used for detailed simulation of the CMS detector response.

4 Analysis procedure

The hadronic jets are reconstructed using the anti-k_{T} sequential recombination algorithm [34] with a distance parameter of $R = 0.4$, provided in the FASTJET framework [35], clustered from all particles reconstructed by the PF algorithm. An underlying event (UE)-subtraction method [36], called constituent subtraction, is applied to remove contributions from the UE soft fragments (constituents) within the jets. Jet energy corrections [37] are derived from simulation studies to ensure that the average energy of reconstructed jets matches that of particle-level jets, which are defined as jets clustered from all stable particles produced in the collision, excluding neutrinos. In situ measurements of the momentum balance in dijet, γ+jet, Z+jet, and multijet events from pp data are used to account for any residual differences in the jet energy scale (JES) between data and simulation. The jet energy resolution (JER) typically amounts to 15–20% at 30 GeV, 10% at 100 GeV, and less than 7% at 400 GeV [37].

The final-state observable is the dijet momentum balance, defined as the p_{T} ratio between the leading j_1 and subleading jets j_2,

$$x_j = \frac{p_{\mathrm{T}}^{j_1}}{p_{\mathrm{T}}^{j_2}}, \tag{4.1}$$

where $p_{\mathrm{T}}^{j_1}$ and $p_{\mathrm{T}}^{j_2}$ are of the highest and second-highest p_{T} jets, respectively. This observable is always less than unity because $p_{\mathrm{T}}^{j_1} > p_{\mathrm{T}}^{j_2}$. The average dijet momentum balance ($\langle x_j \rangle$) is obtained by taking the mean value of the data. These observables have been frequently employed to explore QGP production in nucleus-nucleus collisions [6, 38, 39]. In those systems, we observed that the x_j distributions are significantly imbalanced, compared to pp, shifting toward lower values, indicating that the subleading jet loses more energy as it traverses the medium.

The analysis requires $p_{\mathrm{T}}^{j_1} > 100$ GeV, $p_{\mathrm{T}}^{j_2} > 50$ GeV to guarantee a jet resolution less than 15% and an absolute azimuthal separation ($\Delta\phi_{\text{dijets}} = |\phi^{j_1} - \phi^{j_2}|) > 5\pi/6$ to ensure that the two jets of the pair are back-to-back. In addition, because of the detector acceptance, it is required that $|\eta_{\text{lab}}| < 3.0$ for both jets. To remove jets potentially dominated by spurious contributions from various subdetector components or reconstruction failures, selection criteria similar to those used ref. [40] are applied. In the case of dijet events, there is a non-zero possibility that the selection criteria might remove a leading or subleading jet, resulting in the pairing of other jets in the event. To avoid this issue, the entire event is excluded if the leading or subleading jets do not pass the jet selections criteria. Implementing this approach has resulted in the removal of at most 3% of dijet events.

The analysis is performed by selecting leading and subleading jets in different η_{CM} configurations to study the forward and backward η_{CM} regions, probing jets in both forward

JHEP07(2025)118

(proton-going) and backward (Pb-going) directions, respectively. Three different measurement regions are defined: the forward proton direction ($1.2 < \eta_{\mathrm{CM}} < 2.4$), the backward lead direction ($-3.3 < \eta_{\mathrm{CM}} < -1.2$), and the midrapidity region ($|\eta_{\mathrm{CM}}| < 1$). The boundaries are chosen because of the detector acceptance and the small gap added is introduced to reduce possible correlations between jets and multiplicity. This analysis requires that at least one jet (leading or subleading) is located in the midrapidity region to ensure a sufficient number of events. As a result, five regions are used in this combinations listed below:

1. Both the leading and subleading jets are in the midrapidity region.
2. The leading jet is in the midrapidity region and the subleading jet is in the forward region.
3. The leading jet is in the midrapidity region and the subleading jet is in the backward region.
4. The leading jet is in the forward region and the subleading jet is in the midrapidity region.
5. The leading jet is in the backward region and the subleading jet is in the midrapidity region.

Jets traveling in the backward direction must experience effects from the fragmented nuclei, while jets in the forward direction are exposed to the proton remnant interaction. These regions correspond to different x values, with x_{Pb} describing the nucleus-going side and x_{p} the proton-going side. Jets at backward rapidity probe high-x_{Pb} partons, where initial-state energy loss and multiple scattering dominate, whereas forward jets access low-x_{Pb} partons, where shadowing and gluon saturation effects become relevant. For each of the dijet pseudorapidity combinations, the measurement is performed as a function of the charged $N_{\mathrm{trk}}^{\mathrm{offline}}$ in the following ranges: [10, 60), [60, 120), [120, 185), [185, 250), and [250, 400]. The last two ranges require the use of specific HM triggers, while the data for the other ranges are collected with the MB trigger.

Given the limited detector resolution and additional experimental effects, such as reconstruction efficiency and misidentified contributions, the properties of reconstructed jets can differ from those of jets defined at the particle level. This discrepancy leads to a migration of dijet events within the ranges of the final-state observable, x_j. To enable a direct comparison between the measured data and theoretical particle-level calculations or between the measured data and results from other experiments, the effect of these migrations is accounted for as part of the unfolding procedure.

This analysis performs the first unfolding of x_j using data collected by the CMS experiment. The x_j observable is unfolded using a two-dimensional reconstructed-versus-generated response matrix from PYTHIA8+EPOS LHC, built for each possible pseudorapidity combination and in the 10–60, 60–120, and ≥ 120 multiplicity ranges. The response matrix for multiplicity ≥ 120 is utilized for the data ranges 120–185, 185–250, and 250–400. The kinematic selections are applied to reconstructed quantities, while no requirements are applied to matched generator-level jets. A swapping effect, where the leading jet becomes subleading and vice versa, occurs in approximately 20% of events. This swapping is accounted for in the response matrix by identifying the effect and filling the matrix with $1/x_j$. Generator-level x_j values that satisfy the analysis fiducial region but are not reconstructed because one or both jets do not satisfy the dijet kinematic selection, referred to as missing values, are incorporated into the response matrix using the RooUnfold software package [41, 42]. The contributions from misidentified jets are negligible. The matrices are reweighted using two-dimensional probability distribution maps of the reconstructed $p_{\mathrm{T}}^{j_1}$ and $p_{\mathrm{T}}^{j_2}$ to take into account data and simulation differences. Once the final matrices are produced, the unfolding process employs the iterative method of D'Agostini [43–45], which is implemented in RooUnfold with five nominal iterations.

5 Systematic uncertainties

Six different sources of systematic uncertainty are studied in the present analysis for all of the observables and are outlined as follows:

- *Pileup.* The impact of pileup is evaluated by adjusting the pileup event selection criteria, which consider the distance between reconstructed vertices and the number of associated tracks. The resulting systematic uncertainty is found to be less than 5%.

- *JES.* To evaluate the uncertainty from the JES, the jet p_{T} in the data is shifted up and down according to the JES uncertainties. The sources of uncertainty considered are similar to those described in ref. [46]. The resulting systematics errors vary from 0.05–10% depending on the measurement, pseudorapidity configuration, and multiplicity range. Larger uncertainties are observed at low-x_j values (<0.5).

- *JER.* To evaluate the uncertainty from the JER, the jet p_{T} resolution is smeared by the estimated data-to-simulation difference. The amount of smearing depends on η and is applied to account for differences between data and simulation. The difference from the nominal distribution is taken as the systematic uncertainty. The variation observed is between 0.5–10% similarly to the JES uncertainty.

- *Underlying events.* As an alternative to the nominal method for correcting the underlying event contribution in jets, a jet-area-based background subtraction method, as described in ref. [47], is used. The difference between the two methods is less than 1% and is taken as a systematic uncertainty.

- *Trigger bias.* For the multiplicity dependency study, trigger bias is estimated using an approach that selects events in data from the multiplicity overlap region of the MB and HM triggers. Good agreement in x_j between MB and HM triggers in the same multiplicity range was observed, with deviations of 0.5% for 185–250 and 2.0% for 250–400 multiplicity ranges.

- *Unfolding.* Five iterations were used to perform the unfolding. The results were compared with those obtained using four and six iterations, and the difference of the level of 1% was taken as the systematic uncertainty.

JHEP07(2025)118

All systematic uncertainties were evaluated using a bin-by-bin approach for each observable, and the uncertainties were propagated to the final result. The dominant sources of systematic uncertainty are the JES and JER. All uncertainties are assumed to be uncorrelated and added in quadrature to calculate the total systematic uncertainty, resulting in values between 0.5–12%.

6 Results

The unfolded x_j distributions across different multiplicity ranges for leading and subleading jets in midrapidity and backward regions, respectively, are shown in figure 1. In higher multiplicity events, the x_j distribution shows a suppression near unity, shifting towards lower x_j values, similar to trends seen in nucleus-nucleus collisions. This result suggests increased energy loss in these events, potentially due to the contributions from multijet production or energy conservation. Dijets in different pseudorapidity configurations, resulting in distinct x_{Pb} and x_{p} regimes, for the multiplicity range $185 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 250$ are shown in figure 2. The various η_{CM} arrangements allow the exploration of x_{Pb} and x_{p} within a range of $\sim$0.03 to $\sim$0.28. High-x_{Pb} corresponds to cases where one of the jets is in the backward region; for example, x_{Pb} is approximately 0.28 when the leading and subleading jets are in the backward and midrapidity regions, respectively. In contrast, low-x_{Pb} is around 0.03 for jet pairs where the leading jet is at midrapidity, and the subleading jet is in the forward region. Overall we observe only a slight dependence of x_j across all dijet combinations. Comparisons with generator-level PYTHIA8+EPOS LHC MC simulations are presented, showing similar behavior between the simulation and data. The observed deviations arise from nuclear effects that are not implemented in the PYTHIA8+EPOS LHC MC. Monte Carlo event generation for multiplicities greater than 250 with EPOS was impractical. The remaining figures containing other multiplicity ranges and pseudorapidity combinations can be found in the appendix (figures 6 to 9).

The ratios between higher multiplicity intervals and the multiplicity range of $10 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 60$ can be used to search for quenching effects since a QGP medium is not expected to be formed in such low multiplicity events. Figures 3 and 4 show the high-to-low multiplicity ratios in different $N_{\mathrm{trk}}^{\mathrm{offline}}$ ranges and different η_{CM} configurations for the unfolded values, respectively. The ratio is close to unity, and the values decrease linearly from low to high x_j being less (greater) than unity for $x_j > 0.7$ ($<$0.6). The linear trend becomes more pronounced for higher multiplicities, showing the imbalance behavior discussed previously, and can be understood as a result of transverse momentum conservation [18, 48] due to the presence of multijet events. Similar to the x_j distributions, a small overall multiplicity dependence, within the uncertainties, is observed across the different η_{CM} combinations, indicating a slight dependency of the ratio with x_{Pb} and x_{p}. There is generally an agreement between simulations and data within the uncertainties. The additional figures corresponding to other multiplicity ranges and pseudorapidity configurations are provided in the appendix (figures 10 to 13). The measured (raw) distributions, which have not been unfolded, are also available in the appendix (figures 14 to 24) and support the same conclusions as discussed above for the unfolded distributions.

JHEP07(2025)118

The analysis also measures the $\langle x_j \rangle$ ratio from high-to-low $N_{\mathrm{trk}}^{\mathrm{offline}}$, as shown in figure 5, in bins of $N_{\mathrm{trk}}^{\mathrm{offline}}$ for all jet η_{CM} configurations for unfolded distributions. The results are close to unity, and a slight decrease in trend is aligned with the PYTHIA8+EPOS LHC simulation. This observation is at odds with PbPb collision data trends in [6]. Compared to pp-based reference, which provides an estimate for resolution effects, the PbPb data showed a significant departure from that baseline with progressively lower average x_j values toward more central (higher multiplicity) events. The study of dijet pseudorapidity combinations indicates a weak to no dependence of the dijet p_{T} balance trends on x_{Pb} and x_{p}, with variations less than 2%.

Comparing simulation to data, with simulation not including an energy loss mechanism, constrains the subleading jet energy loss, assuming that $\langle x_j \rangle$ remains unquenched in the multiplicity range of [10, 60). A chi-square test was performed comparing the measurements and MC simulations to extract the limit on the possible downward shift (expected from the energy loss scenario) in the mean x_j values. For high-multiplicity events [185, 250), where both leading and subleading jets are in the midrapidity region, the average subleading jet energy loss is constrained to be less than 1.26% at the one-sided 90% confidence level for an average p_{T} of 103.5 GeV. The result aligns with measurements from other LHC experiments [16, 17] and represents the first constraint on jet energy loss in pPb collisions using dijet observables. Interpreting the combination of this strong upper limit on jet quenching and the previously observed evidence for collective hydrodynamic flow in high multiplicity pPb events will require further theoretical developments incorporating both physics phenomena.

7 Summary

The first search for jet quenching effects on dijet momentum balance in proton-lead collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{_{\mathrm{NN}}}} = 8.16$ TeV was presented. The dijet transverse momentum balance (x_j), defined as the ratio of the subleading over the leading jet in a dijet pair, was studied as a function of charged-particle multiplicity for several dijet kinematic selections. The data collected by the CMS experiment with minimum bias and special high-multiplicity triggers during the 2016 data-taking period corresponds to an integrated luminosity of 174.6 nb^{-1}. These special triggers aided the accumulation of a substantial sample of high multiplicity events (producing up to 400 charged-particles per event) and enabled jet-quenching signal search in high-multiplicity events.

An anti-k_{T} algorithm with a distance parameter of 0.4 was used to reconstruct jets using a combination of tracker and calorimeter information. The dijets were formed by the two highest transverse momentum (p_{T}) jets in the event with the minimum p_{T} requirements of 100 GeV and 50 GeV, respectively, that pass back-to-back selection (azimuthal separation greater than $5\pi/6$). The x_j distributions for such dijets were measured for events in several multiplicity ranges, and modifications of the measured distributions were quantified by taking ratios of the measurements from the higher multiplicity event selections to that of the lowest multiplicity class. These high-to-low multiplicity selection ratios were found to be close to unity and in agreement with simulations that do not include jet-quenching effects. These measurements set an upper limit on medium-induced energy loss of the subleading jet to be less than 1.26% of its transverse momentum at the one-sided 90% confidence level at an average p_{T} of 103.5 GeV for high-multiplicity pPb events, where strong collective signals have

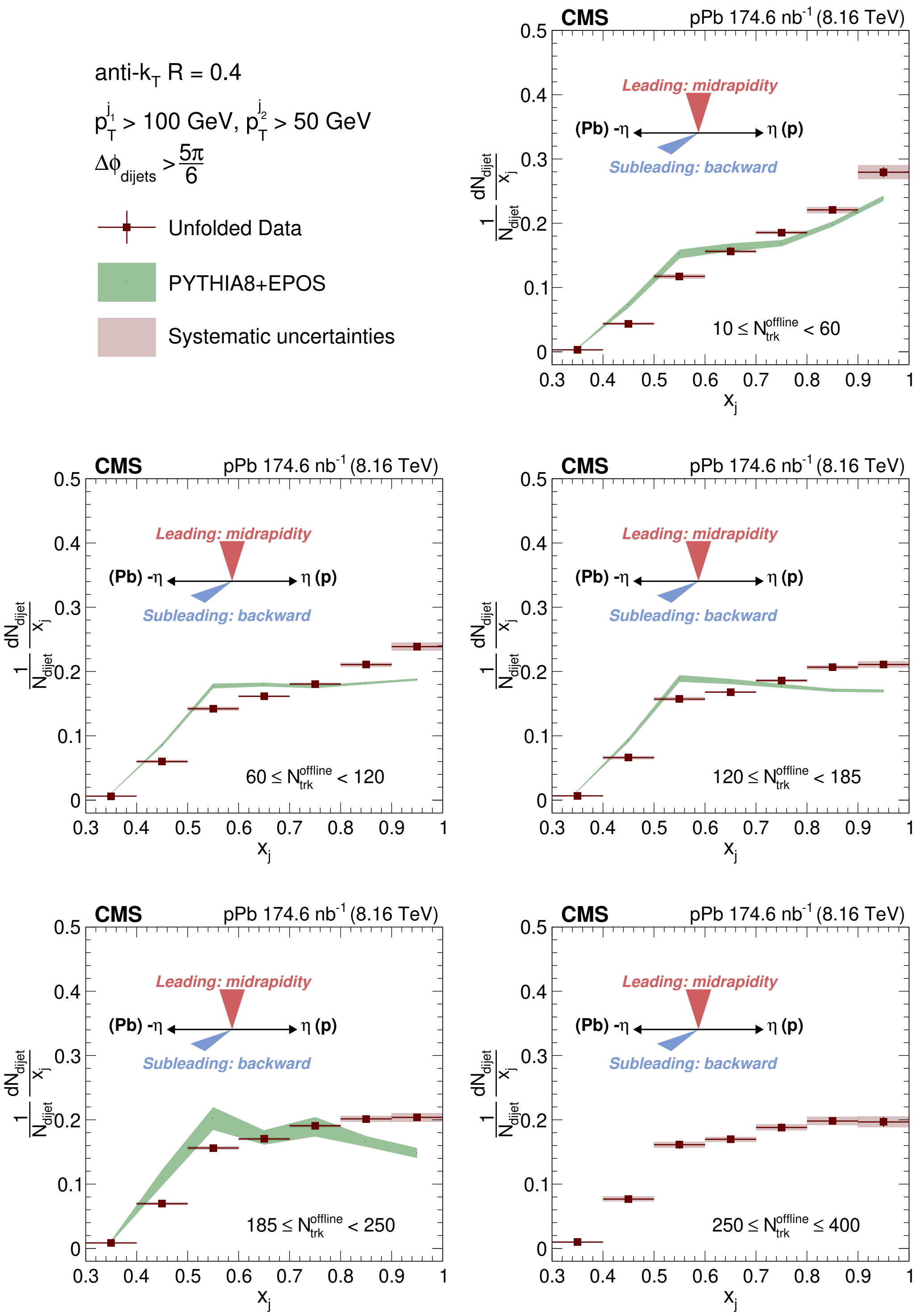

Figure 1. The unfolded x_j distributions, from lower to higher multiplicities, and for leading and subleading jets in the midrapidity and backward regions, respectively, are shown. Comparisons with the generator-level PYTHIA8+EPOS LHC simulation (green band) are also displayed. Monte Carlo event generation for multiplicities greater than 250 was deemed impractical.

