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Dependence of inclusive jet production on the anti-k_{T} distance parameter in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$

The CMS Collaboration[*]

Abstract

The dependence of inclusive jet production in proton-proton collisions with a center-of-mass energy of 13 TeV on the distance parameter R of the anti-k_{T} algorithm is studied using data corresponding to integrated luminosities up to $35.9\,\mathrm{fb}^{-1}$ collected by the CMS experiment in 2016. The ratios of the inclusive cross sections as functions of transverse momentum p_{T} and rapidity y, for R in the range 0.1 to 1.2 to those using $R = 0.4$ are presented in the region $84 < p_{\mathrm{T}} < 1588\,\mathrm{GeV}$ and $|y| < 2.0$. The results are compared to calculations at leading and next-to-leading order in the strong coupling constant using different parton shower models. The variation of the ratio of cross sections with R is well described by calculations including a parton shower model, but not by a leading-order quantum chromodynamics calculation including nonperturbative effects. The agreement between the data and the theoretical predictions for the ratios of cross sections is significantly improved when next-to-leading order calculations with nonperturbative effects are used.

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[*] See Appendix A for the list of collaboration members

1 Introduction

Quantum chromodynamics (QCD) is a gauge theory describing the strong interaction between partons (quarks and gluons). Jets are reconstructed using hadron particles produced by the fragmentation of partons in collisions [1]. Thus jets approximate the original partons created in short-distance scatterings. The production cross sections for high transverse momentum (p_{T}) partons can be calculated using perturbative QCD (pQCD). Specifically, predictions for hadron production in proton-proton collisions require models for parton showering [2–4] and nonperturbative (NP) effects such as hadronization [5] and underlying event (UE) [6]. When the fixed-order prediction in pQCD is not adequate, higher-order terms must be included using resummation methods [7–9].

The results of measurements of inclusive jet production cross sections for proton-proton collisions are typically presented using the anti-k_{T} jet algorithm [10] characterized by a distance parameter R, which is a measure of the jet size in rapidity-azimuth plane. Anti-k_{T} jets with distance parameter R are referred to as AKn jets, where $R = 0.1n$. The CMS Collaboration [11] has reported measurements at center-of-mass energy ($\sqrt{s}$) of 7 TeV [12] and 8 TeV [13] using AK5 and AK7 jets. The CMS results at $\sqrt{s} = 13\,\mathrm{TeV}$ for AK4 and AK7 jets are reported in Ref. [14]. After the application of a correction for NP and electroweak effects, the results for AK7 jets are well described by next-to-leading order (NLO) calculations based on the NLOJET++ [15] program used in the FASTNLO software package [16]. The prediction from the POWHEG [17] generator, which also computes matrix elements at NLO and is used with parton showering simulated with PYTHIA8 [18] or HERWIG++ [19], describes results well for both AK7 and AK4 jets. However, the ATLAS Collaboration has measured the production cross sections for both AK4 and AK6 jets and finds a discrepancy between the measured results and the POWHEG prediction [20]. The ATLAS Collaboration has also compared the measurements of inclusive jet production at $\sqrt{s} = 13\,\mathrm{TeV}$ with the next-to-next-to-leading order (NNLO) prediction in pQCD [21].

The measurement of a jet production cross section as a function of the distance parameter is sensitive to the details of the theoretical modeling of the perturbative and NP processes involved in the evolution of the partons. The measurement of the ratio of cross sections with two jet sizes was first performed by the ALICE Collaboration with AK2 and AK4 jets [22]. A similar study was also produced by the CMS Collaboration with AK5 and AK7 jets [23]. We explore this topic further in the present paper by extending the measurement to various values of jet size. Recently, ALICE Collaboration has also measured both the absolute cross sections of inclusive jet production and the ratio of cross sections for $R = 0.1$–0.6 in $20 < p_{\mathrm{T}} < 140\,\mathrm{GeV}$ [24]. Dependence of inclusive jet production on the distance parameter is also studied in detail in Ref. [25].

Quarks and gluons radiate secondary gluons that can be emitted outside of the catchment area of the jet definition, which is the region in rapidity-azimuth plane contributing to the jet. This lost p_{T} is calculated using a QCD splitting function, with the leading-order (LO) result [26–28] in the small-R approximation ($R \ll 1$)

$$(\delta p_{\mathrm{T}})_{\mathrm{q}} = -C_{\mathrm{F}}\frac{\alpha_{\mathrm{S}} p_{\mathrm{T}}}{\pi}\ln\left(\frac{1}{R}\right)\left(2\ln 2 - \frac{3}{8}\right) + \mathcal{O}(\alpha_{\mathrm{S}}), \tag{1}$$

for quark-initiated jets and

$$(\delta p_{\mathrm{T}})_{\mathrm{g}} = -\frac{\alpha_{\mathrm{S}} p_{\mathrm{T}}}{\pi}\ln\left(\frac{1}{R}\right)\left[C_{\mathrm{A}}(2\ln 2 - \frac{43}{96}) + T_{\mathrm{R}} n_{\mathrm{f}}\frac{7}{48}\right] + \mathcal{O}(\alpha_{\mathrm{S}}), \tag{2}$$

for gluon-initiated jets.

Here $C_F(=\frac{4}{3})$ and $C_A(=3)$ are the Casimir factors for quarks and gluons respectively, $T_R(=\frac{1}{2})$ is the SU(3) quantum number, and n_f is the number of active quark flavors. Larger values of R capture a larger fraction of the radiation.

Properties of jets are also modified by hadronization, an NP process describing the transition of partons into hadrons. As described in Ref. [29], some theoretical models parameterize the effect of hadronization by taking $\alpha_S(\mu) = \mu_I\delta(\mu - \mu_I)$, where μ_I is commensurate with the Landau pole, yielding

$$(\delta p_T)_{\text{had}} \simeq -\frac{2C\mathcal{A}(\mu_I)}{\pi R} + \mathcal{O}(R), \tag{3}$$

in the small-R limit, where $C = C_F(C_A)$ for quark (gluon) initiated jets, and $\mathcal{A}(\mu_I)$ is related to the scale appearing in the calculations of hadronization. Losses are again minimized at larger values of R.

The algorithm defining the jets can also select particles from the underlying event, which in general involves low momentum transfer. These particles typically have low p_T. The energy density (Λ_{UE} per unit y) from these sources is approximately uniform over the jet area, and their contribution to the jet p_T is approximately given [28, 30] by

$$(\delta p_T)_{UE} \simeq \frac{1}{2}\Lambda_{UE}R^2, \tag{4}$$

for small R values.

Since, as discussed above, the contributions of various perturbative and NP effects depend on the jet size, and because radiation and hadronization are different for jets initiated by quarks and by gluons, comparisons of jets with different cone sizes yield information about these processes, and can be used to improve theoretical calculations.

In this paper, we present measurements of the ratio of the cross section for inclusive anti-k_T jets with distance parameters of $R = 0.1, 0.2, \ldots, 1.2$ to that of AK4 jets. The results are compared with predictions from different Monte Carlo (MC) generators, involving matrix element calculations at different orders and utilizing different parton shower and hadronization models. Predictions for cross section ratios have also been obtained using a pQCD calculation at NLO that uses the following convention

$$\text{Ratio}(R, p_T) = \frac{\left(\frac{d\sigma^{(R)}}{dp_T} - \frac{d\sigma^{(0.4)}}{dp_T}\right)}{\frac{d\sigma^{(0.4)}}{dp_T}} + 1, \tag{5}$$

where R is the anti-k_T jet distance parameter, and $R = 0.4$ is taken as the reference jet size. The terms in Eq. (5) are differential cross sections for three-jet production and are calculated at fixed-order using NLOJET++ with terms up to α_S^4 [31, 32]. Measurements are restricted to $p_T < 1588\,\text{GeV}$ because of the large experimental uncertainty in the calibration of high energy jets, which was not optimized for the cross section ratios.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [11].

The silicon tracker measures charged particles within the range $|\eta| < 2.5$. It consists of 1440 silicon pixel and 15 148 silicon strip detector modules. For nonisolated particles of $1 < p_{\mathrm{T}} < 10\,\mathrm{GeV}$ and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_{T} and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [33]. In the barrel section of the ECAL, an energy resolution of about 1% is achieved for unconverted or late-converting photons that have energies in the range of tens of GeV. The remaining barrel photons have a resolution of about 1.3% up to $|\eta| = 1$, rising to about 2.5% at $|\eta| = 1.4$. In the endcaps, the resolution of unconverted or late-converting photons is about 2.5%, while the remaining endcap photons have a resolution between 3 and 4% [34]. In the region $|\eta| < 1.74$, the HCAL cells have widths of 0.087 in η and 0.087 radians in azimuth (ϕ). In the η-ϕ plane, and for $|\eta| < 1.48$, the HCAL cells map on to 5×5 arrays of ECAL crystals to form calorimeter towers projecting radially outwards from close to the nominal interaction point. For $|\eta| > 1.74$, the coverage of the towers increases progressively to a maximum of 0.174 in $\Delta\eta$ and $\Delta\phi$ [35]. Within each tower, the energy deposits in ECAL and HCAL cells are summed to define the calorimeter tower energies, subsequently used to provide the energies and directions of hadronic jets. When combining information from the entire detector, the jet energy resolution amounts typically to 15% at 30 GeV, 10% at 100 GeV, and 5% at 1 TeV at $|\eta| < 0.5$, while at $|\eta| = 2.0$ the jet energy resolution increases by 1–2% at low p_{T} [36].

Events of interest are selected using a two-tiered trigger system [37]. 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. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing that reduces the event rate to around 1 kHz before data storage.

3 Jet reconstruction

The CMS particle-flow algorithm [38] reconstructs and identifies each individual particle in an event with an optimized combination of information from the various elements of the CMS detector. The energy of photons is obtained from the ECAL measurement. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track as determined using the tracker and the muon system. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy deposits.

