Eur. Phys. J. C (2016) 76:372
DOI 10.1140/epjc/s10052-016-4205-7

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Measurement of inclusive jet production and nuclear modifications in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

CMS Collaboration*

CERN,1211 Geneva 23, Switzerland

Received: 8 January 2016 / Accepted: 15 June 2016 / Published online: 4 July 2016
© CERN for the benefit of the CMS collaboration 2016. This article is published with open access at Springerlink.com

Abstract Inclusive jet production in pPb collisions at a nucleon–nucleon (NN) center-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV is studied with the CMS detector at the LHC. A data sample corresponding to an integrated luminosity of 30.1 nb^{-1} is analyzed. The jet transverse momentum spectra are studied in seven pseudorapidity intervals covering the range $-2.0 < \eta_{\mathrm{CM}} < 1.5$ in the NN center-of-mass frame. The jet production yields at forward and backward pseudorapidity are compared and no significant asymmetry about $\eta_{\mathrm{CM}} = 0$ is observed in the measured kinematic range. The measurements in the pPb system are compared to reference jet spectra obtained by extrapolation from previous measurements in pp collisions at $\sqrt{s} = 7$ TeV. In all pseudorapidity ranges, nuclear modifications in inclusive jet production are found to be small, as predicted by next-to-leading order perturbative QCD calculations that incorporate nuclear effects in the parton distribution functions.

1 Introduction

Jet measurements play an important role in the study of the quark gluon plasma (QGP) produced in relativistic heavy ion collisions. A key observable in these studies is the phenomenon of jet quenching [1–6], in which the partons produced in hard scattering lose energy through gluon radiation and elastic scattering in the hot and dense partonic medium. Jet quenching was first observed at RHIC through measurements of high transverse momentum (p_{T}) hadrons [7] and dihadron correlations [8]. At the LHC, this phenomenon was observed more directly as dijet momentum imbalance [9,10] and photon–jet energy imbalance [11] in PbPb collisions. An important ingredient in understanding how the presence of a hot QCD medium affects the jets is the comparison to reference measurements from collision systems that are not expected to produce the QGP. Most often, pp collisions at the same center-of-mass energy are used as a reference. Modifications in jet yields [12,13], shapes [14], and fragmentation patterns [15,16] in PbPb collisions have been found in comparison to expectations based on pp measurements. These modifications are found to depend on the overlap between the colliding nuclei, and are largest in the most central (i.e., largest overlap) PbPb collisions.

The interpretation of the jet modification results in nucleus–nucleus collisions and the understanding of their relation to the properties of the QGP requires detailed knowledge of all nuclear effects that could influence the comparisons with the pp system. Nuclear modifications may already be present at the initial state of the collisions, independently of QGP formation. Such modifications are collectively referred to as cold nuclear matter (CNM) effects and include parton energy loss and multiple scattering before the hard scattering, and modifications of the parton distribution functions in the nucleus (nPDFs) with respect to those of a free nucleon (PDFs). Some nPDF modifications have been previously deduced from measurements of lepton–nucleus deep inelastic scattering and Drell–Yan production of lepton pairs from $q\bar{q}$ annihilation in proton–nucleus collisions [17]. In addition, measurements of π^0 production in deuteron–gold collisions at RHIC [18] are also included in recent nPDF fits to better constrain the nuclear gluon distributions [19]. There are several ranges in the parton fractional momenta x in which the data show suppression or enhancement in the nPDFs relative to the proton PDFs. At small x ($\lesssim$0.01), the nPDFs are found to be suppressed, a phenomenon commonly referred to as "shadowing" [20]. In the range $0.02 \lesssim x \lesssim 0.2$, the nPDFs are enhanced ("antishadowing" [17]), and for $x \gtrsim 0.2$ a suppression has been seen ("EMC effect" [21]).

Proton–lead (pPb) collisions at the LHC provide an opportunity to evaluate the CNM effects and establish an additional reference for the interpretation of measurements performed in PbPb collisions. The results of several pPb studies involving jets or dijets [22–24], electroweak bosons [25,26], and high p_{T} charged particles [27,28] are already available. No significant indication of jet quenching was found so far in the pPb studies of inclusive jet production [22,29], dijet momen-

* e-mail: cms-publication-committee-chair@cern.ch

tum balance [23], dijet acoplanarity [23,24], or charged-hadron measurements [27,28]. The shapes of the dijet [23] and Z boson [25] pseudorapidity distributions are found to be in better agreement with EPS09 nPDF predictions [19] than with the free-proton PDFs for measurements inclusive in the impact parameter. Hints of modifications larger than those presently included in the EPS09 nPDFs have also been seen [25–27]. In particular, the charged hadron spectra [27] are found to be enhanced at high p_T beyond the anti-shadowing included in EPS09. Significant modifications with respect to those included in EPS09 have also been found for impact-parameter-dependent measurements [22,23]. The interpretation of the latter results is more difficult because of the kinematic biases introduced through the event selections [22,23,30–32].

In this paper we present the CMS measurements of inclusive jet production in pPb collisions at a nucleon–nucleon (NN) center-of-mass energy of $\sqrt{s_{NN}} = 5.02$ TeV as a function of p_T in several pseudorapidity regions in the range $-2.0 < \eta_{CM} < 1.5$ in the NN center-of-mass system. No additional event activity selections have been made to avoid the associated kinematic biases. The measurements extend in p_T up to 500 GeV/c and are sensitive to nPDF modifications in the anti-shadowing and EMC effect regions. Since presently there are no experimental results available from pp collisions at $\sqrt{s} = 5.02$ TeV, pp reference jet spectra in pseudorapidity ranges corresponding to the present measurements are obtained by extrapolating jet measurements at $\sqrt{s} = 7$ TeV [33]. The paper is organized as follows: Sect. 2 provides the experimental details, Sect. 3 gives an account of the systematic uncertainties in the measurements, Sect. 4 presents the results, and Sect. 5 summarizes our findings.

2 Data analysis

This measurement is based on a data sample of pPb collisions corresponding to an integrated luminosity of 30.1 nb^{-1} collected by the CMS experiment in 2013. The beam energies were 4 TeV for protons and 1.58 TeV per nucleon for lead nuclei, resulting in a center-of-mass energy per nucleon pair of 5.02 TeV. The direction of the higher-energy proton beam was initially set up to be clockwise within CMS conventions, and was reversed after a data set corresponding to an integrated luminosity of 21 nb^{-1} was recorded. As a result of the energy difference of the colliding beams, the nucleon–nucleon center-of-mass in the pPb collisions is shifted with respect to zero rapidity in the laboratory frame. Both portions of the data set are analyzed independently and the results are found to be compatible within their uncertainties. In order to reduce the statistical uncertainties, the two data sets are then combined. Results from the first data taking period are reflected along the z-axis so that in the combined analysis the proton travels in the positive z and pseudorapidity η direction. In the laboratory frame $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle defined with respect to the proton beam direction. The results are presented in this convention, after transformation to the NN center-of-mass frame, which for massless particles is equivalent to a shift in pseudorapidity: $\eta_{CM} = \eta - 0.465$.

2.1 Experimental setup

A detailed description of the CMS detector and of its coordinate system can be found in Ref. [34]. It features nearly hermetic calorimetric coverage and high-resolution tracking for the reconstruction of energetic jets and charged particles. The calorimeters consist of a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL) with coverage up to $|\eta| = 3$. The quartz/steel hadron forward (HF) calorimeters extend the calorimetry coverage in the region $3.0 < |\eta| < 5.2$, and are used in offline event selection. The calorimeter cells are grouped in projective towers of granularity $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ (where ϕ is the azimuthal angle in radians) for the central pseudorapidity region used in the present jet measurement, and have coarser segmentation (about twice as large) at forward pseudorapidity. The central calorimeters are enclosed in a superconducting solenoid with 3.8 T magnetic field. Charged particles are reconstructed by the tracking system, located inside the calorimeters and the superconducting coil. It consists of silicon pixel and strip layers covering the range $|\eta| < 2.5$, and provides track reconstruction with momentum resolution of about 1.5 % for high-p_T particles. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

2.2 Event selection

The CMS online event selection employs a hardware-based level-1 (L1) trigger and a software-based high-level trigger (HLT). A minimum bias sample is selected by the L1 requirement of a pPb bunch crossing at the interaction point and an HLT requirement of at least one reconstructed track with $p_T > 0.4$ GeV/c in the pixel tracker. This minimum bias trigger was prescaled by a large factor for most of the 5.02 TeV data collection, because of the high instantaneous luminosity of the LHC. In order to increase the p_T range of the measurement, additional HLT triggers were used to select events based on the presence of a jet with $p_T > 20$, 40, 60, 80, or 100 GeV/c reconstructed in the calorimeters.

For the offline analysis, an additional selection of hadronic collisions is applied by requiring a coincidence of at least one HF calorimeter tower with more than 3 GeV of total energy on the positive and negative sides of the interaction point. Events are further required to have at least one reconstructed primary vertex with at least two associated tracks [35]. A maximum distance of 15 cm between the primary vertex and the nominal interaction point along the beam line is required to ensure maximum tracking acceptance. Additionally, track-based selection cuts are applied to suppress of beam-related background events [36]. The instantaneous luminosity of the pPb run in 2013 resulted in a 3 % probability of at least one additional interaction occurring in the same bunch crossing. Events with more than one interaction ("pileup" events) are removed using a rejection algorithm developed in Ref. [27]. The pileup-rejection efficiency of this filter is found to be 90 ± 2 % in minimum bias events and it removes a very small fraction (0.01 %) of the events without pileup. In order to combine the spectra measured from the various jet-triggered data samples, the events included in the analysis are weighted according to the individual HLT prescale factors corresponding to the trigger object with maximum p_{T} in the event. The top panel of Fig. 1 shows the prescale-weighted jet spectra that are reconstructed with the anti-k_{T} [37] algorithm from each HLT trigger path and the combined inclusive jet spectrum. The ratios of each HLT-triggered spectrum to the combined jet spectrum are shown in the bottom panel of Fig. 1. In the range of p_{T} where the triggers are fully efficient, this ratio is unity and independent of jet p_{T}.

2.3 Jet reconstruction and corrections

The CMS particle-flow (PF) algorithm [38,39] identifies stable particles in an event by combining information from all sub-detector systems, classifying them as electrons, muons, photons, and charged and neutral hadrons. The PF candidates are then clustered into jets using the anti-k_{T} sequential recombination algorithm [37] provided in the FastJet framework [40]. The results in this analysis are obtained using a distance parameter $R = 0.3$. The underlying event (UE) contribution to the jet energy is subtracted using an iterative procedure described in Refs. [10,41]. The jet energies are then corrected to contain the energy of all final-state jet constituents as described in Ref. [42]. The jet energy corrections are derived using simulated PYTHIA (6.462, Z2 tune) [43,44] events and measurements of the energy balance of dijet and photon + jet pPb collision events are used to correct differences between data and Monte Carlo (MC) distributions [23,42]. In the jet reconstruction process, there is a possibility that the jet energy is estimated incorrectly, or a jet is found in a region where the UE has an upward fluctuation, but no hard scattering has occurred (a "fake" jet). In MC the "real" and "fake" jets can be distinguished by requiring that the reconstructed jet is matched to a generator-level jet. In data, this cannot be done directly, but the contribution of fake jets could be estimated from MC, provided that it is tuned to describe

