EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2024-345
2025/02/19

CMS-HIN-24-010

Search for medium effects using jet axis decorrelation in inclusive jets from PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$

The CMS Collaboration*

Abstract

The jet axis decorrelation in inclusive jets is studied using lead-lead (PbPb) collisions at a center-of-mass energy per nucleon pair of 5.02 TeV. The jet axis decorrelation is defined as the angular difference between two definitions of the jet axis. It is obtained by applying two recombination schemes on all the constituents of a given jet reconstructed by the anti-k_{T} sequential algorithm with a distance parameter of $R = 0.4$. The data set, corresponding to an integrated luminosity of $0.66\,\mathrm{nb}^{-1}$, was collected in 2018 with the CMS detector at the CERN LHC. The jet axis decorrelations are examined across collision centrality selections and intervals of jet transverse momentum. A centrality dependent evolution of the measured distributions is observed, with a progressive narrowing seen in more central events. This narrowing could result from medium-induced modification of the internal jet structure or reflect color charge effects in energy loss. This new measurement probes jet substructure in previously unexplored kinematic domains and show great promise for providing new insights on the color charge dependence of energy loss to jet-quenching models.

Submitted to the Journal of High Energy Physics

*See Appendix B for the list of collaboration members

1 Introduction

Jets have been used as versatile tools for probing the properties of quark-gluon plasma (QGP) created in high-energy collisions [1, 2]. Jets are collimated streams of particles that form when energetic quarks and gluons (partons) produced in high-momentum-transfer (hard) processes fragment into lower-energy (soft) partons and subsequently hadronize into particles. During the evolution of the jet shower, the outgoing partons can interact with the QGP, resulting in a range of physical phenomena collectively known as "jet quenching." Experimental evidence of jet quenching is provided by many observables at the BNL RHIC [3, 4] and the CERN LHC [5–8]. Jet-medium interactions in the QGP modify the jet shower properties as compared to jets produced in collisions of elementary particles. Various jet substructure observables are employed to study radiation patterns inside jets and the effects of QGP on those distributions. There have been numerous experimental measurements indicating a modification of jet substructure in heavy ion collisions as compared to proton-proton (pp) collisions [9–11]. A recent review of CMS measurements on the subject can be found in Ref. [12].

Energy scale differences between the initial parton and final-state shower constituents, as well as nonperturbative hadronization effects, pose challenges for theoretical predictions of jet quenching. Additional complications arise from the response of the medium to the propagating jet and how this response could further modify the jet shower. Perturbative and nonperturbative contributions, which arise from different energy scales and processes, are treated differently in various theoretical approaches, with a greater degree of variation and uncertainty for the nonperturbative components. It is therefore critical to map out jet modification at different scales and to probe the internal jet substructure with observables that have different sensitivities to the perturbative and nonperturbative domains.

In this paper, a search for possible modifications to jet substructure is conducted using measurements of the jet axis decorrelation between two different jet axes within a given jet, which are expected to have different sensitivities to soft-gluon radiation [13]. The jet axis decorrelation, Δj, is defined as the angular separation between the axes found using the traditional anti-k_T energy-weighted (E-scheme) recombination and the winner-take-all (WTA) recombination schemes [13]:

$$\Delta j = \sqrt{(\eta^{\text{E-scheme}} - \eta^{\text{WTA}})^2 + (\phi^{\text{E-scheme}} - \phi^{\text{WTA}})^2}, \tag{1}$$

where each jet axis direction is characterized by its pseudorapidity (η) and azimuthal angle (ϕ). In the E-scheme recombination algorithm, the four-vector sum of constituents determines the jet axis at each clustering step. This definition includes contributions from soft constituents and provides the momentum-averaged direction of the energy flow. On the other hand, the WTA recombination scheme follows the direction of the hardest prong at each clustering iteration and is more sensitive to collinear radiation inside the jet [13]. The WTA axis is insensitive to soft radiation at leading order, allowing for a more direct interpretation in terms of perturbative quantum chromodynamics (QCD) calculations. Since these two algorithms have different sensitivities to soft radiation, studies of axis decorrelations can provide information about radiative energy loss in QGP. These decorrelations are also sensitive to the details of the parton shower and can reflect modifications of fragmentation patterns as well as their dependence on the parton flavor.

Experimental measurements of Δj provide significant advantages for tuning the parton shower in event generators and for gaining insight on medium effects in heavy ion collisions because of the availability of analytical calculations at next-to-leading logarithmic accuracy [13]. Successful applications for the former can be found in comparisons of numerical calculations for pp

collisions at a center-of-mass energy $\sqrt{s} = 13\,\text{TeV}$ with PYTHIA 8.2 simulations, where excellent agreement has been demonstrated for transverse momenta (p_T) above 100 GeV [13]. However, at lower p_T, discrepancies have been observed, likely attributable to nonperturbative effects and power-suppressed contributions, which arise from soft radiation and hadronization processes that become significant at low energy scales [13].

Recently, the ALICE Collaboration measured jet-axis decorrelations in lead-lead (PbPb) and pp collisions at a center-of-mass energy per nucleon pair ($\sqrt{s_\text{NN}}$) of 5.02 TeV using E-scheme and WTA axes with jets reconstructed from charged particle tracks [11, 14]. The measured distributions for jets in the range $40 < p_\text{T} < 80\,\text{GeV}$ showed a narrowing of the Δj distributions in PbPb collisions compared to the pp reference. These measurements were primarily conducted in a kinematic region where nonperturbative effects, such as contributions from the medium response and underlying event fluctuations, are expected to be more significant. Similarly, the CMS Collaboration also measured jet axis decorrelations in PbPb and pp collisions at $\sqrt{s_\text{NN}} = 5.02\,\text{TeV}$ using isolated photon-tagged jet events in the $30 < p_\text{T} < 100\,\text{GeV}$ range [10]. There, a similar narrowing of the Δj distribution in PbPb compared to pp collisions was seen in the momentum range of $60 < p_\text{T} < 100\,\text{GeV}$.

This paper presents a study of the jet axis decorrelation of anti-k_T jets with a distance parameter of $R = 0.4$ in PbPb collisions at $\sqrt{s_\text{NN}} = 5.02\,\text{TeV}$, using data recorded by the CMS experiment in 2018. Measurements are carried out in four p_T intervals ranging from 120 to 300 GeV and in four centrality intervals from 0 to 80%, where centrality is defined as the fraction of the total nucleus-nucleus cross section, with 0% corresponding to the maximum overlap of the colliding nuclei. Measurements are corrected for detector resolution effects by employing an unfolding procedure. The sensitivity of the Δj distribution shape to the type of parton initiating the jet shower is also employed to explore the potential impact of color charge effects on energy loss, and several model scenarios are examined. Tabulated results are provided in the HEPData record for this analysis [15].

2 Experimental setup and data sample

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Two hadron forward (HF) steel and quartz-fiber calorimeters complement the barrel and endcap detectors, providing coverage to $|\eta| < 5.2$. The HF calorimeters are segmented into multiple 0.175×0.175 ($\Delta\eta \times \Delta\phi$) "towers", where ϕ is the azimuthal angle in radians. Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz [16]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing and reducing the event rate to around 1 kHz before data storage [17]. A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Refs. [18, 19].

This analysis uses approximately 7 million events, corresponding to an integrated luminosity of $0.66\,\text{nb}^{-1}$ [20–22], that were recorded in 2018 using high-level triggers requiring at least one jet with $p_\text{T} > 80\,\text{GeV}$. Background events due to beam-gas interactions and nonhadronic collisions are removed offline by applying the criteria described in Ref. [23]. Events are required to

have at least one primary interaction vertex reconstructed using two or more tracks [24] within a distance of 15 cm from the center of the nominal interaction point along the beam axis. Each event must have at least two calorimeter towers in each HF detector, with energy deposits exceeding 4 GeV per tower, effectively removing the ultraperipheral collision events. The shapes of the clusters in the pixel detector are required to be compatible with those expected in PbPb collisions to prevent contamination from events with multiple collisions [25]. The collision centrality is determined using the total sum of transverse energy (E_{T}) from calorimeter towers in the HF region (covering $2.9 < |\eta| < 5.2$). The measured HF energy distribution is used to divide the event sample into bins, each representing 0.5% of the total nucleus-nucleus hadronic interaction cross section. A detailed description of centrality determination can be found in Ref. [26].