For each event, hadronic jets are clustered from these reconstructed particles (particle-flow candidates) using the infrared- and collinear-safe anti-k_{T} algorithm [10], as implemented in the FASTJET package [39]. The jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5 to 10% of the momentum of the particle-level jets reconstructed using stable particles (lifetime $>30\,\mathrm{ps}$) excluding neutrinos, for jet $p_{\mathrm{T}} > 50\,\mathrm{GeV}$ and rapidity $|y| < 2.5$. Additional proton-proton interactions within the same or nearby bunch crossings (pileup) can contribute additional tracks and calorimetric energy depositions, increasing the apparent jet momentum. To mitigate this effect, tracks identified as originating from pileup vertices are discarded and an offset correction [40] is applied to correct for remaining contributions [41]. Additional selection criteria are applied to each jet to remove jets potentially dominated by instrumental effects or reconstruction failures [42]. These criteria consist of the following conditions: the energy fraction of the jet carried by neutral hadrons and photons should be less than 90%, the jet should have at least two constituents, and at least one of those should be a charged hadron. This set of criteria is more than 99% efficient for genuine jets.

The missing transverse momentum vector ($\vec{p}_{\mathrm{T}}^{\text{miss}}$) is defined as the negative vector sum of the p_{T} of all reconstructed particle-flow objects in an event; its magnitude is denoted using $p_{\mathrm{T}}^{\text{miss}}$. A set of algorithms is used to reject events with anomalous high-$p_{\mathrm{T}}^{\text{miss}}$ arising from a variety of reconstruction failures, detector malfunctions, or noncollision backgrounds; these algorithms are designed to identify more than 85–90% of the spurious high-$p_{\mathrm{T}}^{\text{miss}}$ events with a misidentification rate of less than 0.1% [43].

Jet energy corrections are derived using simulated PYTHIA inclusive jet samples discussed in Sec. 4.2 so that the average measured transverse momentum of jets is the same as the corresponding particle-level jets. This methodology is used to derive nominal jet energy correction factors only for AK4 and AK8 jets. The nominal corrections for AK4 jets are used for AK1 to AK6 jets. For larger jet sizes ($R > 0.6$) the nominal correction factors derived for AK8 jets are applied. To account for the differences in the distance parameter, an extra correction factor (C^{R}) is determined in case of each distance parameter for the average pileup condition based purely on simulation and applied to the corresponding jets. A detailed discussion on the derivation of C^{R} is made later in this section. Measurements of the momentum balance in dijet, photon+jet, Z+jet, and multijet events are used to determine any residual differences between the jet energy scale in data and simulation, and appropriate corrections are made [41]. The in situ techniques are based on the missing transverse momentum projection fraction method, which is fundamentally insensitive to jet size, and on particle-flow reconstruction, whose reliance on tracking and particle-flow hadron calibration further reduces differences in energy response between jets of different radii. Residual corrections are derived using only AK4 jets and applied to jets of all the sizes.

The factor C^{R} is derived in the following way. In simulated PYTHIA inclusive jet samples, the detector- and particle-level jets are required to be geometrically matched satisfying $\Delta R < (0.5 \times \text{jet size})$; the ratio of the average detector-level jet p_{T} to the particle-level jet p_{T} is calculated as a function of the particle-level jet p_{T} for all the jet sizes and then used as an extra correction factor C^{R} for both data and simulation. The C^{R} factors are also derived using simulated HERWIG++ inclusive jet samples, so the jet energy response is calibrated to unity for all the jet sizes in HERWIG++ samples as well. The difference in C^{R} factors derived using PYTHIA and HERWIG++ inclusive jet samples is used to estimate the systematic uncertainties in C^{R} separately for each of the distance parameters. The C^{R} factors are important to ensure that the jet energy resolution in simulation is properly corrected to match the data without changing the jet energy scale, and that PYTHIA and HERWIG++ are on equal footing with respect to jet energy scale and resolution when unfolding the data in Sec 5.1. The value of the C^{R} factor ranges from 0.95 to 1.10 depending on the energy, rapidity, and size of the reconstructed jets; this correction is significant only for very small and very large jet sizes. However, C^R corrects the jet energy response for different jet sizes at the level of simulation only and no dedicated residual correction is derived for data as a function of jet size. Nevertheless, it has been checked that the difference in average p_T between AK8 and AK4 jets pointing in the same direction in data is smaller than the difference of the same between PYTHIA and HERWIG++ simulations.

4 Event samples

4.1 Collision data

Proton-proton collision data collected by the CMS experiment during 2016, corresponding to an integrated luminosity of 35.9 fb^{-1}, are used for this analysis. The data sample is collected using single-jet triggers, which select events containing at least one AK8 jet, formed from particle-flow candidates, with p_T exceeding one of the threshold values listed in Table 1. Absolute trigger efficiency is measured with a tag-and-probe procedure [44] using the events having a back-to-back dijet topology, where the tag jet is matched to a single-jet trigger, and the efficiency is measured using the probe jet.

Because of limited bandwidth and storage space, only a fraction of the events satisfying the triggering condition with lower thresholds are recorded. For this reason, in each jet-p_T bin, only the trigger that has the highest effective integrated luminosity and is also more than 99% efficient is used.

Offline, events are required to contain at least one jet with p_T above that value for which the trigger is 99% efficient. These values are also used to define the p_T bins for the measurement.

Table 1: Trigger p_T thresholds and effective integrated luminosity of the HLT triggers based on AK8 jets. These triggers were not active during the initial part of data taking in 2016, thus the maximum integrated luminosity is less than 35.9 fb^{-1}.

Trigger p_T (GeV) threshold	p_T (GeV) range for analysis	Effective integrated luminosity (fb^{-1})
40	74–97	0.000050
60	97–133	0.00033
80	133–196	0.00104
140	196–272	0.0105
200	272–330	0.084
260	330–395	0.517
320	395–468	1.54
400	468–548	4.68
450	548–∞	33.4

Similarly to other CMS publications [12, 13], we require that $p_T^{\mathrm{miss}} / \sum_i {p_T}^i < 0.3$, where the index i runs over all particle-flow candidates in the event and $\sum_i {p_T}^i$ denotes the scalar sum of transverse momenta; this rejects calorimeter noise and a part of electroweak backgrounds from the production of $\mathrm{W}(\rightarrow \text{lepton}) + \text{jets}$, $\mathrm{Z}(\rightarrow \text{lepton}) + \text{jets}$, and top quarks when the top quarks decay to final states with leptons.

4.2 Simulated samples

The data are compared to predictions from several different MC generators, listed below.

The PYTHIA v8.212 [18] generator computes matrix elements only for 2 → 2 Feynman diagrams at LO; the missing orders in the perturbation series are approximated using p_{T}-ordered dipole showering. The PYTHIA generator employs the empirical Lund string model to hadronize the partons. The NNPDF2.3 [45] LO parton distribution function (PDF) set is used to describe the momentum fractions carried by the partons within the incoming protons; our UE model is the CUETP8M1 tune [46] (CMS Underlying Event Tune for PYTHIA8 based on Monash [47]), which was derived by tuning the model parameters using minimum bias data collected by the CMS Collaboration.

The HERWIG++ v2.7.1 [19] generator also calculates only 2 → 2 scatterings, but has a different fragmentation and hadronization model than PYTHIA. It employs angular-ordered showers to radiate the partons and a cluster model to produce the hadrons. The NNPDF3.0 LO PDF set is used, and the UE modeling is described by the CUETHppS1 tune [46].

The MADGRAPH (MADGRAPH5_aMC@NLO V5 2.2.2) [48] generator provides calculations of matrix elements with up to four outgoing partons in the final state at LO. The partons are showered and hadronized with PYTHIA combined with MADGRAPH, using the MLM merging scheme [49]. The NNPDF3.0 NLO PDF set and the CUETP8M1 UE tune are used here as well.

The POWHEG v2 [17, 50] generator computes the dijet production cross section at NLO in pQCD. Successive parton showering, hadronization, and UE modeling is performed either using PYTHIA with the CUETP8M1 tune (referred to as PH+P8 in the figures) or HERWIG++ with the CUETHppS1 and EE5C [51] tunes (referred to as PH+Herwig in the figures). The NNPDF3.0 NLO PDF set is used for POWHEG as well, and the value of the h_{damp} parameter in POWHEG is 250 GeV.

The HERWIG 7.1.1 [52] generator, used with the NNPDF3.1 NNLO PDF set with $\alpha_{\mathrm{S}}\ (m_{\mathrm{Z}}) = 0.118$, also evaluates the matrix elements for dijet production at NLO, and is matched to the HERWIG7 parton shower using the FxFx [53] jet merging method. The CH2 tune is used to model UE. This prediction is referred to as HERWIG7.

Fixed-order predictions for dijet production at NLO are computed using NLOJET++ within the framework of the FASTNLO package. To account for the effects of hadronization, an additional correction factor is used, which will be discussed in Section 5.2. This prediction is referred to as NLO⊗NP in the figures. Predictions from NLOJET++ are obtained using the CT14NLO PDF set.

Recently, a prediction for single-inclusive jet production using joint resummation in the threshold energy in the small-R limit has been computed at next-to-leading logarithmic (NLL) accuracy in the framework of Soft Collinear Effective Theory in Refs. [9, 54]; the CT14NLO PDF set is also used for this prediction, which is referred to as (NLO+NLL). This prediction is compared with the measurements reported in this paper.