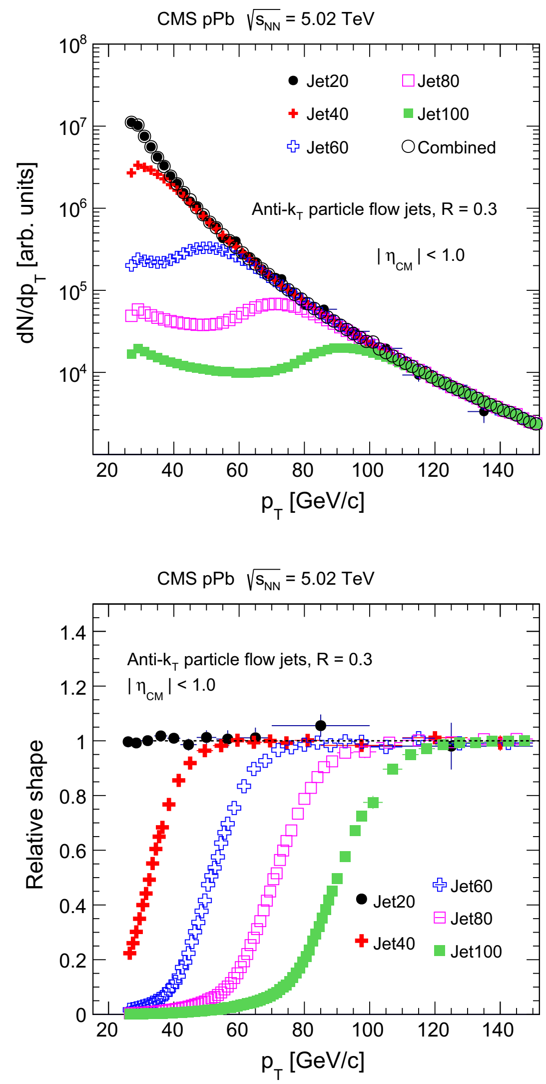

Fig. 1 *Top* the weighted jet spectra using prescale factors from each HLT-triggered event sample and the combined jet spectrum. A subset of the data is plotted to illustrate the procedure. *Bottom* the ratios of each individual HLT-triggered jet spectrum to the combined jet spectrum. Statistical uncertainties are shown as *vertical bars*, and p_{T} bin widths as *horizontal bars*

the data, and specific jet selections are developed to identify and remove the misreconstructed jets. We estimate that about 10 % of the jets reconstructed at $p_{\mathrm{T}} = 50$ GeV/c in pPb collisions are fake, and this fraction quickly drops to a level of 10^{-4} at $p_{\mathrm{T}} \approx 100$ GeV/c. After the jet-identification cuts are applied, we estimate that less than 1 % fake jets remain in the sample.

Because of the finite detector resolution and the steeply falling p_{T} distributions, the measured jet p_{T} spectra are smeared with respect to the true distributions, although the mean value of the reconstructed jet energy is corrected as described above. The jet energy resolution is estimated to be 13 % (8 %) for jet $p_{\mathrm{T}} = 60\,(300)$ GeV/c. A Bayesian unfolding technique [45] is employed to account for such resolution effects, as implemented in the RooUnfold package [46]. The migration of jets in pseudorapidity is not explicitly corrected for; it is instead included as an uncertainty, as discussed in Sect. 3.1. In the unfolding method, a response matrix is built based on MC simulations and is used to obtain the "true" jet p_T distribution from the measured one. Jets are first generated with the PYTHIA event generator and then embedded into pPb collisions simulated with the HIJING event generator (version 1.383) [47], which have particle multiplicity distributions comparable to the pPb data and can account for additional resolution effects associated with the higher detector occupancy. These embedded MC samples are denoted hereafter by PYTHIA + HIJING. The unfolding technique is tested by building the response matrix with detector jets (Reco) and generated jets (Gen) from half of the MC sample and applying it to unfold the other half of the sample. The top panel of Fig. 2 shows the response matrix obtained using the PYTHIA + HIJING simulation, while the bottom panel shows the ratio of the jet spectrum reconstructed from the simulation after unfolding to the generator-level jet spectrum. The unfolded MC jet spectrum is compatible with the generator-level jet spectrum within the statistical uncertainties. The results reported in this paper are based on the Bayesian unfolding technique that uses four iteration steps. Up to eight iteration steps are used in evaluating the systematic uncertainties as discussed in Sect. 3.1. The generator level PYTHIA jet spectrum is used as a prior in the unfolding. The data points are reported in the center of each p_T bin without corrections for binning effects.

The pPb jet cross sections are obtained in several pseudorapidity intervals. To study the evolution of the jet cross section with pseudorapidity, ratios of jet spectra are computed either using symmetric positive and negative pseudorapidity intervals around mid-rapidity, or normalizing the distributions by the mid-rapidity jet spectrum. These ratios are taken in the same p_T bin and the values are reported at the center of the bin. To study nuclear effects on jet production, the jet spectra in pPb collisions are compared to pp reference spectra obtained by extrapolation from previous jet cross section measurements in pp collisions at higher center-of-mass energy. The nuclear modification factor, R_{pPb}, evaluated in several pseudorapidity intervals, is defined as

$$R_{\mathrm{pPb}} = \frac{1}{A}\frac{\mathrm{d}^2\sigma_{\mathrm{jet}}^{\mathrm{pPb}}/\mathrm{d}p_T\,\mathrm{d}\eta}{\mathrm{d}^2\sigma_{\mathrm{jet}}^{\mathrm{pp}}/\mathrm{d}p_T\,\mathrm{d}\eta} = \frac{1}{A}\frac{1}{L}\frac{\mathrm{d}^2N_{\mathrm{jet}}^{\mathrm{pPb}}/\mathrm{d}p_T\,\mathrm{d}\eta}{\mathrm{d}^2\sigma_{\mathrm{jet}}^{\mathrm{pp}}/\mathrm{d}p_T\,\mathrm{d}\eta}, \quad (1)$$

where $L = 30.1\ \mathrm{nb}^{-1}$ is the effective integrated luminosity in the pPb analysis, corrected for event-selection efficiency and trigger prescales, and A is the mass number of the lead nucleus. Since presently there are no available experimental results from pp collisions at $\sqrt{s} = 5.02$ TeV, for this paper

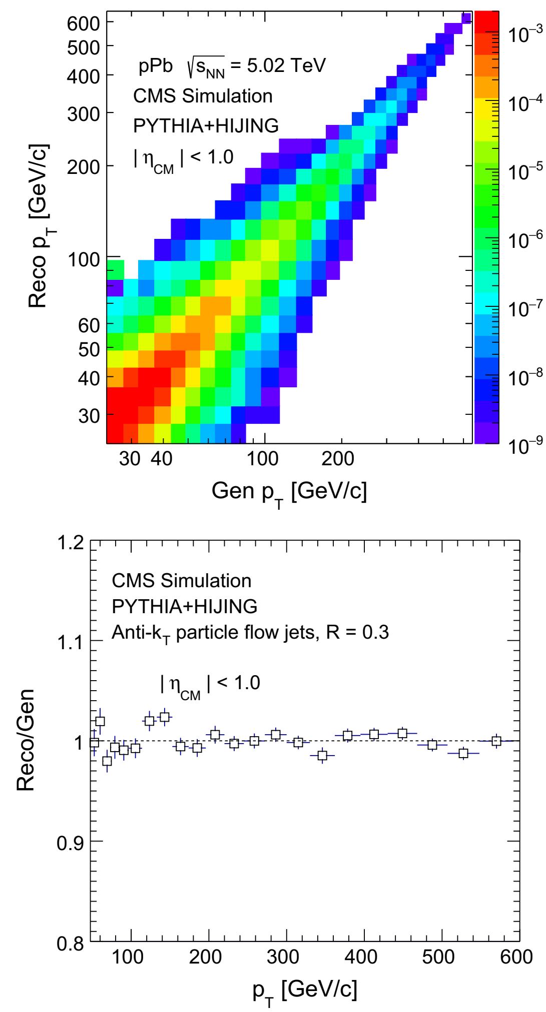

Fig. 2 *Top* response matrix built from PYTHIA + HIJING simulation. *Bottom* the ratios of the Bayesian unfolded jet p_T spectrum reconstructed in the simulation and the generator-level spectrum

we use extrapolated, rather than measured, pp reference spectra. Hence we denote the nuclear modification factors as R^*_{pPb}.

2.4 Proton–proton reference jet spectra

The reference pp spectra are constructed extrapolating previously published inclusive jet spectra measured in pp collisions at $\sqrt{s} = 7$ TeV. Measurements performed with the anti-k_T jet algorithm with two distance parameters, $R = 0.5$ and 0.7 [33], are used in the extrapolation. The extrapolation is based on the PYTHIA generator (6.462, Z2 tune) and is performed in two steps. First, the $\sqrt{s} = 7$ TeV jet cross section measurements are extrapolated to $\sqrt{s} = 5.02$ TeV and then scaled to $R = 0.3$, since a smaller distance parameter is used in the pPb analysis to minimize the UE background fluctuations. The PYTHIA generator is used to estimate p_T-dependent scaling factors. While this scaling is model dependent, the

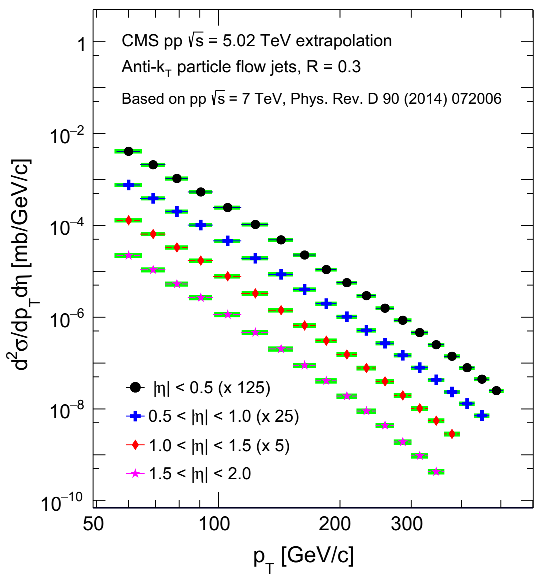

Fig. 3 Jet spectra at $\sqrt{s}$ = 5.02 TeV extrapolated from previous pp measurements at $\sqrt{s}$ = 7 TeV [33]. Additional scaling factors listed in the legend are applied to enhance the visibility. The *horizontal bars* represent the bin size, and the *points* are plotted in the center of the bin. The *shaded boxes* denote the systematic uncertainties in the extrapolation procedure. The statistical uncertainties are smaller than the symbol size

ratio of the jet cross sections measured with $R = 0.5$ and 0.7 appears to be well reproduced in PYTHIA within 3 % [33]. Several alternative methods are used to derive cross section scaling factors in $\sqrt{s}$ and in distance parameter in order to evaluate the systematic uncertainties discussed in Sect. 3.2. The extrapolated jet spectra are shown in Fig. 3. Scaling factors are applied, as noted in the legend, to enhance the visibility.

3 Systematic uncertainties

3.1 Systematic uncertainties in the pPb measurement

There are several sources of systematic uncertainty in the measurements of the jet spectra, the jet yield asymmetry, and the nuclear modification factors R^*_{pPb}. The dominant uncertainties in the spectra measured in pPb collisions come from the unfolding of the spectra and from the jet energy scale (JES) corrections, which are partially correlated since they both aim to correct for the difference between the reconstructed and the true jet energy. The stability of the unfolding procedure and its ability to recover the generator-level jet spectrum have been verified with simulation studies, which included the use of different numbers of iterations (n = 2, 3, 4, 5, 6, 7, 8). In the data, the unfolded spectra for $n = 4$ are compared to the spectra obtained with different values of n and the difference is included in the systematic uncertainty. In addition, since the true jet spectrum may differ in shape from the spectrum in the MC generator, the slope of the prior guess distribution is varied such that the yield at low p_T increases or decreases by a factor of 3, while at high p_T the yield is changed by about 10–20 %. After this variation the spectra are unfolded and then are compared to the nominal unfolded spectra to estimate the uncertainty due to the nominal input distribution. The uncertainties from unfolding are largest (up to 5 %) in the low p_T region and at large absolute pseudorapidity. Uncertainties that arise from the different jet energy resolution in the data and MC simulation are evaluated by smearing the unfolding matrix to account for these differences and then redoing the unfolding. The resulting differences in the final jet spectra are found to be less than 1 %. The JES uncertainty is about 1 % and induces up to 7 % changes at high p_T because of the steeply falling jet spectra.

Additional cross checks are performed comparing the spectra obtained with different jet reconstruction algorithms (such as subtracting the UE in the jet algorithm or correcting for it in the transfer matrix), and comparing the unfolded results when the unfolding matrix uses the reconstructed jet p_T with or without jet energy corrections. The total uncertainty in the jet spectra due to the JES and unfolding varies from about 5 % at low jet p_T at mid-rapidity to about 10 % for high p_T and forward rapidity.