A sample of simulated events is used to correct reconstruction and detector resolution effects and to construct template distributions for jets from different types of partons in modeling studies. The PYTHIA 8.226 [27] event generator with tune CP5 [28] and NNPDF3.1 parton distribution functions at next-to-next-to-leading order [29] is used to describe the hard scattering, parton showering, and hadronization processes for the interaction producing jets of interest. These events are embedded into simulated minimum bias PbPb collisions produced with the HYDJET 1.9 [30] event generator to account for the soft underlying event produced in PbPb collisions. The HYDJET generator is tuned to mirror global PbPb event properties such as the charged-hadron p_{T} spectrum and particle multiplicity. The combined sample of hard PYTHIA interactions and soft HYDJET underlying event is referred to as the PYTHIA+HYDJET sample. Simulation of the CMS detector response is performed using the GEANT4 [31] toolkit.

In PbPb collisions, the frequency of jet production is higher in central events due to the increased number of binary nucleon-nucleon collisions per nuclear interaction. Conversely, the PYTHIA+HYDJET sample exhibits a uniform distribution of jets (from PYTHIA) across centrality bins. Therefore, a centrality-based weighting is applied to the minimum bias MC sample to align its centrality distribution with the jet-triggered PbPb data. Another weighting step is performed to match the distributions of the primary vertex position along the beam direction in the simulated and data samples.

3 Jet reconstruction

In PbPb collisions, jets are reconstructed using the anti-k_{T} algorithm [32] with a distance parameter of $R = 0.4$, implemented in the FASTJET framework [33]. A particle-flow (PF) algorithm, optimized to combine information from various elements of the CMS detector, is used to reconstruct leptons, photons, and charged and neutral hadrons [34]. These PF candidates are the input for reconstructing the jets analyzed in this study. The constituent subtraction method [35] is employed to subtract the contributions of the underlying event. Charged-hadron PF candidates are assumed to have the pion mass. The jets are clustered using the E-scheme recombination scheme [33], wherein particle pairs are iteratively combined to form pseudo-jets. These pseudo-jets are objects that combine particles or other pseudo-jets. The direction of the new pseudo-jet is determined by the vector sum of the four-momenta of its constituent particles. When using E-scheme recombination scheme, the direction of the resulting four-vector is the E-scheme jet axis, expressed in (η, ϕ) coordinates. To calculate the other axis relevant to this work, the WTA axis, the jet is reclustered using the winner-take-all recombination scheme [36, 37] combined with the anti-k_{T} algorithm and the same input PF constituents. During each iteration, the direction of the new pseudo-jet aligns with that of the highest-p_{T} particle or pseudo-jet being combined. Consequently, the WTA axis typically coincides with the direction of the hardest jet

constituent.

Jet energy corrections are derived from simulation studies so that the average measured energy of jets becomes identical to that of particle-level jets. In situ measurements of the momentum balance using dijet events from pp collisions are used to determine any residual differences between the jet energy scale (JES) in data and simulation, and appropriate corrections are made [38]. Additional selection criteria are applied to each jet to remove jets potentially dominated by instrumental effects or reconstruction failures [39].

After jet reconstruction and energy correction, all selected jets are required to have $p_{\mathrm{T}} > 120\,\mathrm{GeV}$ and $|\eta| < 1.6$. In this kinematic range, the jet trigger is fully efficient, and the jet energy response and resolution are optimal. The study is performed in four intervals of jet p_{T}, specifically $120 < p_{\mathrm{T}} < 150\,\mathrm{GeV}$, $150 < p_{\mathrm{T}} < 190\,\mathrm{GeV}$, $190 < p_{\mathrm{T}} < 230\,\mathrm{GeV}$, and $230 < p_{\mathrm{T}} < 300\,\mathrm{GeV}$.

4 Analysis method

The jet axis decorrelation between the E-scheme and WTA axes is calculated according to Eq.(1). The measured $\Delta\mathrm{j}$ distributions are normalized by the total number of jets within each jet p_{T} interval, denoted as $\mathrm{N}(p_{\mathrm{T}}^{\mathrm{jet}})$, yielding the following expression:

$$\frac{1}{\mathrm{N}(p_{\mathrm{T}}^{\mathrm{jet}})}\frac{\mathrm{dN}(p_{\mathrm{T}}^{\mathrm{jet}})}{\mathrm{d}\Delta\mathrm{j}}.$$

Measurements are unfolded to the particle level to correct detector resolution effects and underlying event fluctuations, facilitating comparisons with other experiments and theoretical predictions. The unfolding process employs the iterative D'Agostini's unfolding method [40–42] with early stopping, which is implemented in the RooUnfold software package [43] and requires a response matrix. This matrix is derived from simulated samples and captures the correspondence between the $\Delta\mathrm{j}$ and jet p_{T} at both the generator and detector levels. To capture bin-migration effects, response matrices were constructed using the detector-level p_{T} in the range 80–500 GeV. Within the kinematic range studied, jet reconstruction is fully efficient even in the most central PbPb collisions. Thus, the unfolding procedure does not include additional scaling factors for missed jets. Additionally, erroneous jet contributions from random background fluctuations were found to be negligible for jets above 120 GeV, so no corrections for this effect are applied.

The $\Delta\mathrm{j}$ distributions in the simulated samples exhibit substantial shape differences between quark- and gluon-initiated jets across all p_{T} intervals investigated in this analysis. These generator-level distributions are subsequently used for template fitting to estimate the potential limits of color charge effects in jet energy loss.

5 Systematic uncertainties

The systematic uncertainties are determined by individually varying each analysis criterion, as discussed below.

Event centrality is determined in the data by the E_{T} sum in the HF calorimeters, which involves inherent uncertainties. The boundaries of E_{T} sums in HF for each centrality interval are varied according to these uncertainties to assess their impact on the final result. The resulting difference is taken as a systematic uncertainty.

The systematic uncertainty associated with jet energy resolution (JER) arises from possible discrepancies in the JER between data and simulation. In the nominal analysis, these differences are accounted for by applying a jet-η dependent smearing to the jet p_{T} in the simulation when constructing response matrices. To estimate the systematic uncertainty, new response matrices are generated by adjusting the smearing amount (both up and down) to reflect the uncertainty in the data-to-simulation discrepancy. The unfolding procedure is then performed using these modified response matrices. Additionally, a centrality-dependent systematic uncertainty due to JER is examined to account for potential differences in the background energy density between data and simulation. This uncertainty is estimated by shifting the centrality in the simulation up and down by 2%. The systematic uncertainty due to the JES correction is calculated by shifting the jet p_{T} up and down in the data according to the JES uncertainties [38] and comparing the shifted and nominal results.

In the nominal jet reconstruction method, the constituent subtraction method [35] is used to subtract the contributions of the underlying event from the jet energy. An alternative background subtraction technique, accounting for the effects of hydrodynamical flow via event-by-event Fourier fits to the ϕ distribution of PF candidates [44], is used for the systematic evaluation.