5 Measurement of cross sections and cross section ratios

The inclusive jet cross section is calculated as

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} = \frac{1}{\epsilon\mathcal{L}_{\mathrm{int}}}\frac{N_{\mathrm{jets}}}{\Delta p_{\mathrm{T}}\Delta y}, \tag{6}$$

where N_{jets} is the number of jets in a p_{T} and y bin, $\mathcal{L}_{\mathrm{int}}$ is the integrated luminosity of the data set, ϵ is the product of trigger and event selection efficiencies, and Δp_{T} and Δy are the bin widths in p_{T} and y. The widths of p_{T} bins are proportional to the jet energy resolution and increase with jet p_T. The ratios of cross sections for the different jet sizes with respect to AK4 jets is calculated as the bin-by-bin quotient of the cross sections of AKn ($n= 1, 2, ..., 12$) and AK4 jets respectively; in the ratios, all the terms in Eq. (6) except N_{jets} and ϵ cancel.

5.1 Unfolding

To correct for detector inefficiencies and resolution, a number of methods available in the ROOUNFOLD package [55] are used to unfold the jet p_T spectra.

The nominal choice of unfolding technique in this paper is the D'Agostini unfolding [56] with early stopping. Up to 5–8 iterations are used depending on jet size and rapidity region. An alternative method is singular value decomposition (SVD) [57]. A third method is called bin-by-bin [58], which multiplies the particle-level spectra by the ratio between the detector-level spectra in data and simulation.

The SVD and bin-by-bin techniques are used to cross-check the result of unfolding with the D'Agostini unfolding. As an additional cross-check, unfolding is also performed using a χ^2 minimization without regularization using the TUNFOLD package [59].

Response matrices between p_T spectra of detector-level and generator-level jets are obtained by one-to-one matching of the nearest detector- and particle-level jets, excluding matches with $\Delta R > (0.5 \times \text{jet size})$, where ΔR denotes the distance between detector- and particle-level jets in the rapidity-azimuth plane. This criterion leads to almost 100% matching efficiency between the detector-level and the particle-level jets. Response matrices are constructed, for all rapidity and jet sizes, from the CMS detector simulation based on GEANT4 [60] using simulated samples from three MC event generators, PYTHIA, HERWIG++, and MADGRAPH. For the particle-level results, response matrices based on the PYTHIA simulation are used for the unfolding. The response matrix for AK4 jets in the first rapidity region for the PYTHIA sample is shown in Fig. 1. The response matrix is diagonal, which shows that unfolding works well.

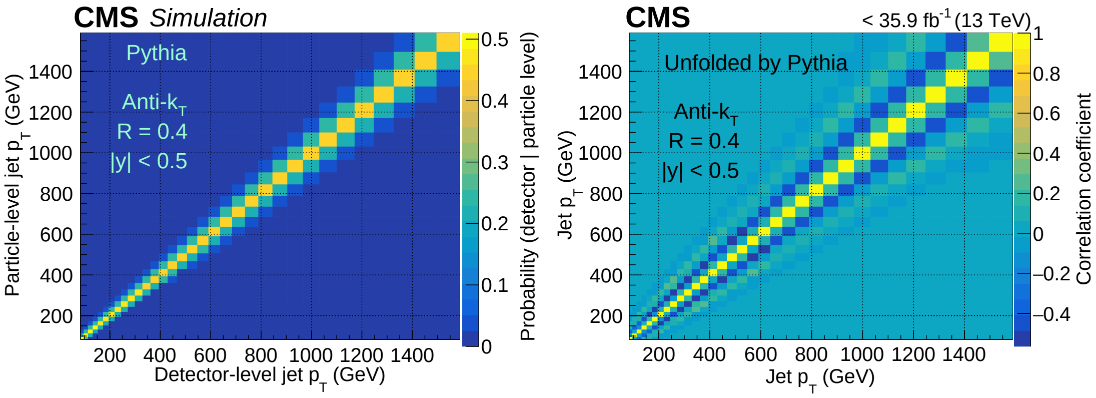

Figure 1: Response matrix constructed from a simulation of a sample generated using PYTHIA, for AK4 jets in the $|y| < 0.5$ bin (left). A correlation matrix generated after data is unfolded by the D'Agostini unfolding using PYTHIA simulation for AK4 jets (right).

For both the D'Agostini and SVD unfolding techniques, the nearest neighbor p_T bins are correlated, and the next-to-nearest bins are anti-correlated (right plot in Fig. 1 for AK4 jets with the D'Agostini unfolding). Next-to-next-to-nearest bins are again correlated.

Several cross-checks are made regarding the unfolding. To investigate possible bias due to the choice of MC generator used to construct the response matrices, event samples are generated using three different generators: PYTHIA, HERWIG++, and MADGRAPH, followed by the detector simulation whose output is scaled and smeared independently for each generator to match the energy scale and resolution of jets in data. Detector-level distributions from each of the samples are unfolded using these three response matrices, and the unfolded distributions are compared to the corresponding particle-level distributions. No evidence for significant bias is observed. Similarly, the data are unfolded using response matrices from these three simulated samples; the differences among the unfolded spectra are within systematic uncertainties corresponding to the correction factor C^R. The same conclusion holds when comparing the unfolded distributions obtained using different unfolding techniques, such as D'Agostini, SVD, bin-by-bin, and χ^2 minimization.

5.2 Nonperturbative corrections for fixed-order calculations

Fixed-order NLO calculations yield predictions for the partonic fields, but in experimental measurements, jets are composed of hadrons. To evolve the parton-level prediction to the hadron level, NP corrections are calculated and applied. Although generators such as PYTHIA and HERWIG come with MC-based phenomenological simulation of these processes, NLOJET++ does not. The impact of NP on the NLOJET++ prediction is approximated as a multiplicative correction factor as follows. The NP correction is the ratio of an observable from a generator, which includes NP effects with hadronization and multiple parton interaction (MPI) processes switched on, to the same observable obtained from the same generator without NP effects, i.e., by switching off hadronization and MPI processes.

Simulated POWHEG+PYTHIA (CUETP8M1 tune) and POWHEG+HERWIG++ (EE5C and CUETHppS1 tunes) samples are used to compute NP factors for all the jet sizes in all the p_{T} and rapidity bins. The average NP correction obtained from the POWHEG+PYTHIA and POWHEG+HERWIG++ (EE5C) samples is defined as the final NP correction, and the envelope of the differences is taken as its uncertainty.

Figure 2 depicts the NP corrections for the cross section ratio of the AK2 and AK8 jets with respect to the AK4 jets. Hadronization corrections are larger for smaller jet sizes, and MPI introduces a larger correction for large-R jets. Because both hadronization and MPI are important for low-p_{T} jets, the NP correction is also significant in the low-p_{T} portion of phase space; in the high-p_{T} region, the NP correction factor approaches 1. For AK4 jets, the corrections for hadronization and MPI almost cancel, and the resulting NP correction is close to unity throughout the p_{T} range. At around $p_{\mathrm{T}} = 85\,\mathrm{GeV}$, the correction goes down to 0.8 for AK2 jets, and it goes up to 1.25 for AK8 jets.

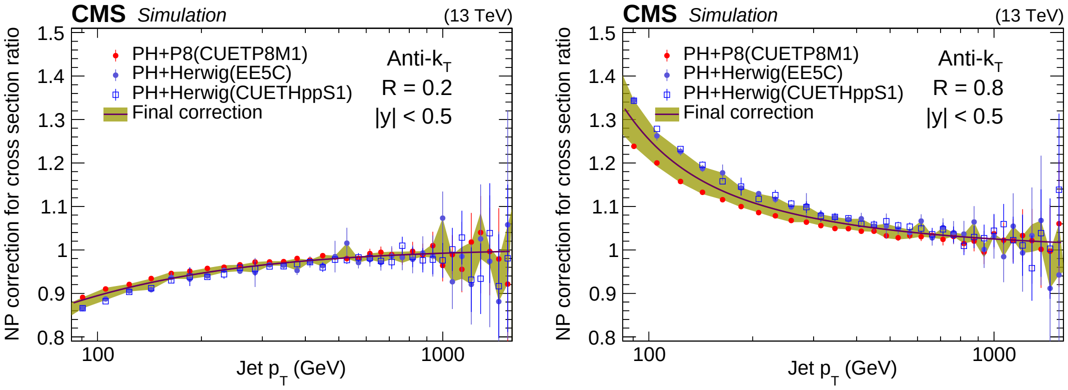

Figure 2: Nonperturbative correction factor for the cross section ratio of inclusive AK2 (left) and AK8 jets (right) with respect to the AK4 jets in the rapidity bin $|y| < 0.5$. Vertical error bars represent the statistical uncertainty of the NP correction for different predictions.

6 Experimental uncertainties in the measurement

Multiple sources of uncertainty affect the precision of the measurement: statistical, jet energy scale (JES) uncertainties, jet energy resolution (JER) uncertainties, and uncertainties in the pileup condition. We also include systematic uncertainties corresponding to the use of JES corrections derived for one R along with the R-dependent C^R factor on jets formed using another R.

To estimate the statistical uncertainty in data, the *jackknife resampling* [61] method is used. In this technique, ten different data samples, each containing 90% events of the full data sample, are constructed such that the removed 10% of the events are complementary for each subsample. These subsamples are chosen in such a way that they correspond to very similar phase space regions. The statistical uncertainty is the standard deviation of the ten distributions multiplied by $\sqrt{9} = 3$. The resulting statistical uncertainty is roughly <1% for jet $p_{\mathrm{T}} < 1\,\mathrm{TeV}$, and increases at high jet p_{T}. A similar procedure is followed to estimate the statistical uncertainty due to the response matrices used for unfolding. Here also, ten subsets of the simulated sample are considered, each with a nonoverlapping 10% of events removed. The distributions in data are unfolded using each subsample, and the standard deviation of ten unfolded distributions, multiplied by a factor of 3, is the statistical uncertainty due to the response matrices; in this case the statistical uncertainty is roughly 0.5–1.0% for the cross section ratio throughout the p_{T} range.