The fake jet contribution is estimated on the basis of a MC study of various jet quality variables that are used to identify genuine and misreconstructed jet contributions. In the PYTHIA + HIJING embedded samples these variables are optimized to remove misreconstructed jets, while preserving the largest fraction of genuine jets. The uncertainty in the misreconstructed jet contribution in the jet spectra is estimated by varying the jet quality requirements and comparing the resulting spectra in data and in simulation. It is about 1 % for all pseudorapidity ranges.

The unfolding procedure does not correct for possible misreconstruction of the jet axis, and therefore jets may migrate from one pseudorapidity interval to another thus altering the jet spectra measured in different η ranges. The uncertainty associated with the jet pointing resolution is estimated by building the unfolding matrix using either the generated or the reconstructed jet axis, and comparing the resulting unfolded jet spectra. This uncertainty is found to be of the order of 1 % in the central pseudorapidity region and 2 % at large absolute pseudorapidity.

The jet spectra in pPb collisions are also subject to an overall scale uncertainty, due to the uncertainties in the integrated luminosity measurement. The scale uncertainty is estimated to be 3.5 %, as described in Ref. [48].

The systematic uncertainty in the inclusive jet production asymmetry only includes those factors that depend on the jet pseudorapidity, such as the JES, unfolding, and misreconstructed jet contribution uncertainties. The overall scale uncertainty due to the luminosity normalization cancels out. As a cross check, the jet yield asymmetry uncertainties are evaluated using a combination of the two data sets with different beam directions. In that case, the jet yield asymmetry can be measured using detector elements that are only in the positive η or in the negative η ranges in the laboratory frame. Since the detector is symmetric, these regions have similar acceptance and performance and we expect that systematic effects are also similar. Alternatively, the jet yield asymmetry is measured from each portion of the data independently, and the results of this comparison confirm the systematic uncertainty estimate obtained by evaluating each source of uncertainty separately.

3.2 Systematic uncertainties in the pp reference

The uncertainties in the extrapolated pp reference spectra take into account the uncertainties in the distance parameter dependence of the cross sections at $\sqrt{s} = 7\,\text{TeV}$ and the scaling to the smaller $R = 0.3$ value, the uncertainty in the $\sqrt{s}$ dependent scaling, as well as the uncertainties of the input spectra used in the extrapolation. The uncertainties in the inclusive jet measurements from pp collisions at $\sqrt{s} = 7\,\text{TeV}$ reported in Ref. [33] are taken as the upper and lower limits of the cross sections used in the extrapolation, and are reflected in the uncertainties of the resulting reference spectra. The following alternative approaches are used to derive scaling factors and evaluate their uncertainties.

1. PYTHIA 8, CUETP8M1 tune [49,50]: In the kinematic range studied, this tune has a different quark-to-gluon jet ratio and different jet shapes than the PYTHIA 6, Z2 tune used for the nominal result.
2. POWHEG + PYTHIA event generator [51,52]: The POWHEG generator is used to compute the cross section at next-to-leading order (NLO) accuracy, and PYTHIA (6.462, Z2 tune) is used to describe the parton showering and hadronization.
3. NLO calculations [53,54] with several different parametrizations of the parton distribution functions [55] and non-perturbative corrections based on PYTHIA (6.462, Z2 tune).
4. Jet cross section measurements with $R = 0.7$ at $\sqrt{s} = 7\,\text{TeV}$ [33] and $\sqrt{s} = 2.76\,\text{TeV}$ [56] are used to evaluate $\sqrt{s}$ dependent scaling factors using x_T-based interpolation ($x_T \equiv 2p_T c/\sqrt{s}$).

The jet cross sections for $R = 0.3$ and $R = 0.5$ at $\sqrt{s} = 5.02\,\text{TeV}$ are evaluated using (1), (2), and (3). Then the ratios between the cross sections obtained with these two distance parameters, in the default PYTHIA calculation (6.462, Z2 tune) and in the alternative methods, are compared to each other, leading to an uncertainty in the distance parameter scaling of around 5 %. The $\sqrt{s}$ scaling factors are evaluated with (2) and (3) for $R = 0.5$, and with (2), (3), and (4) for $R = 0.7$. These scaling factors are compared to the results from PYTHIA (6.462, Z2 tune). The uncertainties in the $\sqrt{s}$ scaling factors range from 4 % at low jet p_T in the mid-rapidity region to 7 % at high p_T and at forward rapidity. The total uncertainty in the pp reference extrapolation is found to range between 9 % at mid-rapidity and 11 % at forward rapidity. These uncertainties include a 2.4 % scale uncertainty from the integrated luminosity measurement [33].

3.3 Summary of systematic uncertainties

A summary of the systematic uncertainties in the jet spectra in pPb collisions, the jet yield asymmetry measurements in pPb collisions, the reference pp spectra, and the nuclear modification factors R^*_{pPb} are listed in Table 1. The uncertainties depend on the jet p_T and pseudorapidity, and the table shows representative values in two jet p_T and η_{CM} ranges. The uncertainties vary smoothly between these ranges. The total systematic uncertainties listed for the nuclear modification factors R^*_{pPb} do not include the scale uncertainty of 4.3 % from the integrated luminosity measurements in pPb (3.5 %) and pp (2.4 %) collisions. The luminosity uncertainties cancel in the measurements of the jet yield asymmetry. The remaining uncertainties are partially correlated in jet p_T, with the unfolding uncertainty dominating at low jet p_T and the JES uncertainty dominating at high jet p_T.

4 Results and discussion

The inclusive jet differential cross sections in pPb collisions at $\sqrt{s_{\text{NN}}} = 5.02\,\text{TeV}$ are shown in Fig. 4 for six consecutive η intervals in the range $-2.0 < \eta_{\text{CM}} < 1.5$ and the range $|\eta_{\text{CM}}| < 1.0$ for reference purposes. The distributions are scaled by arbitrary factors described in the legend to enhance visibility. These spectra are used to study the pseudorapidity dependence of inclusive jet production in pPb collisions and possible nuclear effects. In symmetric collisions, such as in the pp system, the kinematic range in the fractional momentum x probed with the jets in forward and backward pseudorapidity is the same and the production is symmetric about $\eta_{\text{CM}} = 0$. In the pPb system, the jets produced at forward pseudorapidity (proton beam direction) correlate with smaller x values from the Pb nucleus than those produced at backward pseudorapidity. Based on a generator-level study made with PYTHIA, the average x values from the Pb nucleus (Fig. 5) that are probed in the kinematic range covered by the present measurement are estimated to be in the range $0.03 \lesssim \langle x_{\text{Pb}} \rangle \lesssim 0.5$. Values of p_T that correspond to $\langle x_{\text{Pb}} \rangle \lesssim 0.2$ are associated with anti-shadowing in the nPDFs. The region $\langle x_{\text{Pb}} \rangle \gtrsim 0.2$ is associated with a

Table 1 Systematic uncertainties in the measurement of the jet spectra in pPb collisions are shown in the first four lines. The sources and corresponding systematic uncertainties in the extrapolated pp reference are presented in the next four lines. The total uncertainties in the jet spectra in pPb collisions, the reference pp spectra, the jet yield asymmetry in pPb collisions, and R^{*}_{pPb} are shown in the bottom four lines. The uncertainties depend on the jet p_{T} and pseudorapidity, and the table shows representative values in two jet p_{T} and η_{CM} ranges. The uncertainties vary smoothly between these two ranges. Total systematic uncertainties listed for the nuclear modification factors R^{*}_{pPb} do not include the scale uncertainty of 4.3 % due to the uncertainty in the integrated luminosity measurements in pPb (3.5 %) and pp (2.4 %) collisions

	Source	Jet $p_{\mathrm{T}} < 80$ GeV/c		Jet $p_{\mathrm{T}} > 150$ GeV/c	
		$\lvert\eta_{\mathrm{CM}}\rvert < 1$ (%)	$\lvert\eta_{\mathrm{CM}}\rvert > 1.5$ (%)	$\lvert\eta_{\mathrm{CM}}\rvert < 1$ (%)	$\lvert\eta_{\mathrm{CM}}\rvert > 1.5$ (%)
pPb	JES and unfolding	5	8	7	10
	Misreconstructed jet contribution	1	1	1	1
	Jet pointing resolution	1	2	1	2
	Integrated luminosity	3.5	3.5	3.5	3.5
pp	Input data	6	8	5	7
	Cone-size dependence	5	5	5	5
	Collision-energy dependence	4	5	6	7
	Integrated luminosity	2.4	2.4	2.4	2.4
Total	pPb spectra	6	9	8	11
	pPb asymmetry	7	11	10	14
	pp reference	9	11	10	11
	R^{*}_{pPb}	10	14	12	15

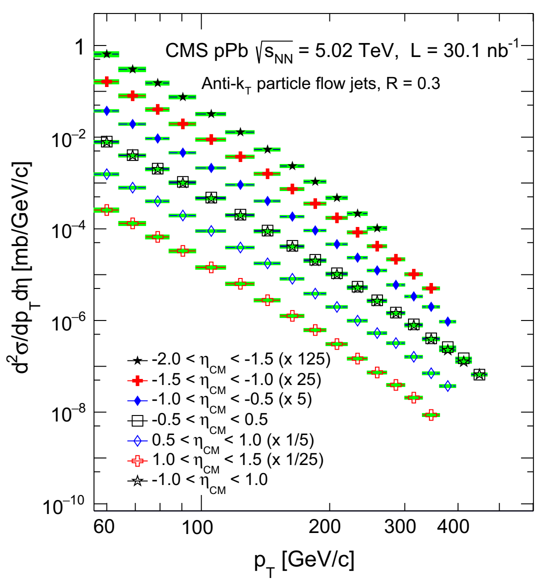

Fig. 4 Inclusive jet differential cross section in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV in six consecutive eta bins plus the range $\lvert\eta_{\mathrm{CM}}\rvert < 1.0$. The spectra are scaled by arbitrary factors for better visibility. The *horizontal bars* represent the bin width, and the *filled boxes* indicate the systematic uncertainties. The statistical uncertainties are smaller than the symbol size

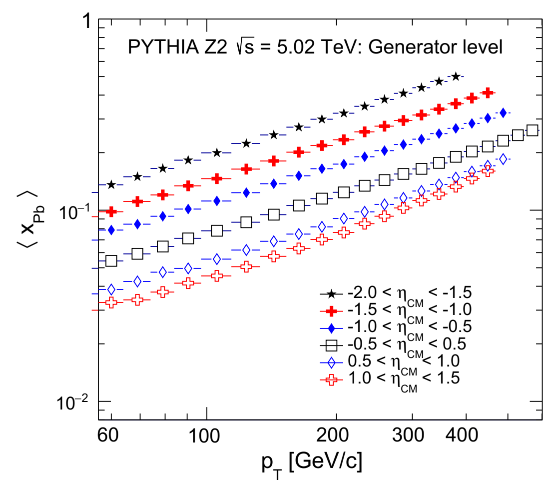

Fig. 5 Mean x values of partons in the Pb nucleus, $\langle x_{\mathrm{Pb}}\rangle$, corresponding to the jet p_{T} and pseudorapidity ranges covered in the measurements. The $\langle x_{\mathrm{Pb}}\rangle$ values are determined using the PYTHIA event generator [43]

suppression in the nPDFs with respect to the free-nucleon PDFs (EMC effect), and can be reached at high jet p_{T} in the backward pseudorapidity region ($\eta < -1$).

The forward–backward asymmetry of the jet production is evaluated by taking the ratio between the jet yields in the Pb-going and the proton-going directions for two pseudorapidity intervals: $0.5 < \lvert\eta_{\mathrm{CM}}\rvert < 1.0$ and $1.0 < \lvert\eta_{\mathrm{CM}}\rvert < 1.5$. The results are shown in Fig. 6 as a function of jet p_{T}. There is no significant asymmetry observed in the jet production within the covered pseudorapidity range, although a small effect at high p_{T} cannot be excluded with the present systematic uncertainties. The modifications in the nPDFs, if present, are of similar magnitude in the x ranges covered by the measurements in the forward and backward directions. This result is similar to the findings from the CMS charged-hadron measurements at high p_{T} [27].