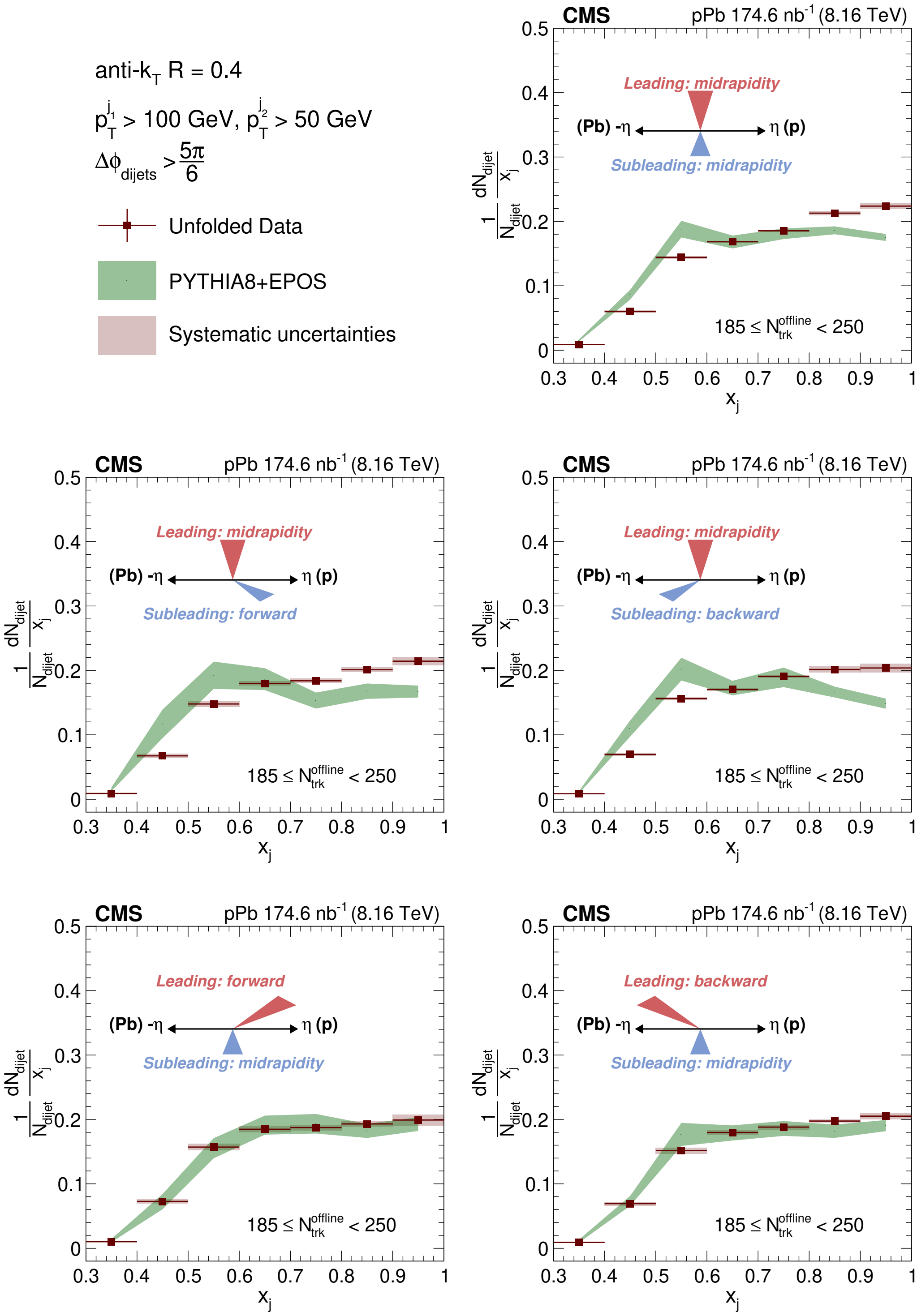

Figure 2. The unfolded x_j distributions, in the multiplicity range $185 \leq N_{\text{trk}}^{\text{offline}} < 250$ from different leading and subleading jet combinations for the midrapidity, forward, and backward regions, are shown. Comparisons with the generator-level PYTHIA8+EPOS LHC simulation (green band) are also displayed.

JHEP07(2025)118

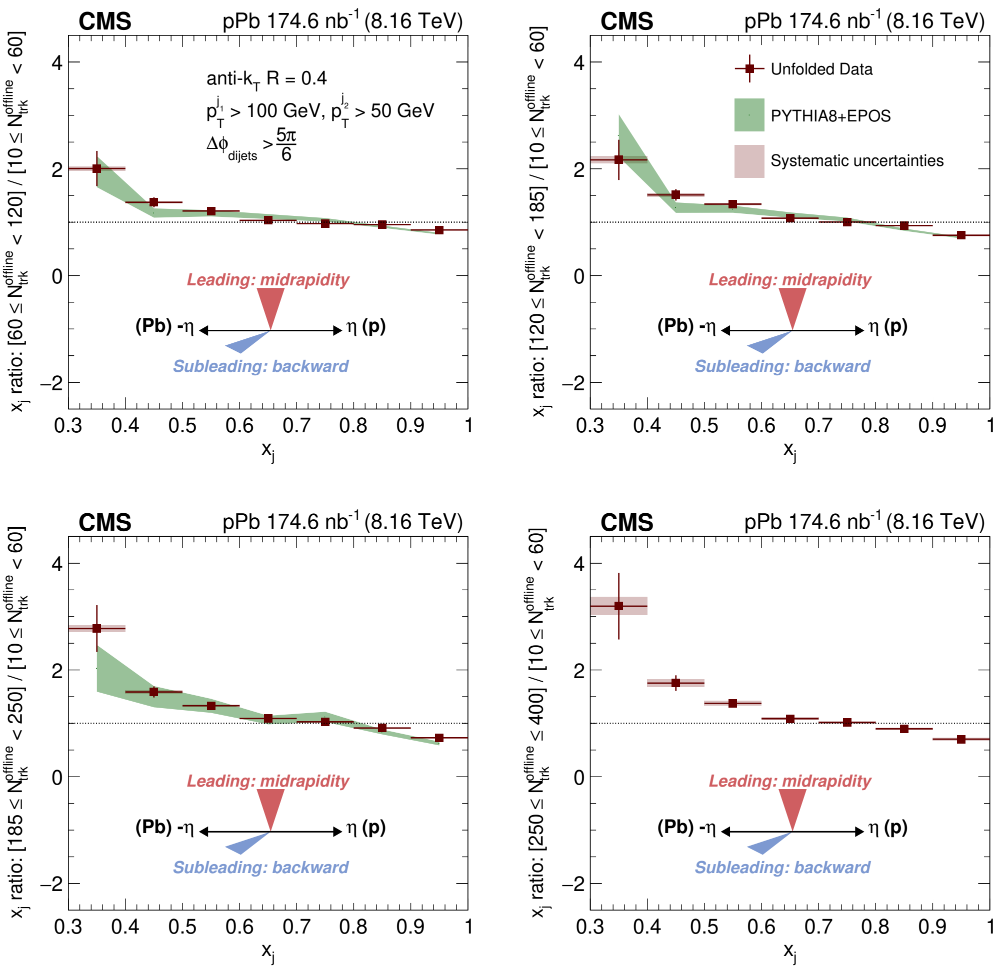

Figure 3. The unfolded x_j ratio in the range $10 \leq N_{\rm trk}^{\rm offline} < 60$, from lower to higher multiplicities for leading and subleading jets in the midrapidity and backward regions, respectively, are shown. Comparison with the generator-level PYTHIA8+EPOS LHC simulation (green band) are also displayed. Monte Carlo event generation for multiplicities greater than 250 was deemed impractical.

been reported. Interpreting this upper limit on jet quenching and the previously observed evidence for collective behavior in small systems will require further theoretical developments to reproduce all observations.

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

JHEP07(2025)118

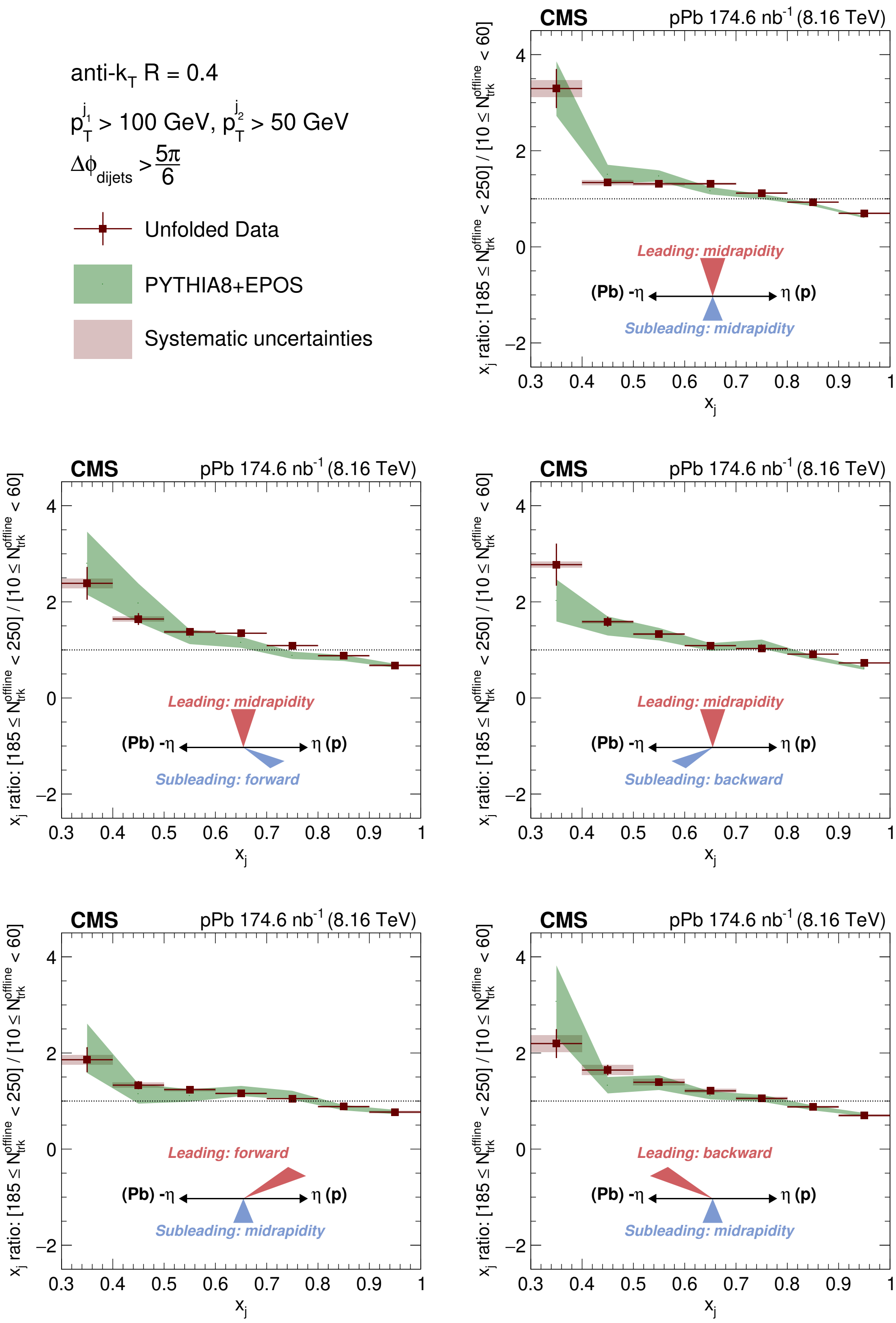

Figure 4. The ratio of unfolded x_j distributions between dijet events from multiplicity range $185 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 250$ to $10 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 60$ is shown for leading and subleading jet combinations at mid-, forward, and backward rapidity regions. Comparisons with the generator-level PYTHIA8+EPOS LHC simulation (green band) are also displayed.

JHEP07(2025)118

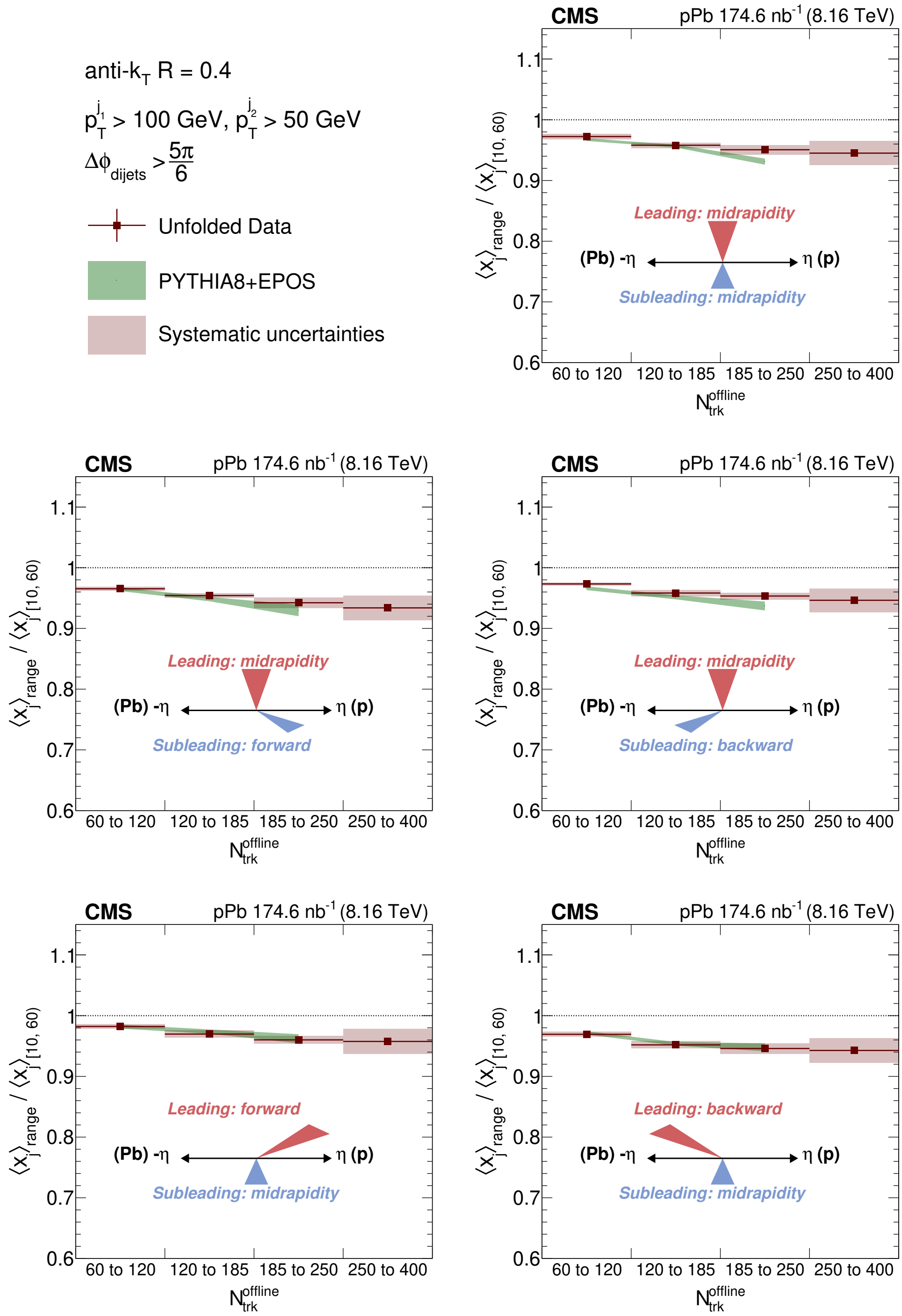

Figure 5. The ratio of the mean x_j values ratio $\langle x_j \rangle$ for dijet events from different multiplicity classes to that of events with the lowest multiplicity selection in the range $10 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 60$. The ratios of $\langle x_j \rangle$ values, extracted from unfolded x_j distributions, are presented for different leading and subleading jet selections from mid-, forward and backward rapidity regions. Comparison with the generator-level (green band) PYTHIA8+EPOS LHC are also displayed. The multiplicity range shown on the x-axis represents the multiplicity selection for the numerator of the ratio.

JHEP07(2025)118

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); ERC PRG, RVTT3 and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); 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); LMTLT (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); MICIU/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, 101115353, 101002207, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee, project no. 22rl-037 (Armenia); the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Beijing Municipal Science & Technology Commission, No. Z191100007219010 and Fundamental Research Funds for the Central Universities (China); 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), among others, 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 131991, K 133046, K 138136, K 143460, K 143477, K 146913, K 146914, K 147048, 2020-2.2.1-ED-2021-00181, TKP2021-NKTA-64, and 2021-4.1.2-NEMZ_KI-2024-00036 (Hungary); the Council of Science and Industrial Research, India; ICSC — National Research Center for High Performance Computing, Big Data and Quantum Computing and FAIR — Future Artificial Intelligence Research, funded by the NextGenerationEU program (Italy); 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; MICIU/AEI/10.13039/501100011033, ERDF/EU, "European Union NextGenerationEU/PRTR", 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 B39G670016 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (U.S.A.).

A The x_j distributions for various event multiplicities and jet rapidity selections

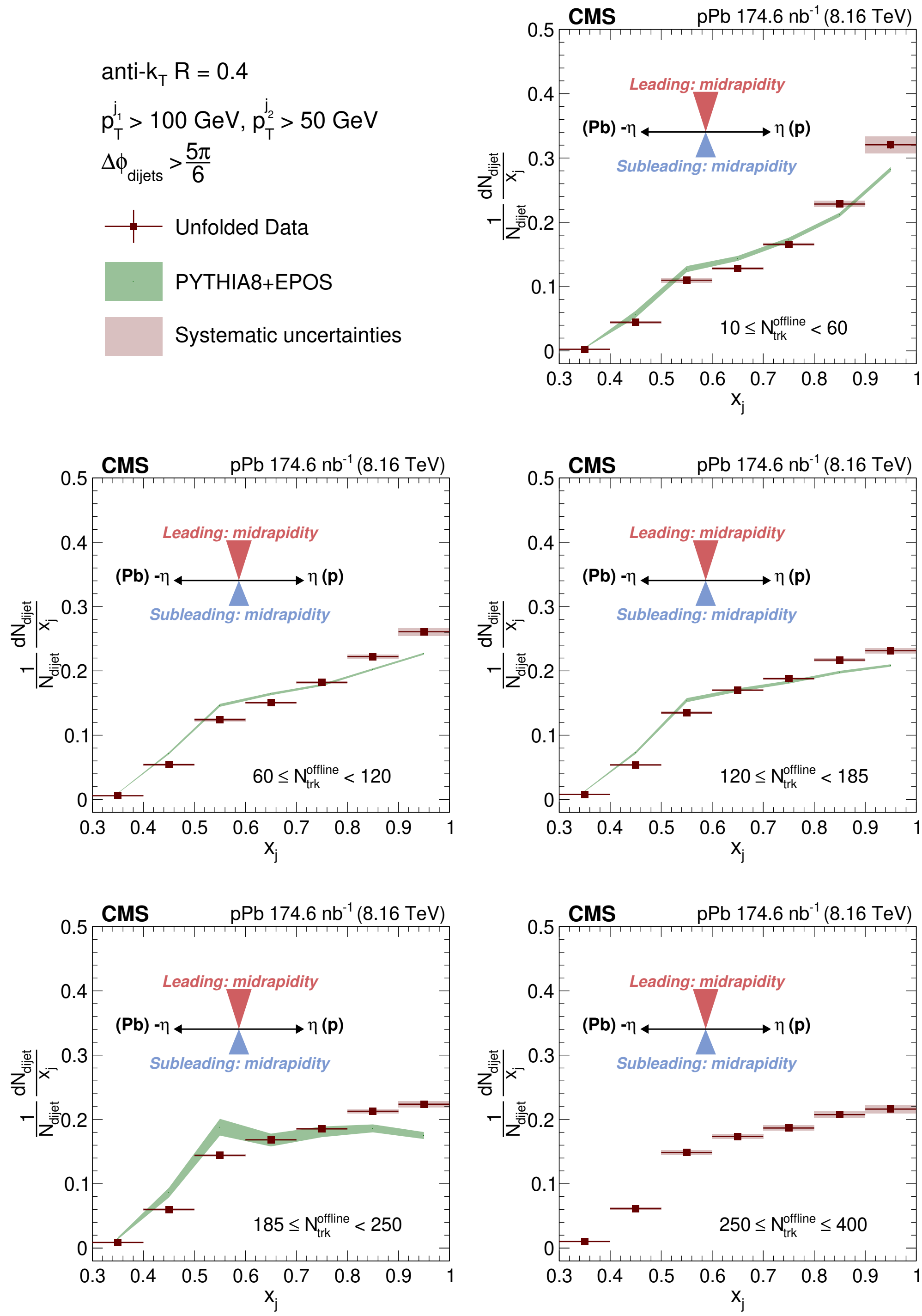

Figure 6. The unfolded x_j distributions, from lower to higher multiplicities and for both leading and subleading jets in the midrapidity region, are shown. Comparisons with the generator-level PYTHIA8+EPOS LHC simulation (green band) are also displayed.