The jet energy scale corrections have a number of uncertainties corresponding to the techniques used and the amount of pileup. The JES has an uncertainty of about 1–2% in the central region [62]. The uncertainty is larger in the forward region and at low jet p_{T}. To evaluate the uncertainty in the measurement of the cross section ratio, the JES is varied upwards and downwards by the uncertainties corresponding to different sources. The difference in the unfolded cross section ratios using the nominal and varied JES is the uncertainty. Twenty-seven different sources of JES uncertainty are considered individually and added in quadrature. The uncertainty because of JES is very similar for all the jet sizes, except for the pileup component. The uncertainties mostly cancel out in the ratio, but there is a small residual, which is about 0.5–1.0% for $|y| \leq 2.0$ up to 1 TeV of jet p_{T} and goes up to 2% for very high jet p_{T}.

To estimate the uncertainty in the ratio of cross sections with respect to that of AK4 jets because of using JES corrections derived for one value of R with jets from other values of R and then applying the C^R factor, the standard calibration factors from the AK8 jets are applied to AK1 to AK6 jets, and, for jets of other sizes, the calibration factors for the AK4 jets are used. The C^R factors for jets of all sizes are derived for this scenario. The systematic uncertainties in the inclusive jet cross section ratios are evaluated using the difference between the results obtained by these two procedures. The uncertainty coming from the C^R correction is more significant for larger jet sizes.

The C^R calibration factors are derived using both PYTHIA and HERWIG++ simulations as a function of jet p_{T} in different rapidity bins for all jet sizes. The difference in the resulting C^R corrections is an 'R-dependent' uncertainty, and it is defined such that it vanishes for AK4 jets, which is used as the reference.

The JER and its associated uncertainty are obtained from a dijet balance technique [62]. The JER in data is worse than in simulation. To match the JER in data and simulation, a spreading is added to the jets in simulation. Here also, as in the case for the JES, cross section ratios are obtained using upward and downward variations of the energy resolution factors for simulation while unfolding the data. The difference with respect to the nominal unfolding is used as

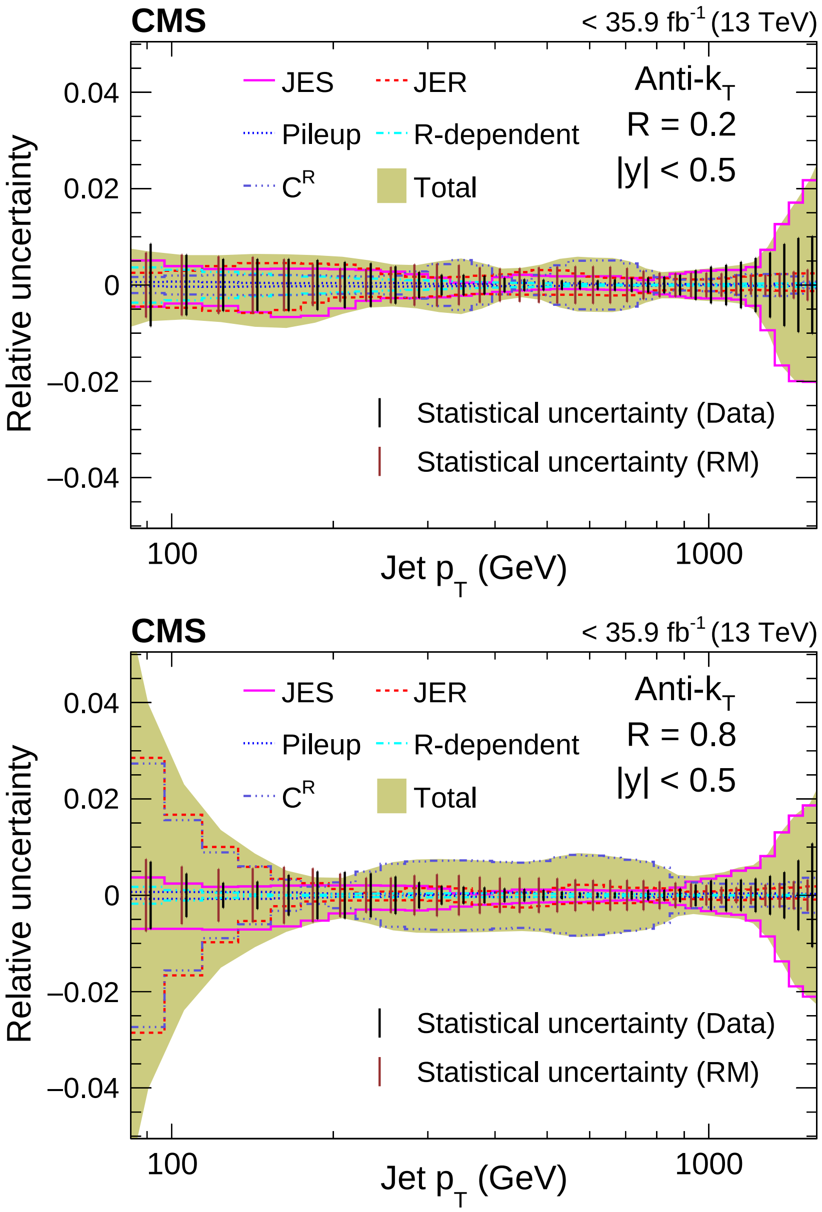

Figure 3: Total uncertainty (relative) from experimental sources for the ratio of cross section of inclusive jets of size 0.2 (top) and 0.8 (bottom) with respect to that of AK4 jets in the rapidity bin $|y| < 0.5$. Statistical uncertainties are also overlaid as vertical black (red) bars for data (response matrices, RM, in simulation).

an estimate of the uncertainty. The uncertainty due to JER is more important for large-R jets at low p_{T}. The uncertainty also grows in regions of larger rapidities.

To match the pileup conditions in data and in MC simulation, pileup profile weighting is performed for the simulated samples. The weighting factors depend on the total inelastic cross section; we vary its nominal value of 67.5 mb [63] up and down by its uncertainty of 2.6% when reconstructing the response matrices, and take the difference in the unfolded data as the uncertainty. This source of systematic uncertainty is larger at low p_{T} for large jet sizes, although its absolute value is small.

The uncertainties from different experimental sources are added in quadrature, and the total uncertainty is shown in Fig. 3 for the cross section ratios of the AK2 and AK8 jets with respect to the AK4 jets.

In the cross section ratio, many of the systematic uncertainties almost cancel, so the final uncertainty is small. The statistical component of the uncertainty is also shown in the same figure.

The experimental systematic uncertainty at low p_{T} and large R is dominated by the pileup uncertainty. The JER uncertainty is also larger there because of additional spreading caused by pileup. At intermediate p_{T}, the uncertainty is dominated by the C^R uncertainty; at high p_{T} the JES dominates the experimental uncertainty because the cross sections fall very steeply and event counts are small at high jet p_{T}. The sizes of the statistical uncertainties are similar to those of the total systematic uncertainties and are dominated by data at high p_{T} and by the uncertainty in the response matrix because of the number of MC events at intermediate p_{T}. At low p_{T}, the data have similar statistical uncertainties as the simulated sample, since the corresponding triggers are prescaled.

Another source of uncertainty, which is relevant only for jets with $R > 0.8$, is the uncertainty in the trigger efficiency correction. The AK8 single-jet triggers are not fully efficient for larger jet sizes near the trigger turn-on points for AK8 jets; an efficiency correction is applied for those jet sizes following Eq. (6). The difference in the absolute value of the trigger efficiency from the curve used to model the variation of trigger efficiency as a function of jet p_{T} is the uncertainty. The size of this uncertainty is 0.5–1.0% throughout the p_{T} range.

7 Theoretical uncertainties

Apart from the systematic uncertainties due to experimental sources, theoretical calculations and generators have uncertainties in their predictions for the cross section ratio. For the fixed-order predictions, the contributing factors include the choice of renormalization and factorization scales (scale), the PDF uncertainty (PDF), the uncertainty from α_{S}, and the uncertainty due to the NP corrections (NP correction).

In the matrix element computation, the coupling (α_{S} for QCD) is evaluated at an energy scale known as the renormalization scale (μ_{R}). Another scale is chosen to compute the PDF, in order to resum initial-state radiation below that scale, called the factorization scale (μ_{F}). For the fixed-order calculations, both are set equal to the p_{T} of individual jets. The scale uncertainty is evaluated using the following combinations of factors for (μ_{R}, μ_{F}) : (2, 1), (1, 2), (0.5, 1), (1, 0.5), (2, 2), (0.5, 0.5). The envelope of the variations is the scale uncertainty in the prediction. Scale variations in the numerator and the denominator of the ratio of cross sections are fully correlated since the underlying parton configuration is the same. This is one of the largest sources of theoretical uncertainties.

The PDFs are determined using data from several experiments. The PDFs therefore have uncertainties from the experimental measurements, modeling, and parameterization assumptions. The resulting uncertainty is calculated according to the prescription of CT14 [64] at the 90% confidence level and then scaled to the 68.3% confidence level. The PDF uncertainty is independent of jet size within statistical uncertainties, and thus cancels in the ratios.

The cross section measurement for inclusive jets depends on the value of α_S. In the NLOJET++ prediction, its value (0.118) is varied by ±0.001. The uncertainty is taken as the difference between the results with varied and nominal values of α_S and this difference is scaled to correspond to $\Delta\alpha_S \simeq 0.0015$, as recommended in Ref. [65]. For the jet cross section ratio, the uncertainty due to the α_S variation in the numerator and denominator cancels.

As mentioned in Section 5.2, the envelope of the differences between the NP correction factors obtained using different parton showering algorithms to determine the NP correction is the uncertainty in the NP correction. The uncertainty is significant only at low p_T.

All these uncertainties are added in quadrature, and are collectively referred as the theoretical uncertainty in what follows.

The correlation between the experimental and the theoretical uncertainties is not studied.