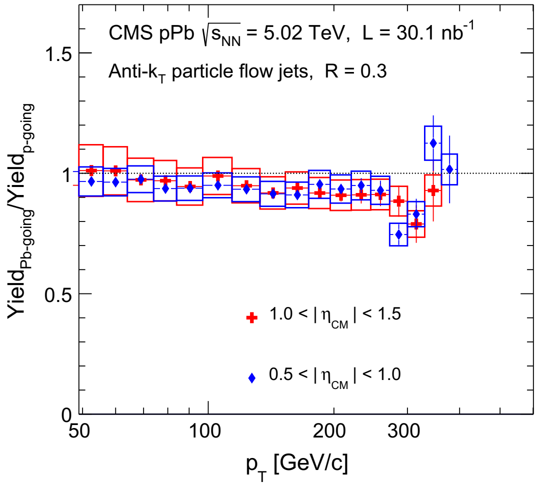

Fig. 6 Inclusive jet asymmetry as a function of jet p_T for $0.5 < |\eta_{CM}| < 1.0$ and $1.0 < |\eta_{CM}| < 1.5$. The asymmetry is calculated as the ratio between the jet yields at negative pseudorapidity (Pb beam direction) and positive pseudorapidity (proton-going side). The *vertical bars* represent the statistical uncertainties and the *open boxes* represent the systematic ones

The evolution of the jet spectra with pseudorapidity can also be studied by normalizing each spectrum to the one obtained in the mid-rapidity range ($|\eta_{CM}| < 1$). The normalized jet cross section distributions are shown in the top panel of Fig. 7. In the bottom panel of Fig. 7 we examine the pseudorapidity dependence in the normalized jet cross sections in three fixed p_T bins. The data points are offset for visibility. No significant pseudorapidity asymmetry is observed as can also be seen by comparing the open and closed stars or open and closed crosses in the top panel. The jet spectra become softer away from the mid-rapidity region, and the pseudorapidity distributions become narrower with increasing jet p_T as a result of the softening of the distributions at forward and backward pseudorapidity.

The inclusive jet nuclear modification factors R^*_{pPb} as a function of jet p_T are shown in Fig. 8 for six center-of-mass pseudorapidity bins, along with an NLO perturbative QCD (pQCD) calculation [57] using the EPS09 nPDFs [19]. For most of the measured p_T and η_{CM} ranges, the experimental R^*_{pPb} values are systematically above the theoretical prediction. However, this difference is not significant, given the size of the systematic uncertainties and the fact that they are strongly correlated in p_T. The R^*_{pPb} values are approximately independent of p_T. In the theoretical prediction there is a decrease in R_{pPb} with p_T in the backward pseudorapidity region, which is associated with the onset of the EMC effect at high values of x in the Pb nucleus. In the range of p_T where the measurements probe the anti-shadowing region, the R^*_{pPb} values show a hint of an enhancement with respect to the pp reference, e.g. for $|\eta_{CM}| < 0.5$ and $56 < p_T < 300\,\text{GeV}/c$, $R^*_{pPb} = 1.17 \pm 0.01\,(\text{stat}) \pm 0.12\,(\text{syst})$. This enhancement

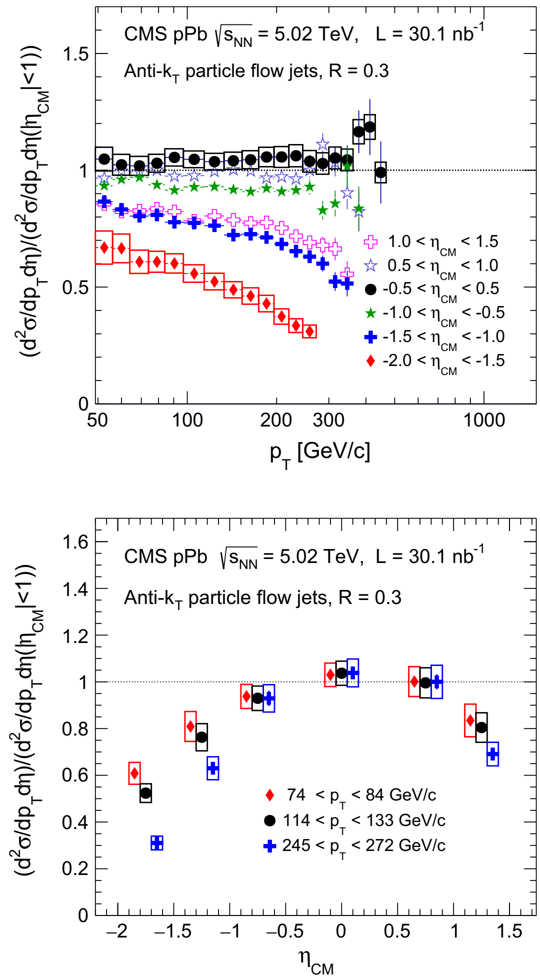

Fig. 7 *Top* inclusive jet cross section in pPb collisions as a function of jet p_T normalized to the production at mid-rapidity ($|\eta_{CM}| < 1$) for six η_{CM} intervals. The *vertical bars* represent the statistical uncertainties. The systematic uncertainties at mid-rapidity and in the most backward pseudorapidity are shown with *open boxes*. The uncertainties in the other pseudorapidity ranges have similar magnitude. *Bottom* inclusive jet cross section in pPb collisions as a function of η_{CM} normalized to the cross section at $|\eta_{CM}| < 1$, for three jet p_T ranges. The *open boxes* represent the systematic uncertainties. The data points are shifted in pseudorapidity to enhance the visibility. The η_{CM} bin boundaries are as specified in the *top panel*. The statistical uncertainties are smaller than the symbols

is smaller than the one observed in the charged-hadron measurement [27] and closer to the theoretical prediction. Direct measurements of the jet and charged-hadron reference spectra in pp collisions at $\sqrt{s} = 5\,\text{TeV}$ are needed to reduce the systematic uncertainties in the measurements of the nuclear modification factors and provide better constraints to the theory.

The results of the jet R^*_{pPb} measurements presented here are consistent with those reported by the ATLAS collaboration [22]. In Fig. 9 we compare our results to the ATLAS measurement at mid-rapidity, $|y_{CM}| < 0.3$, for the 0–90 %

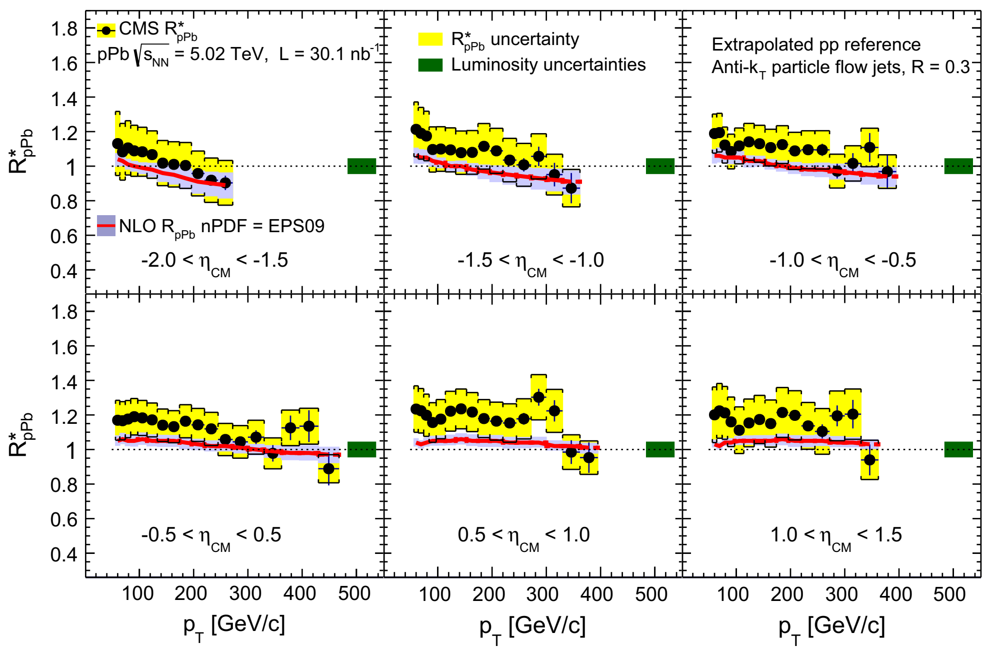

Fig. 8 Inclusive jet nuclear modification factor R^*_{pPb} as a function of jet p_T in $\sqrt{s_{NN}} = 5.02$ TeV pPb collisions, using a pp reference extrapolated from previous measurements [33] at $\sqrt{s} = 7$ TeV. The *vertical bars* represent the statistical uncertainties, and the *open boxes* represent the systematic ones. The *filled rectangular boxes* around $R^*_{pPb} = 1$ represent the luminosity uncertainties in the pPb and pp measurements. The CMS measurements are compared to a NLO pQCD calculation [57] that is based on the EPS09 nPDFs [19]. The theoretical calculations are shown with *solid lines*, and the *shaded bands* around them represent the theoretical uncertainties

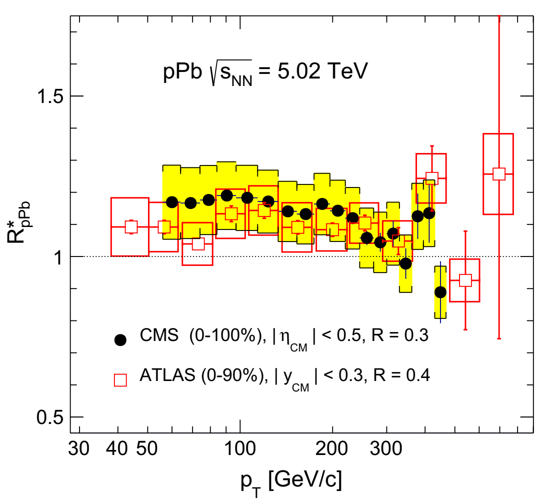

Fig. 9 Inclusive jet R^*_{pPb} integrated over centrality and in the $|\eta_{CM}| < 0.5$ range for anti-k_T jets with distance parameter $R = 0.3$ from this work, compared to ATLAS results [22] at $|y_{CM}| < 0.3$ for the 0–90 % most central collisions with distance parameter $R = 0.4$. The *vertical bars* show the statistical uncertainties, and the *open boxes* represent the systematic uncertainties

most central collisions, performed using a distance parameter $R = 0.4$. Although the event selections and the jet reconstruction are not exactly the same in the two measurements, the results are in good agreement.

5 Summary

The inclusive jet spectra and nuclear modification factors in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV have been measured. The data, corresponding to an integrated luminosity of 30.1 nb^{-1}, were collected by the CMS experiment in 2013. The jet transverse momentum spectra were measured for $p_T > 56$ GeV/c in six pseudorapidity intervals covering the range $-2 < \eta_{CM} < 1.5$ in the NN center-of-mass system. The jet spectra were found to be softer away from mid-rapidity. The jet production at forward and backward pseudorapidity were compared, and no significant asymmetry about $\eta_{CM} = 0$ was observed in the measured kinematic range.

The differential jet cross section results were compared with extrapolated pp reference spectra based on jet measurements in pp collisions at $\sqrt{s} = 7$ TeV. The inclusive jet nuclear modification factors R^*_{pPb} were observed to have small enhancements compared to the reference pp jet spectra at low jet p_T in all η_{CM} ranges. In the anti-shadowing region, for $|\eta_{CM}| < 0.5$ and $56 < p_T < 300$ GeV/c, the value $R^*_{pPb} = 1.17 \pm 0.01\,(\text{stat}) \pm 0.12\,(\text{syst})$ was found. The R^*_{pPb} appears to be approximately independent of p_T, except in the most backward pseudorapidity range. The R^*_{pPb} measurements were found to be compatible with theoretical predictions from NLO pQCD calculations that use EPS09 nPDFs.