The optimal number of unfolding iterations is determined by analyzing the convergence behavior and the bias-variance trade-off through cross-unfolding different MC samples (unfolding reweighted MC samples using response matrices from nominal MC and vice versa). The iterative procedure is stopped when, for all bins, the magnitude of the bias becomes smaller than the statistical uncertainty, ensuring a balance between accuracy and overfitting. Based on this criterion, the optimal number of iterations is three. Results obtained using two and four iterations are compared to assess the systematic uncertainty associated with the iteration count. The response matrices used in the unfolding procedure are derived from the PYTHIA+HYDJET sample, which has limited statistical precision. The statistical uncertainty inherent in these response matrices can influence the unfolding process. To account for the resulting uncertainty, fifty alternative response matrices are constructed by randomly varying each response matrix bin content according to the statistical uncertainty of the nominal response matrix and repeating the unfolding process. The resulting systematic uncertainty is determined by calculating the root-mean-square value from the fifty unfolding outputs and evaluating the differences from the nominal values. To study the systematic effect of the response matrix populated from a specific MC sample, a new response matrix is obtained by varying the quark- and gluon-like fractions in the simulation based on limits obtained from data and performing the unfolding. The PYTHIA+HYDJET sample, where the jet p_{T} is weighted to match the data, is used to construct the nominal response matrices. The unfolding procedure is repeated with a new response matrix constructed using the unweighted jet p_{T} distribution to evaluate the uncertainty related to the prior shape.

The energy scale uncertainty of PF candidates was checked by scaling the four-momenta of the charged hadron and photon PF candidates by $\pm 1\%$ and of neutral hadron PF candidates by $\pm 3\%$ [9]. The impact of these variations was found to be negligible.

When multiple variations are considered for a single uncertainty source, the maximum deviation from the nominal value is used. The total systematic uncertainty is obtained by summing the uncertainties from each source in quadrature. In this analysis, systematic uncertainties are categorized as either correlated or uncorrelated.

The systematic uncertainties due to the JER and JES are treated as correlated sources, while all other uncertainties are treated as uncorrelated. The systematic variations due to JER and the

JES affect the jet p_{T}, which is anti-correlated with Δj. The dominant systematic uncertainty in this analysis is from the JES. The absolute contributions from each source, as well as the total systematic uncertainties, are summarized in Table 1 for Δj distributions.

Table 1: Summary of absolute systematic uncertainties, averaged over the Δj distributions for different centrality intervals. The range of uncertainty values reflects the maximum variation across different p_{T} intervals.

Uncertainty source	Centrality			
	50–80%	30–50%	10–30%	0–10%
Centrality	0.001–0.011	0.001–0.004	0.000–0.002	0.000–0.002
JER	0.053–0.088	0.068–0.123	0.054–0.180	0.189–0.290
JES	0.304–0.574	0.355–0.443	0.407–0.487	0.423–0.498
Background subtraction	0.006–0.041	0.023–0.048	0.037–0.068	0.067–0.091
Iteration choice	0.007–0.053	0.009–0.041	0.020–0.057	0.017–0.086
Response matrix event count	0.000–0.001	0.000–0.001	0.000–0.001	0.000–0.001
Scaled flavor fraction in sim.	0.000–0.002	0.001–0.002	0.003–0.006	0.005–0.012
Prior choice	0.001–0.002	0.001–0.002	0.001–0.003	0.006–0.013
Total correlated uncertainty	0.316–0.581	0.362–0.459	0.443–0.490	0.463–0.534
Total uncorrelated uncertainty	0.015–0.066	0.026–0.054	0.065–0.072	0.088–0.110

6 Results and discussion

Figure 1 shows the unfolded normalized Δj distributions in different jet p_{T} intervals ranging from $120 < p_{\mathrm{T}} < 150\,\mathrm{GeV}$ to $230 < p_{\mathrm{T}} < 300\,\mathrm{GeV}$. Each plot consists of four distributions corresponding to four centrality intervals, distinguished by different marker colors. The lower panels show ratios of Δj distributions in a given centrality range to that of the 50–80% centrality interval. Correlated systematic uncertainties, the dominant sources of uncertainty in this analysis, are mitigated in the ratios by dividing each distribution by the corresponding distribution from the 50–80% centrality interval. The Δj distributions dip towards the smallest Δj values ($\Delta\mathrm{j} \approx 0$), indicating a low probability of finding both the E-scheme and WTA axes of a jet aligned in the same direction. These distributions peak between $0.01 < \Delta\mathrm{j} < 0.03$, and then decline sharply with increasing Δj.

A progressive narrowing of the Δj distributions, evident in the enhancement of small-Δj yields and a compensating suppression at higher Δj values, is observed from peripheral to central collisions across all p_{T} intervals. The narrowing is most significant in the most central events and could be attributed to modifications of the internal structure of the jet induced by interactions with the QGP medium. However, one could expect some broadening because of in-medium gluon radiation influencing the direction of the jet axes (particularly the E-scheme axis). It has also been argued in another substructure measurement that such narrowing in inclusive jets could be a consequence of a selection bias [9], with different amounts of energy loss experienced by jets with different internal structures due to, e.g., color coherence effects. Additionally, as higher p_{T} jets have narrower Δj distributions compared to lower-p_{T} jets across all centrality intervals, the apparent narrowing could be an artifact of out-of-cone partonic energy loss affecting the JES. That is, the reconstruction of the quenched jet does not preserve the same correspondence to the initial parton energy as the jets that fragmented in the vacuum, causing a momentum selection bias that would be present in the heavy ion data.

While a direct comparison to the ALICE results [11] from the same collision system and energy

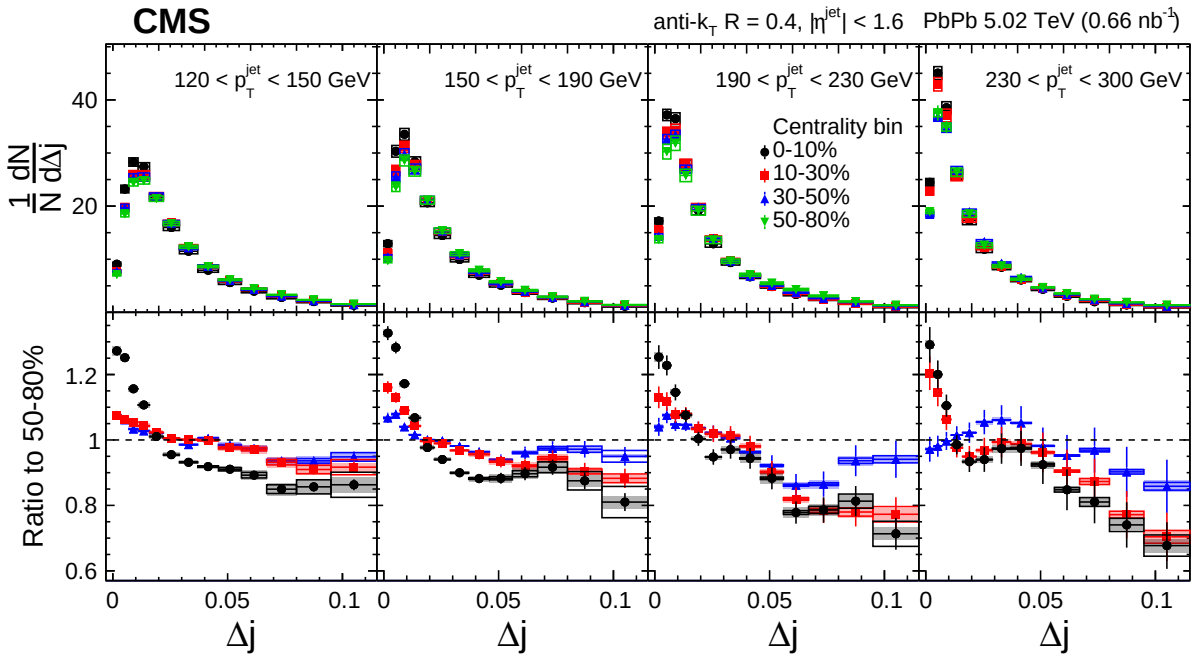

Figure 1: The unfolded normalized Δj distributions are measured across different centrality and p_T intervals. Each panel displays distributions for four centrality intervals within a specific p_T bin, with p_T ranges (indicated in each panel) increasing from left to right. In each panel, the black circles show measurements for 0–10% centrality interval, the red squares for 10–30%, and the blue-up and green-down triangles for 30–50% and 50–80% centrality intervals, respectively. The vertical solid lines represent the statistical uncertainties, while the rectangles and shaded areas represent the correlated and uncorrelated systematic uncertainties, respectively.

is precluded by the differences in the technical aspects of jet reconstruction and jet axis definitions, the physics observations related to the narrowing of jet axis decorrelation are consistent between the two experiments within the overlapping kinematic range.