JHEP07(2025)118

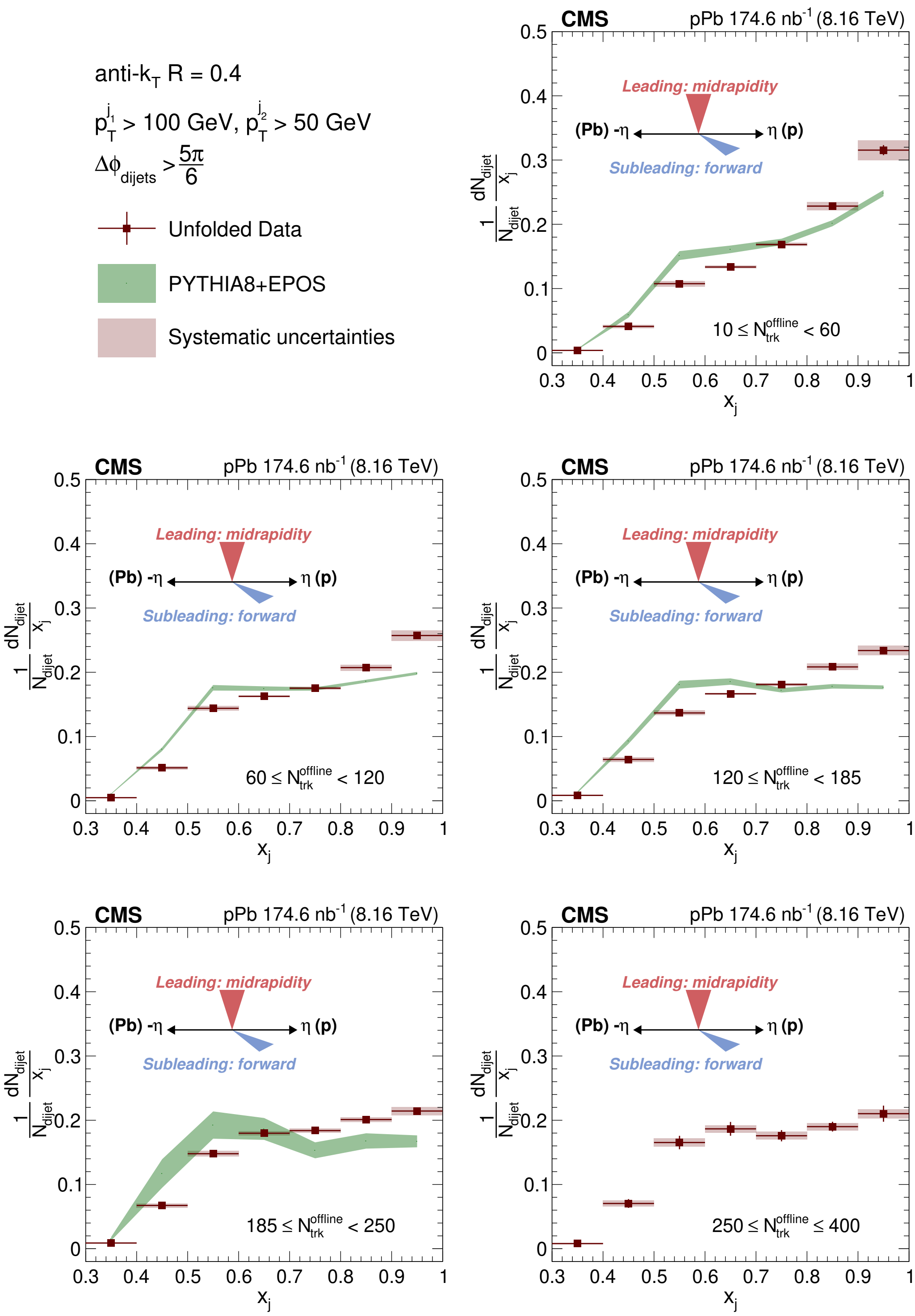

Figure 7. The unfolded x_j distributions, from lower to higher multiplicities, and for leading and subleading jets in the midrapidity and forward regions, respectively, are shown. Comparisons with the generator-level PYTHIA8+EPOS LHC simulation (green band) are also displayed.

JHEP07(2025)118

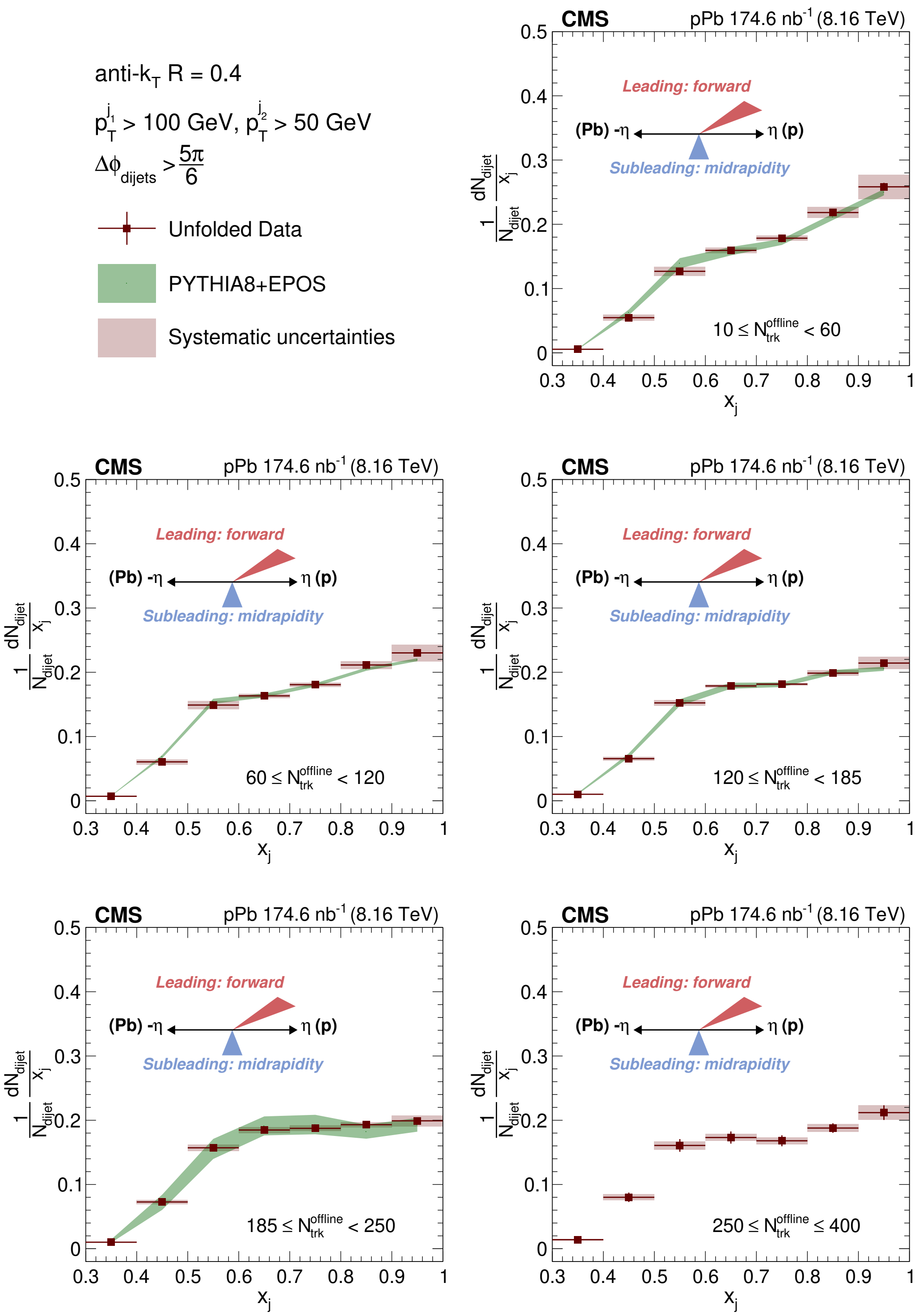

Figure 8. The unfolded x_j distributions, from lower to higher multiplicities, and for leading and subleading jets in the forward and midrapidity regions, respectively, are shown. Comparisons with the generator-level PYTHIA8+EPOS LHC simulation (green band) are also displayed.

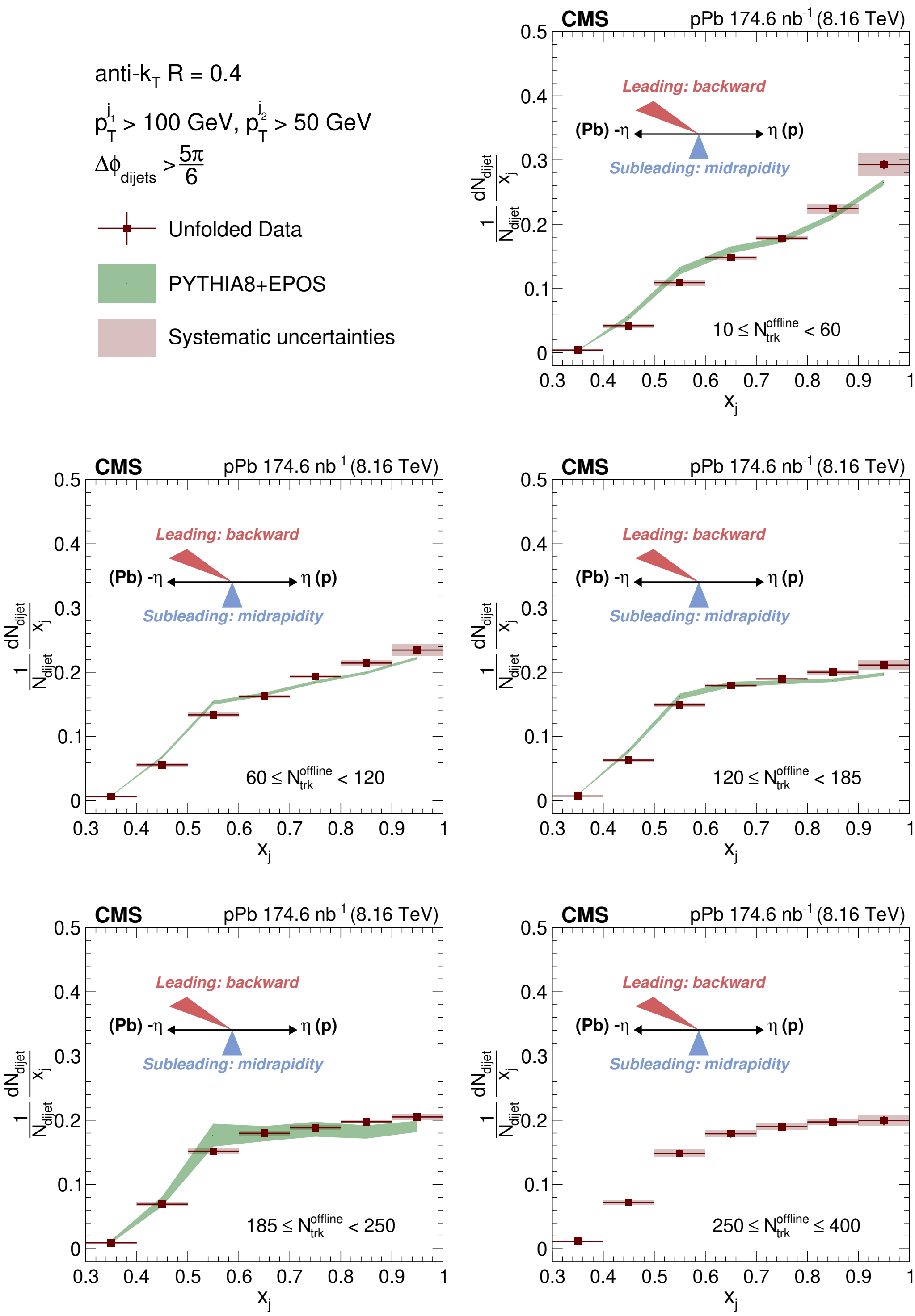

Figure 9. The unfolded x_j distributions, from lower to higher multiplicities, and for leading and subleading jets in the backward and midrapidity regions, respectively, are shown. Comparisons with the generator-level PYTHIA8+EPOS LHC simulation (green band) are also displayed.

JHEP07(2025)118

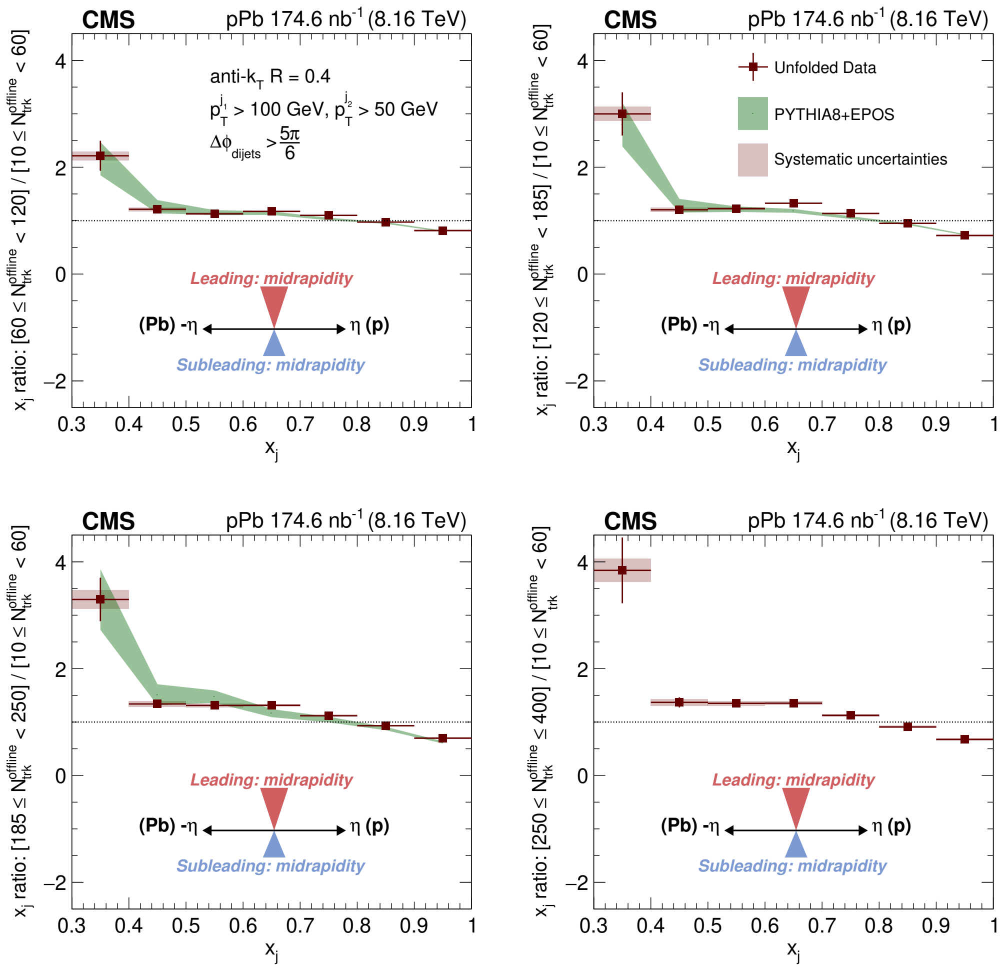

Figure 10. The unfolded x_j ratio in the range $10 \leq N_{\text{trk}}^{\text{offline}} < 60$, from lower to higher multiplicities for both leading and subleading jets in the midrapidity region, are shown. Comparison with the generator-level PYTHIA8+EPOS LHC simulation (green band) are also displayed.

JHEP07(2025)118

JHEP07(2025)118

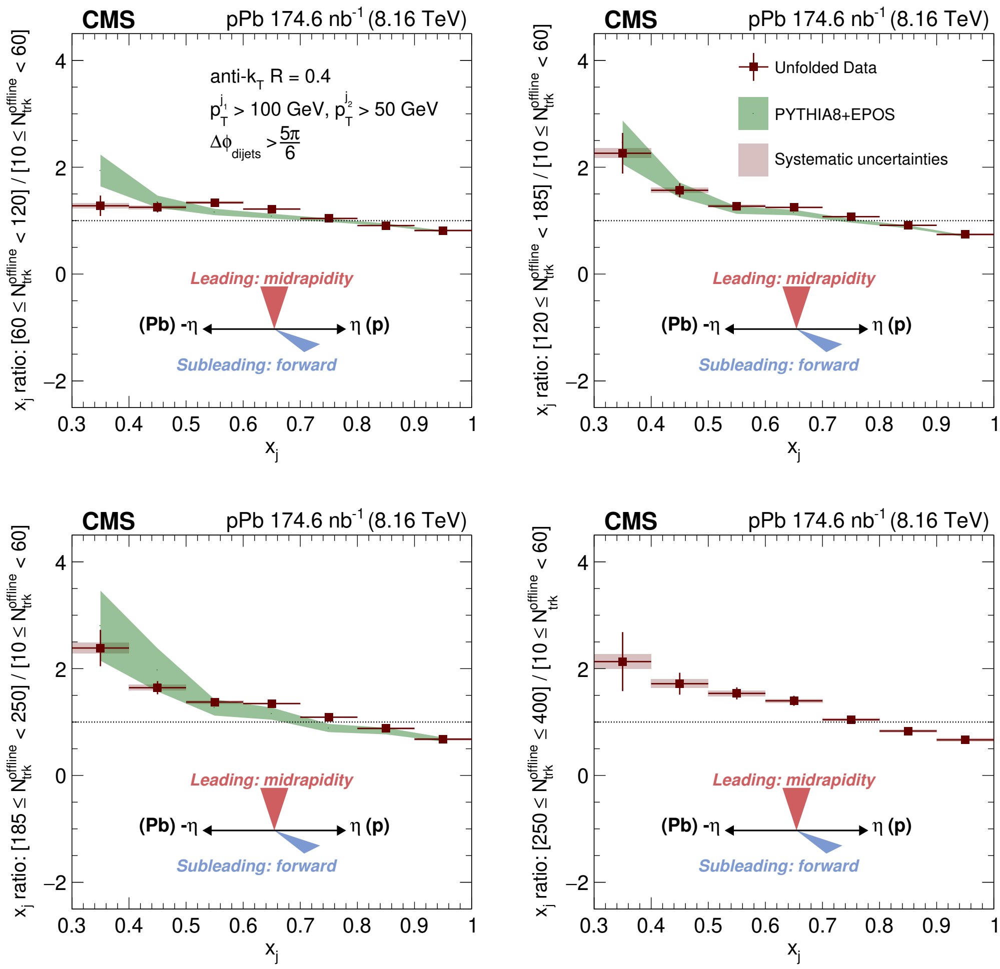

Figure 11. The unfolded x_j ratio in the range $10 \leq N_{\text{trk}}^{\text{offline}} < 60$, from lower to higher multiplicities for leading and subleading jets in the midrapidity and forward regions, respectively, are shown. Comparison with the generator-level PYTHIA8+EPOS LHC simulation (green band) are also displayed.

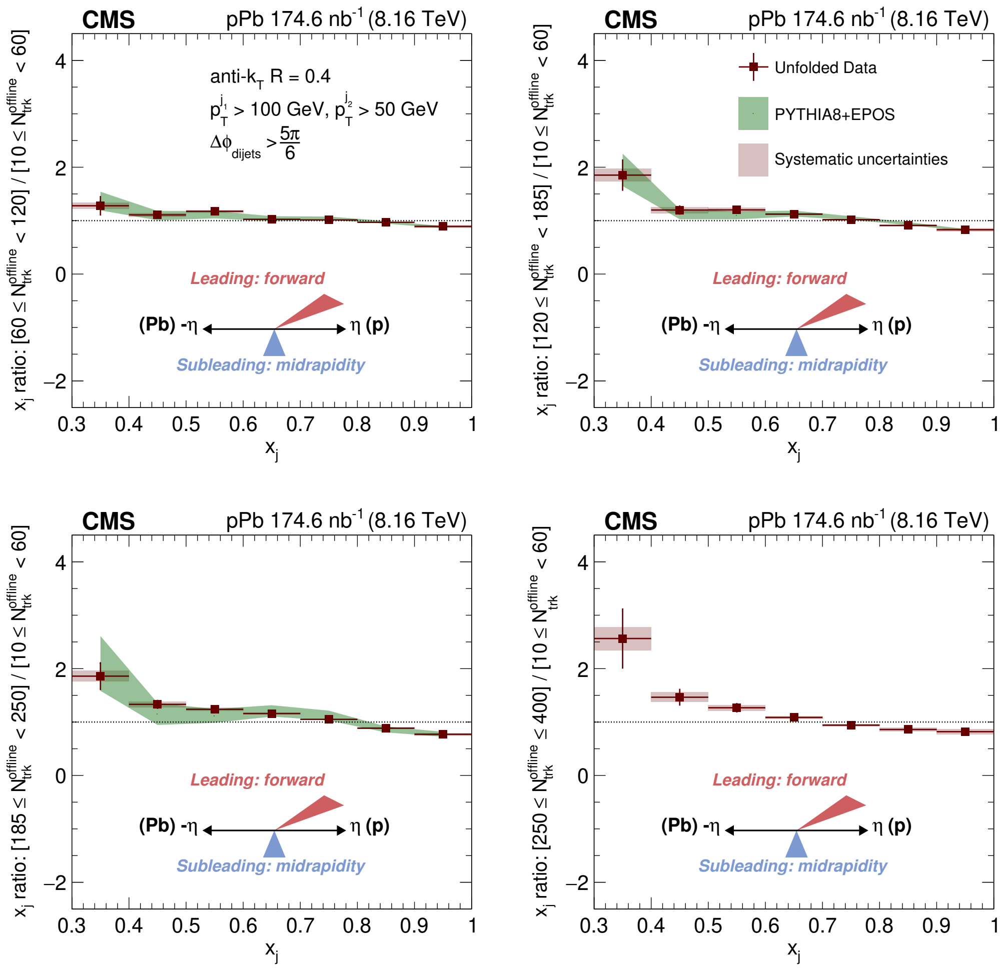

Figure 12. The unfolded x_j ratio in the range $10 \leq N_{\rm trk}^{\rm offline} < 60$, from lower to higher multiplicities for leading and subleading jets in the forward and midrapidity regions, respectively, are shown. Comparison with the generator-level PYTHIA8+EPOS LHC simulation (green band) are also displayed.