8 Results

8.1 Comparison of ratio of cross sections

The ratios of cross sections with respect to the AK4 jets are shown in Fig. 4 in the central region ($|y| < 0.5$) for all the jet sizes using unfolded data and the prediction from the NLO MC generator POWHEG with PYTHIA parton showering; they are offset by fixed quantities for clarity.

The NLO POWHEG generator, interfaced with the parton showering model, describes the data well at moderate values of jet size, but there is a deviation at low p_T for very large values of jet size.

The ratios of the cross sections of inclusive AK2 and AK8 jets with respect to those of AK4 jets are computed at LO and NLO in pQCD, following Eq. (5), with NLOJET++ for the most central region ($|y| < 0.5$). The comparison with data is shown in Fig. 5. Both the LO and NLO predictions are systematically below data for AK8 jets and above data for AK2 jets. The NP correction is essential to describe the trend in data below medium jet p_T values. Also, the NLO calculation improves data-theory agreement significantly over LO, bringing data and theoretical prediction into agreement within statistical and systematic uncertainties at $p_T > 1000\,\text{GeV}$ for both AK2 and AK8 jets. Resummed calculations bring the theoretical prediction even closer to the data, especially for AK8 jets. The uncertainty corresponding to the resummed calculations is within 5% for cross section ratio, and is not shown here to avoid congestion in the figure.

8.2 Variation of the ratio of cross sections with jet size

The cross section is determined as a function of p_T for both data and theoretical predictions. The numbers are then divided by the cross section for the AK4 jets in the same p_T and rapidity window separately for data and each theoretical prediction, and presented in Fig. 6, in three ranges of p_T for the most central ($|y| < 0.5$) and the most forward ($1.5 < |y| < 2.0$) regions as a function of jet size. Almost all the MC simulations involving resummation via parton shower can describe the trend with jet size seen in data, whereas the LO calculation exhibits different

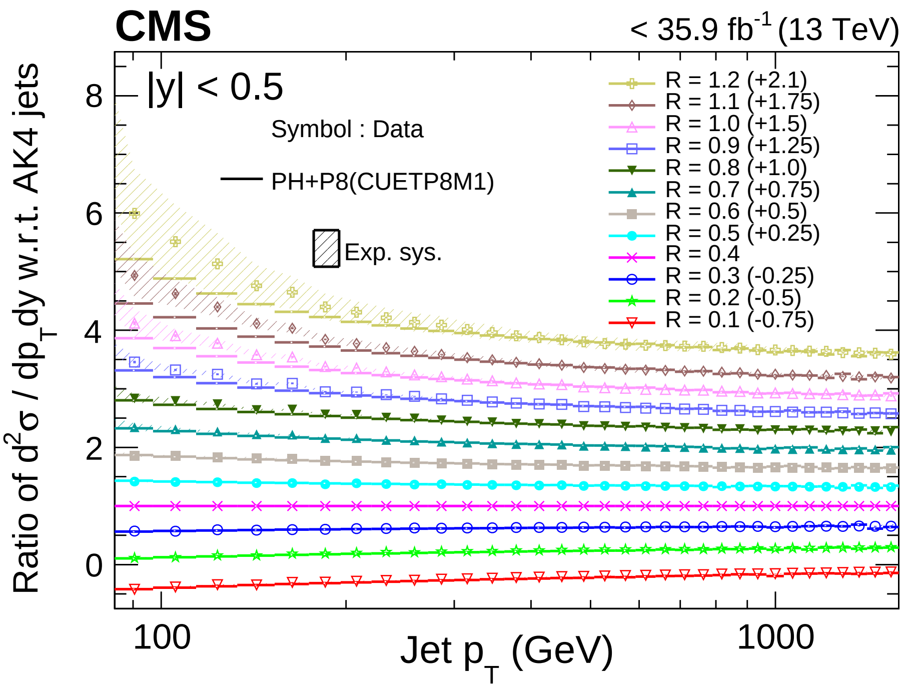

Figure 4: Comparison of the ratio of the differential cross sections of jets of different sizes with respect to that of AK4 jets from data and from NLO predictions using POWHEG+PYTHIA (CUETP8M1 tune) in the region $|y| < 0.5$. Colored symbols indicate data and colored lines represent prediction from simulation. Offsets by the amount written in the parentheses have been added to the corresponding data points to separate the results for different jet sizes.

behavior. Prediction from NLO calculation, as shown in $|y| < 0.5$, improves significantly the description of cross section ratio, as observed in data, for small jet sizes, and lies between the LO prediction and data for large jet sizes. Analytic calculations with joint resummation, available for jet sizes up to 0.8, provide an advancement with respect to fixed-order predictions, and lead to a better agreement with data. Similar behavior is observed in all the rapidity regions reported.

9 Summary

A measurement has been made of the ratio of cross sections of inclusive anti-k_T jets of multiple sizes with respect to jets with the distance parameter $R = 0.4$; this is the first such result from the CMS Collaboration. Because of cancellation of many experimental and theoretical systematic uncertainties for the ratio, it is more sensitive to perturbative and nonperturbative effects than the absolute cross section measurement; the experimental systematic uncertainty in the cross section ratio is of similar size as the statistical uncertainty, whereas the theoretical uncertainty is dominated by the choice of the renormalization and factorization scales.

From the ratio measurement, we observe that the nonperturbative correction is important in describing the data at low transverse momentum. Thus, the modeling of nonperturbative effects, such as hadronization and the underlying event has a significant impact on the description of the data in different regions of phase space.

Finally, the variation of the ratio of cross sections with jet size R emphasizes the importance of the inclusion of parton showering algorithms to capture the effects of higher-order terms in the perturbation series by the resummation approach, which are absent in the case of fixed-order

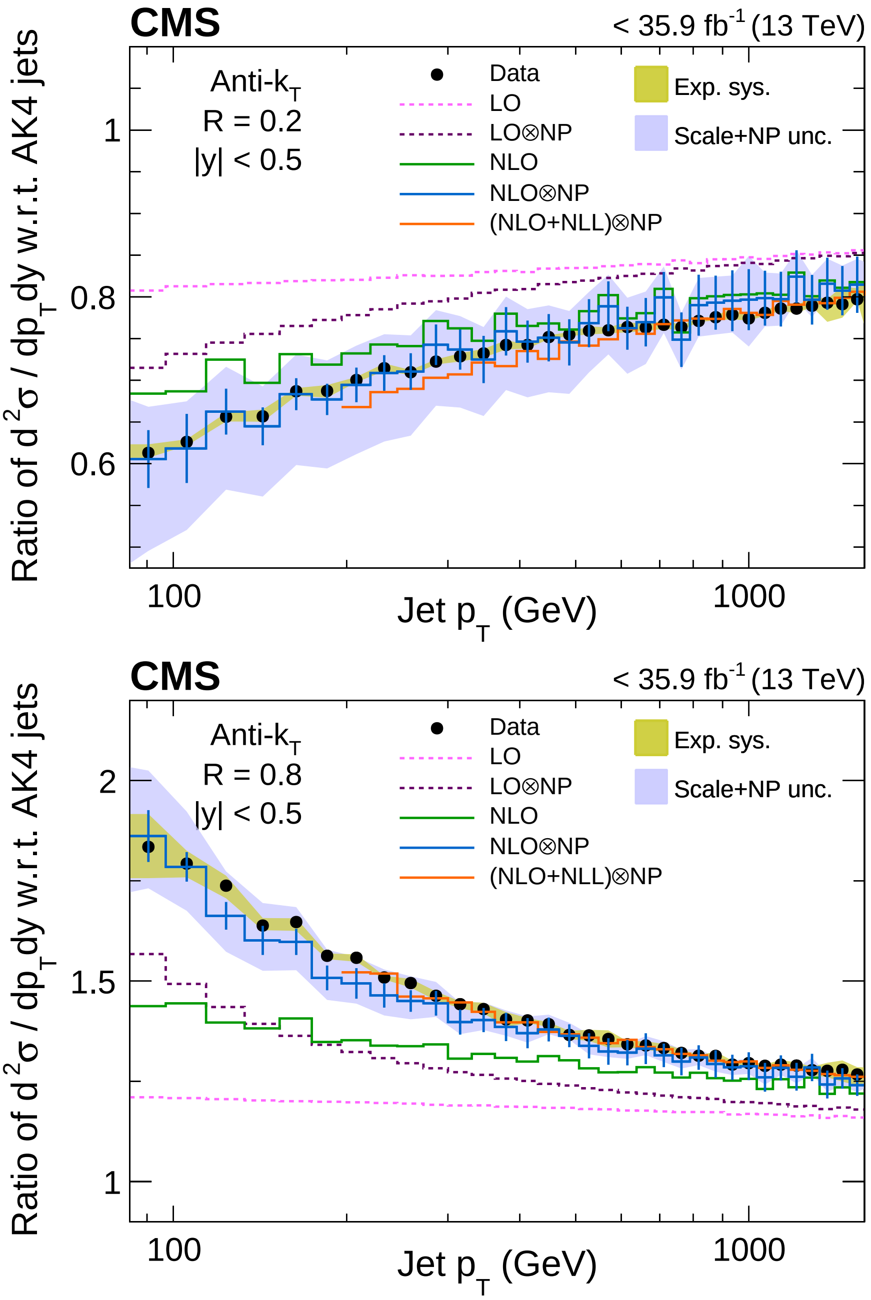

Figure 5: Comparison of the ratios of differential cross sections for the AK2 (upper) and AK8 (lower) jets with respect to that of AK4 jets from data and pQCD predictions using NLOJET++ in the region $|y| < 0.5$. Black symbols indicate data and colored lines represent pQCD predictions. Statistical uncertainties are shown as vertical bars for the data and the NLO⊗NP prediction. The yellowish olive region around data represents the experimental systematic uncertainty whereas the region shaded in light blue color around NLO⊗NP prediction shows the theoretical uncertainty in the prediction.