The new results are compared with the PYTHIA8 MC generator using the CP5 tune [27, 28] and HERWIG7 using the CH3 tune [45–48], represented by the pink and orange bands, respectively, in Figs. 2–5. The ratios between data and simulation are shown in the lower panels. The comparison presented in Figs. 2–5 shows that the PYTHIA predictions align well with the measured data for all p_{T} intervals of the most peripheral events studied, while HERWIG expects wider distributions at each p_{T}. Larger discrepancies become evident across all p_{T} ranges from the centrality interval of 10–30%, and HERWIG exhibits a consistently larger deviation from data as compared to PYTHIA. The level of agreement continues to deteriorate toward more central events, as the data distributions become progressively narrower.

The prediction from the JEWEL 2.2.0 model [49], represented by hatched lines for the 0–10% centrality interval, is shown in Fig. 5. The JEWEL model is a dynamic framework for jet evolution in a dense background, based on perturbative QCD. However, the model qualitatively fails to describe the 0–10% centrality collision data across all p_{T} intervals. While differences exist with and without medium recoil effects, these primarily influence the yield of recoiling jets rather than the distribution shape.

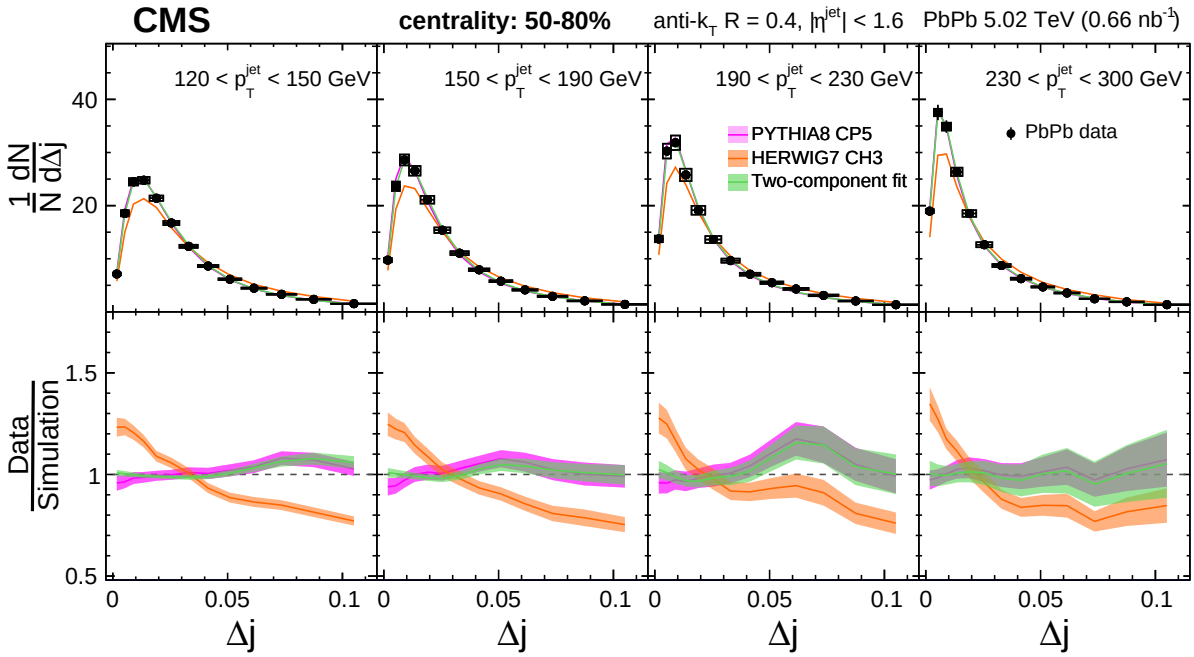

Figure 2: The unfolded Δj distributions (black circles) are compared with simulations from PYTHIA, HERWIG, and a two-component, represented as colored bands, for the 50–80% centrality range across different p_{T} intervals. The vertical solid lines represent the statistical uncertainties, while the rectangles and shaded areas represent the correlated and uncorrelated systematic uncertainties, respectively. Only statistical uncertainties are shown for the simulated distributions.

The predicted color charge dependence of partonic energy loss should result in a more significant migration of gluon-initiated jets toward lower final-state energy values compared to quark jets. This is because of the higher color charge associated with gluons, which allows them to interact more strongly with the medium [12, 50]. Since the Δj distributions of gluon jets are significantly broader than those of quark jets, differences in energy loss could also lead

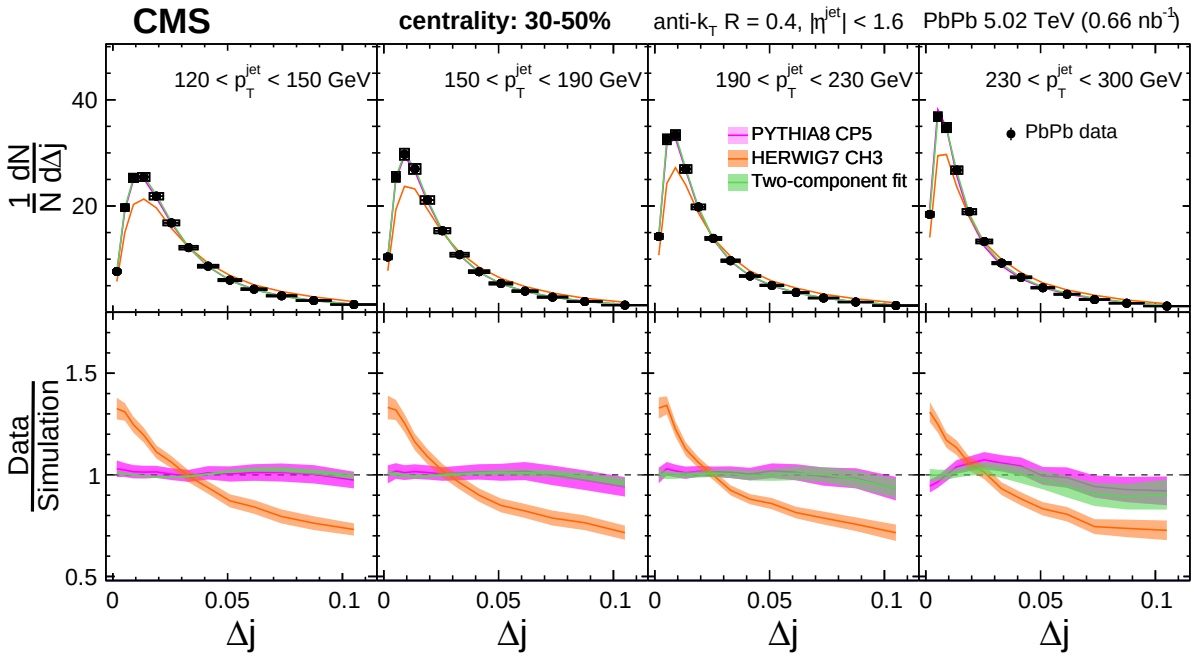

Figure 3: The unfolded Δj distributions (black circles) are compared with simulations from PYTHIA, HERWIG, and a two-component, represented as colored bands, for the 30–50% centrality range across different p_{T} intervals. The vertical solid lines represent the statistical uncertainties, while the rectangles and shaded areas represent the correlated and uncorrelated systematic uncertainties, respectively. Only statistical uncertainties are shown for the simulated distributions.