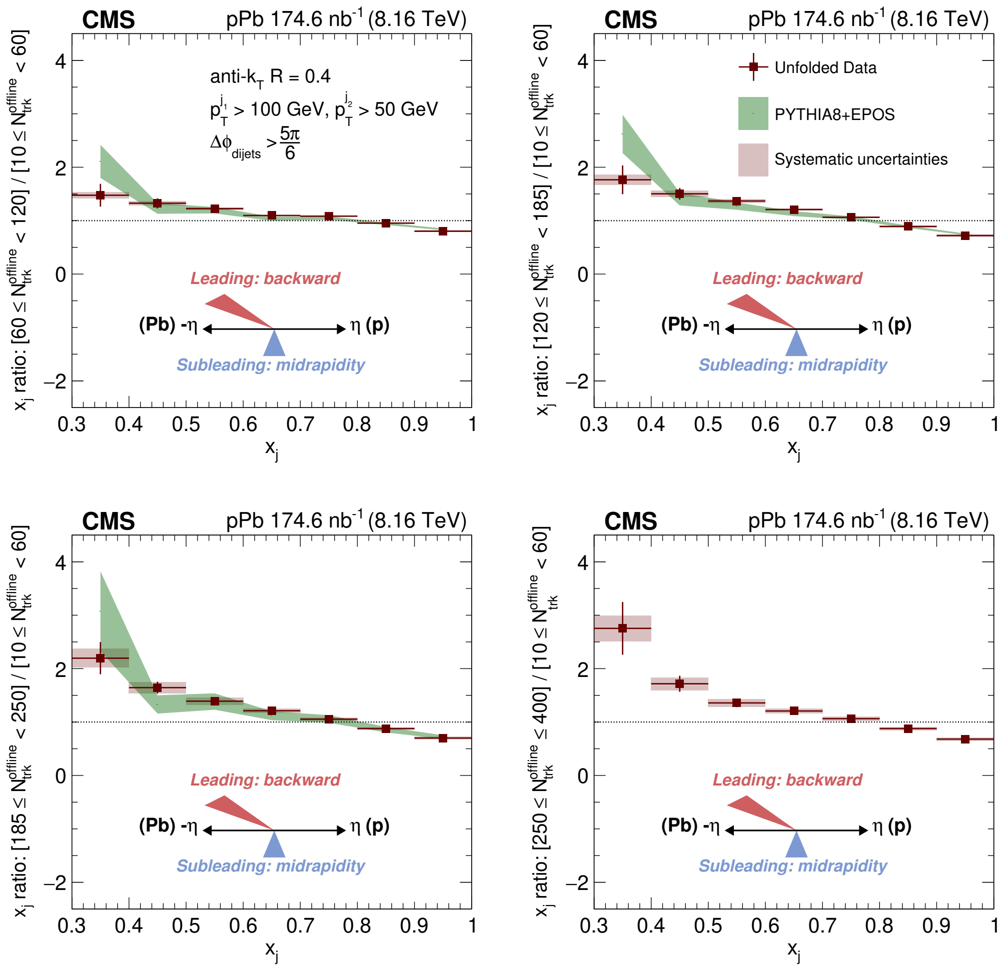

Figure 13. The unfolded x_j ratio in the range $10 \leq N_{\rm trk}^{\rm offline} < 60$, from lower to higher multiplicities for leading and subleading jets in the backward and midrapidity regions, respectively, are shown. Comparison with the generator-level PYTHIA8+EPOS LHC simulation (green band) are also displayed.

JHEP07(2025)118

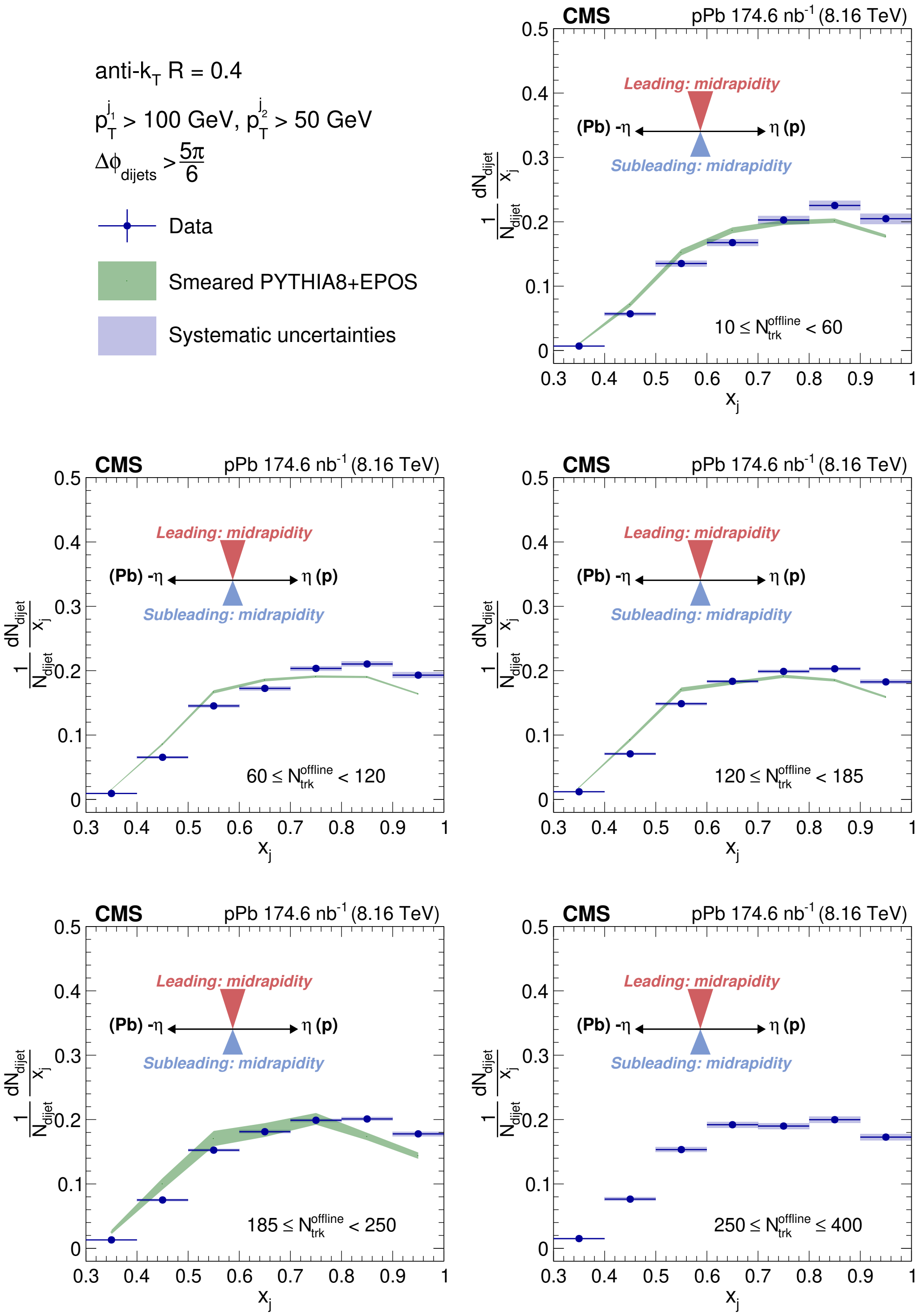

Figure 14. The measured (raw) x_j distributions, from lower to higher multiplicities and for both leading and subleading jets in the midrapidity region, are shown. Comparisons with the reconstruction-level PYTHIA8+EPOS LHC simulation (green band) are also displayed.

JHEP07(2025)118

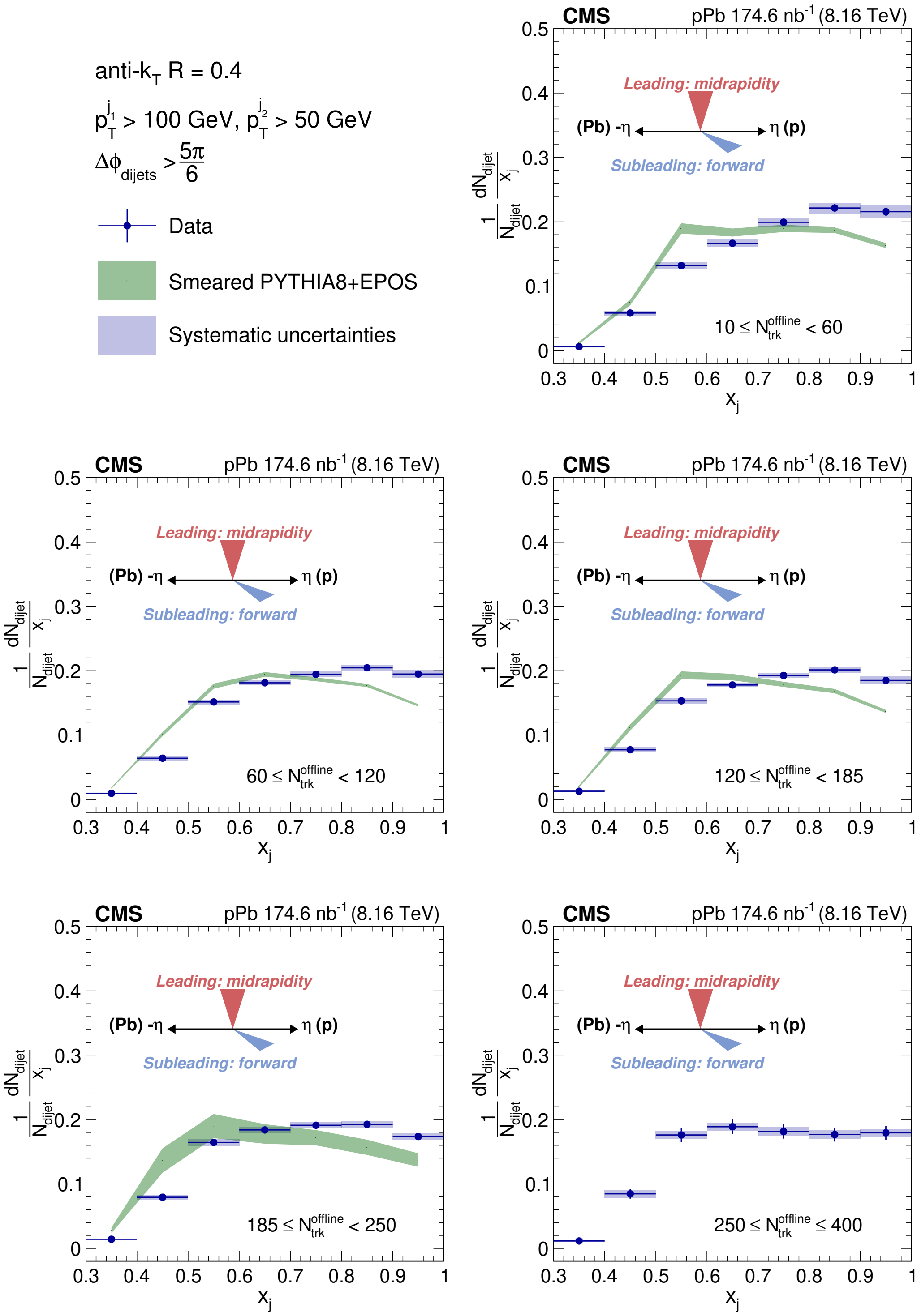

Figure 15. The measured (raw) x_j distributions, from lower to higher multiplicities and for leading and subleading jets in the midrapidity and forward regions, respectively, are shown. Comparisons with the reconstruction-level PYTHIA8+EPOS LHC simulation (green band) are also displayed.

JHEP07(2025)118

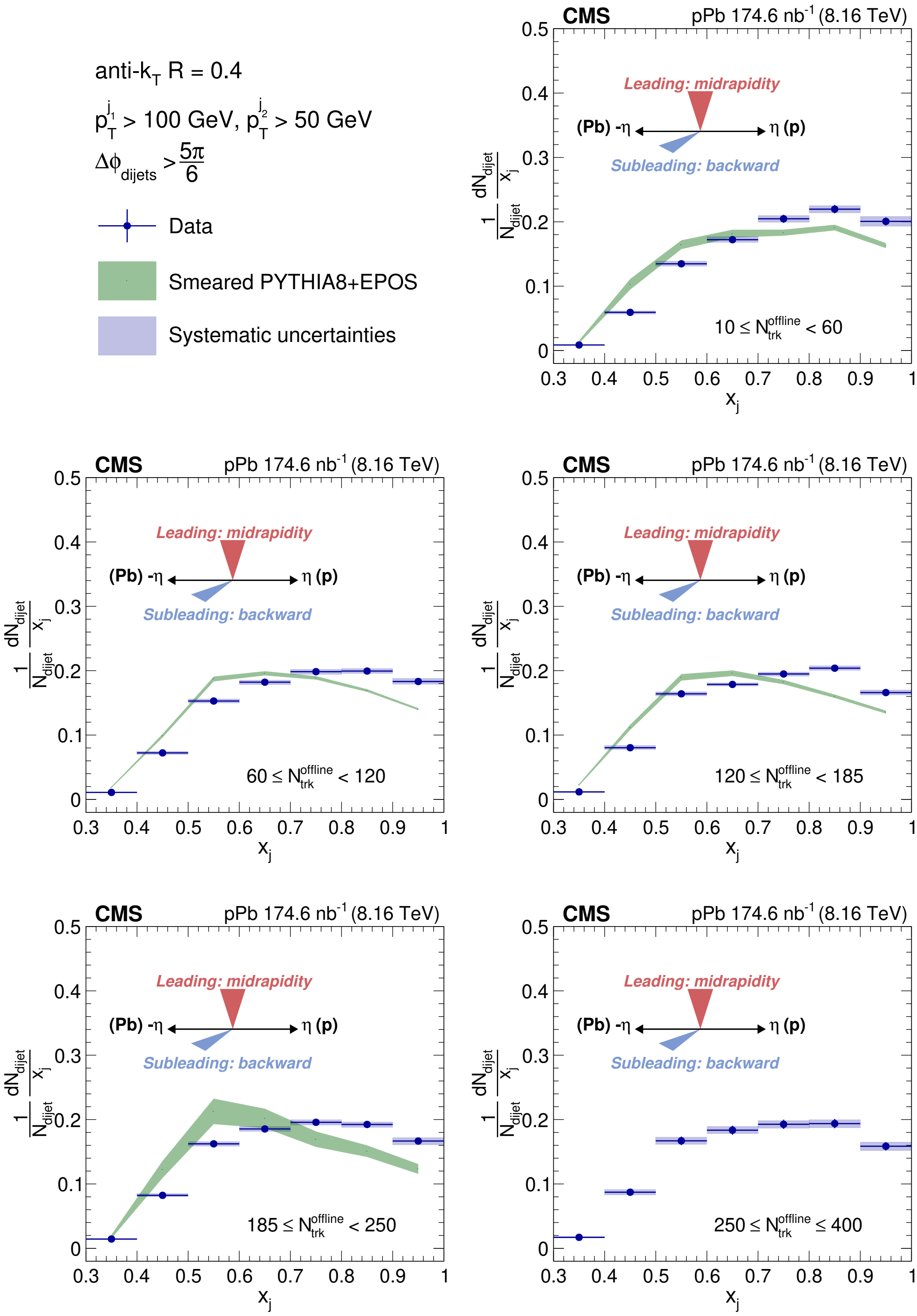

Figure 16. The measured (raw) x_j distributions, from lower to higher multiplicities and for leading and subleading jets in the midrapidity and backward regions, respectively, are shown. Comparisons with the reconstruction-level PYTHIA8+EPOS LHC simulation (green band) are also displayed.

JHEP07(2025)118

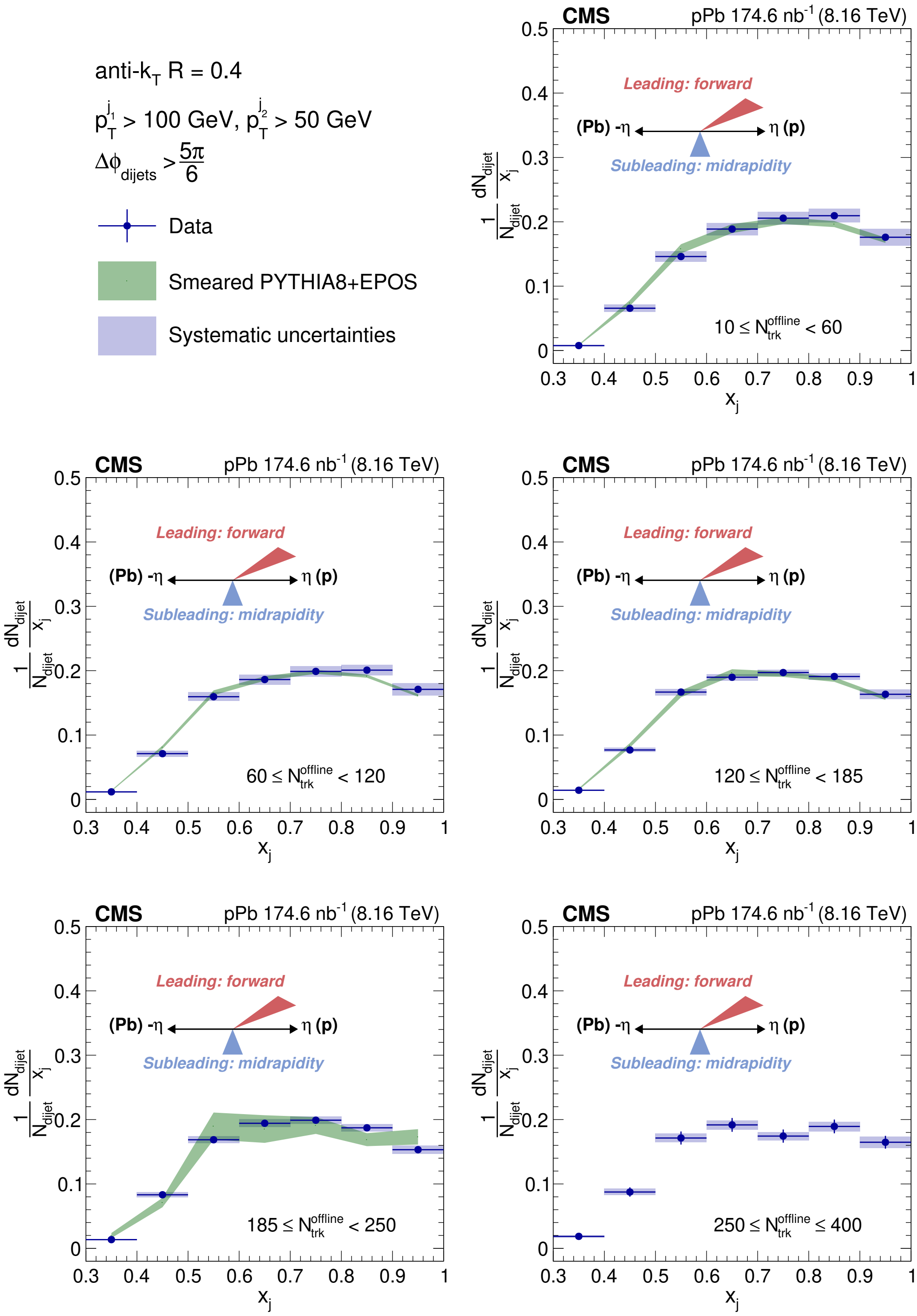

Figure 17. The measured (raw) x_j distributions, from lower to higher multiplicities and for leading and subleading jets in the forward and midrapidity regions, respectively, are shown. Comparisons with the reconstruction-level PYTHIA8+EPOS LHC simulation (green band) are also displayed.