Acknowledgments We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: the Austrian Federal Ministry of Science, Research and Economy and the Austrian Science Fund; the Belgian Fonds de la Recherche Scientifique, and Fonds voor Wetenschappelijk Onderzoek; the Brazilian Funding Agencies (CNPq, CAPES, FAPERJ, and FAPESP); the Bulgarian Ministry of Education and Science; CERN; the Chinese Academy of Sciences, Ministry of Science and Technology, and National Natural Science Foundation of China; the Colombian Funding Agency (COLCIENCIAS); the Croatian Ministry of Science, Education and Sport, and the Croatian Science Foundation; the Research Promotion Foundation, Cyprus; the Ministry of Education and Research, Estonian Research Council via IUT23-4 and IUT23-6 and European Regional Development Fund, Estonia; the Academy of Finland, Finnish Ministry of Education and Culture, and Helsinki Institute of Physics; the Institut National de Physique Nucléaire et de Physique des Particules/CNRS, and Commissariat à l'Énergie Atomique et aux Énergies Alternatives/CEA, France; the Bundesministerium für Bildung und Forschung, Deutsche Forschungsgemeinschaft, and Helmholtz-Gemeinschaft Deutscher Forschungszentren, Germany; the General Secretariat for Research and Technology, Greece; the National Scientific Research Foundation, and National Innovation Office, Hungary; the Department of Atomic Energy and the Department of Science and Technology, India; the Institute for Studies in Theoretical Physics and Mathematics, Iran; the Science Foundation, Ireland; the Istituto Nazionale di Fisica Nucleare, Italy; the Ministry of Science, ICT and Future Planning, and National Research Foundation (NRF), Republic of Korea; the Lithuanian Academy of Sciences; the Ministry of Education, and University of Malaya (Malaysia); the Mexican Funding Agencies (CINVESTAV, CONACYT, SEP, and UASLP-FAI); the Ministry of Business, Innovation and Employment, New Zealand; the Pakistan Atomic Energy Commission; the Ministry of Science and Higher Education and the National Science Centre, Poland; the Fundação para a Ciência e a Tecnologia, Portugal; JINR, Dubna; the Ministry of Education and Science of the Russian Federation, the Federal Agency of Atomic Energy of the Russian Federation, Russian Academy of Sciences, and the Russian Foundation for Basic Research; the Ministry of Education, Science and Technological Development of Serbia; the Secretaría de Estado de Investigación, Desarrollo e Innovación and Programa Consolider-Ingenio 2010, Spain; the Swiss Funding Agencies (ETH Board, ETH Zurich, PSI, SNF, UniZH, Canton Zurich, and SER); the Ministry of Science and Technology, Taipei; the Thailand Center of Excellence in Physics, the Institute for the Promotion of Teaching Science and Technology of Thailand, Special Task Force for Activating Research and the National Science and Technology Development Agency of Thailand; the Scientific and Technical Research Council of Turkey, and Turkish Atomic Energy Authority; the National Academy of Sciences of Ukraine, and State Fund for Fundamental Researches, Ukraine; the Science and Technology Facilities Council, UK; the US Department of Energy, and the US National Science Foundation. Individuals have received support from the Marie-Curie program and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund; the OPUS program of the National Science Center (Poland); the Compagnia di San Paolo (Torino); MIUR project 20108T4XTM (Italy); the Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the National Priorities Research Program by Qatar National Research Fund; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University (Thailand); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); and the Welch Foundation, contract C-1845.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.
Funded by SCOAP[3].

References

1. J.D. Bjorken, Energy loss of energetic partons in quark-gluon plasma: possible extinction of high p_TJets in hadron–hadron collisions. Technical Report FERMILAB-PUB-82-059-T, Fermilab (1982). http://lss.fnal.gov/archive/preprint/fermilab-pub-82-059-t.shtml
2. D. d'Enterria, Jet quenching. Springer Mater. Landolt-Börnstein Database **23**, 471 (2010). doi:10.1007/978-3-642-01539-7_16. arXiv:0902.2011
3. J. Casalderrey-Solana, C.A. Salgado, Introductory lectures on jet quenching in heavy ion collisions. Acta Phys. Polon. B **38**, 3731 (2007). arXiv:0712.3443
4. D.A. Appel, Jets as a probe of quark-gluon plasmas. Phys. Rev. B **33**, 717 (1986). doi:10.1103/PhysRevD.33.717
5. J.P. Blaizot, L.D. McLerran, Jets in expanding quark-gluon plasmas. Phys. Rev. D **34**, 2739 (1986). doi:10.1103/PhysRevD.34.2739
6. J.-W. Qiu, I. Vitev, Transverse momentum diffusion and broadening of the back- to-back di-hadron correlation function. Phys. Lett. B **570**, 161 (2003). doi:10.1016/j.physletb.2003.08.009. arXiv:nucl-th/0306039
7. PHENIX Collaboration, Suppression of hadrons with large transverse momentum in central Au + Au collisions at $\sqrt{s_{NN}} = 130$ GeV. Phys. Rev. Lett. **88**, 022301 (2002). doi:10.1103/PhysRevLett.88.022301. arXiv:nucl-ex/0109003
8. STAR Collaboration, Disappearance of back-to-back high p_T hadron correlations in central Au + Au collisions at $\sqrt{s_{NN}} =$ 200 GeV. Phys. Rev. Lett. **90**, 082302 (2003). doi:10.1103/PhysRevLett.90.082302. arXiv:nucl-ex/0210033
9. ATLAS Collaboration, Observation of a centrality-dependent dijet asymmetry in lead–lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector at the LHC. Phys. Rev. Lett. **105**, 252303 (2010). doi:10.1103/PhysRevLett.105.252303. arXiv:1011.6182
10. CMS Collaboration, Observation and studies of jet quenching in PbPb collisions at nucleon–nucleon center-of-mass energy = 2.76 TeV. Phys. Rev. C **84**, 024906 (2011). doi:10.1103/PhysRevC.84.024906. arXiv:1102.1957
11. CMS Collaboration, Studies of jet quenching using isolated-photon+jet correlations in PbPb and pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Phys. Lett. B **718**, 773 (2013). doi:10.1016/j.physletb.2012.11.003. arXiv:1205.0206
12. ATLAS Collaboration, Measurements of the nuclear modification factor for jets in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector. Phys. Rev. Lett. **114**, 072302 (2015). doi:10.1103/PhysRevLett.114.072302. arXiv:1411.2357

13. ALICE Collaboration, Measurement of jet suppression in central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Phys. Lett. B **746**, 1 (2015). doi:10.1016/j.physletb.2015.04.039. arXiv:1502.01689
14. CMS Collaboration, Modification of jet shapes in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Phys. Lett. B **730**, 243 (2014). doi:10.1016/j.physletb.2014.01.042. arXiv:1310.0878
15. ATLAS Collaboration, Measurement of inclusive jet charged-particle fragmentation functions in Pb + Pb collisions at $\sqrt{s_{NN}} =$ 2.76 TeV with the ATLAS detector. Phys. Lett. B **739**, 320 (2014). doi:10.1016/j.physletb.2014.10.065. arXiv:1406.2979
16. CMS Collaboration, Measurement of jet fragmentation in PbPb and pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Phys. Rev. C **90**, 024908 (2014). doi:10.1103/PhysRevC.90.024908. arXiv:1406.0932
17. M. Arneodo, Nuclear effects in structure functions. Phys. Rep. **240**, 301 (1994). doi:10.1016/0370-1573(94)90048-5
18. PHENIX Collaboration, Centrality dependence of π^0 and η production at large transverse momentum in $\sqrt{s_{NN}} = 200$ GeV d+Au collisions. Phys. Rev. Lett. **98**, 172302 (2007). doi:10.1103/PhysRevLett.98.172302. arXiv:nucl-ex/0610036
19. K.J. Eskola, H. Paukkunen, C.A. Salgado, EPS09: a new generation of NLO and LO nuclear parton distribution functions. JHEP **04**, 065 (2009). doi:10.1088/1126-6708/2009/04/065. arXiv:0902.4154
20. L.L. Frankfurt, M.I. Strikman, Hard nuclear processes and microscopic nuclear structure. Phys. Rep. **160**, 235 (1988). doi:10.1016/0370-1573(88)90179-2
21. P.R. Norton, The EMC effect. Rep. Prog. Phys. **66**, 1253 (2003). doi:10.1088/0034-4885/66/8/201
22. ATLAS Collaboration, Centrality and rapidity dependence of inclusive jet production in $\sqrt{s_{NN}} = 5.02$ TeV proton-lead collisions with the ATLAS detector. Phys. Lett. B **748**, 392 (2015). doi:10.1016/j.physletb.2015.07.023. arXiv:1412.4092
23. CMS Collaboration, Studies of dijet transverse momentum balance and pseudorapidity distributions in pPb collisions at $\sqrt{s_{NN}} =$ 5.02 TeV. Eur. Phys. J. C **74**, 2951 (2014). doi:10.1140/epjc/s10052-014-2951-y. arXiv:1401.4433
24. ALICE Collaboration, Measurement of dijet k_T in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Phys. Lett. B **746**, 385 (2015). doi:10.1016/j.physletb.2015.05.033. arXiv:1503.03050
25. ATLAS Collaboration, Z boson production in p + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV measured with the ATLAS detector. Phys. Rev. C **92**, 044915 (2015). doi:10.1103/PhysRevC.92.044915. arXiv:1507.06232
26. CMS Collaboration, Study of W boson production in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Phys. Lett. B **750**, 565 (2015). doi:10.1016/j.physletb.2015.09.057. arXiv:1503.05825
27. CMS Collaboration, Nuclear effects on the transverse momentum spectra of charged particles in pPb collisions at $\sqrt{s_{NN}} =$ 5.02 TeV. Eur. Phys. J. C **75**, 237 (2015). doi:10.1140/epjc/s10052-015-3435-4. arXiv:1502.05387
28. ALICE Collaboration, Transverse momentum dependence of inclusive primary charged-particle production in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Eur. Phys. J. C **74**, 3054 (2014). doi:10.1140/epjc/s10052-014-3054-5. arXiv:1405.2737
29. ALICE Collaboration, Measurement of charged jet production cross sections and nuclear modification in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Phys. Lett. B **749**, 68 (2015). doi:10.1016/j.physletb.2015.07.054. arXiv:1503.00681
30. N. Armesto, D.C. Gulhan, J.G. Milhano, Kinematic bias on centrality selection of jet events in pPb collisions at the LHC. Phys. Lett. B **747**, 441 (2015). doi:10.1016/j.physletb.2015.06.032. arXiv:1502.02986
31. PHENIX Collaboration, Centrality categorization for $R_{p(d)+A}$ in high-energy collisions. Phys. Rev. C **90**, 034902 (2014). doi:10.1103/PhysRevC.90.034902. arXiv:1310.4793
32. ALICE Collaboration, Centrality dependence of particle production in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Phys. Rev. C **91**, 064905 (2015). doi:10.1103/PhysRevC.91.064905. arXiv:1412.6828
33. CMS Collaboration, Measurement of the ratio of inclusive jet cross sections using the anti-k_T algorithm with radius parameters R = 0.5 and 0.7 in pp collisions at $\sqrt{s} = 7$ TeV. Phys. Rev. D **90**, 072006 (2014). doi:10.1103/PhysRevD.90.072006. arXiv:1406.0324
34. CMS Collaboration, The CMS experiment at the CERN LHC. JINST **3**, S08004 (2008). doi:10.1088/1748-0221/3/08/S08004
35. CMS Collaboration, Transverse momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 0.9$ and 2.36 TeV. JHEP **02**, 041 (2010). doi:10.1007/JHEP02(2010)041. arXiv:1002.0621
36. CMS Collaboration, CMS tracking performance results from early LHC operation. Eur. Phys. J. C **70**, 1165 (2010). doi:10.1140/epjc/s10052-010-1491-3. arXiv:1007.1988
37. M. Cacciari, G.P. Salam, G. Soyez, The anti-k_t jet clustering algorithm. JHEP **04**, 063 (2008). doi:10.1088/1126-6708/2008/04/063. arXiv:0802.1189
38. CMS Collaboration, Particle-Flow Event Reconstruction in CMS and Performance for Jets, Taus, and E_T^{miss}. CMS Physics Analysis Summary CMS-PAS-PFT-09-001 (2009)
39. CMS Collaboration, Commissioning of the Particle-Flow Reconstruction in Minimum-Bias and Jet Events from pp Collisions at 7 TeV. CMS Physics Analysis Summary CMS-PAS-PFT-10-002 (2010). http://cdsweb.cern.ch/record/1279341
40. M. Cacciari, G.P. Salam, G. Soyez, FastJet user manual. Eur. Phys. J. C **72**, 1896 (2012). doi:10.1140/epjc/s10052-012-1896-2. arXiv:1111.6097
41. O. Kodolova, I. Vardanian, A. Nikitenko, A. Oulianov, The performance of the jet identification and reconstruction in heavy ions collisions with CMS detector. Eur. Phys. J. C **50**, 117 (2007). doi:10.1140/epjc/s10052-007-0223-9
42. CMS Collaboration, Determination of jet energy calibration and transverse momentum resolution in CMS. JINST **6**, P11002 (2011). doi:10.1088/1748-0221/6/11/P11002. arXiv:1107.4277
43. T. Sjöstrand, S. Mrenna, P. Skands, PYTHIA 6.4 physics and manual. JHEP **05**, 026 (2006). doi:10.1088/1126-6708/2006/05/026. arXiv:hep-ph/0603175
44. R. Field, Min-Bias and the underlying event at the LHC. Acta Phys. Polon. B **42**, 2631 (2011). doi:10.5506/APhysPolB.42.2631. arXiv:1110.5530
45. G. D'Agostini, A multidimensional unfolding method based on Bayes' theorem. Nucl. Instrum. Methods A **362**, 487 (1995). doi:10.1016/0168-9002(95)00274-X
46. T. Adye, Unfolding algorithms and tests using RooUnfold, in *Proceedings of the PHYSTAT 2011 Workshop, CERN, Geneva, Switzerland, January 2011, CERN-2011-006*, p. 313 (2011). arXiv:1105.1160
47. X.-N. Wang, M. Gyulassy, HIJING 1.0: a Monte Carlo program for parton and particle production in high energy hadronic and nuclear collisions. Comput. Phys. Commun. **83**, 307 (1994). doi:10.1016/0010-4655(94)90057-4. arXiv:nucl-th/9502021
48. CMS Collaboration, Measurement of the inelastic cross section in proton–lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV Submitted to Phys. Lett. B (2015). doi:10.1016/j.physletb.2016.06.027. arXiv:1509.03893
49. T. Sjöstrand, S. Mrenna, P. Skands, A brief introduction to PYTHIA 8.1. Comput. Phys. Commun. **178**, 852 (2008). doi:10.1016/j.cpc.2008.01.036. arXiv:0710.3820
50. CMS Collaboration, Event generator tunes obtained from underlying event and multiparton scattering measurements. Eur. Phys. J. C **76**(3), 155 (2016). doi:10.1140/epjc/s10052-016-3988-x. arXiv:1512.00815