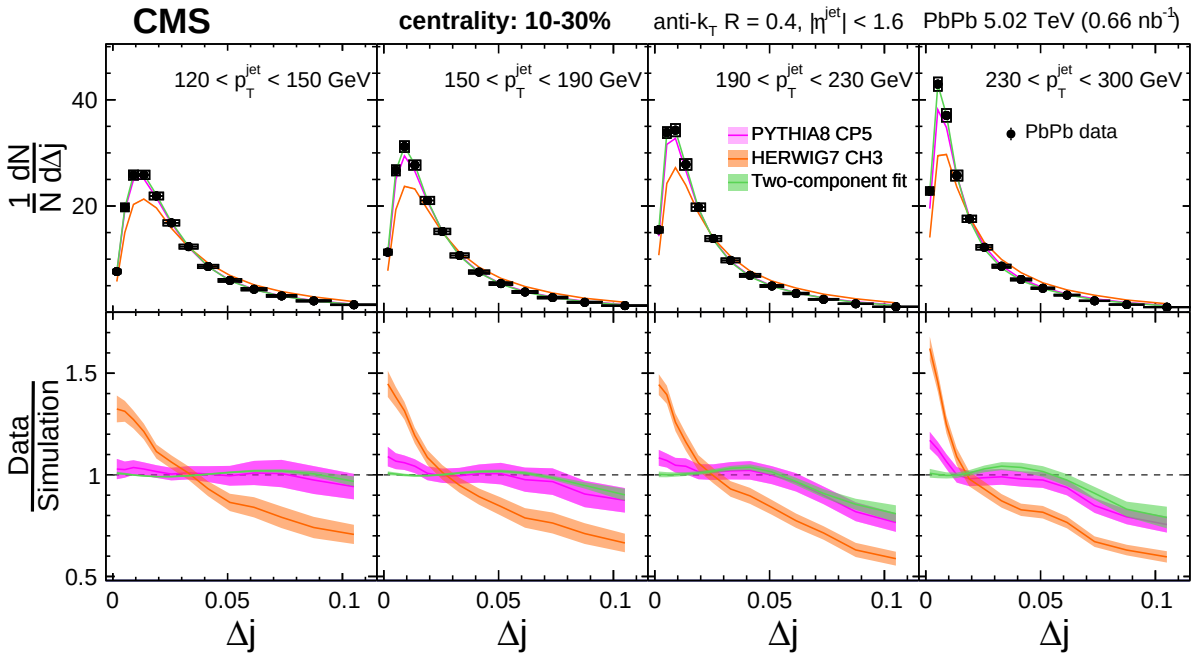

Figure 4: The unfolded Δj distributions (black circles) are compared with simulations from PYTHIA, HERWIG, and a two-component, represented as colored bands, for the 10–30% centrality range across different p_T intervals. The vertical solid lines represent the statistical uncertainties, while the rectangles and shaded areas represent the correlated and uncorrelated systematic uncertainties, respectively. Only statistical uncertainties are shown for the simulated distributions.

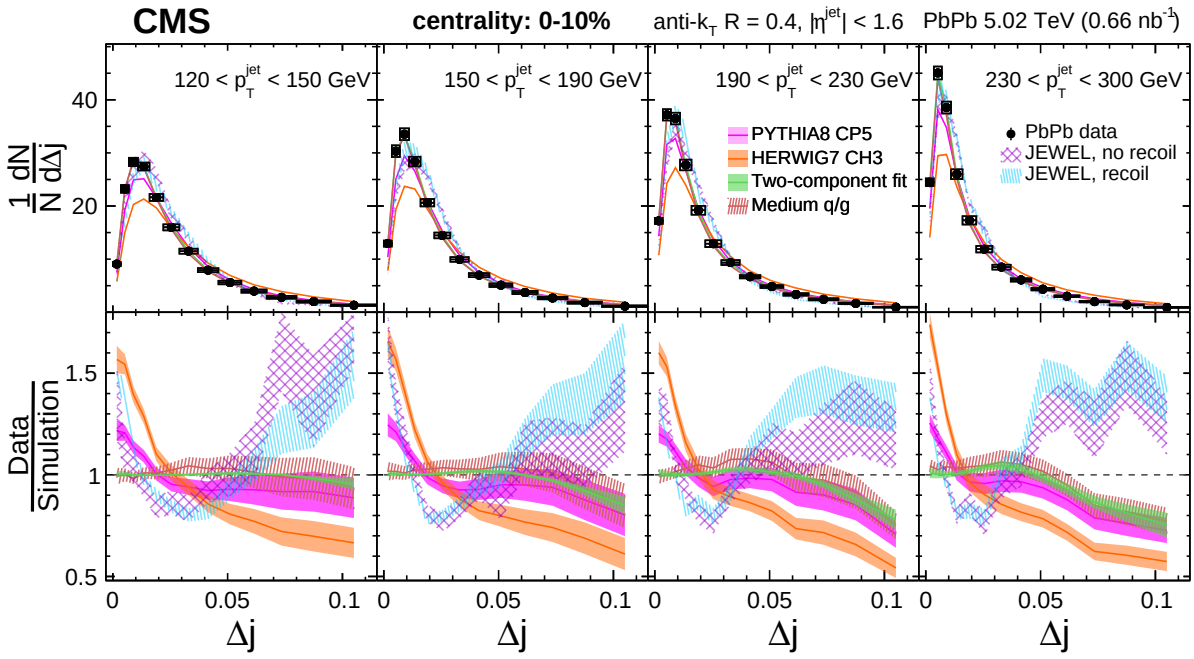

Figure 5: The unfolded Δj distributions (black circles) are compared with simulations from PYTHIA, HERWIG, and a two-component (represented as colored bands), as well as medium q/g and JEWEL predictions (represented as hatched lines) for the 0–10% centrality range across different p_T intervals. The vertical solid lines represent the statistical uncertainties, while the rectangles and shaded areas represent the correlated and uncorrelated systematic uncertainties, respectively. Only statistical uncertainties are shown for the simulated distributions.

to the narrowing of jet axis decorrelations. To illustrate this effect, the data are compared to a PYTHIA-based Δj distribution constructed using predictions from phenomenological models [51, 52], where medium-induced modifications of jet functions result in changes to the fraction of quark- and gluon-initiated jets in PbPb collisions compared to elementary collisions. Such a model, labeled as "medium q/g" in Fig. 5, describes the most central data points (for which predictions were available) across the majority of the measured Δj range. At higher Δj in the higher p_{T} bins, the PYTHIA-based Δj distributions are above the data, even when considering mostly narrow (quark-initiated) jets in simulation. This suggests that while the bulk of the distribution is well described by the model, the large-Δj behavior cannot be reconciled through changes in quark/gluon composition of the sample alone, indicating the need to account for medium-induced substructure changes.

In Figs. 2–5, we have added a set of curves labeled "two-component", based on a simple model. These curves correspond to a fit of PYTHIA8 with the CP5 tune to the unfolded data, aimed at further testing whether the modified quark/gluon fractions from the model discussed above provide an optimal description of the measured data. In this study, all quark flavors are combined into a single quark template (with different flavor contributions varied for uncertainty evaluations), and a two-component PYTHIA-based quark/gluon template fit is performed on the fully unfolded measured distributions. This simple model attributes the entire modification to changes in the flavor composition of the sample, thereby providing only a lower limit for the broadest (gluon-like) contribution. The gluon-like jet fraction preferred by the fit aligns with PYTHIA expectations in the 50–80% centrality range, but a preference for a much lower fraction is observed in more central events. Notably, the estimated limit on the gluon fraction for 0–10% central collisions from this simplified model is in excellent agreement with predictions from the "medium q/g" model [51, 52] (as shown in Appendix A), as also indicated by the ratio of the Δj distributions with the best fit in the lower panel.