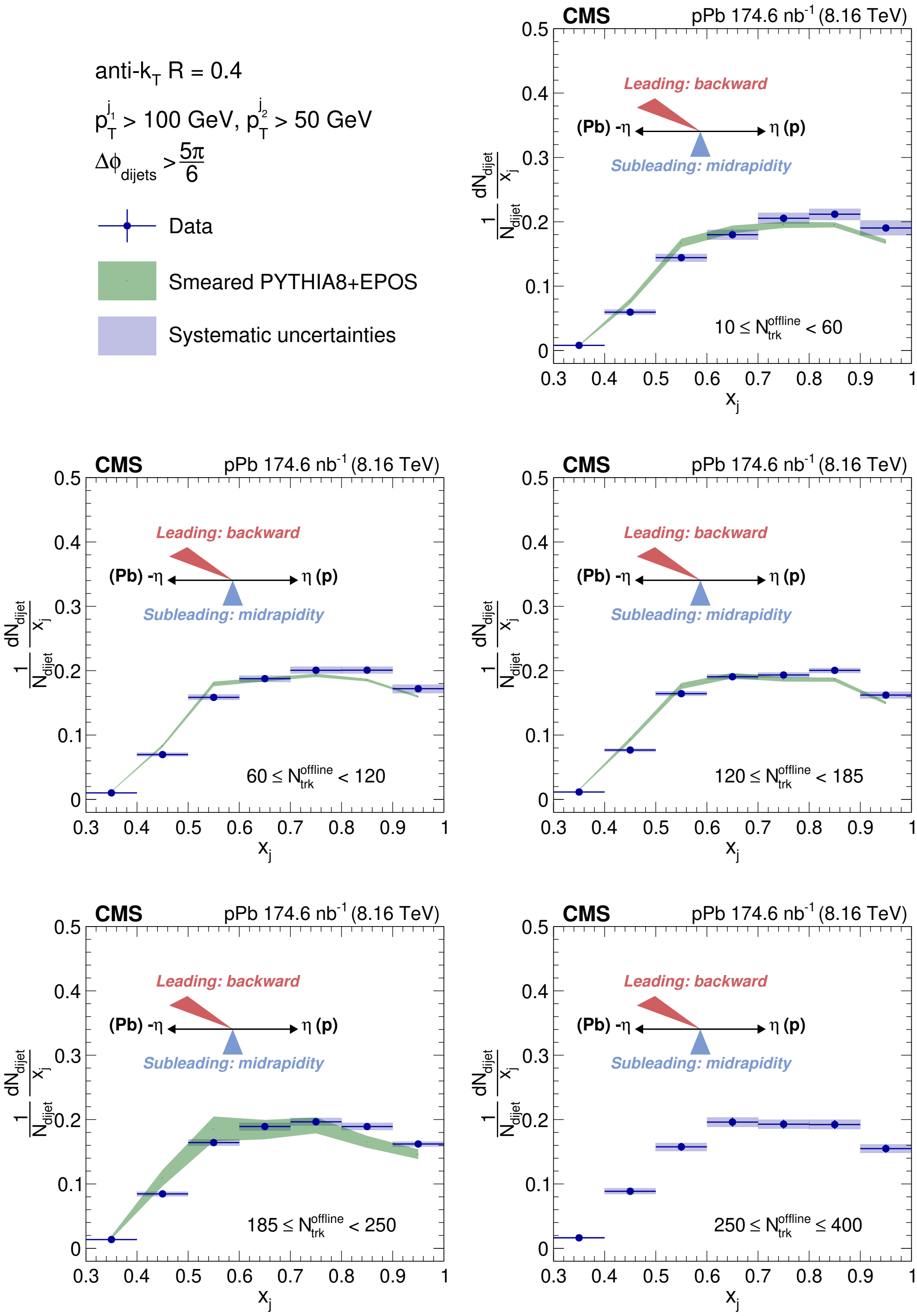

Figure 18. The measured (raw) x_j distributions, from lower to higher multiplicities and for leading and subleading jets in the backward and midrapidity regions, respectively, are shown. Comparisons with the reconstruction-level PYTHIA8+EPOS LHC simulation (green band) are also displayed.

JHEP07(2025)118

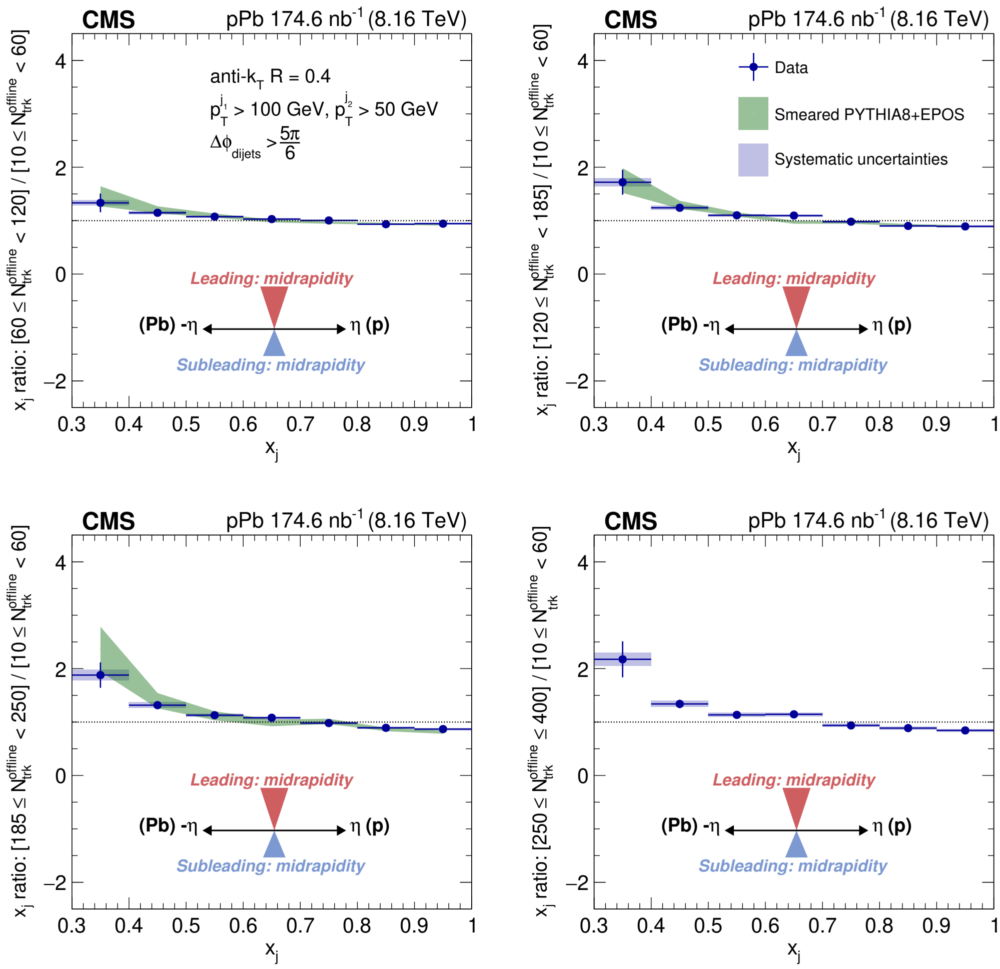

Figure 19. The measured (raw) x_j ratio in the range $10 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 60$, from lower to higher multiplicities for both leading and subleading jets in the midrapidity region, are shown. Comparison with the reconstruction-level PYTHIA8+EPOS LHC simulation (green band) are also displayed.

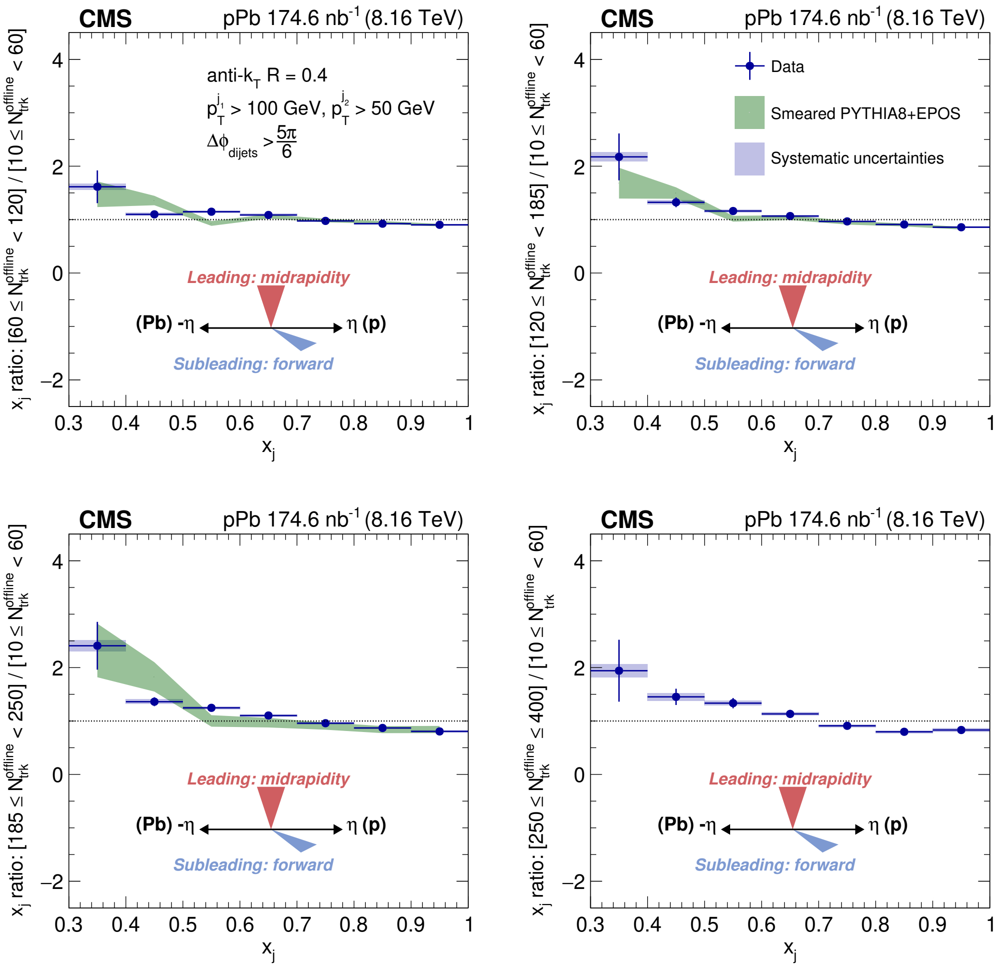

Figure 20. The measured (raw) x_j ratio in the range $10 \leq N_{\text{trk}}^{\text{offline}} < 60$, from lower to higher multiplicities for leading and subleading jets in the midrapidity and forward regions, respectively, are shown. Comparison with the reconstruction-level PYTHIA8+EPOS LHC simulation (green band) are also displayed.

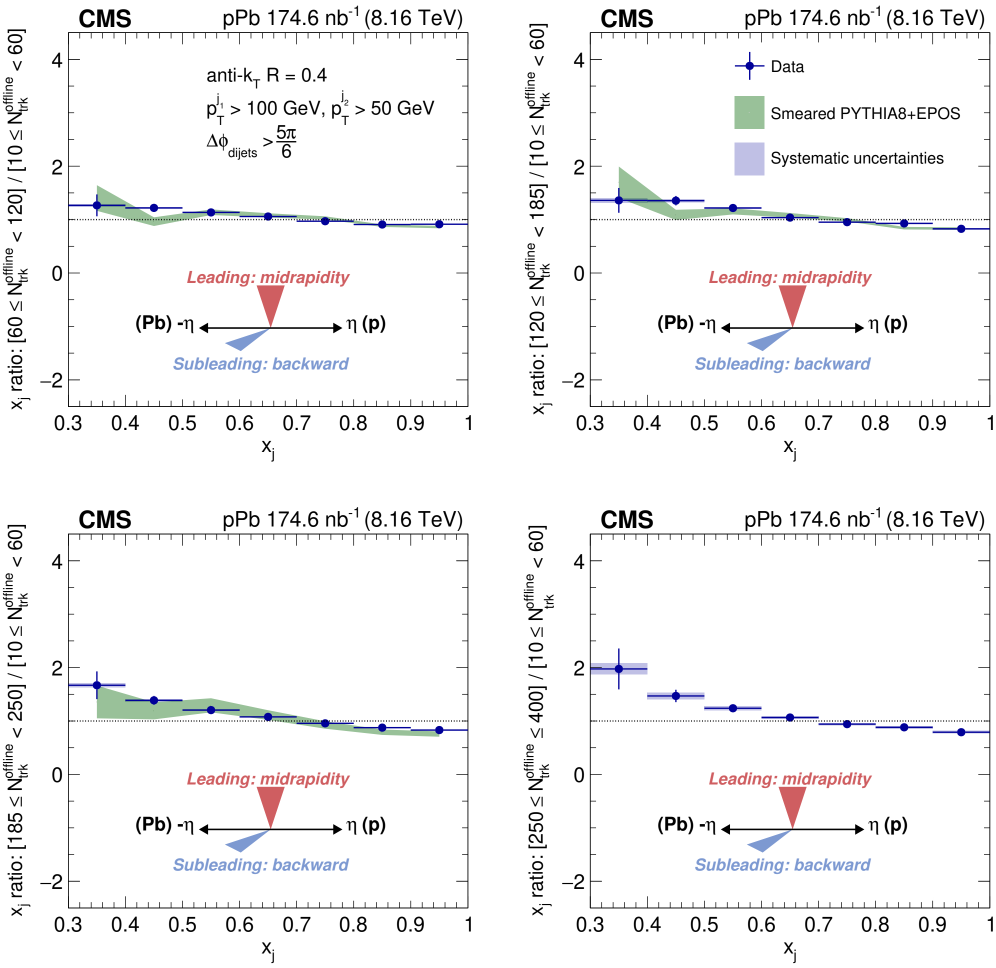

Figure 21. The measured (raw) x_j ratio in the range $10 \leq N_{\text{trk}}^{\text{offline}} < 60$, from lower to higher multiplicities for leading and subleading jets in the midrapidity and backward regions, respectively, are shown. Comparison with the reconstruction-level PYTHIA8+EPOS LHC simulation (green band) are also displayed.

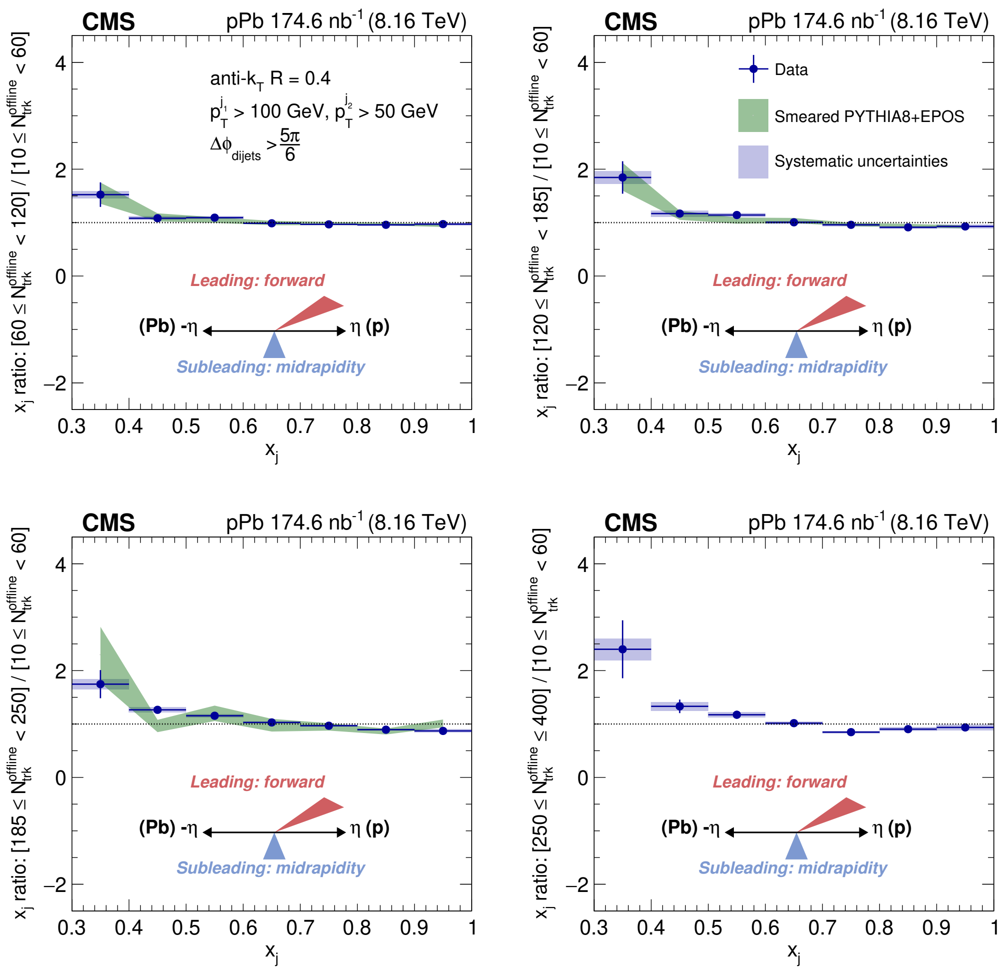

Figure 22. The measured (raw) x_j ratio in the range $10 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 60$, from lower to higher multiplicities for leading and subleading jets in the forward and midrapidity regions, respectively, are shown. Comparison with the reconstruction-level PYTHIA8+EPOS LHC simulation (green band) are also displayed.

JHEP07(2025)118

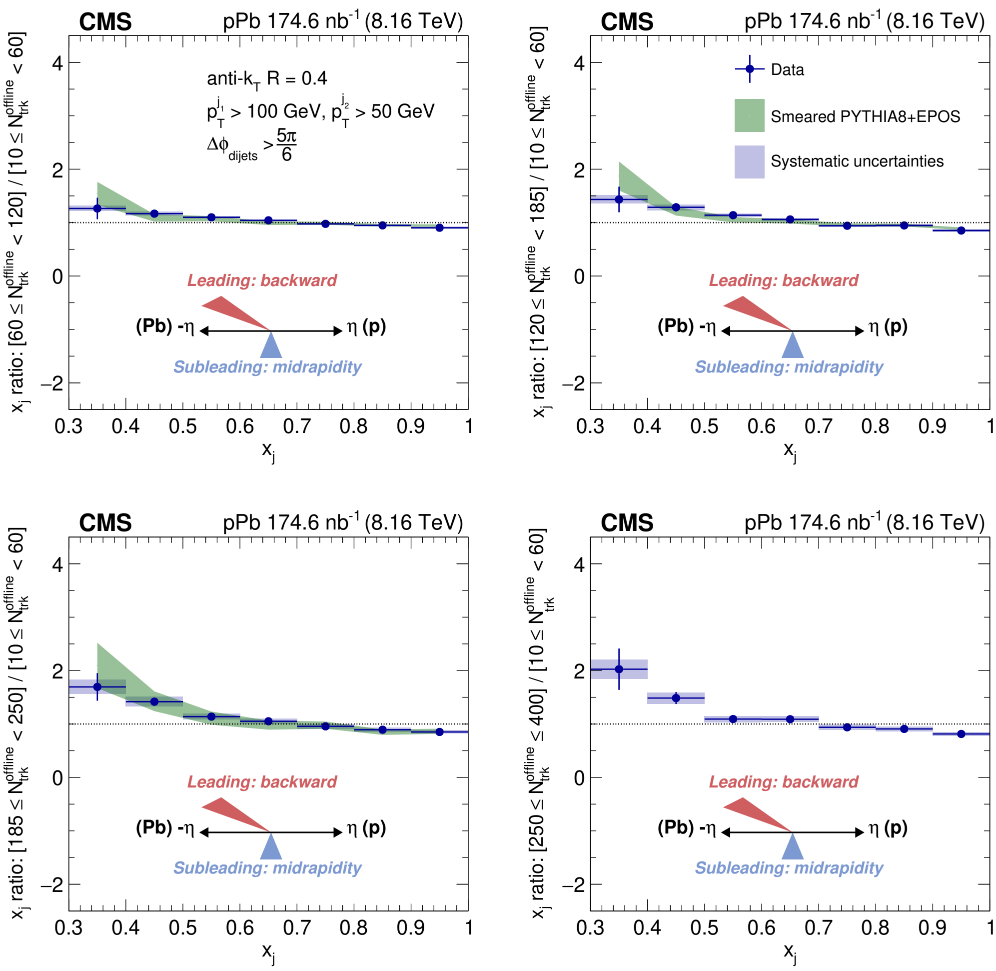

Figure 23. The measured (raw) x_j ratio in the range $10 \leq N_{\text{trk}}^{\text{offline}} < 60$, from lower to higher multiplicities for leading and subleading jets in the backward and midrapidity regions, respectively, are shown. Comparison with the reconstruction-level PYTHIA8+EPOS LHC simulation (green band) are also displayed.