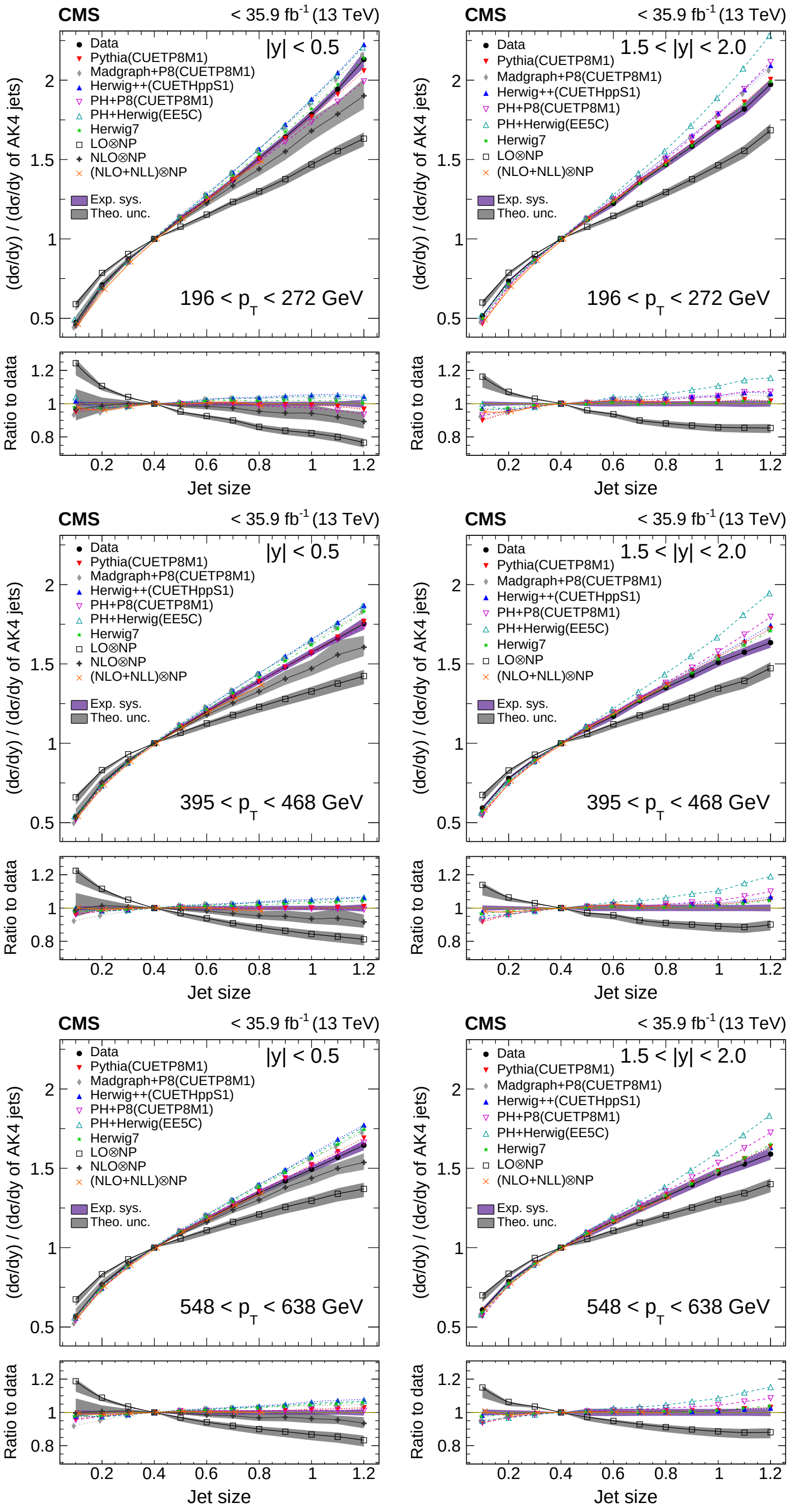

Figure 6: Comparison of the ratio of cross sections of inclusive jets of various sizes with respect to AK4 jets, as a function of jet size in different regions of jet p_T in data, and for multiple theoretical predictions in rapidity bins $|y| < 0.5$ (left column) and $1.5 < |y| < 2.0$ (right column) at particle level. When the dijet production cross section ratio is presented using pure NLO predictions for two jet sizes, the ratio becomes LO at α_S; this is quoted as LO⊗NP in the figure. Points corresponding to a particular prediction are connected via lines to guide the eye. Experimental uncertainties in the ratio of cross sections are shown with bands around the data points, whereas theoretical uncertainties are shown with the bands around the fixed-order predictions.

computation. This is also demonstrated by the analytic calculations using joint resummation in threshold for single jet production, and jet size. Therefore, this study shows the importance of final-state radiation modeled in Monte Carlo simulation to describe the data, and also implies that the differences between various parton showering and hadronization models are significant.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A.M. Sirunyan[†], A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria
W. Adam, F. Ambrogi, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth[1], M. Jeitler[1], N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, J. Schieck[1], R. Schöfbeck, M. Spanring, D. Spitzbart, W. Waltenberger, C.-E. Wulz[1], M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus
V. Drugakov, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
M.R. Darwish, E.A. De Wolf, D. Di Croce, X. Janssen, A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haevermaet, P. Van Mechelen, S. Van Putte, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium
F. Blekman, E.S. Bols, S.S. Chhibra, J. D'Hondt, J. De Clercq, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders

Université Libre de Bruxelles, Bruxelles, Belgium
D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, L. Favart, A. Grebenyuk, A.K. Kalsi, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom

Ghent University, Ghent, Belgium
T. Cornelis, D. Dobur, I. Khvastunov[2], M. Niedziela, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
O. Bondu, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, V. Lemaitre, J. Prisciandaro, A. Saggio, M. Vidal Marono, P. Vischia, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
F.L. Alves, G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato[3], E. Coelho, E.M. Da Costa, G.G. Da Silveira[4], D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, J. Martins[5], D. Matos Figueiredo, M. Medina Jaime[6], M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote[3], F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista [a], Universidade Federal do ABC [b], São Paulo, Brazil
C.A. Bernardes[a], L. Calligaris[a], T.R. Fernandez Perez Tomei[a], E.M. Gregores[b], D.S. Lemos, P.G. Mercadante[b], S.F. Novaes[a], SandraS. Padula[a]

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

University of Sofia, Sofia, Bulgaria
M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China
W. Fang[7], X. Gao[7], L. Yuan

Department of Physics, Tsinghua University, Beijing, China
M. Ahmad, Z. Hu, Y. Wang

Institute of High Energy Physics, Beijing, China
G.M. Chen, H.S. Chen, M. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang[8], J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Q. Wang

Zhejiang University, Hangzhou, China
M. Xiao

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C. Florez, C.F. González Hernández, M.A. Segura Delgado

Universidad de Antioquia, Medellin, Colombia
J. Mejia Guisao, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

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

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

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, M. Roguljic, A. Starodumov[9], T. Susa

University of Cyprus, Nicosia, Cyprus
M.W. Ather, A. Attikis, E. Erodotou, A. Ioannou, M. Kolosova, S. Konstantinou, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, D. Tsiakkouri

Charles University, Prague, Czech Republic
M. Finger[10], M. Finger Jr.[10], A. Kveton, J. Tomsa

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
Y. Assran[11,12], S. Elgammal[12]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

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

Helsinki Institute of Physics, Helsinki, Finland
F. Garcia, J. Havukainen, J.K. Heikkilä, V. Karimäki, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[13], M. Titov

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, France
S. Ahuja, C. Amendola, F. Beaudette, P. Busson, C. Charlot, B. Diab, G. Falmagne, R. Granier de Cassagnac, I. Kucher, A. Lobanov, C. Martin Perez, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[14], J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte[14], J.-C. Fontaine[14], D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, F. Lagarde, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia
T. Toriashvili[15]

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[10]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M.P. Rauch, J. Schulz, M. Teroerde, B. Wittmer

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
M. Erdmann, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, T. Quast, M. Radziej, Y. Rath, H. Reithler, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
G. Flügge, W. Haj Ahmad[16], O. Hlushchenko, T. Kress, T. Müller, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl[17]

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, P. Asmuss, I. Babounikau, H. Bakhshiansohi, K. Beernaert, O. Behnke, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras[18], V. Botta, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, A. Elwood, E. Eren, E. Gallo[19], A. Geiser, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, A. Jafari, N.Z. Jomhari, H. Jung, A. Kasem[18], M. Kasemann, H. Kaveh, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann[20], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, A. Mussgiller, V. Myronenko, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saibel, M. Savitskyi, V. Scheurer, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, M. Van De Klundert, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev, R. Zlebcik

University of Hamburg, Hamburg, Germany
R. Aggleton, S. Bein, L. Benato, A. Benecke, V. Blobel, T. Dreyer, A. Ebrahimi, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, T. Lange, A. Malara, J. Multhaup, C.E.N. Niemeyer, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, B. Vormwald, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
M. Akbiyik, C. Barth, M. Baselga, S. Baur, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, M. Giffels, P. Goldenzweig, A. Gottmann, M.A. Harrendorf, F. Hartmann[17], U. Husemann, S. Kudella, S. Mitra, M.U. Mozer, D. Müller, Th. Müller, M. Musich, A. Nürnberg, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Wassmer, M. Weber, C. Wöhrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, P. Asenov, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki

National and Kapodistrian University of Athens, Athens, Greece
M. Diamantopoulou, G. Karathanasis, P. Kontaxakis, A. Manousakis-katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, A. Stakia, K. Theofilatos, K. Vellidis, E. Vourliotis

National Technical University of Athens, Athens, Greece
G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitara, N. Manthos, I. Papadopoulos, J. Strologas, F.A. Triantis, D. Tsitsonis

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Bartók[21], R. Chudasama, M. Csanad, P. Major, K. Mandal, A. Mehta, M.I. Nagy, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath[22], F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi[21], A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, D. Teyssier, Z.L. Trocsanyi, B. Ujvari

Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary
T. Csorgo, W.J. Metzger, F. Nemes, T. Novak

Indian Institute of Science (IISc), Bangalore, India
S. Choudhury, J.R. Komaragiri, P.C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India
S. Bahinipati[24], C. Kar, G. Kole, P. Mal, V.K. Muraleedharan Nair Bindhu, A. Nayak[25], D.K. Sahoo[24], S.K. Swain

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Virdi

University of Delhi, Delhi, India
A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, Ashok Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
R. Bhardwaj[26], M. Bharti[26], R. Bhattacharya, S. Bhattacharya, U. Bhawandeep[26], D. Bhowmik, S. Dutta, S. Ghosh, M. Maity[27], K. Mondal, S. Nandan, A. Purohit, P.K. Rout, G. Saha, S. Sarkar, T. Sarkar[27], M. Sharan, B. Singh[26], S. Thakur[26]

Indian Institute of Technology Madras, Madras, India
P.K. Behera, P. Kalbhor, A. Muhammad, P.R. Pujahari, A. Sharma, A.K. Sikdar

Bhabha Atomic Research Centre, Mumbai, India
D. Dutta, V. Jha, V. Kumar, D.K. Mishra, P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, RavindraKumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo, S. Sawant

Indian Institute of Science Education and Research (IISER), Pune, India
S. Dube, V. Hegde, B. Kansal, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[28], E. Eskandari Tadavani, S.M. Etesami[28], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi

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], R. Aly[a,b,29], C. Calabria[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], W. Elmetenawee[a,b], L. Fiore[a], A. Gelmi[a,b], G. Iaselli[a,c], M. Ince[a,b], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], G. Miniello[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a], F.M. Simone[a,b], R. Venditti[a], P. Verwilligen[a]

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a,b], S. Braibant-Giacomelli[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], C. Ciocca[a], G. Codispoti[a,b], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], E. Fontanesi[a,b], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], F. Iemmi[a,b], S. Lo Meo[a,30], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b], N. Tosi[a]

INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy
S. Albergo[a,b,31], S. Costa[a,b], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,31], C. Tuve[a,b]

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

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, D. Piccolo

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

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
A. Benaglia[a], A. Beschi[a,b], F. Brivio[a,b], V. Ciriolo[a,b,17], S. Di Guida[a,b,17], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a,b], M. Malberti[a], S. Malvezzi[a], D. Menasce[a], F. Monti[a,b], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b], D. Zuolo[a,b]

INFN Sezione di Napoli [a], Università di Napoli 'Federico II' [b], Napoli, Italy, Università della Basilicata [c], Potenza, Italy, Università G. Marconi [d], Roma, Italy
S. Buontempo[a], N. Cavallo[a,c], A. De Iorio[a,b], A. Di Crescenzo[a,b], F. Fabozzi[a,c], F. Fienga[a], G. Galati[a], A.O.M. Iorio[a,b], L. Lista[a,b], S. Meola[a,d,17], P. Paolucci[a,17], B. Rossi[a], C. Sciacca[a,b], E. Voevodina[a,b]

INFN Sezione di Padova [a], Università di Padova [b], Padova, Italy, Università di Trento [c], Trento, Italy
P. Azzi[a], N. Bacchetta[a], D. Bisello[a,b], A. Boletti[a,b], A. Bragagnolo[a,b], R. Carlin[a,b], P. Checchia[a], P. De Castro Manzano[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], S.Y. Hoh[a,b], P. Lujan[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], J. Pazzini[a,b], M. Presilla[b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], A. Tiko[a], M. Tosi[a,b], M. Zanetti[a,b], P. Zotto[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
A. Braghieri[a], D. Fiorina[a,b], P. Montagna[a,b], S.P. Ratti[a,b], V. Re[a], M. Ressegotti[a,b], C. Riccardi[a,b], P. Salvini[a], I. Vai[a], P. Vitulo[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
M. Biasini[a,b], G.M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], P. Lariccia[a,b], R. Leonardi[a,b], E. Manoni[a], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a]

INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa, Italy
K. Androsov[a], P. Azzurri[a], G. Bagliesi[a], V. Bertacchi[a,c], L. Bianchini[a], T. Boccali[a], R. Castaldi[a], M.A. Ciocci[a,b], R. Dell'Orso[a], S. Donato[a], G. Fedi[a], L. Giannini[a,c], A. Giassi[a], M.T. Grippo[a], F. Ligabue[a,c], E. Manca[a,c], G. Mandorli[a,c], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], G. Rolandi[32], S. Roy Chowdhury, A. Scribano[a], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a], A. Venturi[a], P.G. Verdini[a]

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

INFN Sezione di Torino [a], Università di Torino [b], Torino, Italy, Università del Piemonte Orientale [c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], A. Bellora, C. Biino[a], A. Cappati[a,b], N. Cartiglia[a], S. Cometti[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], B. Kiani[a,b], F. Legger, C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], E. Monteil[a,b], M. Monteno[a], M.M. Obertino[a,b], G. Ortona[a,b], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G.L. Pinna Angioni[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Salvatico[a,b], V. Sola[a], A. Solano[a,b], D. Soldi[a,b], A. Staiano[a]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], A. Da Rold[a,b], G. Della Ricca[a,b], F. Vazzoler[a,b], A. Zanetti[a]

Kyungpook National University, Daegu, Korea
B. Kim, D.H. Kim, G.N. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, S. Sekmen, D.C. Son, Y.C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D.H. Moon, G. Oh

Hanyang University, Seoul, Korea
B. Francois, T.J. Kim, J. Park

Korea University, Seoul, Korea
S. Cho, S. Choi, Y. Go, S. Ha, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, Y. Roh, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Republic of Korea
J. Goh

Sejong University, Seoul, Korea
H.S. Kim

Seoul National University, Seoul, Korea
J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, H. Lee, K. Lee, S. Lee, K. Nam, M. Oh, S.B. Oh, B.C. Radburn-Smith, U.K. Yang, H.D. Yoo, I. Yoon, G.B. Yu

University of Seoul, Seoul, Korea
D. Jeon, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, I.J Watson

Sungkyunkwan University, Suwon, Korea
Y. Choi, C. Hwang, Y. Jeong, J. Lee, Y. Lee, I. Yu

Riga Technical University, Riga, Latvia
V. Veckalns[33]

Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
Z.A. Ibrahim, F. Mohamad Idris[34], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[35], R. Lopez-Fernandez, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

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

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

University of Montenegro, Podgorica, Montenegro
J. Mijuskovic, N. Raicevic

University of Auckland, Auckland, New Zealand
D. Krofcheck

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

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

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

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

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk[36], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, P. Bargassa, D. Bastos, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, J. Seixas, K. Shchelina, G. Strong, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
V. Alexakhin, Y. Ershov, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev[37,38], P. Moisenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, B.S. Yuldashev[39], A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
L. Chtchipounov, V. Golovtcov, Y. Ivanov, V. Kim[40], E. Kuznetsova[41], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko[42], V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
M. Chadeeva[43], P. Parygin, D. Philippov, E. Popova, V. Rusinov

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, M. Dubinin[44], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia
A. Barnyakov[45], V. Blinov[45], T. Dimova[45], L. Kardapoltsev[45], Y. Skovpen[45]

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, A. Iuzhakov, V. Okhotnikov

Tomsk State University, Tomsk, Russia
V. Borchsh, V. Ivanchenko, E. Tcherniaev

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Serbia
P. Adzic[46], P. Cirkovic, M. Dordevic, P. Milenovic, J. Milosevic, M. Stojanovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, Á. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz, R. Reyes-Almanza

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez,

P.J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Russo[47], L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
D.U.J. Sonnadara

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

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, P. Bortignon, E. Bossini, C. Botta, E. Brondolin, T. Camporesi, A. Caratelli, G. Cerminara, E. Chapon, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, O. Davignon, A. De Roeck, M. Deile, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita[48], D. Fasanella, S. Fiorendi, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, A. Gilbert, K. Gill, F. Glege, L. Gouskos, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, Y. Iiyama, V. Innocente, T. James, P. Janot, O. Karacheban[20], J. Kaspar, J. Kieseler, M. Krammer[1], N. Kratochwil, C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, J. Niedziela, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo[17], L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, M. Rieger, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas[49], J. Steggemann, S. Summers, V.R. Tavolaro, D. Treille, A. Tsirou, G.P. Van Onsem, A. Vartak, M. Verzetti, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
L. Caminada[50], K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
M. Backhaus, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, R.A. Manzoni, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland
T.K. Aarrestad, C. Amsler[51], D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, B. Kilminster, S. Leontsinis, V.M. Mikuni, I. Neutelings, G. Rauco, P. Robmann, K. Schweiger, C. Seitz, Y. Takahashi, S. Wertz, A. Zucchetta

National Central University, Chung-Li, Taiwan
T.H. Doan, C.M. Kuo, W. Lin, A. Roy, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas, N. Suwonjandee

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
A. Bat, F. Boran, A. Celik[52], S. Cerci[53], S. Damarseckin[54], Z.S. Demiroglu, F. Dolek, C. Dozen[55],

I. Dumanoglu, G. Gokbulut, EmineGurpinar Guler[56], Y. Guler, I. Hos[57], C. Isik, E.E. Kangal[58], O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[59], S. Ozturk[60], A.E. Simsek, D. Sunar Cerci[53], U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
B. Isildak[61], G. Karapinar[62], M. Yalvac