7 Summary

This paper presents the first measurement of jet axis decorrelation (Δj) between two types of jet axes for inclusive jets from lead-lead (PbPb) collision data collected with the CMS detector at the LHC, at a nucleon-nucleon center-of-mass energy of 5.02 TeV. These measurements are performed using anti-k_{T} jets with a radius parameter $R = 0.4$ and with pseudorapidity $|\eta| < 1.6$ in four centrality intervals and four transverse momentum p_{T} intervals ranging from 120 to 300 GeV. Significant modifications of Δj distributions are observed in central compared to peripheral collisions, with a progressive narrowing of the distributions toward more central events. This narrowing behavior could result from medium-induced modifications of the internal jet structure, although the possibility of a selection bias towards a less-quenched sample should be considered. Such a bias could arise from the predicted color charge dependence of partonic energy loss, with gluon jets expected to lose more energy than quark jets. The measured distributions from peripheral collisions are described by the PYTHIA8 event generator without any jet quenching effects. Progressive narrowing of the Δj distribution is observed toward more central events for all p_{T} intervals studied. Comparisons with phenomenological and simple simulation-based models indicate that the observed narrowing in the Δj distributions in central PbPb collisions may be largely described by a decrease in the relative gluon jet abundance, except for higher jet p_{T} intervals. Deviations at high p_{T} suggest that accounting for jet substructure modifications or a more sophisticated implementation of color charge effects in energy loss is needed to fully describe the data. These new measurements explore jet substructure in previously unexplored kinematic domains and show great promise for providing new insights into the color charge dependence of energy loss.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); 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 (USA).

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 (USA).

References

[1] L. Apolinário, Y.-J. Lee, and M. Winn, "Heavy quarks and jets as probes of the QGP", *Prog. Part. Nucl. Phys.* **127** (2022) 103990, doi:10.1016/j.ppnp.2022.103990, arXiv:2203.16352.

[2] L. Cunqueiro and A. M. Sickles, "Studying the QGP with jets at the LHC and RHIC", *Prog. Part. Nucl. Phys.* **124** (2022) 103940, doi:10.1016/j.ppnp.2022.103940, arXiv:2110.14490.

[3] PHENIX Collaboration, "Suppression of hadrons with large transverse momentum in central Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 130\,\mathrm{GeV}$", *Phys. Rev. Lett.* **88** (2002) 022301, doi:10.1103/PhysRevLett.88.022301, arXiv:nucl-ex/0109003.

[4] STAR Collaboration, "Centrality dependence of high p_{T} hadron suppression in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 130\,\mathrm{GeV}$", *Phys. Rev. Lett.* **89** (2002) 202301, doi:10.1103/PhysRevLett.89.202301, arXiv:nucl-ex/0206011.

[5] CMS Collaboration, "First measurement of large area jet transverse momentum spectra in heavy-ion collisions", *JHEP* **05** (2021) 284, doi:10.1007/JHEP05(2021)284, arXiv:2102.13080.

[6] CMS Collaboration, "In-medium modification of dijets in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$", *JHEP* **05** (2021) 116, doi:10.1007/JHEP05(2021)116, arXiv:2101.04720.

[7] ATLAS Collaboration, "Measurement of suppression of large-radius jets and its dependence on substructure in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ with the ATLAS detector", *Phys. Rev. Lett.* **131** (2023) 172301, doi:10.1103/PhysRevLett.131.172301, arXiv:2301.05606.

[8] ALICE Collaboration, "Measurement of the radius dependence of charged-particle jet suppression in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$", *Phys. Lett. B* **849** (2024) 138412, doi:10.1016/j.physletb.2023.138412, arXiv:2303.00592.

[9] CMS Collaboration, "Girth and groomed radius of jets recoiling against isolated photons in lead-lead and proton-proton collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$", 2024. arXiv:2405.02737. Accepted by Phys. Lett. B.

[10] CMS Collaboration, "First measurement of jet axis decorrelation with photon-tagged jets in pp and PbPb collisions at 5.02 TeV", CMS Physics Analysis Summary CMS-PAS-HIN-21-019, 2024.

[11] ALICE Collaboration, "Measurement of the angle between jet axes in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$", 2023. arXiv:2303.13347. Submitted to Phys. Rev. Lett.

[12] CMS Collaboration, "Overview of high-density QCD studies with the CMS experiment at the LHC", 2024. arXiv:2405.10785. Accepted by Phys. Rept.

[13] P. Cal, D. Neill, F. Ringer, and W. J. Waalewijn, "Calculating the angle between jet axes", *JHEP* **04** (2020) 211, doi:10.1007/JHEP04(2020)211, arXiv:1911.06840.

[14] ALICE Collaboration, "Measurement of the angle between jet axes in pp collisions at $\sqrt{s} = 5.02$ TeV", *JHEP* **07** (2022) 201, doi:10.1007/JHEP07(2023)201, arXiv:2211.08928.

[15] HEPData record for this analysis, 2024. doi:10.17182/hepdata.156182.

[16] CMS Collaboration, "Performance of the CMS level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV", *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.

[17] CMS Collaboration, "The CMS trigger system", *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[18] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[19] CMS Collaboration, "Development of the CMS detector for the CERN LHC Run 3", *JINST* **19** (2024) P05064, doi:10.1088/1748-0221/19/05/P05064, arXiv:2309.05466.

[20] 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, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.

[21] CMS Collaboration, "CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV", CMS Physics Analysis Summary CMS-PAS-LUM-17-004, 2018.

[22] CMS Collaboration, "CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV", CMS Physics Analysis Summary CMS-PAS-LUM-18-002, 2019.

[23] CMS Collaboration, "Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV", *JHEP* **04** (2017) 039, doi:10.1007/JHEP04(2017)039, arXiv:1611.01664.

[24] CMS Collaboration, "Description and performance of track and primary-vertex reconstruction with the CMS tracker", *JINST* **9** (2014) P10009, doi:10.1088/1748-0221/9/10/p10009, arXiv:1405.6569.

[25] CMS Collaboration, "Transverse-momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 0.9$ and 2.36 TeV", *JHEP* **02** (2010) 041, doi:10.1007/JHEP02(2010)041, arXiv:1002.0621.

[26] CMS Collaboration, "Observation and studies of jet quenching in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV", *Phys. Rev. C* **84** (2011) 024906, doi:10.1103/PhysRevC.84.024906, arXiv:1102.1957.

[27] T. Sjöstrand et al., "An introduction to PYTHIA 8.2", *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[28] CMS Collaboration, "Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements", *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.

[29] NNPDF Collaboration, "Parton distributions from high-precision collider data", *Eur. Phys. J. C* **77** (2017) 663, doi:10.1140/epjc/s10052-017-5199-5, arXiv:1706.00428.

[30] I. P. Lokhtin and A. M. Snigirev, "A model of jet quenching in ultrarelativistic heavy ion collisions and high-p_T hadron spectra at RHIC", *Eur. Phys. J. C* **45** (2006) 211, doi:10.1140/epjc/s2005-02426-3, arXiv:hep-ph/0506189.

[31] GEANT4 Collaboration, "GEANT4—a simulation toolkit", *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

[32] M. Cacciari, G. P. Salam, and G. Soyez, "The anti-k_T jet clustering algorithm", *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.

[33] M. Cacciari, G. P. Salam, and G. Soyez, "FastJet user manual", *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.

[34] CMS Collaboration, "Particle-flow reconstruction and global event description with the CMS detector", *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.

[35] P. Berta, M. Spousta, D. W. Miller, and R. Leitner, "Particle-level pileup subtraction for jets and jet shapes", *JHEP* **06** (2014) 092, doi:10.1007/JHEP06(2014)092, arXiv:1403.3108.

[36] D. Bertolini, T. Chan, and J. Thaler, "Jet observables without jet algorithms", *JHEP* **04** (2014) 013, doi:10.1007/JHEP04(2014)013, arXiv:1310.7584.

[37] A. J. Larkoski, D. Neill, and J. Thaler, "Jet shapes with the broadening axis", *JHEP* **04** (2014) 017, doi:10.1007/JHEP04(2014)017, arXiv:1401.2158.

[38] CMS Collaboration, "Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV", *JINST* **12** (2017) P02014, doi:10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.

[39] CMS Collaboration, "Pileup mitigation at CMS in 13 TeV data", *JINST* **15** (2020) P09018, doi:10.1088/1748-0221/15/09/P09018, arXiv:2003.00503.

[40] G. D'Agostini, "A multidimensional unfolding method based on Bayes' theorem", *Nucl. Instrum. Meth. A* **362** (1995) 487, doi:10.1016/0168-9002(95)00274-X.