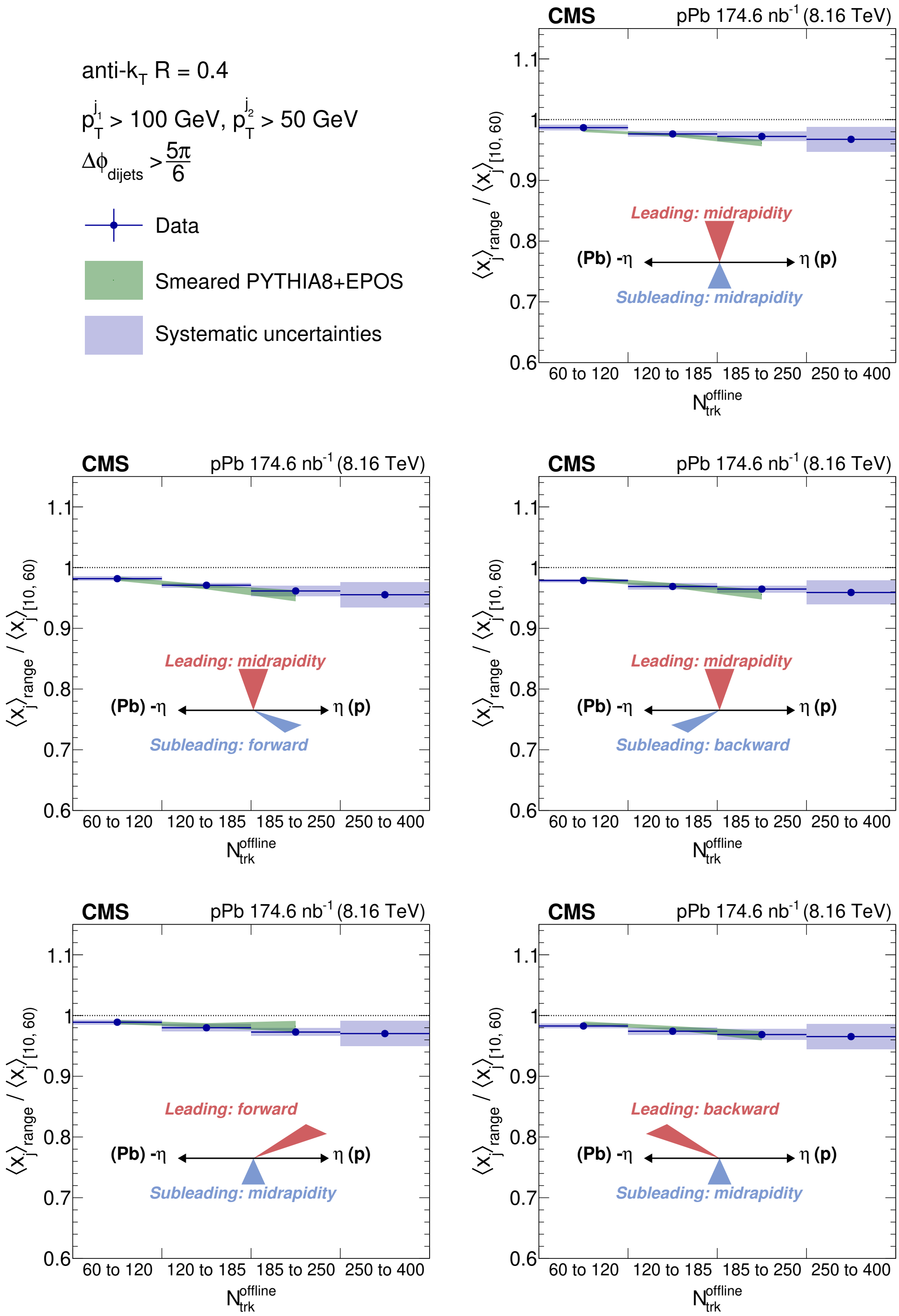

Figure 24. Mean x_j ratio, $\langle x_j \rangle$, in the range $10 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 60$ as measured (raw) for different multiplicities, for different leading and subleading jet combinations for the midrapidity, forward, and backward regions, are shown. Comparison with the reconstruction-level (green band) PYTHIA8+EPOS LHC are also displayed. The $\langle x_j \rangle_{\mathrm{range}}$ corresponds to the higher multiplicity ranges shown in the x-axis.

JHEP07(2025)118

Data Availability Statement. Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy.

Code Availability Statement. This article has associated code in a code repository. The CMS core software is publicly available on GitHub

References

[1] J.D. Bjorken, *Energy Loss of Energetic Partons in Quark-Gluon Plasma: Possible Extinction of High p(t) Jets in Hadron-Hadron Collisions*, FERMILAB-PUB-82-059-THY (1982) [INSPIRE].

[2] CMS collaboration, *Observation and studies of jet quenching in PbPb collisions at* $\sqrt{s_{\rm NN}} = 2.76$ *TeV*, Phys. Rev. C **84** (2011) 024906 [arXiv:1102.1957] [INSPIRE].

[3] ATLAS collaboration, *Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at* $\sqrt{s_{\rm NN}} = 2.77$ *TeV with the ATLAS Detector at the LHC*, Phys. Rev. Lett. **105** (2010) 252303 [arXiv:1011.6182] [INSPIRE].

[4] STAR collaboration, *Measurements of jet quenching with semi-inclusive hadron+jet distributions in Au+Au collisions at* $\sqrt{s_{\rm NN}} = 200$ *GeV*, Phys. Rev. C **96** (2017) 024905 [arXiv:1702.01108] [INSPIRE].

[5] STAR collaboration, *Beam Energy Dependence of Jet-Quenching Effects in Au+Au Collisions at* $\sqrt{s_{\rm NN}} = 7.7$*, 11.5, 14.5, 19.6, 27, 39, and 62.4 GeV*, Phys. Rev. Lett. **121** (2018) 032301 [arXiv:1707.01988] [INSPIRE].

[6] CMS collaboration, *Comparing transverse momentum balance of b jet pairs in pp and PbPb collisions at* $\sqrt{s_{\rm NN}} = 5.02$ *TeV*, JHEP **03** (2018) 181 [arXiv:1802.00707] [INSPIRE].

[7] CMS collaboration, *Overview of high-density QCD studies with the CMS experiment at the LHC*, Phys. Rept. **1115** (2025) 219 [arXiv:2405.10785] [INSPIRE].

[8] CMS collaboration, *Measurement of long-range near-side two-particle angular correlations in pp collisions at* $\sqrt{s} = 13$ *TeV*, Phys. Rev. Lett. **116** (2016) 172302 [arXiv:1510.03068] [INSPIRE].

[9] CMS collaboration, *Evidence for collectivity in pp collisions at the LHC*, Phys. Lett. B **765** (2017) 193 [arXiv:1606.06198] [INSPIRE].

[10] CMS collaboration, *Observation of Long-Range Near-Side Angular Correlations in Proton-Lead Collisions at the LHC*, Phys. Lett. B **718** (2013) 795 [arXiv:1210.5482] [INSPIRE].

[11] PHENIX collaboration, *Creation of quark-gluon plasma droplets with three distinct geometries*, Nature Phys. **15** (2019) 214 [arXiv:1805.02973] [INSPIRE].

[12] ALICE collaboration, *Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions*, Nature Phys. **13** (2017) 535 [arXiv:1606.07424] [INSPIRE].

[13] CMS collaboration, *Studies of Dijet Transverse Momentum Balance and Pseudorapidity Distributions in pPb Collisions at* $\sqrt{s_{\rm NN}} = 5.02$ *TeV*, Eur. Phys. J. C **74** (2014) 2951 [arXiv:1401.4433] [INSPIRE].

JHEP07(2025)118

[14] PHENIX collaboration, *Centrality-dependent modification of jet-production rates in deuteron-gold collisions at $\sqrt{s_{NN}}$=200 GeV*, *Phys. Rev. Lett.* **116** (2016) 122301 [arXiv:1509.04657] [INSPIRE].

[15] CMS collaboration, *Measurement of inclusive jet production and nuclear modifications in pPb collisions at $\sqrt{s_{_{\rm NN}}}$ = 5.02 TeV*, *Eur. Phys. J. C* **76** (2016) 372 [arXiv:1601.02001] [INSPIRE].

[16] ALICE collaboration, *Constraints on jet quenching in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV measured by the event-activity dependence of semi-inclusive hadron-jet distributions*, *Phys. Lett. B* **783** (2018) 95 [arXiv:1712.05603] [INSPIRE].

[17] ATLAS collaboration, *Strong Constraints on Jet Quenching in Centrality-Dependent p+Pb Collisions at 5.02 TeV from ATLAS*, *Phys. Rev. Lett.* **131** (2023) 072301 [arXiv:2206.01138] [INSPIRE].

[18] STAR collaboration, *Correlations of event activity with hard and soft processes in p+Au collisions at $\sqrt{s_{_{\rm NN}}}$ = 200 GeV at the RHIC STAR experiment*, *Phys. Rev. C* **110** (2024) 044908 [arXiv:2404.08784] [INSPIRE].

[19] CMS collaboration, *Precision luminosity measurement in proton-proton collisions at $\sqrt{s}$ = 13 TeV in 2015 and 2016 at CMS*, *Eur. Phys. J. C* **81** (2021) 800 [arXiv:2104.01927] [INSPIRE].

[20] CMS collaboration, *CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV*, CMS-PAS-LUM-17-004, CERN, Geneva (2018).

[21] CMS collaboration, *CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV*, CMS-PAS-LUM-18-002, CERN, Geneva (2019).

[22] HEPData record for this analysis, (2025), [DOI:10.17182/hepdata.156764].

[23] CMS collaboration, *The CMS Experiment at the CERN LHC*, 2008 *JINST* **3** S08004 [INSPIRE].

[24] CMS collaboration, *Particle-flow reconstruction and global event description with the CMS detector*, 2017 *JINST* **12** P10003 [arXiv:1706.04965] [INSPIRE].

[25] CMS collaboration, *Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s}$ = 13 TeV*, 2020 *JINST* **15** P10017 [arXiv:2006.10165] [INSPIRE].

[26] CMS collaboration, *The CMS trigger system*, 2017 *JINST* **12** P01020 [arXiv:1609.02366] [INSPIRE].

[27] CMS collaboration, *Constraints on the chiral magnetic effect using charge-dependent azimuthal correlations in pPb and PbPb collisions at the CERN Large Hadron Collider*, *Phys. Rev. C* **97** (2018) 044912 [arXiv:1708.01602] [INSPIRE].

[28] CMS collaboration, *Observation of Correlated Azimuthal Anisotropy Fourier Harmonics in pp and $p+Pb$ Collisions at the LHC*, *Phys. Rev. Lett.* **120** (2018) 092301 [arXiv:1709.09189] [INSPIRE].

[29] CMS collaboration, *Description and Performance of Track and Primary-Vertex Reconstruction with the CMS Tracker*, 2014 *JINST* **9** P10009 [arXiv:1405.6569] [INSPIRE].

[30] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, *Comput. Phys. Commun.* **191** (2015) 159 [arXiv:1410.3012] [INSPIRE].

[31] T. Pierog et al., *EPOS LHC: Test of collective hadronization with data measured at the CERN Large Hadron Collider*, *Phys. Rev. C* **92** (2015) 034906 [arXiv:1306.0121] [INSPIRE].

[32] CMS collaboration, *Event generator tunes obtained from underlying event and multiparton scattering measurements*, *Eur. Phys. J. C* **76** (2016) 155 [arXiv:1512.00815] [INSPIRE].

JHEP07(2025)118

[33] GEANT4 collaboration, *GEANT4 — A Simulation Toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [INSPIRE].

[34] M. Cacciari, G.P. Salam and G. Soyez, *The anti-k_t jet clustering algorithm*, *JHEP* **04** (2008) 063 [arXiv:0802.1189] [INSPIRE].

[35] M. Cacciari, G.P. Salam and G. Soyez, *FastJet User Manual*, *Eur. Phys. J. C* **72** (2012) 1896 [arXiv:1111.6097] [INSPIRE].

[36] P. Berta, M. Spousta, D.W. Miller and R. Leitner, *Particle-level pileup subtraction for jets and jet shapes*, *JHEP* **06** (2014) 092 [arXiv:1403.3108] [INSPIRE].

[37] CMS collaboration, *Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV*, 2017 *JINST* **12** P02014 [arXiv:1607.03663] [INSPIRE].

[38] CMS collaboration, *Jet Momentum Dependence of Jet Quenching in PbPb Collisions at* $\sqrt{s_{\mathrm{NN}}} = 2.76$ *TeV*, *Phys. Lett. B* **712** (2012) 176 [arXiv:1202.5022] [INSPIRE].

[39] ATLAS collaboration, *Measurements of the suppression and correlations of dijets in Pb+Pb collisions at* $\sqrt{s_{_\mathrm{NN}}} = 5.02$ *TeV*, *Phys. Rev. C* **107** (2023) 054908 [*Erratum ibid.* **109** (2024) 029901] [arXiv:2205.00682] [INSPIRE].

[40] CMS collaboration, *Pileup mitigation at CMS in 13 TeV data*, 2020 *JINST* **15** P09018 [arXiv:2003.00503] [INSPIRE].

[41] T. Adye, *Unfolding algorithms and tests using RooUnfold*, in the proceedings of the *PHYSTAT 2011*, Geneva, Switzerland, January 17–20 (2011) [DOI:10.5170/CERN-2011-006.313] [arXiv:1105.1160] [INSPIRE].

[42] L. Brenner et al., *Comparison of unfolding methods using RooFitUnfold*, *Int. J. Mod. Phys. A* **35** (2020) 2050145 [arXiv:1910.14654] [INSPIRE].

[43] G. D'Agostini, *A multidimensional unfolding method based on Bayes' theorem*, *Nucl. Instrum. Meth. A* **362** (1995) 487 [INSPIRE].

[44] W.H. Richardson, *Bayesian-Based Iterative Method of Image Restoration*, *J. Opt. Soc. Am.* **62** (1972) 55 [INSPIRE].

[45] L.B. Lucy, *An iterative technique for the rectification of observed distributions*, *Astron. J.* **79** (1974) 745 [INSPIRE].

[46] CMS collaboration, *Determination of Jet Energy Calibration and Transverse Momentum Resolution in CMS*, 2011 *JINST* **6** P11002 [arXiv:1107.4277] [INSPIRE].

[47] CMS collaboration, *First measurement of large area jet transverse momentum spectra in heavy-ion collisions*, *JHEP* **05** (2021) 284 [arXiv:2102.13080] [INSPIRE].

[48] M. Kordell and A. Majumder, *Jets in d(p)-A Collisions: Color Transparency or Energy Conservation*, *Phys. Rev. C* **97** (2018) 054904 [arXiv:1601.02595] [INSPIRE].

JHEP07(2025)118

The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia
V. Chekhovsky, A. Hayrapetyan, V. Makarenko, A. Tumasyan[1]

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

Universiteit Antwerpen, Antwerpen, Belgium
T. Janssen, H. Kwon, T. Van Laer, P. Van Mechelen

Vrije Universiteit Brussel, Brussel, Belgium
J. Bierkens, N. Breugelmans, J. D'Hondt, S. Dansana, A. De Moor, M. Delcourt, F. Heyen, Y. Hong, S. Lowette, I. Makarenko, D. Müller, S. Tavernier, M. Tytgat[3], G.P. Van Onsem, S. Van Putte, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium
B. Bilin, B. Clerbaux, A.K. Das, I. De Bruyn, G. De Lentdecker, H. Evard, L. Favart, P. Gianneios, A. Khalilzadeh, F.A. Khan, A. Malara, M.A. Shahzad, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer, F. Zhang

Ghent University, Ghent, Belgium
M. De Coen, D. Dobur, G. Gokbulut, J. Knolle, L. Lambrecht, D. Marckx, K. Skovpen, N. Van Den Bossche, J. van der Linden, J. Vandenbroeck, L. Wezenbeek

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Bein, A. Benecke, A. Bethani, G. Bruno, A. Cappati, J. De Favereau De Jeneret, C. Delaere, A. Giammanco, A.O. Guzel, Sa. Jain, V. Lemaitre, J. Lidrych, P. Mastrapasqua, S. Turkcapar

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, E. Coelho, G. Correia Silva, C. Hensel, T. Menezes De Oliveira, C. Mora Herrera[4], P. Rebello Teles, M. Soeiro, E.J. Tonelli Manganote[5], A. Vilela Pereira[4]

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[6], E.M. Da Costa, G.G. Da Silveira[7], D. De Jesus Damiao, S. Fonseca De Souza, R. Gomes De Souza, S. S. Jesus, T. Laux Kuhn[7], M. Macedo, K. Mota Amarilo, L. Mundim, H. Nogima, J.P. Pinheiro, A. Santoro, A. Sznajder, M. Thiel

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
C.A. Bernardes[7], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, I. Maietto Silverio, P.G. Mercadante, S.F. Novaes, B. Orzari, Sandra S. Padula, V. Scheurer

JHEP07(2025)118

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

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

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

Beihang University, Beijing, China
T. Cheng, Q. Guo, T. Javaid, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
Z. Hu, Z. Liang, J. Liu

Institute of High Energy Physics, Beijing, China
G.M. Chen[8], H.S. Chen[8], M. Chen[8], Q. Hou, F. Iemmi, C.H. Jiang, A. Kapoor[9], H. Liao, Z.-A. Liu[10], R. Sharma[11], J.N. Song[10], J. Tao, C. Wang[8], 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, S. Deng, B. Guo, C. Jiang, A. Levin, C. Li, Q. Li, Y. Mao, S. Qian, S.J. Qian, X. Qin, X. Sun, D. Wang, H. Yang, Y. Zhao, C. Zhou

Guangdong Provincial Key Laboratory of Nuclear Science and Guangdong-Hong Kong Joint Laboratory of Quantum Matter, South China Normal University, Guangzhou, China
S. Yang

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

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

Nanjing Normal University, Nanjing, China
G. Bauer[12], B. Li[13], H. Wang, K. Yi[14], J. Zhang

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
Y. Li

Zhejiang University, Hangzhou, Zhejiang, China
Z. Lin, C. Lu, M. Xiao[15]

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. Jaramillo, C. Rendón, M. Rodriguez, A.A. Ruales Barbosa, J.D. Ruiz Alvarez

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

University of Split, Faculty of Science, Split, Croatia
M. Kovac, A. Petkovic, T. Sculac

Institute Rudjer Boskovic, Zagreb, Croatia
P. Bargassa, V. Brigljevic, B.K. Chitroda, D. Ferencek, K. Jakovcic, A. Starodumov, T. Susa

University of Cyprus, Nicosia, Cyprus
A. Attikis, K. Christoforou, A. Hadjiagapiou, C. Leonidou, J. Mousa, C. Nicolaou, L. Paizanos, 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
B. El-mahdy[16], S. Khalil[17], E. Salama[18,19]

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

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

Department of Physics, University of Helsinki, Helsinki, Finland
K. Osterberg, M. Voutilainen

JHEP07(2025)118

Helsinki Institute of Physics, Helsinki, Finland
N. Bin Norjoharuddeen, E. Brücken, F. Garcia, P. Inkaew, K.T.S. Kallonen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, M. Myllymäki, M.m. Rantanen, S. Saariokari, J. Tuominiemi

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
H. Kirschenmann, P. Luukka, H. Petrow

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, M. Kumar, V. Lohezic, J. Malcles, F. Orlandi, L. Portales, S. Ronchi, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[20], P. Simkina, M. Titov, M. Tornago

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
F. Beaudette, G. Boldrini, P. Busson, C. Charlot, M. Chiusi, T.D. Cuisset, F. Damas, O. Davignon, A. De Wit, I.T. Ehle, B.A. Fontana Santos Alves, S. Ghosh, A. Gilbert, R. Granier de Cassagnac, L. Kalipoliti, G. Liu, M. Manoni, M. Nguyen, S. Obraztsov, C. Ochando, R. Salerno, J.B. Sauvan, Y. Sirois, G. Sokmen, L. Urda Gómez, E. Vernazza, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[21], J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, S. Falke, U. Goerlach, R. Haeberle, A.-C. Le Bihan, M. Meena, O. Poncet, G. Saha, M.A. Sessini, P. Vaucelle

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
A. Di Florio

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
D. Amram, S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, D. Contardo, P. Depasse, C. Dozen[22], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, E. Jourd'huy, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, A. Purohit, M. Vander Donckt, P. Verdier, J. Xiao

Georgian Technical University, Tbilisi, Georgia
D. Chokheli, I. Lomidze, Z. Tsamalaidze[23]

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

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, F. Engelke, J. Erdmann, M. Erdmann, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, A. Jung, N. Kumar,

JHEP07(2025)118

M.y. Lee, F. Mausolf, M. Merschmeyer, A. Meyer, F. Nowotny, A. Pozdnyakov, Y. Rath, W. Redjeb, F. Rehm, H. Reithler, V. Sarkisovi, A. Schmidt, C. Seth, A. Sharma, J.L. Spah, F. Torres Da Silva De Araujo[24], S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
C. Dziwok, G. Flügge, 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, S. Amoroso, Y. An, J. Bach, S. Baxter, M. Bayatmakou, H. Becerril Gonzalez, O. Behnke, A. Belvedere, F. Blekman[25], K. Borras[26], A. Campbell, S. Chatterjee, F. Colombina, M. De Silva, G. Eckerlin, D. Eckstein, E. Gallo[25], A. Geiser, V. Guglielmi, M. Guthoff, A. Hinzmann, L. Jeppe, B. Kaech, M. Kasemann, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka[27], W. Lohmann[28], F. Lorkowski, R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, A.B. Meyer, G. Milella, K. Moral Figueroa, A. Mussgiller, L.P. Nair, J. Niedziela, A. Nürnberg, J. Park, E. Ranken, A. Raspereza, D. Rastorguev, L. Rygaard, M. Scham[29,26], S. Schnake[26], P. Schütze, C. Schwanenberger[25], D. Selivanova, K. Sharko, M. Shchedrolosiev, D. Stafford, F. Vazzoler, A. Ventura Barroso, R. Walsh, D. Wang, Q. Wang, K. Wichmann, L. Wiens[26], C. Wissing, Y. Yang, S. Zakharov, A. Zimermmane Castro Santos

University of Hamburg, Hamburg, Germany
A. Albrecht, M. Antonello, S. Bollweg, M. Bonanomi, P. Connor, K. El Morabit, Y. Fischer, M. Frahm, E. Garutti, A. Grohsjean, J. Haller, D. Hundhausen, H.R. Jabusch, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, C.c. Kuo, V. Kutzner, F. Labe, J. Lange, A. Lobanov, C. Matthies, L. Moureaux, M. Mrowietz, A. Nigamova, K. Nikolopoulos, Y. Nissan, A. Paasch, K.J. Pena Rodriguez, T. Quadfasel, B. Raciti, M. Rieger, D. Savoiu, J. Schindler, P. Schleper, M. Schröder, J. Schwandt, M. Sommerhalder, H. Stadie, G. Steinbrück, A. Tews, R. Ward, B. Wiederspan, M. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
S. Brommer, E. Butz, Y.M. Chen, T. Chwalek, A. Dierlamm, G.G. Dincer, U. Elicabuk, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[30], R. Hofsaess, M. Horzela, U. Husemann, J. Kieseler, M. Klute, O. Lavoryk, J.M. Lawhorn, M. Link, A. Lintuluoto, S. Maier, M. Mormile, Th. Müller, M. Neukum, M. Oh, E. Pfeffer, M. Presilla, G. Quast, K. Rabbertz, B. Regnery, R. Schmieder, N. Shadskiy, I. Shvetsov, H.J. Simonis, L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms, B. Topko, N. Trevisani, T. Voigtländer, R.F. Von Cube, J. Von Den Driesch, M. Wassmer, S. Wieland, F. Wittig, R. Wolf, W.D. Zeuner, X. Zuo

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, A. Kyriakis, A. Papadopoulos[30], A. Stakia

JHEP07(2025)118

National and Kapodistrian University of Athens, Athens, Greece
G. Melachroinos, Z. Painesis, I. Paraskevas, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, I. Zisopoulos

National Technical University of Athens, Athens, Greece
T. Chatzistavrou, G. Karapostoli, K. Kousouris, E. Siamarkou, G. Tsipolitis

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

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
D. Druzhkin, C. Hajdu, D. Horvath[31,32], K. Márton, A.J. Rádl[33], F. Sikler, V. Veszpremi

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanád, K. Farkas, A. Fehérkuti[34], M.M.A. Gadallah[35], Á. Kadlecsik, G. Pásztor, G.I. Veres

Faculty of Informatics, University of Debrecen, Debrecen, Hungary
L. Olah, B. Ujvari

HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
T. Csorgo[34], F. Nemes[34], T. Novak

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[36], A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, T. Sheokand, J.B. Singh, A. Singla

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

Indian Institute of Technology Kanpur, Kanpur, India
S. Mukherjee

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
S. Baradia, S. Barman[37], S. Bhattacharya, S. Das Gupta, S. Dutta, S. Dutta, S. Sarkar

Indian Institute of Technology Madras, Madras, India
M.M. Ameen, P.K. Behera, S.C. Behera, S. Chatterjee, G. Dash, A. Dattamunsi, P. Jana, P. Kalbhor, S. Kamble, J.R. Komaragiri[38], D. Kumar[38], T. Mishra,

B. Parida[39], P.R. Pujahari, N.R. Saha, A.K. Sikdar, R.K. Singh, P. Verma, S. Verma, A. Vijay

Tata Institute of Fundamental Research-A, Mumbai, India
S. Dugad, G.B. Mohanty, M. Shelake, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India
A. Bala, S. Banerjee, S. Bhowmik[40], R.M. Chatterjee, M. Guchait, Sh. Jain, A. Jaiswal, B.M. Joshi, S. Kumar, G. Majumder, K. Mazumdar, S. Parolia, A. Thachayath

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
S. Bahinipati[41], D. Maity[42], P. Mal, K. Naskar[42], A. Nayak[42], S. Nayak, K. Pal, R. Raturi, P. Sadangi, S.K. Swain, S. Varghese[42], D. Vats[42]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Acharya[43], A. Alpana, S. Dube, B. Gomber[43], P. Hazarika, B. Kansal, A. Laha, B. Sahu[43], S. Sharma, K.Y. Vaish

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[44], A. Jafari[45], M. Zeinali[46]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Bashiri, S. Chenarani[47], S.M. Etesami, Y. Hosseini, M. Khakzad, E. Khazaie, M. Mohammadi Najafabadi, S. Tizchang[48]

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], M. Barbieri[a,b], M. Buonsante[a,b], A. Colaleo[a,b], D. Creanza[a,c], B. D'Anzi[a,b], N. De Filippis[a,c], M. De Palma[a,b], W. Elmetenawee[a,b,49], N. Ferrara[a,b], L. Fiore[a], G. Iaselli[a,c], L. Longo[a], M. Louka[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a], 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,b], D. Ramos[a], A. Ranieri[a], L. Silvestris[a], F.M. Simone[a,c], Ü. Sözbilir[a], A. Stamerra[a,b], D. Troiano[a,b], R. Venditti[a,b], P. Verwilligen[a], A. Zaza[a,b]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[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], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,50], M. Lorusso[a,b], L. Lunerti[a], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], G. Paggi[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], S. Rossi Tisbeni[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,51], A. Di Mattia[a], A. Lapertosa[a], R. Potenza[a,b], A. Tricomi[a,b,51]

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

J. Altork[a,b], P. Assiouras[a], G. Barbagli[a], G. Bardelli[a], M. Bartolini[a,b], A. Calandri[a,b], B. Camaiani[a,b], A. Cassese[a], R. Ceccarelli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], L. Damenti[a,b], E. Focardi[a,b], T. Kello[a], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a], M. Meschini[a], S. Paoletti[a], A. Papanastassiou[a,b], G. Sguazzoni[a], L. Viliani[a]

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, S. Meola[52], D. Piccolo

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

M. Alves Gallo Pereira[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], F. Brivio[a], F. Cetorelli[a,b], F. De Guio[a,b], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], R. Gerosa[a,b], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a], G. Lavizzari[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], S. Palluotto[a,b], D. Pedrini[a], A. Perego[a,b], B.S. Pinolini[a], G. Pizzati[a,b], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy; Università della Basilicata[c], Potenza, Italy; Scuola Superiore Meridionale (SSM)[d], Napoli, Italy

S. Buontempo[a], A. Cagnotta[a,b], F. Carnevali[a,b], N. Cavallo[a,c], C. Di Fraia[a,b], F. Fabozzi[a,c], L. Favilla[a,d], A.O.M. Iorio[a,b], L. Lista[a,b,53], P. Paolucci[a,30], B. Rossi[a]

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,54], D. Bisello[a,b], P. Bortignon[a], G. Bortolato[a,b], A.C.M. Bulla[a], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a,55], U. Gasparini[a,b], S. Giorgetti[a], E. Lusiani[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], J. Pazzini[a,b], P. Ronchese[a,b], R. Rossin[a,b], M. Sgaravatto[a], F. Simonetto[a,b], M. Tosi[a,b], A. Triossi[a,b], S. Ventura[a], 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

A. Braghieri[a], S. Calzaferri[a], D. Fiorina[a], P. Montagna[a,b], M. Pelliccioni[a], 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

S. Ajmal[a,b], M.E. Ascioti[a,b], G.M. Bilei[a], C. Carrivale[a,b], D. Ciangottini[a,b], L. Fanò[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,56], 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

C. Aimè[a,b], C.A. Alexe[a,c], P. Asenov[a,b], P. Azzurri[a], G. Bagliesi[a], R. Bhattacharya[a], L. Bianchini[a,b], T. Boccali[a], E. Bossini[a], D. Bruschini[a,c], R. Castaldi[a], F. Cattafesta[a,c], M.A. Ciocci[a,b], M. Cipriani[a,b], V. D'Amante[a,d], R. Dell'Orso[a], S. Donato[a,b], R. Forti[a,b], A. Giassi[a], F. Ligabue[a,c], A.C. Marini[a,b], D. Matos Figueiredo[a], A. Messineo[a,b], S. Mishra[a], V.K. Muraleedharan Nair Bindhu[a,b], M. Musich[a,b], S. Nandan[a], F. Palla[a], M. Riggirello[a,c], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a,40], T. Sarkar[a], A. Scribano[a], P. Spagnolo[a], F. Tenchini[a,b], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], F. Vaselli[a,c], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma[a], Sapienza Università di Roma[b], Roma, Italy

P. Akrap[a,b], C. Basile[a,b], F. Cavallari[a], L. Cunqueiro Mendez[a,b], F. De Riggi[a,b], D. Del Re[a,b], E. Di Marco[a,b], M. Diemoz[a], F. Errico[a,b], L. Frosina[a,b], R. Gargiulo[a,b], B. Harikrishnan[a,b], F. Lombardi[a,b], E. Longo[a,b], L. Martikainen[a,b], J. Mijuskovic[a,b], G. Organtini[a,b], N. Palmeri[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], V. Vladimirov[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,c], R. Bellan[a,b], C. Biino[a], C. Borca[a,b], N. Cartiglia[a], M. Costa[a,b], G. Cotto[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], L. Markovic[a,b], S. Maselli[a], A. Mecca[a,b], L. Menzio[a,b], P. Meridiani[a], 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. Ruspa[a,c], F. Siviero[a,b], V. Sola[a,b], A. Solano[a,b], C. Tarricone[a,b], D. Trocino[a], G. Umoret[a,b], R. White[a,b]

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

J. Babbar[a,b], S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], K. De Leo[a], G. Della Ricca[a,b], R. Delli Gatti[a,b]

Kyungpook National University, Daegu, Korea

S. Dogra, J. Hong, J. Kim, D. Lee, H. Lee, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, M.S. Ryu, S. Sekmen, B. Tae, Y.C. Yang

Department of Mathematics and Physics - GWNU, Gangneung, Korea

M.S. Kim

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

G. Bak, P. Gwak, H. Kim, D.H. Moon

Hanyang University, Seoul, Korea

E. Asilar, J. Choi[57], D. Kim, T.J. Kim, J.A. Merlin, Y. Ryou

Korea University, Seoul, Korea

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

Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh, J. Shin, S. Yang

JHEP07(2025)118

Sejong University, Seoul, Korea
Y. Kang, H. S. Kim, Y. Kim, S. Lee

Seoul National University, Seoul, Korea
J. Almond, J.H. Bhyun, J. Choi, J. Choi, W. Jun, J. Kim, Y.W. Kim, S. Ko, H. Lee, J. Lee, J. Lee, B.H. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

University of Seoul, Seoul, Korea
W. Jang, D.Y. Kang, S. Kim, B. Ko, J.S.H. Lee, Y. Lee, I.C. Park, Y. Roh, I.J. Watson

Yonsei University, Department of Physics, Seoul, Korea
G. Cho, S. Ha, K. Hwang, B. Kim, K. Lee, H.D. Yoo

Sungkyunkwan University, Suwon, Korea
M. Choi, M.R. Kim, Y. Lee, I. Yu

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

Kuwait University - College of Science - Department of Physics, Safat, Kuwait
F. Alazemi

Riga Technical University, Riga, Latvia
K. Dreimanis, A. Gaile, C. Munoz Diaz, D. Osite, G. Pikurs, A. Potrebko, M. Seidel, D. Sidiropoulos Kontos

University of Latvia (LU), Riga, Latvia
N.R. Strautnieks

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

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Yusuff[58], Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, L.E. Cuevas Picos, 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, H. Crotte Ledesma, E. De La Cruz-Burelo, I. Heredia-De La Cruz[59], R. Lopez-Fernandez, J. Mejia Guisao, A. Sánchez Hernández

Universidad Iberoamericana, Mexico City, Mexico
C. Oropeza Barrera, D.L. Ramirez Guadarrama, M. Ramírez García

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Bautista, F.E. Neri Huerta, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

University of Montenegro, Podgorica, Montenegro
I. Bubanja, N. Raicevic

University of Canterbury, Christchurch, New Zealand
P.H. Butler

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

AGH University of Krakow, Krakow, Poland
V. Avati, A. Bellora[60], L. Forthomme, L. Grzanka, M. Malawski, K. Piotrzkowski

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, 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, A. Muhammad

Warsaw University of Technology, Warsaw, Poland
P. Fokow, K. Pozniak, W. Zabolotny

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, D. Bastos, C. Beirão Da Cruz E Silva, A. Boletti, M. Bozzo, T. Camporesi, G. Da Molin, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, G.B. Marozzo, A. Petrilli, M. Pisano, J. Seixas, J. Varela, J.W. Wulff

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

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
D. Devetak, M. Dordevic, J. Milosevic, L. Nadderd, V. Rekovic, M. Stojanovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, Cristina F. Bedoya, J.A. Brochero Cifuentes, Oliver M. Carretero, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, 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. Llorente Merino, C. Martin Perez, E. Martin Viscasillas, D. Moran, C. M. Morcillo Perez, Á. Navarro Tobar, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, J. Sastre, J. Vazquez Escobar

JHEP07(2025)118

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, A. Cardini, J. Cuevas, J. Del Riego Badas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, P. Leguina, E. Palencia Cortezon, J. Prado Pico, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, C. Vico Villalba, P. Vischia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
S. Blanco Fernández, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, G. Gomez, C. Lasaosa García, R. Lopez Ruiz, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, E. Navarrete Ramos, J. Piedra Gomez, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
B. Kailasapathy[61], D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna[62], K. Liyanage, N. Perera

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, C. Amendola, E. Auffray, J. Baechler, D. Barney, A. Bermúdez Martínez, M. Bianco, A.A. Bin Anuar, A. Bocci, L. Borgonovi, C. Botta, A. Bragagnolo, E. Brondolin, C.E. Brown, C. Caillol, G. Cerminara, N. Chernyavskaya, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, M. Glowacki, A. Gruber, J. Hegeman, J.K. Heikkilä, B. Huber, V. Innocente, T. James, P. Janot, O. Kaluzinska, O. Karacheban[28], G. Karathanasis, S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, M. Magherini, L. Malgeri, M. Mannelli, M. Matthewman, A. Mehta, F. Meijers, S. Mersi, E. Meschi, M. Migliorini, V. Milosevic, F. Monti, F. Moortgat, M. Mulders, I. Neutelings, S. Orfanelli, F. Pantaleo, G. Petrucciani, A. Pfeiffer, M. Pierini, M. Pitt, H. Qu, D. Rabady, B. Ribeiro Lopes, F. Riti, M. Rovere, H. Sakulin, R. Salvatico, S. Sanchez Cruz, S. Scarfi, C. Schwick, M. Selvaggi, A. Sharma, K. Shchelina, P. Silva, P. Sphicas[63], A.G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, D. Walter, J. Wanczyk[64], J. Wang, S. Wuchterl, P. Zehetner, P. Zejdl

PSI Center for Neutron and Muon Sciences, Villigen, Switzerland
T. Bevilacqua[65], L. Caminada[65], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[65], L. Noehte[65], T. Rohe, A. Samalan

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
T.K. Aarrestad, M. Backhaus, G. Bonomelli, C. Cazzaniga, K. Datta, P. De Bryas Dexmiers D'archiac[64], A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà,

JHEP07(2025)118

F. Eble, M. Galli, K. Gedia, F. Glessgen, C. Grab, N. Härringer, T.G. Harte, W. Lustermann, A.-M. Lyon, M. Malucchi, R.A. Manzoni, M. Marchegiani, L. Marchese, A. Mascellani[64], F. Nessi-Tedaldi, F. Pauss, V. Perovic, S. Pigazzini, B. Ristic, R. Seidita, J. Steggemann[64], A. Tarabini, D. Valsecchi, R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[66], P. Bärtschi, M.F. Canelli, G. Celotto, K. Cormier, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, F. Meng, J. Motta, A. Reimers, P. Robmann, M. Senger, E. Shokr, F. Stäger, R. Tramontano

National Central University, Chung-Li, Taiwan
C. Adloff[67], D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout, P.C. Tiwari[38]

National Taiwan University (NTU), Taipei, Taiwan
L. Ceard, K.F. Chen, Z.g. Chen, A. De Iorio, W.-S. Hou, T.h. Hsu, Y.w. Kao, S. Karmakar, G. Kole, Y.y. Li, R.-S. Lu, E. Paganis, X.f. Su, J. Thomas-Wilsker, L.s. Tsai, D. Tsionou, H.y. Wu, E. Yazgan

High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand
C. Asawatangtrakuldee, N. Srimanobhas, V. Wachirapusitanand

Tunis El Manar University, Tunis, Tunisia
Y. Maghrbi

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
D. Agyel, F. Boran, F. Dolek, I. Dumanoglu[68], E. Eskut, Y. Guler[69], E. Gurpinar Guler[69], C. Isik, O. Kara, A. Kayis Topaksu, Y. Komurcu, G. Onengut, K. Ozdemir[70], A. Polatoz, B. Tali[71], U.G. Tok, E. Uslan, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey
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[68,76], S. Sen[77]

Istanbul University, Istanbul, Turkey
O. Aydilek[78], B. Hacisahinoglu, I. Hos[79], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, C. Zorbilmez

Yildiz Technical University, Istanbul, Turkey
S. Cerci, B. Isildak[80], D. Sunar Cerci, T. Yetkin[22]

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

A. Boyaryntsev, 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, F. Bury, E. Clement, D. Cussans, H. Flacher, J. Goldstein, H.F. Heath, M.-L. Holmberg, L. Kreczko, S. Paramesvaran, L. Robertshaw, J. Segal, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom

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

Imperial College, London, United Kingdom

I. Andreou, R. Bainbridge, P. Bloch, O. Buchmuller, C.A. Carrillo Montoya, D. Colling, J.S. Dancu, I. Das, P. Dauncey, G. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, H.R. Hoorani, A. Howard, G. Iles, C.R. Knight, P. Krueper, J. Langford, K.H. Law, J. León Holgado, L. Lyons, A.-M. Magnan, B. Maier, S. Mallios, M. Mieskolainen, J. Nash[82], M. Pesaresi, P.B. Pradeep, B.C. Radburn-Smith, A. Richards, A. Rose, L. Russell, K. Savva, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, T. Virdee[30], M. Vojinovic, N. Wardle, D. Winterbottom

Brunel University, Uxbridge, United Kingdom

J.E. Cole, A. Khan, P. Kyberd, I.D. Reid

Baylor University, Waco, Texas, USA

S. Abdullin, A. Brinkerhoff, E. Collins, M.R. Darwish, J. Dittmann, K. Hatakeyama, V. Hegde, J. Hiltbrand, B. McMaster, J. Samudio, S. Sawant, C. Sutantawibul, J. Wilson

Catholic University of America, Washington, DC, USA

R. Bartek, A. Dominguez, S. Raj, A.E. Simsek, S.S. Yu

The University of Alabama, Tuscaloosa, Alabama, USA

B. Bam, A. Buchot Perraguin, R. Chudasama, S.I. Cooper, C. Crovella, G. Fidalgo, S.V. Gleyzer, E. Pearson, C.U. Perez, P. Rumerio[83], E. Usai, R. Yi

Boston University, Boston, Massachusetts, USA

G. De Castro, Z. Demiragli, C. Erice, C. Fangmeier, C. Fernandez Madrazo, E. Fontanesi, D. Gastler, F. Golf, S. Jeon, J. O'cain, I. Reed, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, A.G. Zecchinelli

Brown University, Providence, Rhode Island, USA
G. Barone, G. Benelli, D. Cutts, S. Ellis, L. Gouskos, M. Hadley, U. Heintz, K.W. Ho, J.M. Hogan[84], T. Kwon, G. Landsberg, K.T. Lau, J. Luo, S. Mondal, T. Russell, S. Sagir[85], X. Shen, M. Stamenkovic, N. Venkatasubramanian

University of California, Davis, Davis, California, USA
S. Abbott, B. Barton, C. Brainerd, R. Breedon, H. Cai, M. Calderon De La Barca Sanchez, M. Chertok, M. Citron, J. Conway, P.T. Cox, R. Erbacher, F. Jensen, O. Kukral, G. Mocellin, M. Mulhearn, S. Ostrom, W. Wei, S. Yoo

University of California, Los Angeles, California, USA
K. Adamidis, M. Bachtis, D. Campos, R. Cousins, A. Datta, G. Flores Avila, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, Y.f. Lo, E. Manca, A. Nunez Del Prado, D. Saltzberg, V. Valuev

University of California, Riverside, Riverside, California, USA
R. Clare, J.W. Gary, G. Hanson

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

University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
A. Barzdukas, L. Brennan, C. Campagnari, K. Downham, C. Grieco, M.M. Hussain, J. Incandela, J. Kim, A.J. Li, P. Masterson, H. Mei, J. Richman, S.N. Santpur, U. Sarica, R. Schmitz, F. Setti, J. Sheplock, D. Stuart, T.Á. Vámi, X. Yan, D. Zhang

California Institute of Technology, Pasadena, California, USA
A. Albert, S. Bhattacharya, A. Bornheim, O. Cerri, J. Mao, H.B. Newman, G. Reales Gutiérrez, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
J. Alison, S. An, P. Bryant, M. Cremonesi, V. Dutta, T. Ferguson, T.A. Gómez Espinosa, A. Harilal, A. Kallil Tharayil, M. Kanemura, C. Liu, T. Mudholkar, S. Murthy, P. Palit, K. Park, M. Paulini, A. Roberts, A. Sanchez, W. Terrill

University of Colorado Boulder, Boulder, Colorado, USA
J.P. Cumalat, W.T. Ford, A. Hart, A. Hassani, N. Manganelli, J. Pearkes, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper, D. Zuolo

JHEP07(2025)118

Cornell University, Ithaca, New York, USA
J. Alexander, X. Chen, D.J. Cranshaw, J. Dickinson, J. Fan, X. Fan, J. Grassi, S. Hogan, P. Kotamnives, J. Monroy, G. Niendorf, M. Oshiro, J.R. Patterson, 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, C. Cosby, G. Cummings, I. Dutta, V.D. Elvira, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, A. Grummer, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, C. Lee, D. Lincoln, R. Lipton, T. Liu, K. Maeshima, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, S. Norberg, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[86], F. Ravera, A. Reinsvold Hall[87], L. Ristori, M. Safdari, 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, C. Wang, I. Zoi

University of Florida, Gainesville, Florida, USA
C. Aruta, P. Avery, D. Bourilkov, P. Chang, V. Cherepanov, R.D. Field, C. Huh, E. Koenig, M. Kolosova, J. Konigsberg, A. Korytov, K. Matchev, N. Menendez, G. Mitselmakher, K. Mohrman, A. Muthirakalayil Madhu, N. Rawal, S. Rosenzweig, V. Sulimov, Y. Takahashi, J. Wang

Florida State University, Tallahassee, Florida, USA
T. Adams, A. Al Kadhim, A. Askew, S. Bower, R. Hashmi, R.S. Kim, S. Kim, T. Kolberg, G. Martinez, H. Prosper, P.R. Prova, M. Wulansatiti, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, Florida, USA
B. Alsufyani, S. Butalla, S. Das, T. Elkafrawy[19], M. Hohlmann, M. Lavinsky, E. Yanes

University of Illinois Chicago, Chicago, Illinois, USA
M.R. Adams, A. Baty, C. Bennett, R. Cavanaugh, R. Escobar Franco, O. Evdokimov, C.E. Gerber, H. Gupta, M. Hawksworth, A. Hingrajiya, D.J. Hofman, J.h. Lee, D. S. Lemos, C. Mills, S. Nanda, B. Ozek, T. Phan, D. Pilipovic, R. Pradhan, E. Prifti, P. Roy, T. Roy, N. Singh, M.B. Tonjes, N. Varelas, M.A. Wadud, Z. Ye, J. Yoo

The University of Iowa, Iowa City, Iowa, USA
M. Alhusseini, D. Blend, K. Dilsiz[88], L. Emediato, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[89], O. Neogi, H. Ogul[90], Y. Onel, A. Penzo, C. Snyder, E. Tiras[91]

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

JHEP07(2025)118

The University of Kansas, Lawrence, Kansas, USA
A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, S. Arteaga Escatel, P. Baringer, A. Bean, Z. Flowers, D. Grove, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, J. Marquez, M. Murray, M. Nickel, S. Popescu[92], C. Rogan, C. Royon, S. Rudrabhatla, S. Sanders, C. Smith, G. Wilson

Kansas State University, Manhattan, Kansas, USA
B. Allmond, R. Gujju Gurunadha, A. Ivanov, K. Kaadze, Y. Maravin, J. Natoli, D. Roy, G. Sorrentino

University of Maryland, College Park, Maryland, USA
A. Baden, A. Belloni, J. Bistany-riebman, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, B. Kronheim, S. Lascio, P. Major, A.C. Mignerey, S. Nabili, C. Palmer, C. Papageorgakis, M.M. Paranjpe, E. Popova[93], A. Shevelev, L. Wang, L. Zhang

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
C. Baldenegro Barrera, J. Bendavid, S. Bright-Thonney, I.A. Cali, P.c. Chou, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, G. Grosso, P. Harris, D. Hoang, D. Kovalskyi, J. Krupa, L. Lavezzo, Y.-J. Lee, K. Long, C. Mcginn, A. Novak, M.I. Park, C. Paus, C. Reissel, C. Roland, G. Roland, S. Rothman, G.S.F. Stephans, Z. Wang, B. Wyslouch, T. J. Yang

University of Minnesota, Minneapolis, Minnesota, USA
B. Crossman, C. Kapsiak, M. Krohn, D. Mahon, J. Mans, B. Marzocchi, M. Revering, R. Rusack, R. Saradhy, N. Strobbe

University of Nebraska-Lincoln, Lincoln, Nebraska, USA
K. Bloom, D.R. Claes, G. Haza, J. Hossain, C. Joo, I. Kravchenko, A. Rohilla, J.E. Siado, W. Tabb, A. Vagnerini, A. Wightman, F. Yan, D. Yu

State University of New York at Buffalo, Buffalo, New York, USA
H. Bandyopadhyay, L. Hay, H.w. Hsia, I. Iashvili, A. Kalogeropoulos, A. Kharchilava, A. Mandal, M. Morris, D. Nguyen, S. Rappoccio, H. Rejeb Sfar, A. Williams, P. Young

Northeastern University, Boston, Massachusetts, USA
G. Alverson, E. Barberis, J. Bonilla, B. Bylsma, M. Campana, J. Dervan, Y. Haddad, Y. Han, I. Israr, A. Krishna, P. Levchenko, J. Li, M. Lu, R. Mccarthy, D.M. Morse, T. Orimoto, A. Parker, L. Skinnari, C.S. Thoreson, E. Tsai, D. Wood

Northwestern University, Evanston, Illinois, USA
S. Dittmer, K.A. Hahn, D. Li, Y. Liu, M. Mcginnis, Y. Miao, D.G. Monk, M.H. Schmitt, A. Taliercio, M. Velasco

University of Notre Dame, Notre Dame, Indiana, USA
G. Agarwal, R. Band, R. Bucci, S. Castells, A. Das, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, T. Ivanov, C. Jessop, A. Karneyeu, K. Lannon, J. Lawrence,

N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, C. Moore, Y. Musienko[23], H. Nelson, M. Osherson, A. Piccinelli, R. Ruchti, A. Townsend, Y. Wan, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

The Ohio State University, Columbus, Ohio, USA

A. Basnet, M. Carrigan, L.S. Durkin, C. Hill, M. Joyce, M. Nunez Ornelas, K. Wei, D.A. Wenzl, B.L. Winer, B. R. Yates

Princeton University, Princeton, New Jersey, USA

H. Bouchamaoui, K. Coldham, P. Das, G. Dezoort, P. Elmer, P. Fackeldey, A. Frankenthal, B. Greenberg, N. Haubrich, K. Kennedy, G. Kopp, S. Kwan, Y. Lai, D. Lange, A. Loeliger, D. Marlow, I. Ojalvo, J. Olsen, F. Simpson, D. Stickland, C. Tully, L.H. Vage

University of Puerto Rico, Mayaguez, Puerto Rico, USA

S. Malik, R. Sharma

Purdue University, West Lafayette, Indiana, USA

A.S. Bakshi, S. Chandra, R. Chawla, A. Gu, L. Gutay, M. Jones, A.W. Jung, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, J.F. Schulte, A. K. Virdi, F. Wang, A. Wildridge, W. Xie, Y. Yao, Y. Zhong

Purdue University Northwest, Hammond, Indiana, USA

J. Dolen, N. Parashar, A. Pathak

Rice University, Houston, Texas, USA

D. Acosta, A. Agrawal, T. Carnahan, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, T. Huang, I. Krommydas, W. Li, J. Lin, O. Miguel Colin, B.P. Padley, R. Redjimi, J. Rotter, E. Yigitbasi, Y. Zhang

University of Rochester, Rochester, New York, USA

A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, N. Parmar, P. Parygin[93], R. Taus

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA

B. Chiarito, J.P. Chou, S.V. Clark, D. Gadkari, Y. Gershtein, E. Halkiadakis, M. Heindl, C. Houghton, D. Jaroslawski, S. Konstantinou, I. Laflotte, A. Lath, J. Martins, R. Montalvo, K. Nash, B. Rand, J. Reichert, P. Saha, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora

University of Tennessee, Knoxville, Tennessee, USA

D. Ally, A.G. Delannoy, S. Fiorendi, J. Harris, S. Higginbotham, T. Holmes, A.R. Kanuganti, N. Karunarathna, J. Lawless, L. Lee, E. Nibigira, S. Spanier

Texas A&M University, College Station, Texas, USA

D. Aebi, M. Ahmad, T. Akhter, K. Androsov, A. Bolshov, O. Bouhali[94], R. Eusebi, J. Gilmore, T. Kamon, H. Kim, S. Luo, R. Mueller, A. Safonov

JHEP07(2025)118

Texas Tech University, Lubbock, Texas, USA

N. Akchurin, J. Damgov, Y. Feng, N. Gogate, Y. Kazhykarim, K. Lamichhane, S.W. Lee, C. Madrid, A. Mankel, T. Peltola, I. Volobouev

Vanderbilt University, Nashville, Tennessee, USA

E. Appelt, Y. Chen, S. Greene, A. Gurrola, W. Johns, R. Kunnawalkam Elayavalli, A. Melo, D. Rathjens, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen

University of Virginia, Charlottesville, Virginia, USA

B. Cardwell, H. Chung, B. Cox, J. Hakala, R. Hirosky, A. Ledovskoy, C. Mantilla, C. Neu, C. Ramón Álvarez

Wayne State University, Detroit, Michigan, USA

S. Bhattacharya, P.E. Karchin

University of Wisconsin - Madison, Madison, Wisconsin, USA

A. Aravind, S. Banerjee, K. Black, T. Bose, E. Chavez, S. Dasu, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C.K. Koraka, A. Lanaro, S. Lomte, R. Loveless, A. Mallampalli, A. Mohammadi, S. Mondal, G. Parida, L. Pétré, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, H.F. Tsoi, W. Vetens, A. Warden

Authors affiliated with an international laboratory covered by a cooperation agreement with CERN

S. Afanasiev, V. Alexakhin, Yu. Andreev, T. Aushev, D. Budkouski, R. Chistov[95], M. Danilov[95], T. Dimova[95], A. Ershov[95], S. Gninenko, I. Golutvin[†], I. Gorbunov, A. Gribushin[95], V. Karjavine, M. Kirsanov, V. Klyukhin[95], O. Kodolova[96,93], V. Korenkov, A. Kozyrev[95], N. Krasnikov, A. Lanev, A. Malakhov, V. Matveev[95], A. Nikitenko[97,96], V. Palichik, V. Perelygin, S. Petrushanko[95], S. Polikarpov[95], O. Radchenko[95], M. Savina, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen[95], V. Smirnov, O. Teryaev, I. Tlisova[95], A. Toropin, N. Voytishin, B.S. Yuldashev[†,98], A. Zarubin, I. Zhizhin

[†] *Deceased*
[1] *Also at Yerevan State University, Yerevan, Armenia*
[2] *Also at TU Wien, Vienna, Austria*
[3] *Also at Ghent University, Ghent, Belgium*
[4] *Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[5] *Also at FACAMP - Faculdades de Campinas, Sao Paulo, Brazil*
[6] *Also at Universidade Estadual de Campinas, Campinas, Brazil*
[7] *Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil*
[8] *Also at University of Chinese Academy of Sciences, Beijing, China*
[9] *Also at China Center of Advanced Science and Technology, Beijing, China*
[10] *Also at University of Chinese Academy of Sciences, Beijing, China*
[11] *Also at China Spallation Neutron Source, Guangdong, China*
[12] *Now at Henan Normal University, Xinxiang, China*
[13] *Also at University of Shanghai for Science and Technology, Shanghai, China*
[14] *Now at The University of Iowa, Iowa City, Iowa, USA*
[15] *Also at Center for High Energy Physics, Peking University, Beijing, China*

[16] *Also at Cairo University, Cairo, Egypt*
[17] *Also at Zewail City of Science and Technology, Zewail, Egypt*
[18] *Also at British University in Egypt, Cairo, Egypt*
[19] *Now at Ain Shams University, Cairo, Egypt*
[20] *Also at Purdue University, West Lafayette, Indiana, USA*
[21] *Also at Université de Haute Alsace, Mulhouse, France*
[22] *Also at Istinye University, Istanbul, Turkey*
[23] *Also at an institute formerly covered by a cooperation agreement with CERN*
[24] *Also at The University of the State of Amazonas, Manaus, Brazil*
[25] *Also at University of Hamburg, Hamburg, Germany*
[26] *Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
[27] *Also at Bergische University Wuppertal (BUW), Wuppertal, Germany*
[28] *Also at Brandenburg University of Technology, Cottbus, Germany*
[29] *Also at Forschungszentrum Jülich, Juelich, Germany*
[30] *Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland*
[31] *Also at HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary*
[32] *Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania*
[33] *Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*
[34] *Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary*
[35] *Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt*
[36] *Also at Punjab Agricultural University, Ludhiana, India*
[37] *Also at University of Visva-Bharati, Santiniketan, India*
[38] *Also at Indian Institute of Science (IISc), Bangalore, India*
[39] *Also at Amity University Uttar Pradesh, Noida, India*
[40] *Also at UPES - University of Petroleum and Energy Studies, Dehradun, India*
[41] *Also at IIT Bhubaneswar, Bhubaneswar, India*
[42] *Also at Institute of Physics, Bhubaneswar, India*
[43] *Also at University of Hyderabad, Hyderabad, India*
[44] *Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany*
[45] *Also at Isfahan University of Technology, Isfahan, Iran*
[46] *Also at Sharif University of Technology, Tehran, Iran*
[47] *Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran*
[48] *Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran*
[49] *Also at Helwan University, Cairo, Egypt*
[50] *Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy*
[51] *Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy*
[52] *Also at Università degli Studi Guglielmo Marconi, Roma, Italy*
[53] *Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy*
[54] *Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
[55] *Also at Lulea University of Technology, Lulea, Sweden*
[56] *Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy*
[57] *Also at Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France*
[58] *Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia*
[59] *Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico*
[60] *Also at INFN Sezione di Torino, Università di Torino, Torino, Italy; Università del Piemonte Orientale, Novara, Italy*
[61] *Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka*
[62] *Also at Saegis Campus, Nugegoda, Sri Lanka*
[63] *Also at National and Kapodistrian University of Athens, Athens, Greece*
[64] *Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland*

JHEP07(2025)118

[65] *Also at Universität Zürich, Zurich, Switzerland*
[66] *Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria*
[67] *Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France*
[68] *Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey*
[69] *Also at Konya Technical University, Konya, Turkey*
[70] *Also at Izmir Bakircay University, Izmir, Turkey*
[71] *Also at Adiyaman University, Adiyaman, Turkey*
[72] *Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey*
[73] *Also at Marmara University, Istanbul, Turkey*
[74] *Also at Milli Savunma University, Istanbul, Turkey*
[75] *Also at Kafkas University, Kars, Turkey*
[76] *Now at Istanbul Okan University, Istanbul, Turkey*
[77] *Also at Hacettepe University, Ankara, Turkey*
[78] *Also at Erzincan Binali Yildirim University, Erzincan, Turkey*
[79] *Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey*
[80] *Also at Yildiz Technical University, Istanbul, Turkey*
[81] *Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom*
[82] *Also at Monash University, Faculty of Science, Clayton, Australia*
[83] *Also at Università di Torino, Torino, Italy*
[84] *Also at Bethel University, St. Paul, Minnesota, USA*
[85] *Also at Karamanoğlu Mehmetbey University, Karaman, Turkey*
[86] *Also at California Institute of Technology, Pasadena, California, USA*
[87] *Also at United States Naval Academy, Annapolis, Maryland, USA*
[88] *Also at Bingol University, Bingol, Turkey*
[89] *Also at Georgian Technical University, Tbilisi, Georgia*
[90] *Also at Sinop University, Sinop, Turkey*
[91] *Also at Erciyes University, Kayseri, Turkey*
[92] *Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania*
[93] *Now at another institute formerly covered by a cooperation agreement with CERN*
[94] *Also at Texas A&M University at Qatar, Doha, Qatar*
[95] *Also at another institute formerly covered by a cooperation agreement with CERN*
[96] *Also at Yerevan Physics Institute, Yerevan, Armenia*
[97] *Also at Imperial College, London, United Kingdom*
[98] *Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan*

JHEP07(2025)118