Bogazici University, Istanbul, Turkey
I.O. Atakisi, E. Gülmez, M. Kaya[63], O. Kaya[64], Ö. Özçelik, S. Tekten, E.A. Yetkin[65]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak, Y. Komurcu, S. Sen[66]

Istanbul University, Istanbul, Turkey
B. Kaynak, S. Ozkorucuklu

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
E. Bhal, S. Bologna, J.J. Brooke, D. Burns[67], E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, B. Penning, T. Sakuma, S. Seif El Nasr-Storey, V.J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev[68], C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Imperial College, London, United Kingdom
R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, GurpreetSingh CHAHAL[69], D. Colling, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, P. Everaerts, G. Hall, G. Iles, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, A. Morton, J. Nash[70], V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, T. Strebler, A. Tapper, K. Uchida, T. Virdee[17], N. Wardle, D. Winterbottom, J. Wright, A.G. Zecchinelli, S.C. Zenz

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, USA
K. Call, B. Caraway, J. Dittmann, K. Hatakeyama, C. Madrid, B. McMaster, N. Pastika, C. Smith

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, USA
A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA
A. Albert, D. Arcaro, Z. Demiragli, D. Gastler, C. Richardson, J. Rohlf, D. Sperka, I. Suarez, L. Sulak, D. Zou

Brown University, Providence, USA
G. Benelli, B. Burkle, X. Coubez[18], D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan[71], K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, Z. Mao, M. Narain, S. Sagir[72], R. Syarif, E. Usai, D. Yu, W. Zhang

University of California, Davis, Davis, USA
R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

University of California, Los Angeles, USA
M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, W.A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

University of California, Riverside, Riverside, USA
K. Burt, Y. Chen, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, E. Kennedy, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, S. Wimpenny, B.R. Yates, Y. Zhang

University of California, San Diego, La Jolla, USA
J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, D. Klein, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA
N. Amin, R. Bhandari, C. Campagnari, M. Citron, V. Dutta, M. Franco Sevilla, J. Incandela, B. Marsh, H. Mei, A. Ovcharova, H. Qu, J. Richman, U. Sarica, D. Stuart, S. Wang

California Institute of Technology, Pasadena, USA
D. Anderson, A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, T.Q. Nguyen, J. Pata, M. Spiropulu, J.R. Vlimant, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, USA
J.P. Cumalat, W.T. Ford, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, Y. Cheng, J. Chu, A. Datta, A. Frankenthal, K. Mcdermott, J.R. Patterson, D. Quach, A. Ryd, S.M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, AllisonReinsvold Hall, J. Hanlon, R.M. Harris, S. Hasegawa, R. Heller, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, J. Lewis, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena, G. Rakness, F. Ravera, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha,

W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, R. Vidal, M. Wang, H.A. Weber

University of Florida, Gainesville, USA
D. Acosta, P. Avery, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, V. Cherepanov, F. Errico, R.D. Field, S.V. Gleyzer, B.M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K.H. Lo, P. Ma, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Wang, S. Wang, X. Zuo

Florida International University, Miami, USA
Y.R. Joshi

Florida State University, Tallahassee, USA
T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, T. Perry, H. Prosper, C. Schiber, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, C. Mills, T. Roy, M.B. Tonjes, N. Varelas, J. Viinikainen, H. Wang, X. Wang, Z. Wu

The University of Iowa, Iowa City, USA
M. Alhusseini, B. Bilki[56], W. Clarida, K. Dilsiz[73], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[74], A. Moeller, J. Nachtman, H. Ogul[75], Y. Onel, F. Ozok[76], A. Penzo, C. Snyder, E. Tiras, J. Wetzel

Johns Hopkins University, Baltimore, USA
B. Blumenfeld, A. Cocoros, N. Eminizer, A.V. Gritsan, W.T. Hung, S. Kyriacou, P. Maksimovic, J. Roskes, M. Swartz

The University of Kansas, Lawrence, USA
C. Baldenegro Barrera, P. Baringer, A. Bean, S. Boren, J. Bowen, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, D. Majumder, W. Mcbrayer, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

Kansas State University, Manhattan, USA
S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

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

University of Maryland, College Park, USA
A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, S. Nabili, F. Ricci-Tam, M. Seidel, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

Massachusetts Institute of Technology, Cambridge, USA
D. Abercrombie, B. Allen, A. Baty, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus,

D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

University of Minnesota, Minneapolis, USA
R.M. Chatterjee, A. Evans, S. Guts†, P. Hansen, J. Hiltbrand, Sh. Jain, Y. Kubota, Z. Lesko, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, M.A. Wadud

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA
K. Bloom, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, R. Kamalieddin, I. Kravchenko, J.E. Siado, G.R. Snow†, B. Stieger, W. Tabb

State University of New York at Buffalo, Buffalo, USA
G. Agarwal, C. Harrington, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, A. Parker, J. Pekkanen, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA
G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, B. Marzocchi, D.M. Morse, T. Orimoto, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA
S. Bhattacharya, J. Bueghly, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA
R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, C. Mueller, Y. Musienko[37], M. Planer, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA
J. Alimena, B. Bylsma, L.S. Durkin, B. Francis, C. Hill, W. Ji, A. Lefeld, T.Y. Ling, B.L. Winer

Princeton University, Princeton, USA
G. Dezoort, P. Elmer, J. Hardenbrook, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully, Z. Wang

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

Purdue University, West Lafayette, USA
A. Barker, V.E. Barnes, S. Das, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, B. Mahakud, D.H. Miller, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, H. Qiu, J.F. Schulte, N. Trevisani, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, USA
T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, USA
U. Behrens, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, Arun Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, W. Shi, A.G. Stahl Leiton, Z. Tu, A. Zhang

University of Rochester, Rochester, USA
A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus

Rutgers, The State University of New Jersey, Piscataway, USA
B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas

University of Tennessee, Knoxville, USA
H. Acharya, A.G. Delannoy, S. Spanier

Texas A&M University, College Station, USA
O. Bouhali[77], M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[78], S. Luo, S. Malhotra, D. Marley, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, F. De Guio, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

Vanderbilt University, Nashville, USA
S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij

University of Virginia, Charlottesville, USA
M.W. Arenton, P. Barria, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA
R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa

University of Wisconsin - Madison, Madison, WI, USA
T. Bose, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, F. Fiori, C. Galloni, B. Gomber[79], H. He, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Loeliger, K. Long, R. Loveless, J. Madhusudanan Sreekala, D. Pinna, T. Ruggles, A. Savin, V. Sharma, W.H. Smith, D. Teague, S. Trembath-reichert, N. Woods

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
3: Also at Universidade Estadual de Campinas, Campinas, Brazil
4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
5: Also at UFMS, Nova Andradina, Brazil
6: Also at Universidade Federal de Pelotas, Pelotas, Brazil
7: Also at Université Libre de Bruxelles, Bruxelles, Belgium
8: Also at University of Chinese Academy of Sciences, Beijing, China
9: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia
10: Also at Joint Institute for Nuclear Research, Dubna, Russia
11: Also at Suez University, Suez, Egypt
12: Now at British University in Egypt, Cairo, Egypt
13: Also at Purdue University, West Lafayette, USA
14: Also at Université de Haute Alsace, Mulhouse, France

15: Also at Tbilisi State University, Tbilisi, Georgia
16: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
17: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
18: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
19: Also at University of Hamburg, Hamburg, Germany
20: Also at Brandenburg University of Technology, Cottbus, Germany
21: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary
22: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
23: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary, Budapest, Hungary
24: Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India
25: Also at Institute of Physics, Bhubaneswar, India
26: Also at Shoolini University, Solan, India
27: Also at University of Visva-Bharati, Santiniketan, India
28: Also at Isfahan University of Technology, Isfahan, Iran, Isfahan, Iran
29: Now at INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
30: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
31: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
32: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
33: Also at Riga Technical University, Riga, Latvia, Riga, Latvia
34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
37: Also at Institute for Nuclear Research, Moscow, Russia
38: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
39: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
40: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
41: Also at University of Florida, Gainesville, USA
42: Also at Imperial College, London, United Kingdom
43: Also at P.N. Lebedev Physical Institute, Moscow, Russia
44: Also at California Institute of Technology, Pasadena, USA
45: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
46: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
47: Also at Università degli Studi di Siena, Siena, Italy
48: Also at INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy, Pavia, Italy
49: Also at National and Kapodistrian University of Athens, Athens, Greece
50: Also at Universität Zürich, Zurich, Switzerland
51: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria
52: Also at Burdur Mehmet Akif Ersoy University, BURDUR, Turkey
53: Also at Adiyaman University, Adiyaman, Turkey
54: Also at Şırnak University, Sirnak, Turkey
55: Also at Department of Physics, Tsinghua University, Beijing, China, Beijing, China
56: Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey
57: Also at Istanbul Aydin University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey

58: Also at Mersin University, Mersin, Turkey
59: Also at Piri Reis University, Istanbul, Turkey
60: Also at Gaziosmanpasa University, Tokat, Turkey
61: Also at Ozyegin University, Istanbul, Turkey
62: Also at Izmir Institute of Technology, Izmir, Turkey
63: Also at Marmara University, Istanbul, Turkey
64: Also at Kafkas University, Kars, Turkey
65: Also at Istanbul Bilgi University, Istanbul, Turkey
66: Also at Hacettepe University, Ankara, Turkey
67: Also at Vrije Universiteit Brussel, Brussel, Belgium
68: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
69: Also at IPPP Durham University, Durham, United Kingdom
70: Also at Monash University, Faculty of Science, Clayton, Australia
71: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA
72: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
73: Also at Bingol University, Bingol, Turkey
74: Also at Georgian Technical University, Tbilisi, Georgia
75: Also at Sinop University, Sinop, Turkey
76: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
77: Also at Texas A&M University at Qatar, Doha, Qatar
78: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea
79: Also at University of Hyderabad, Hyderabad, India