[41] W. H. Richardson, "Bayesian-based iterative method of image restoration", *Opt. Soc. Am.* **62** (1972) 55, doi:10.1364/JOSA.62.000055.

[42] L. B. Lucy, "An iterative technique for the rectification of observed distributions", *Astron. J.* **79** (1974) 745, doi:10.1086/111605.

[43] T. Adye, "Unfolding algorithms and tests using RooUnfold", in *Proc. PHYSTATS 2011 Workshop, CERN, Geneva, Switzerland, January 2011, CERN-2011-006*, p. 313. 2011. arXiv:1105.1160.

[44] CMS Collaboration, "Energy-energy correlators from PbPb and pp collisions at 5.02 TeV", CMS Physics Analysis Summary CMS-PAS-HIN-23-004, 2024.

[45] S. Gieseke, P. Stephens, and B. Webber, "New formalism for QCD parton showers", *JHEP* **12** (2003) 045, doi:10.1088/1126-6708/2003/12/045, arXiv:hep-ph/0310083.

[46] NNPDF Collaboration, "Parton distributions for the LHC Run 2", *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.

[47] B. R. Webber, "A QCD model for jet fragmentation including soft gluon interference", *Nucl. Phys. B* **238** (1984) 492, doi:10.1016/0550-3213(84)90333-X.

[48] CMS Collaboration, "Development and validation of HERWIG 7 tunes from CMS underlying-event measurements", *Eur. Phys. J. C* **81** (2021) 312, doi:10.1140/epjc/s10052-021-08949-5, arXiv:2011.03422.

[49] R. Kunnawalkam Elayavalli and K. C. Zapp, "Medium response in JEWEL and its impact on jet shape observables in heavy ion collisions", *JHEP* **07** (2017) 141, doi:10.1007/JHEP07(2017)141, arXiv:1707.01539.

[50] S.-L. Zhang, E. Wang, H. Xing, and B.-W. Zhang, "Flavor dependence of jet quenching in heavy-ion collisions from a Bayesian analysis", *Phys. Lett. B* **850** (2024) 138549, doi:10.1016/j.physletb.2024.138549, arXiv:2303.14881.

[51] J.-W. Qiu, F. Ringer, N. Sato, and P. Zurita, "Factorization of jet cross sections in heavy-ion collisions", *Phys. Rev. Lett.* **122** (2019) 252301, doi:10.1103/PhysRevLett.122.252301, arXiv:1903.01993.

[52] J.-W. Qiu, F. Ringer, N. Sato, and P. Zurita, "QCD factorization and universality of jet cross sections in heavy-ion collisions", *Nucl. Phys. A* **1005** (2021) 121853, doi:10.1016/j.nuclphysa.2020.121853, arXiv:2002.01652.

A Expected gluon fraction in inclusive jets in vacuum and medium

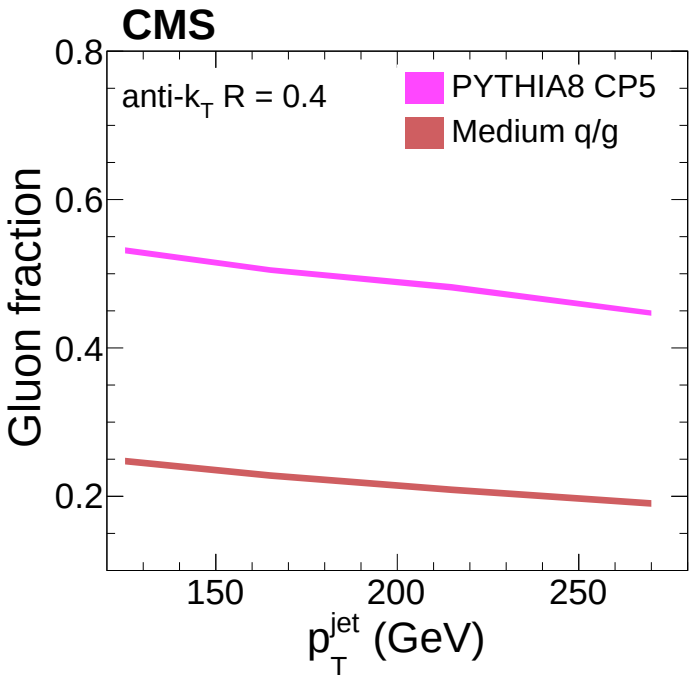

Figure A.1: Expected gluon fraction in inclusive $R = 0.4$ jet sample in the vacuum (based on PYTHIA8 with tune CP5) and in medium (based on Refs. [51, 52]).

B 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, S. Chatterjee, K. Damanakis, M. Dragicevic, 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
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

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, C. Caputo, J. De Favereau De Jeneret, C. Delaere, I.S. Donertas, A. Giammanco, A.O. Guzel, Sa. Jain, V. Lemaitre, J. Lidrych, P. Mastrapasqua, T.T. Tran, 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, T. Laux Kuhn[7], M. Macedo, J. Martins, 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

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, 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], 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, Z. Wang[8], 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

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
D. Giljanovic, 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[15],

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
A.A. Abdelalim[16,17], S. Elgammal[18], A. Ellithi Kamel[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

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, 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, 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, A. Cappati, 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, B. Harikrishnan, 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. Van Hove, 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
I. Lomidze, T. Toriashvili[23], Z. Tsamalaidze[15]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Botta, S. Consuegra Rodríguez, L. Feld, K. Klein, M. Lipinski, D. Meuser, 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, 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, A. Cardini, F. Colombina, M. De Silva, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, 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, J. Rübenach, 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, S. Albrecht, M. Antonello, S. Bollweg, M. Bonanomi, P. Connor, K. El Morabit, Y. Fischer, 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, 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, B. Wiederspan, M. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
S. Brommer, E. Butz, 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, 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

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
G. Bakas, T. Chatzistavrou, G. Karapostoli, K. Kousouris, I. Papakrivopoulos, 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
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, P. Major, G. Pásztor, G.I. Veres

Faculty of Informatics, University of Debrecen, Debrecen, Hungary
B. Ujvari, G. Zilizi

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, 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], C. Kar, 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], 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,16], 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,49], 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,50], A. Di Mattia[a], A. Lapertosa[a], R. Potenza[a,b], A. Tricomi[a,b,50]

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

P. Assiouras[a], G. Barbagli[a], G. Bardelli[a,b], M. Bartolini[a,b], B. Camaiani[a,b], A. Cassese[a], R. Ceccarelli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[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[51], 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], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a,b,52], 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,53], 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,54], F. Gasparini[a,b], U. Gasparini[a,b], S. Giorgetti[a], E. Lusiani[a], M. Margoni[a,b], G. Maron[a,55], A.T. Meneguzzo[a,b], M. Migliorini[a,b], J. Pazzini[a,b], P. Ronchese[a,b], R. Rossin[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], 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], 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], M.A. Ciocci[a,b], M. Cipriani[a,b], V. D'Amante[a,d], R. Dell'Orso[a], S. Donato[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,42], M. Musich[a,b], S. Nandan[a], F. Palla[a], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a], 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. Barria[a], C. Basile[a,b], F. Cavallari[a], L. Cunqueiro Mendez[a,b], D. Del Re[a,b],

E. Di Marco[a,b], M. Diemoz[a], F. Errico[a,b], R. Gargiulo[a,b], E. Longo[a,b], L. Martikainen[a,b], J. Mijuskovic[a,b], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a], 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], R. Bellan[a,b], C. Biino[a], C. Borca[a,b], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], L. Finco[a], M. Grippo[a,b], B. Kiani[a,b], F. Legger[a], F. Luongo[a,b], C. Mariotti[a], 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. Pelliccioni[a], M. Ruspa[a,c], F. Siviero[a,b], V. Sola[a,b], A. Solano[a,b], A. Staiano[a], 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]

Kyungpook National University, Daegu, Korea
S. Dogra, J. Hong, J. Kim, D. Lee, H. 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, S. Yang

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
S. Ha, K. Hwang, B. Kim, K. Lee, H.D. Yoo