51. S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX. JHEP **06**, 043 (2010). doi:10.1007/JHEP06(2010)043. arXiv:1002.2581
52. S. Alioli et al., Jet pair production in POWHEG. JHEP **04**, 081 (2011). doi:10.1007/JHEP04(2011)081. arXiv:1012.3380
53. Z. Nagy, Three jet cross-sections in hadron hadron collisions at next-to-leading order. Phys. Rev. Lett. **88**, 122003 (2002). doi:10.1103/PhysRevLett.88.122003. arXiv:hep-ph/0110315
54. Z. Nagy, Next-to-leading order calculation of three-jet observables in hadron hadron collisions. Phys. Rev. D **68**, 094002 (2003). doi:10.1103/PhysRevD.68.094002. arXiv:hep-ph/0307268
55. D. Britzger, K. Rabbertz, F. Stober, M. Wobisch, New features in version 2 of the fastNLO project, in *20th International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS 2012)*, p. 217. Bonn, Germany, March 26–30, 2012. doi:10.3204/DESY-PROC-2012-02/165. arXiv:1208.3641
56. CMS Collaboration, Measurement of the inclusive jet cross section in pp collisions at $\sqrt{s} = 2.76$ TeV. Eur. Phys. J. C **76**(5), 265 (2016). doi:10.1140/epjc/s10052-016-4083-z. arXiv:1512.06212
57. J. Albacete et al., Predictions for p + Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5$ TeV. Int. J. Mod. Phys. E **22**, 1330007 (2013). doi:10.1142/S0218301313300075. arXiv:1301.3395

CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
V. Khachatryan, A. M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria
W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth[1], V. M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler[1], V. Knünz, A. König, M. Krammer[1], I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady[2], N. Rad, B. Rahbaran, H. Rohringer, J. Schieck[1], R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz[1]

National Centre for Particle and High Energy Physics, Minsk, Belarus
V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
S. Alderweireldt, T. Cornelis, E. A. De Wolf, X. Janssen, A. Knutsson, J. Lauwers, S. Luyckx, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussels, Belgium
S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous, J. Keaveney, S. Lowette, L. Moreels, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G. P. Van Onsem, I. Van Parijs

Université Libre de Bruxelles, Brussels, Belgium
P. Barria, H. Brun, C. Caillol, B. Clerbaux, G. De Lentdecker, W. Fang, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, T. Maerschalk, A. Marinov, L. Perniè, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang[3]

Ghent University, Ghent, Belgium
K. Beernaert, L. Benucci, A. Cimmino, S. Crucy, D. Dobur, A. Fagot, G. Garcia, M. Gul, J. Mccartin, A. A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva, M. Sigamani, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, C. Beluffi[4], O. Bondu, S. Brochet, G. Bruno, A. Caudron, L. Ceard, C. Delaere, M. Delcourt, D. Favart, L. Forthomme, A. Giammanco, A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Mertens, M. Musich, C. Nuttens, L. Perrini, K. Piotrzkowski, A. Popov[5], L. Quertenmont, M. Selvaggi, M. Vidal Marono

Université de Mons, Mons, Belgium
N. Beliy, G. H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
W. L. Aldá Júnior, F. L. Alves, G. A. Alves, L. Brito, M. Correa Martins Junior, M. Hamer, C. Hensel, A. Moraes, M. E. Pol, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato[6], A. Custódio, E. M. Da Costa, D. De Jesus Damiao,

C. De Oliveira Martins, S. Fonseca De Souza, L. M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, C. Mora Herrera, L. Mundim, H. Nogima, W. L. Prado Da Silva, A. Santoro, A. Sznajder, E. J. Tonelli Manganote[6], A. Vilela Pereira

Universidade Estadual Paulista[a], Universidade Federal do ABC[b], São Paulo, Brazil
S. Ahuja[a], C. A. Bernardes[b], A. De Souza Santos[b], S. Dogra[a], T. R. Fernandez Perez Tomei[a], E. M. Gregores[b], P. G. Mercadante[b], C. S. Moon[a,7], S. F. Novaes[a], Sandra S. Padula[a], D. Romero Abad[b], J. C. Ruiz Vargas

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria
A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China
M. Ahmad, J. G. Bian, G. M. Chen, H. S. Chen, M. Chen, T. Cheng, R. Du, C. H. Jiang, D. Leggat, R. Plestina[8], F. Romeo, S. M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, H. Zhang

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
C. Asawatangtrakuldee, Y. Ban, Q. Li, S. Liu, Y. Mao, S. J. Qian, D. Wang, Z. Xu

Universidad de Los Andes, Bogotà, Colombia
C. Avila, A. Cabrera, L. F. Chaparro Sierra, C. Florez, J. P. Gomez, B. Gomez Moreno, J. C. Sanabria

Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia
N. Godinovic, D. Lelas, I. Puljak, P. M. Ribeiro Cipriano

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

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, K. Kadija, J. Luetic, S. Micanovic, L. Sudic

University of Cyprus, Nicosia, Cyprus
A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P. A. Razis, H. Rykaczewski

Charles University, Prague, Czech Republic
M. Bodlak, M. Finger[9], M. Finger Jr.[9]

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
A. A. Abdelalim[10,11], A. Awad, A. Mahrous[10], A. Radi [12,13]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
B. Calpas, M. Kadastik, M. Murumaa, M. Raidal, A. Tiko, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
J. Härkönen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Peltola, J. Tuominiemi, E. Tuovinen, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland
J. Talvitie, T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J. L. Faure, C. Favaro, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, O. Davignon, N. Filipovic, R. Granier de Cassagnac, M. Jo, S. Lisniak, L. Mastrolorenzo, P. Miné, I. N. Naranjo, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, J. B. Sauvan, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram[14], J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E. C. Chabert, N. Chanon, C. Collard, E. Conte[14], X. Coubez, J.-C. Fontaine[14], D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, J. A. Merlin[2], K. Skovpen, P. Van Hove

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

Institut de Physique Nucléaire de Lyon, Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Villeurbanne, France
S. Beauceron, C. Bernet, G. Boudoul, E. Bouvier, C. A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, F. Lagarde, I. B. Laktineh, M. Lethuillier, L. Mirabito, A. L. Pequegnot, S. Perries, J. D. Ruiz Alvarez, D. Sabes, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret

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

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[9]

Physikalisches Institut, RWTH Aachen University, I, Aachen, Germany
C. Autermann, S. Beranek, L. Feld, A. Heister, M. K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, S. Schael, J. F. Schulte, T. Verlage, H. Weber, V. Zhukov[5]

Physikalisches Institut A, RWTH Aachen University, III, Aachen, Germany
M. Ata, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, P. Papacz, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teyssier, S. Thüer

Physikalisches Institut B, RWTH Aachen University, III, Aachen, Germany
V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, F. Hoehle, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, A. Nehrkorn, A. Nowack, I. M. Nugent, C. Pistone, O. Pooth, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, I. Asin, N. Bartosik, O. Behnke, U. Behrens, K. Borras[16], A. Burgmeier, A. Campbell, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Dolinska, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, E. Gallo[17], J. Garay Garcia, A. Geiser, A. Gizhko, P. Gunnellini, J. Hauk, M. Hempel[18], H. Jung, A. Kalogeropoulos, O. Karacheban[18], M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann[18], R. Mankel, I.-A. Melzer-Pellmann, A. B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, S. Naumann-Emme, A. Nayak, E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M. Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, C. Seitz, S. Spannagel, N. Stefaniuk, K. D. Trippkewitz, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany
V. Blobel, M. Centis Vignali, A. R. Draeger, J. Erfle, E. Garutti, K. Goebel, D. Gonzalez, M. Görner, J. Haller, M. Hoffmann, R. S. Höing, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, D. Nowatschin, J. Ott, F. Pantaleo[2], T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, D. Rathjens, C. Sander, C. Scharf, P. Schleper, E. Schlieckau, A. Schmidt, S. Schumann, J. Schwandt, V. Sola, H. Stadie, G. Steinbrück, F. M. Stober, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Kernphysik, Karlsruhe, Germany
C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Descroix, A. Dierlamm, S. Fink, F. Frensch, R. Friese, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann[2], S. M. Heindl, U. Husemann, I. Katkov[5], A. Kornmayer[2], P. Lobelle Pardo, B. Maier, H. Mildner, M. U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, M. Schröder, G. Sieber, H. J. Simonis, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, T. Geralis, V. A. Giakoumopoulou, A. Kyriakis, D. Loukas, A. Psallidas, I. Topsis-Giotis

National and Kapodistrian University of Athens, Athens, Greece
A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

University of Ioánnina, Ioannina, Greece
I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, A. Hazi, P. Hidas, D. Horvath[19], F. Sikler, V. Veszpremi, G. Vesztergombi[20], A. J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi[21], J. Molnar, Z. Szillasi[2]

University of Debrecen, Debrecen, Hungary
M. Bartók[22], A. Makovec, P. Raics, Z. L. Trocsanyi, B. Ujvari

National Institute of Science Education and Research, Bhubaneswar, India
S. Choudhury[23], P. Mal, K. Mandal, D. K. Sahoo, N. Sahoo, S. K. Swain

Panjab University, Chandigarh, India
S. Bansal, S. B. Beri, V. Bhatnagar, R. Chawla, R. Gupta, U. Bhawandeep, A. K. Kalsi, A. Kaur, M. Kaur, R. Kumar, A. Mehta, M. Mittal, J. B. Singh, G. Walia

University of Delhi, Delhi, India
Ashok Kumar, A. Bhardwaj, B. C. Choudhary, R. B. Garg, S. Malhotra, M. Naimuddin, N. Nishu, K. Ranjan, R. Sharma, V. Sharma

Saha Institute of Nuclear Physics, Kolkata, India
S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutta, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India
R. Chudasama, D. Dutta, V. Jha, V. Kumar, A. K. Mohanty[2], L. M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research, Mumbai, India
T. Aziz, S. Banerjee, S. Bhowmik[24], R. M. Chatterjee, R. K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu[25], Sa. Jain, G. Kole, S. Kumar, B. Mahakud, M. Maity[24], G. Majumder, K. Mazumdar, S. Mitra, G. B. Mohanty, B. Parida, T. Sarkar[24], N. Sur, B. Sutar, N. Wickramage[26]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, A. Kapoor, K. Kothekar, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
H. Bakhshiansohi, H. Behnamian, S. M. Etesami[27], A. Fahim[28], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh[29], M. Zeinali

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], C. Calabria[a,b], C. Caputo[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], L. Fiore[a], G. Iaselli[a,c], G. Maggi[a,c], M. Maggi[a], G. Miniello[a,b], S. My[a,c], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a,b], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a,2], R. Venditti[a,b],

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], C. Battilana[2], D. Bonacorsi[a,b], S. Braibant-Giacomelli[a,b], L. Brigliadori[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F. R. Cavallo[a], S. S. Chhibra[a,b], G. Codispoti[a,b], M. Cuffiani[a,b], G. M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a,b], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], S. Marcellini[a], G. Masetti[a], A. Montanari[a], F. L. Navarria[a,b], A. Perrotta[a], A. M. Rossi[a,b], T. Rovelli[a,b], G. P. Siroli[a,b], N. Tosi[a,b,2],

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy
G. Cappello[b], M. Chiorboli[a,b], S. Costa[a,b], A. Di Mattia[a], F. Giordano[a,b], R. Potenza[a,b], A. Tricomi[a,b], C. Tuve[a,b]

INFN Sezione di Firenze[a], Università di Firenze[b], Florence, Italy
G. Barbagli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], V. Gori[a,b], P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], L. Viliani[a,b,2]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera[2]

INFN Sezione di Genova[a], Università di Genova[b], Genova, Italy
V. Calvelli[a,b], F. Ferro[a], M. Lo Vetere[a,b], M. R. Monge[a,b], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milan, Italy
L. Brianza, M. E. Dinardo[a,b], S. Fiorendi[a,b], S. Gennai[a], R. Gerosa[a,b], A. Ghezzi[a,b], P. Govoni[a,b], S. Malvezzi[a], R. A. Manzoni[a,b,2], B. Marzocchi[a,b], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], N. Redaelli[a], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy, Università della Basilicata[c], Potenza, Italy, Università G. Marconi[d], Rome, Italy
S. Buontempo[a], N. Cavallo[a,c], S. Di Guida[a,d,2], M. Esposito[a,b], F. Fabozzi[a,c], A. O. M. Iorio[a,b], G. Lanza[a], L. Lista[a], S. Meola[a,d,2], M. Merola[a], P. Paolucci[a,2], C. Sciacca[a,b], F. Thyssen

INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy, Università di Trento[c], Trento, Italy
P. Azzi[a,2], N. Bacchetta[a], L. Benato[a,b], D. Bisello[a,b], A. Boletti[a,b], A. Branca[a,b,], R. Carlin[a,b], P. Checchia[a], M. Dall'Osso[a,b,2], T. Dorigo[a], U. Dosselli[a], F. Fanzago[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], K. Kanishchev[a,c], S. Lacaprara[a], M. Margoni[a,b], A. T. Meneguzzo[a,b], J. Pazzini[a,b,2], N. Pozzobon[a,b], P. Ronchese[a,b], F. Simonetto[a,b], E. Torassa [a], M. Tosi[a,b], M. Zanetti, P. Zotto[a,b], A. Zucchetta[a,b,2], G. Zumerle[a,b]

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

INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy
L. Alunni Solestizi[a,b], G. M. Bilei[a], D. Ciangottini[a,b,2], L. Fanò[a,b], P. Lariccia[a,b], G. Mantovani[a,b], M. Menichelli[a], A. Saha[a], A. Santocchia[a,b]

INFN Sezione di Pisa[a], Università di Pisa[b], Scuola Normale Superiore di Pisa[c], Pisa, Italy
K. Androsov[a,30], P. Azzurri[a,2], G. Bagliesi[a], J. Bernardini[a], T. Boccali[a], R. Castaldi[a], M. A. Ciocci[a,30], R. Dell'Orso[a], S. Donato[a,c,2], G. Fedi, L. Foà[a,c†], A. Giassi[a], M. T. Grippo[a,30], F. Ligabue[a,c], T. Lomtadze[a], L. Martini[a,b], A. Messineo[a,b], F. Palla[a,], A. Rizzi[a,b], A. Savoy-Navarro[a,31], A. T. Serban[a], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], P. G. Verdini[a]

INFN Sezione di Roma[a], Università di Roma[b], Rome, Italy
L. Barone[a,b], F. Cavallari[a], G. D'imperio[a,b,2], D. Del Re[a,b,2], M. Diemoz[a], S. Gelli[a,b], C. Jorda[a], E. Longo[a,b], F. Margaroli[a,b], P. Meridiani[a], G. Organtini[a,b], R. Paramatti[a], F. Preiato[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], P. Traczyk[a,b,2]

INFN Sezione di Torino[a], Università di Torino[b], Turin, Italy, Università del Piemonte Orientale[c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c,2], S. Argiro[a,b], M. Arneodo[a,c], R. Bellan[a,b], C. Biino[a], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], A. Degano[a,b], N. Demaria[a], L. Finco[a,b,2], B. Kiani[a,b], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], E. Monteil[a,b], M. M. Obertino[a,b], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G. L. Pinna Angioni[a,b], F. Ravera[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], A. Solano[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], G. Della Ricca[a,b], B. Gobbo[a], C. La Licata[a,b], M. Marone[a,b], A. Schizzi[a,b], A. Zanetti[a]

Kangwon National University, Chunchon, Korea
A. Kropivnitskaya, S. K. Nam

Kyungpook National University, Daegu, Korea
D. H. Kim, G. N. Kim, M. S. Kim, D. J. Kong, S. Lee, Y. D. Oh, A. Sakharov, D. C. Son

Chonbuk National University, Jeonju, Korea
J. A. Brochero Cifuentes, H. Kim, T. J. Kim

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

Korea University, Seoul, Korea
S. Cho, S. Choi, Y. Go, D. Gyun, B. Hong, H. Kim, Y. Kim, B. Lee, K. Lee, K. S. Lee, S. Lee, J. Lim, S. K. Park, Y. Roh

Seoul National University, Seoul, Korea
H. D. Yoo

University of Seoul, Seoul, Korea
M. Choi, H. Kim, J. H. Kim, J. S. H. Lee, I. C. Park, G. Ryu, M. S. Ryu

Sungkyunkwan University, Suwon, Korea
Y. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Ahmed, Z. A. Ibrahim, J. R. Komaragiri, M. A. B. Md Ali[32], F. Mohamad Idris[33], W. A. T. Wan Abdullah, M. N. Yusli, Z. Zolkapli

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[34], A. Hernandez-Almada, R. Lopez-Fernandez, J. Mejia Guisao, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, F. Vazquez Valencia

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

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

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
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, T. Khurshid, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
G. Brona, K. Bunkowski, A. Byszuk[35], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisbon, Portugal
P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P. G. Ferreira Parracho, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, F. Nguyen, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadruccio, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev[36,37], P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim[38], E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, 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, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, E. Vlasov, A. Zhokin

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
M. Chadeeva, R. Chistov, M. Danilov, V. Rusinov, E. Tarkovskii

P. N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin[37], I. Dremin[37], M. Kirakosyan, A. Leonidov[37], G. Mesyats, S. V. Rusakov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Baskakov, A. Belyaev, E. Boos, A. Ershov, A. Gribushin, A. Kaminskiy[39], O. Kodolova, V. Korotkikh, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A Snigirev, I. Vardanyan

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

Faculty of Physics and Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
P. Adzic[40], P. Cirkovic, D. Devetak, J. Milosevic, V. Rekovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J. P. Fernández Ramos, J. Flix, M. C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J. M. Hernandez, M. I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M. S. Soares

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J. F. de Trocóniz, M. Missiroli, D. Moran

Universidad de Oviedo, Oviedo, Spain
J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, J. M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I. J. Cabrillo, A. Calderon, J. R. Castiñeiras De Saa, E. Curras, P. De Castro Manzano, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A. H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, G. M. Berruti, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco[41], M. Dobson, M. Dordevic, B. Dorney, T. du Pree, D. Duggan, M. Dünser, N. Dupont, A. Elliott-Peisert, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, H. Kirschenmann, M. J. Kortelainen, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, M. T. Lucchini, N. Magini, L. Malgeri, M. Mannelli, A. Martelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, M. V. Nemallapudi, H. Neugebauer, S. Orfanelli[42], L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, A. Racz, T. Reis, G. Rolandi[43], M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, M. Simon, P. Sphicas[44], J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Triossi, A. Tsirou, G. I. Veres[20], N. Wardle, H. K. Wöhri, A. Zagozdzinska[35], W. D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H. C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
F. Bachmair, L. Bäni, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, P. Lecomte[†], W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, M. T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Rossini, M. Schönenberger, A. Starodumov[45], M. Takahashi, V. R. Tavolaro, K. Theofilatos, R. Wallny

Universität Zürich, Zurich, Switzerland
T. K. Aarrestad, C. Amsler[46], L. Caminada, M. F. Canelli, V. Chiochia, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, Y. Yang

National Central University, Chung-Li, Taiwan
K. H. Chen, T. H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C. M. Kuo, W. Lin, Y. J. Lu, A. Pozdnyakov, S. S. Yu

National Taiwan University (NTU), Taipei, Taiwan
Arun Kumar, P. Chang, Y. H. Chang, Y. W. Chang, Y. Chao, K. F. Chen, P. H. Chen, C. Dietz, F. Fiori, U. Grundler, W.-S. Hou, Y. Hsiung, Y. F. Liu, R.-S. Lu, M. Miñano Moya, E. Petrakou, J. F. Tsai, Y. M. Tzeng

Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand
B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas, N. Suwonjandee

Cukurova University, Adana, Turkey
A. Adiguzel, S. Damarseckin, Z. S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E. E. Kangal[47], A. Kayis Topaksu, G. Onengut[48], K. Ozdemir[49], S. Ozturk[50], D. Sunar Cerci[51], B. Tali[51], H. Topakli[50], C. Zorbilmez

Physics Department, Middle East Technical University, Ankara, Turkey
B. Bilin, S. Bilmis, B. Isildak[52], G. Karapinar[53], M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
E. Gülmez, M. Kaya[54], O. Kaya[55], E. A. Yetkin[56], T. Yetkin[57]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak, S. Sen[58], F. I. Vardarlı

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

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

University of Bristol, Bristol, UK
R. Aggleton, F. Ball, L. Beck, J. J. Brooke, D. Burns, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G. P. Heath, H. F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D. M. Newbold[59], S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, D. Smith, V. J. Smith

Rutherford Appleton Laboratory, Didcot, UK
A. Belyaev[60], C. Brew, R. M. Brown, L. Calligaris, D. Cieri, D. J. A. Cockerill, J. A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C. H. Shepherd-Themistocleous, A. Thea, I. R. Tomalin, T. Williams, S. D. Worm

Imperial College, London, UK
M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, P. Dunne, A. Elwood, D. Futyan, G. Hall, G. Iles, R. Lane, R. Lucas[59], L. Lyons, A.-M. Magnan, S. Malik, J. Nash, A. Nikitenko[45], J. Pela, M. Pesaresi, D. M. Raymond, A. Richards, A. Rose, C. Seez, A. Tapper, K. Uchida, M. Vazquez Acosta[61], T. Virdee, S. C. Zenz

Brunel University, Uxbridge, UK
J. E. Cole, P. R. Hobson, A. Khan, P. Kyberd, D. Leslie, I. D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA
A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika

The University of Alabama, Tuscaloosa, USA
O. Charaf, S. I. Cooper, C. Henderson, P. Rumerio

Boston University, Boston, USA
D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, USA
J. Alimena, G. Benelli, E. Berry, D. Cutts, A. Ferapontov, A. Garabedian, J. Hakala, U. Heintz, O. Jesus, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, R. Syarif

University of California, Davis, Davis, USA
R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P. T. Cox, R. Erbacher, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Los Angeles, USA
R. Cousins, P. Everaerts, A. Florent, J. Hauser, M. Ignatenko, D. Saltzberg, E. Takasugi, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA
K. Burt, R. Clare, J. Ellison, J. W. Gary, G. Hanson, J. Heilman, M. Ivova Paneva, P. Jandir, E. Kennedy, F. Lacroix, O. R. Long, M. Malberti, M. Olmedo Negrete, A. Shrinivas, H. Wei, S. Wimpenny, B. R. Yates

University of California, San Diego, La Jolla, USA
J. G. Branson, G. B. Cerati, S. Cittolin, R. T. D'Agnolo, M. Derdzinski, A. Holzner, R. Kelley, D. Klein, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech[62], C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara, Santa Barbara, USA
J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, J. Incandela, N. Mccoll, S. D. Mullin, J. Richman, D. Stuart, I. Suarez, C. West, J. Yoo

California Institute of Technology, Pasadena, USA
D. Anderson, A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, A. Mott, H. B. Newman, C. Pena, M. Spiropulu, J. R. Vlimant, S. Xie, R. Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
M. B. Andrews, V. Azzolini, A. Calamba, B. Carlson, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev

University of Colorado Boulder, Boulder, USA
J. P. Cumalat, W. T. Ford, A. Gaz, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, U. Nauenberg, K. Stenson, S. R. Wagner

Cornell University, Ithaca, USA
J. Alexander, A. Chatterjee, J. Chaves, J. Chu, S. Dittmer, N. Eggert, N. Mirman, G. Nicolas Kaufman, J. R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, W. Sun, S. M. Tan, W. D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, P. Wittich

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, G. Apollinari, S. Banerjee, L. A. T. Bauerdick, A. Beretvas, J. Berryhill, P. C. Bhat, G. Bolla, K. Burkett, J. N. Butler, H. W. K. Cheung, F. Chlebana, S. Cihangir, V. D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, D. Hare, R. M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, J. Lewis, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, J. M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, C. Newman-Holmes[†], V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, E. Sexton-Kennedy, A. Soha, W. J. Spalding, L. Spiegel, S. Stoynev, N. Strobbe, L. Taylor, S. Tkaczyk, N. V. Tran, L. Uplegger, E. W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H. A. Weber, A. Whitbeck

University of Florida, Gainesville, USA
D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, S. Das, R. D. Field, I. K. Furic, J. Konigsberg, A. Korytov, K. Kotov, P. Ma, K. Matchev, H. Mei, P. Milenovic[63], G. Mitselmakher, D. Rank, R. Rossin, L. Shchutska, M. Snowball, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

Florida International University, Miami, USA
S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J. L. Rodriguez

Florida State University, Tallahassee, USA
A. Ackert, J. R. Adams, T. Adams, A. Askew, S. Bein, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K. F. Johnson, A. Khatiwada, H. Prosper, M. Weinberg

Florida Institute of Technology, Melbourne, USA
M. M. Baarmand, V. Bhopatkar, S. Colafranceschi[64], M. Hohlmann, H. Kalakhety, D. Noonan, T. Roy, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M. R. Adams, L. Apanasevich, D. Berry, R. R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C. E. Gerber, D. J. Hofman, P. Kurt, C. O'Brien, I. D. Sandoval Gonzalez, P. Turner, N. Varelas, Z. Wu, M. Zakaria, J. Zhang

The University of Iowa, Iowa City, USA
B. Bilki[65], W. Clarida, K. Dilsiz, S. Durgut, R. P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya[66], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok[67], A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA
I. Anderson, B. A. Barnett, B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A. V. Gritsan, P. Maksimovic, M. Osherson, J. Roskes, U. Sarica, M. Swartz, M. Xiao, Y. Xin, C. You

The University of Kansas, Lawrence, USA
P. Baringer, A. Bean, C. Bruner, R. P. KennyIII, D. Majumder, M. Malek, W. Mcbrayer, M. Murray, S. Sanders, R. Stringer, Q. Wang

Kansas State University, Manhattan, USA
A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, A. Mohammadi, L. K. Saini, N. Skhirtladze, S. Toda

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

University of Maryland, College Park, USA
C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S. C. Eno, C. Ferraioli, J. A. Gomez, N. J. Hadley, S. Jabeen, R. G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A. C. Mignerey, Y. H. Shin, A. Skuja, M. B. Tonjes, S. C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA
A. Apyan, R. Barbieri, A. Baty, R. Bi, K. Bierwagen, S. Brandt, W. Busza, I. A. Cali, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Gulhan, Y. Iiyama, G. M. Innocenti, M. Klute, D. Kovalskyi, Y. S. Lai, Y.-J. Lee, A. Levin, P. D. Luckey, A. C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G. S. F. Stephans, K. Sumorok, K. Tatar, M. Varma, D. Velicanu, J. Veverka, J. Wang, T. W. Wang, B. Wyslouch, M. Yang, V. Zhukova

University of Minnesota, Minneapolis, USA
A. C. Benvenuti, B. Dahmes, A. Evans, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S. C. Kao, K. Klapoetke, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

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

University of Nebraska-Lincoln, Lincoln, USA
E. Avdeeva, R. Bartek, K. Bloom, S. Bose, D. R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, D. Knowlton, I. Kravchenko, F. Meier, J. Monroy, F. Ratnikov, J. E. Siado, G. R. Snow

State University of New York at Buffalo, Buffalo, USA
M. Alyari, J. Dolen, J. George, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA
G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, A. Hortiangtham, A. Massironi, D. M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood, J. Zhang

Northwestern University, Evanston, USA
S. Bhattacharya, K. A. Hahn, A. Kubik, J. F. Low, N. Mucia, N. Odell, B. Pollack, M. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA
N. Dev, M. Hildreth, C. Jessop, D. J. Karmgard, N. Kellams, K. Lannon, N. Marinelli, F. Meng, C. Mueller, Y. Musienko[36], M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, N. Valls, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA
L. Antonelli, J. Brinson, B. Bylsma, L. S. Durkin, S. Flowers, A. Hart, C. Hill, R. Hughes, W. Ji, T. Y. Ling, B. Liu, W. Luo, D. Puigh, M. Rodenburg, B. L. Winer, H. W. Wulsin

Princeton University, Princeton, USA
O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S. A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully, A. Zuranski

University of Puerto Rico, Mayagüez, USA
S. Malik

Purdue University, West Lafayette, USA
A. Barker, V. E. Barnes, D. Benedetti, D. Bortoletto, L. Gutay, M. K. Jha, M. Jones, A. W. Jung, K. Jung, A. Kumar, D. H. Miller, N. Neumeister, B. C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu

Purdue University Calumet, Hammond, USA
N. Parashar, J. Stupak

Rice University, Houston, USA
A. Adair, B. Akgun, Z. Chen, K. M. Ecklund, F. J. M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B. P. Padley, R. Redjimi, J. Roberts, J. Rorie, Z. Tu, J. Zabel

University of Rochester, Rochester, USA
B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K. H. Lo, P. Tan, M. Verzetti

Rutgers, The State University of New Jersey, Piscataway, USA
J. P. Chou, E. Contreras-Campana, D. Ferencek, Y. Gershtein, E. Halkiadakis, M. Heindl, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, A. Lath, K. Nash, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA
M. Foerster, G. Riley, K. Rose, S. Spanier, A. York, K. Thapa

Texas A&M University, College Station, USA
O. Bouhali[68], A. Castaneda Hernandez[68], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[69], V. Krutelyov, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, A. Rose, A. Safonov, A. Tatarinov, K. A. Ulmer[2]

Texas Tech University, Lubbock, USA
N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P. R. Dudero, J. Faulkner, S. Kunori, K. Lamichhane, S. W. Lee, T. Libeiro, S. Undleeb, I. Volobouev

Vanderbilt University, Nashville, USA
E. Appelt, A. G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, Y. Mao, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, USA
M. W. Arenton, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, J. Wood, F. Xia

Wayne State University, Detroit, USA
C. Clarke, R. Harr, P. E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

University of Wisconsin-Madison, Madison, WI, USA
D. A. Belknap, D. Carlsmith, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G. A. Pierro, G. Polese, T. Ruggles, T. Sarangi, A. Savin, A. Sharma, N. Smith, W. H. Smith, D. Taylor, P. Verwilligen, N. Woods

† **Deceased**

1: Also at Vienna University of Technology, Vienna, Austria
2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
3: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
4: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
5: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
6: Also at Universidade Estadual de Campinas, Campinas, Brazil
7: Also at Centre National de la Recherche Scientifique (CNRS)-IN2P3, Paris, France
8: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
9: Also at Joint Institute for Nuclear Research, Dubna, Russia
10: Also at Helwan University, Cairo, Egypt
11: Now at Zewail City of Science and Technology, Zewail, Egypt
12: Also at British University in Egypt, Cairo, Egypt
13: Now at Ain Shams University, Cairo, Egypt
14: Also at Université de Haute Alsace, Mulhouse, France
15: Also at Tbilisi State University, Tbilisi, Georgia
16: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
17: Also at University of Hamburg, Hamburg, Germany
18: Also at Brandenburg University of Technology, Cottbus, Germany

19: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
20: Also at Eötvös Loránd University, Budapest, Hungary
21: Also at University of Debrecen, Debrecen, Hungary
22: Also at Wigner Research Centre for Physics, Budapest, Hungary
23: Also at Indian Institute of Science Education and Research, Bhopal, India
24: Also at University of Visva-Bharati, Santiniketan, India
25: Now at King Abdulaziz University, Jeddah, Saudi Arabia
26: Also at University of Ruhuna, Matara, Sri Lanka
27: Also at Isfahan University of Technology, Isfahan, Iran
28: Also at University of Tehran, Department of Engineering Science, Tehran, Iran
29: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
30: Also at Università degli Studi di Siena, Siena, Italy
31: Also at Purdue University, West Lafayette, USA
32: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
33: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
34: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
35: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
36: Also at Institute for Nuclear Research, Moscow, Russia
37: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
38: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
39: Also at INFN Sezione di Padova; Università di Padova; Università di Trento (Trento), Padova, Italy
40: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
41: Also at INFN Sezione di Roma; Università di Roma, Roma, Italy
42: Also at National Technical University of Athens, Athens, Greece
43: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
44: Also at National and Kapodistrian University of Athens, Athens, Greece
45: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
46: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
47: Also at Mersin University, Mersin, Turkey
48: Also at Cag University, Mersin, Turkey
49: Also at Piri Reis University, Istanbul, Turkey
50: Also at Gaziosmanpasa University, Tokat, Turkey
51: Also at Adiyaman University, Adiyaman, Turkey
52: Also at Ozyegin University, Istanbul, Turkey
53: Also at Izmir Institute of Technology, Izmir, Turkey
54: Also at Marmara University, Istanbul, Turkey
55: Also at Kafkas University, Kars, Turkey
56: Also at Istanbul Bilgi University, Istanbul, Turkey
57: Also at Yildiz Technical University, Istanbul, Turkey
58: Also at Hacettepe University, Ankara, Turkey
59: Also at Rutherford Appleton Laboratory, Didcot, UK
60: Also at School of Physics and Astronomy, University of Southampton, Southampton, UK
61: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
62: Also at Utah Valley University, Orem, USA
63: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
64: Also at Facoltà Ingegneria, Università di Roma, Rome, Italy
65: Also at Argonne National Laboratory, Argonne, USA
66: Also at Erzincan University, Erzincan, Turkey
67: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
68: Also at Texas A&M University at Qatar, Doha, Qatar
69: Also at Kyungpook National University, Daegu, Korea