Sungkyunkwan University, Suwon, Korea
M. Choi, M.R. Kim, H. Lee, 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, 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, H.R. Hoorani, W.A. Khan

AGH University of Krakow, Krakow, Poland
V. Avati, A. Bellora, 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

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

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, 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[60], D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna[61], 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, G. Franzoni, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, M. Glowacki, 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, 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[62], A.G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, D. Walter,

J. Wanczyk[63], J. Wang, S. Wuchterl, P. Zehetner, P. Zejdl, W.D. Zeuner

PSI Center for Neutron and Muon Sciences, Villigen, Switzerland
T. Bevilacqua[64], L. Caminada[64], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[64], L. Noehte[64], T. Rohe, A. Samalan

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
T.K. Aarrestad, M. Backhaus, G. Bonomelli, A. Calandri, C. Cazzaniga, K. Datta, P. De Bryas Dexmiers D'archiac[63], A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, C. Grab, N. Härringer, T.G. Harte, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M. Marchegiani, L. Marchese, A. Mascellani[63], F. Nessi-Tedaldi, F. Pauss, V. Perovic, S. Pigazzini, B. Ristic, R. Seidita, J. Steggemann[63], A. Tarabini, D. Valsecchi, R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[65], P. Bärtschi, M.F. Canelli, 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[66], 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[67], E. Eskut, Y. Guler[68], E. Gurpinar Guler[68], C. Isik, O. Kara, A. Kayis Topaksu, Y. Komurcu, G. Onengut, K. Ozdemir[69], A. Polatoz, B. Tali[70], U.G. Tok, E. Uslan, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey
M. Yalvac[71]

Bogazici University, Istanbul, Turkey
B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[72], O. Kaya[73], S. Tekten[74]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[67,75], S. Sen[76]

Istanbul University, Istanbul, Turkey
O. Aydilek[77], B. Hacisahinoglu, I. Hos[78], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, C. Zorbilmez

Yildiz Technical University, Istanbul, Turkey
S. Cerci, B. Isildak[79], D. Sunar Cerci, T. Yetkin

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. Parameswaran, L. Robertshaw, V.J. Smith, K. Walkingshaw Pass

Rutherford Appleton Laboratory, Didcot, United Kingdom
A.H. Ball, K.W. Bell, A. Belyaev[80], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, A. Elliot, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, 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, G.S. Chahal[81], D. Colling, J.S. Dancu, I. Das, P. Dauncey, G. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, 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, 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, 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, S.V. Gleyzer, E. Pearson, C.U. Perez, P. Rumerio[83], E. Usai, R. Yi

Boston University, Boston, Massachusetts, USA
A. Akpinar, C. Cosby, 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, F. Zhang

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
S. Bhattacharya, A. Bornheim, O. Cerri, J. Mao, H.B. Newman, G. Reales Gutiérrez, M. Spiropulu, J.R. Vlimant, C. Wang, 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

Cornell University, Ithaca, New York, USA
J. Alexander, X. Chen, D.J. Cranshaw, J. Dickinson, J. Fan, X. Fan, S. Hogan, P. Kotamnives, J. Monroy, 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, 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, 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, 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[88], M. Hohlmann, 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, G. Oh, B. Ozek, D. Pilipovic, R. Pradhan, E. Prifti, P. Roy, T. Roy, S. Rudrabhatla, 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[89], L. Emediato, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[90], O. Neogi, H. Ogul[91], Y. Onel, A. Penzo, C. Snyder, E. Tiras[92]

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

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[93], C. Rogan, C. Royon, 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, Y.M. Chen, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, B. Kronheim, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer, C. Papageorgakis, M.M. Paranjpe, E. Popova[94], 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, 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, 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, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, C. Moore, Y. Musienko[15], 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, A.M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, J.F. Schulte, A. K. Virdi, F. Wang, A. Wildridge, W. Xie, Y. Yao

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, 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[94], 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, R. Montalvo, K. Nash, 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, S. Higginbotham, T. Holmes, A.R. Kanuganti, N. Karunarathna, L. Lee, E. Nibigira, S. Spanier

Texas A&M University, College Station, Texas, USA
D. Aebi, M. Ahmad, T. Akhter, K. Androsov[63], O. Bouhali[95], R. Eusebi, J. Gilmore, T. Huang, T. Kamon[96], H. Kim, S. Luo, R. Mueller, D. Overton, A. Safonov

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, R. Loveless, J. Madhusudanan Sreekala, 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
G. Gavrilov, V. Golovtcov, Y. Ivanov, V. Kim[97], V. Murzin, V. Oreshkin, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev[†]

Authors affiliated with an institute formerly covered by a cooperation agreement with CERN
S. Afanasiev, V. Alexakhin, D. Budkouski, I. Golutvin[†], I. Gorbunov, V. Karjavine, O. Kodolova[98,94], V. Korenkov, A. Lanev, A. Malakhov, V. Matveev[97], A. Nikitenko[99,98], V. Palichik, V. Perelygin, M. Savina, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev[†100], A. Zarubin,

I. Zhizhin, Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, D. Kirpichnikov, M. Kirsanov, N. Krasnikov, I. Tlisova, A. Toropin, T. Aushev, K. Ivanov, V. Gavrilov, N. Lychkovskaya, V. Popov, A. Zhokin, M. Chadeeva[97], R. Chistov[97], S. Polikarpov[97], V. Andreev, M. Azarkin, M. Kirakosyan, A. Terkulov, E. Boos, A. Demiyanov, A. Ershov, A. Gribushin, L. Khein, V. Korotkikh, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan, V. Blinov[97], T. Dimova[97], A. Kozyrev[97], O. Radchenko[97], Y. Skovpen[97], V. Kachanov, S. Slabospitskii, A. Uzunian, A. Babaev, V. Borshch, D. Druzhkin

†: 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 an institute formerly covered by a cooperation agreement with CERN
[16]Also at Helwan University, Cairo, Egypt
[17]Now at Zewail City of Science and Technology, Zewail, Egypt
[18]Now at British University in Egypt, Cairo, Egypt
[19]Now at Cairo 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 Tbilisi State University, Tbilisi, Georgia
[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 Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
[50]Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
[51]Also at Università degli Studi Guglielmo Marconi, Roma, Italy
[52]Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
[53]Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[54]Also at Lulea University of Technology, Lulea, Sweden
[55]Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy
[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 Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
[61]Also at Saegis Campus, Nugegoda, Sri Lanka
[62]Also at National and Kapodistrian University of Athens, Athens, Greece
[63]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
[64]Also at Universität Zürich, Zurich, Switzerland
[65]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
[66]Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
[67]Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
[68]Also at Konya Technical University, Konya, Turkey
[69]Also at Izmir Bakircay University, Izmir, Turkey
[70]Also at Adiyaman University, Adiyaman, Turkey
[71]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
[72]Also at Marmara University, Istanbul, Turkey
[73]Also at Milli Savunma University, Istanbul, Turkey
[74]Also at Kafkas University, Kars, Turkey
[75]Now at Istanbul Okan University, Istanbul, Turkey
[76]Also at Hacettepe University, Ankara, Turkey
[77]Also at Erzincan Binali Yildirim University, Erzincan, Turkey
[78]Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
[79]Also at Yildiz Technical University, Istanbul, Turkey
[80]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
[81]Also at IPPP Durham University, Durham, 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 Ain Shams University, Cairo, Egypt
[89]Also at Bingol University, Bingol, Turkey
[90]Also at Georgian Technical University, Tbilisi, Georgia
[91]Also at Sinop University, Sinop, Turkey
[92]Also at Erciyes University, Kayseri, Turkey
[93]Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
[94]Now at another institute formerly covered by a cooperation agreement with CERN
[95]Also at Texas A&M University at Qatar, Doha, Qatar
[96]Also at Kyungpook National University, Daegu, Korea
[97]Also at another institute formerly covered by a cooperation agreement with CERN
[98]Also at Yerevan Physics Institute, Yerevan, Armenia
[99]Also at Imperial College, London, United Kingdom
[100]Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan