

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

CMS Collaboration*

CERN, 1211 Geneva 23, Switzerland

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Abstract Inclusive jet production in pPb collisions at a nucleon–nucleon (NN) center-of-mass energy of $\sqrt{s_{\text{NN}}} = 5.02$ 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 $-2.0 < \eta_{\text{CM}} < 1.5$ in the NN center-of-mass frame. The jet production yields at forward and backward pseudorapidity are compared and no significant asymmetry about $\eta_{\text{CM}} = 0$ 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. Modifi-

cations 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 $p_T > 0.4 \text{ GeV}/c$ 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 $100 \text{ GeV}/c$ 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

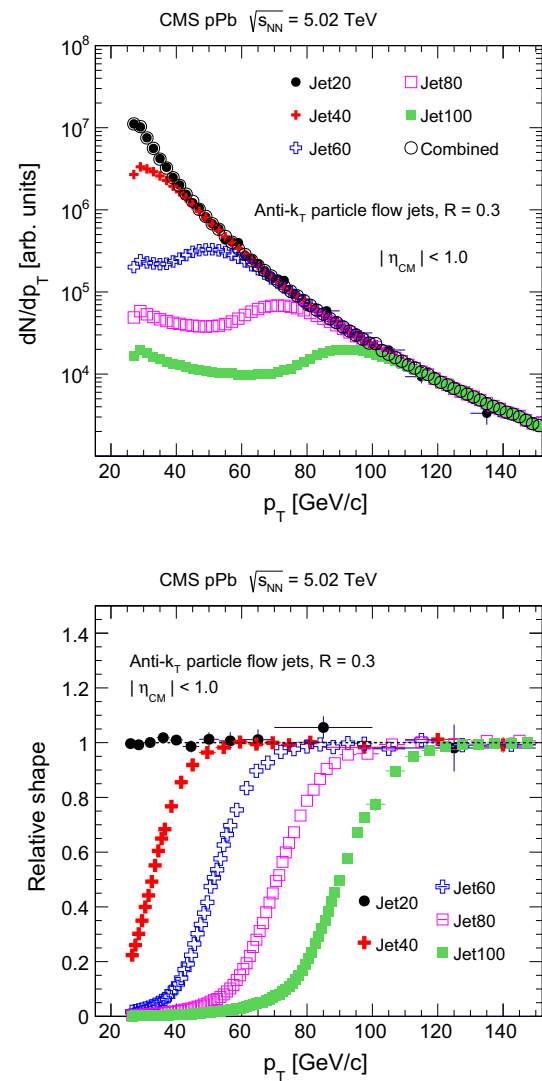


Fig. 1 Top the weighted jet spectra using prescale factors from each HLT-triggered event sample and the combined jet spectrum. A subset of the data is plotted to illustrate the procedure. Bottom the ratios of each individual HLT-triggered jet spectrum to the combined jet spectrum. Statistical uncertainties 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 $p_T = 50$ GeV/c in pPb collisions are fake, and this fraction quickly drops to a level of 10^{-4} at $p_T \approx 100$ 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 $p_T = 60$ (300) GeV/c. A Bayesian unfold-

ing 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

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

where $L = 30.1 \text{ nb}^{-1}$ 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 $\sqrt{s} = 5.02 \text{ TeV}$, for this paper

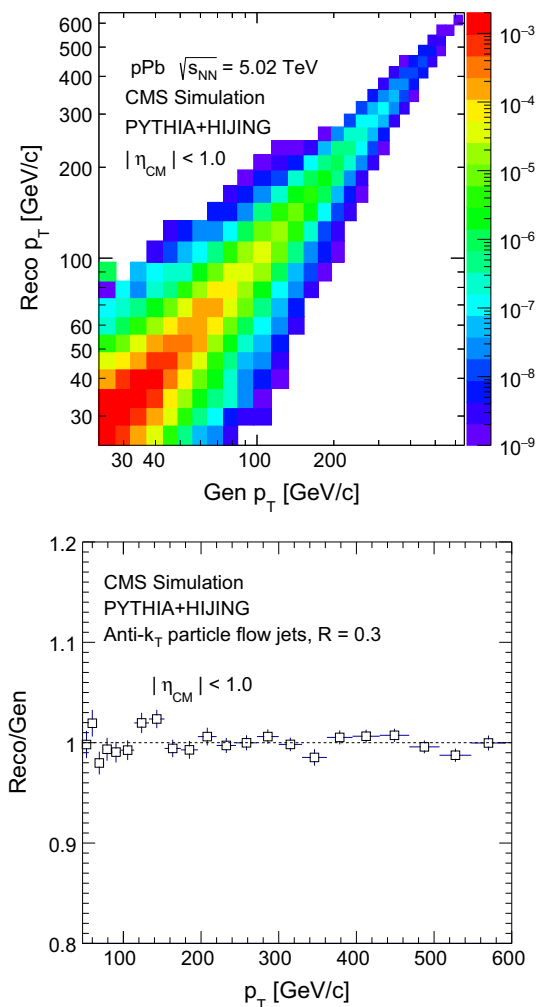


Fig. 2 Top response matrix built from PYTHIA + HIJING simulation. Bottom the ratios of the Bayesian unfolded jet p_T spectrum reconstructed in the simulation and the generator-level spectrum

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 $\sqrt{s} = 7 \text{ TeV}$. 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 $\sqrt{s} = 7 \text{ TeV}$ jet cross section measurements are extrapolated to $\sqrt{s} = 5.02 \text{ TeV}$ 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

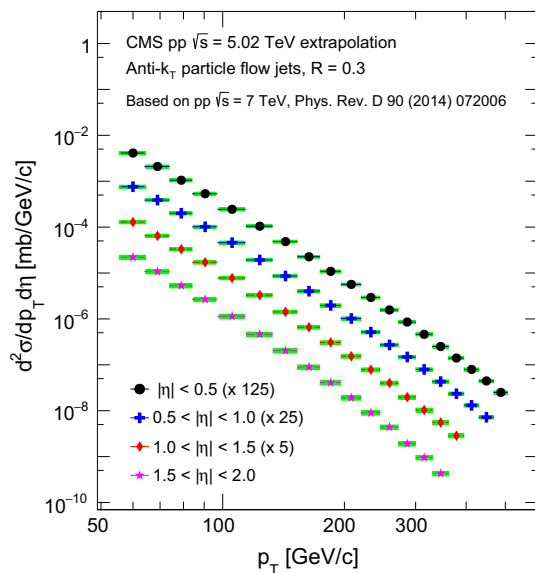


Fig. 3 Jet spectra at $\sqrt{s} = 5.02$ TeV extrapolated from previous pp measurements at $\sqrt{s} = 7$ TeV [33]. Additional scaling factors listed in the legend are applied to enhance the visibility. The horizontal bars represent the bin size, and the points are plotted in the center of the bin. The 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 uncer-

tainty. 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 $\sqrt{s} = 7$ 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 $\sqrt{s} = 7$ 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 $\sqrt{s} = 7$ TeV [33] and $\sqrt{s} = 2.76$ TeV [56] are used to evaluate \sqrt{s} dependent scaling factors using x_T -based interpolation ($x_T \equiv 2p_{Tc}/\sqrt{s}$).

The jet cross sections for $R = 0.3$ and $R = 0.5$ at $\sqrt{s} = 5.02$ 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 $\sqrt{s_{NN}} = 5.02$ TeV are shown in Fig. 4 for six consecutive η intervals in the range $-2.0 < \eta_{CM} < 1.5$ and the range $|\eta_{CM}| < 1.0$ 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 $\eta_{CM} = 0$. 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 $0.03 \lesssim \langle x_{Pb} \rangle \lesssim 0.5$. Values of p_T that correspond to $\langle x_{Pb} \rangle \lesssim 0.2$ are associated with anti-shadowing in the nPDFs. The region $\langle x_{Pb} \rangle \gtrsim 0.2$ 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 uncer-

tainties 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 $p_T < 80 \text{ GeV}/c$		Jet $p_T > 150 \text{ GeV}/c$	
		$ \eta_{\text{CM}} < 1 \text{ (%)}$	$ \eta_{\text{CM}} > 1.5 \text{ (%)}$	$ \eta_{\text{CM}} < 1 \text{ (%)}$	$ \eta_{\text{CM}} > 1.5 \text{ (%)}$
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

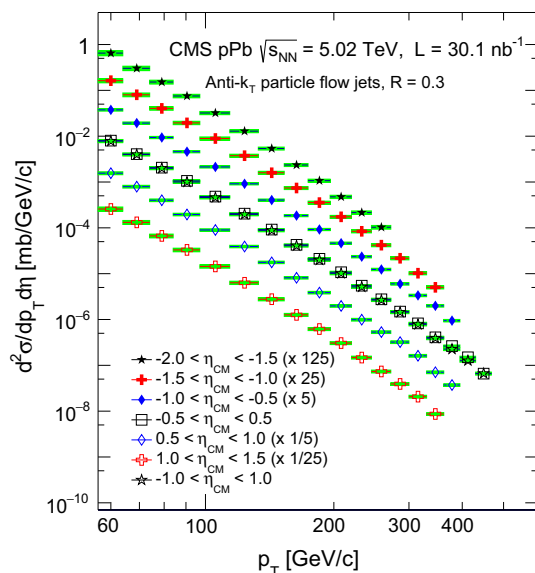


Fig. 4 Inclusive jet differential cross section in pPb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ in six consecutive eta bins plus the range $|\eta_{\text{CM}}| < 1.0$. The spectra are scaled by arbitrary factors for better visibility. The horizontal bars represent the bin width, and the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

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

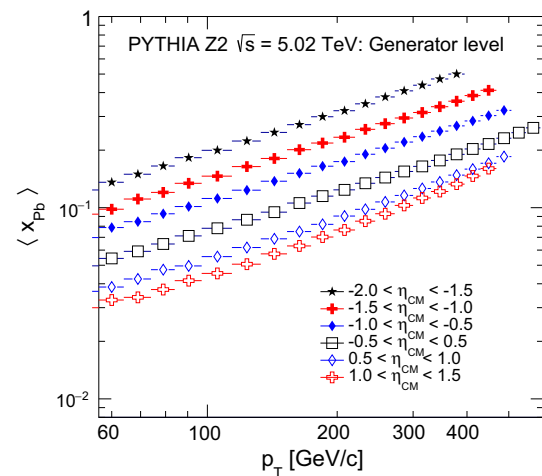


Fig. 5 Mean x values of partons in the Pb nucleus, $\langle x_{\text{Pb}} \rangle$, corresponding to the jet p_T and pseudorapidity ranges covered in the measurements. The $\langle x_{\text{Pb}} \rangle$ values are determined using the PYTHIA event generator [43]

intervals: $0.5 < |\eta_{\text{CM}}| < 1.0$ and $1.0 < |\eta_{\text{CM}}| < 1.5$. 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].

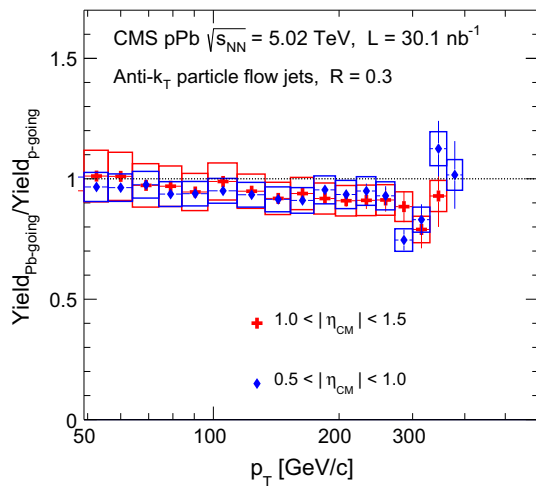


Fig. 6 Inclusive jet asymmetry as a function of jet p_T for $0.5 < |\eta_{CM}| < 1.0$ and $1.0 < |\eta_{CM}| < 1.5$. The asymmetry is calculated as the ratio between the jet yields at negative pseudorapidity (Pb beam direction) and positive pseudorapidity (proton-going side). The *vertical bars* represent 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 $56 < p_T < 300$ GeV/c, $R_{pPb}^* = 1.17 \pm 0.01$ (stat) ± 0.12 (syst). This enhancement

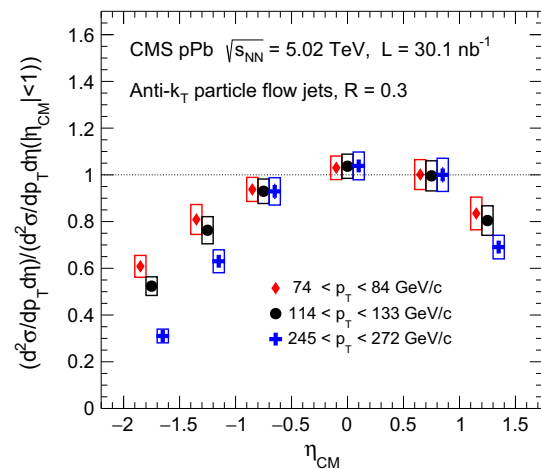
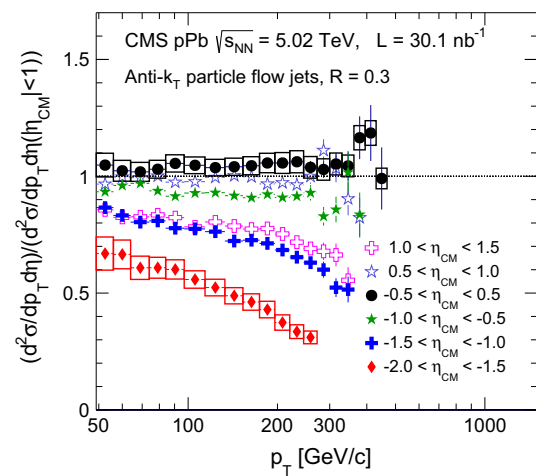


Fig. 7 *Top* inclusive jet cross section in pPb collisions as a function of jet p_T normalized to the production at mid-rapidity ($|\eta_{CM}| < 1$) for six η_{CM} intervals. The *vertical bars* represent the statistical uncertainties. The systematic uncertainties at mid-rapidity and in the most backward 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 $\sqrt{s} = 5$ 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, $|\eta_{CM}| < 0.3$, for the 0–90 %

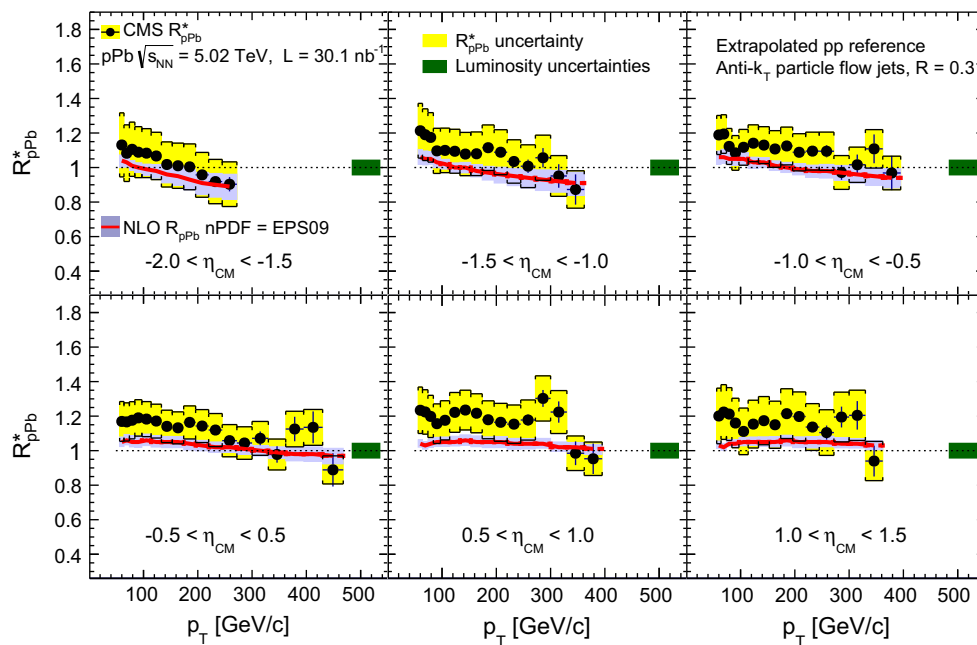


Fig. 8 Inclusive jet nuclear modification factor R_{pPb}^* as a function of jet p_T in $\sqrt{s_{\text{NN}}} = 5.02$ TeV pPb collisions, using a pp reference extrapolated from previous measurements [33] at $\sqrt{s} = 7$ TeV. The vertical bars represent the statistical uncertainties, and the open boxes represent the systematic ones. The filled rectangular boxes around $R_{\text{pPb}}^* = 1$

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

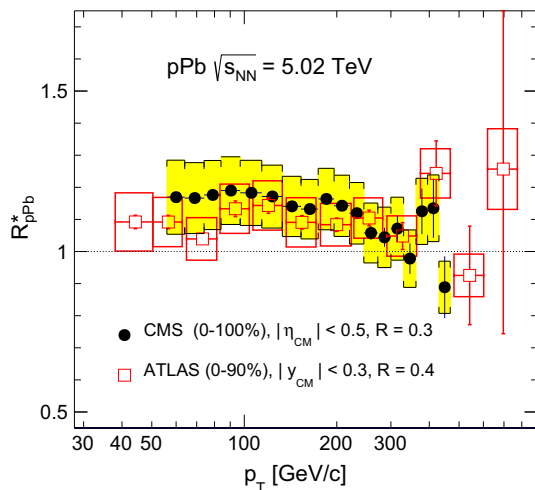


Fig. 9 Inclusive jet R_{pPb}^* integrated over centrality and in the $|\eta_{\text{CM}}| < 0.5$ range for anti- k_T jets with distance parameter $R = 0.3$ from this work, compared to ATLAS results [22] at $|y_{\text{CM}}| < 0.3$ for the 0–90 % most central collisions with distance parameter $R = 0.4$. 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 $\sqrt{s_{\text{NN}}} = 5.02$ 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 $p_T > 56 \text{ GeV}/c$ in six pseudorapidity intervals covering the range $-2 < \eta_{\text{CM}} < 1.5$ 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 $\eta_{\text{CM}} = 0$ 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 $|\eta_{\text{CM}}| < 0.5$ and $56 < p_T < 300 \text{ GeV}/c$, the value $R_{\text{pPb}}^* = 1.17 \pm 0.01 (\text{stat}) \pm 0.12 (\text{syst})$ 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.

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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. Frühwirth¹, V. M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler¹, V. Knünz, A. König, M. Krammer¹, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabadý², N. Rad, B. Rahbaran, H. Rohringer, J. Schieck¹, R. Schöffbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz¹

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 Haeve, 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. Zhang³

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. Beluffi⁴, 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. Piotrkowski, A. Popov⁵, L. Quertenmont, M. Selvaggi, M. Vidal Marono

Université de Mons, Mons, Belgium

N. Belyi, 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. Chinellato⁶, 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 Manganote⁶, 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. Plestina⁸, 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, Bogotá, 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. Finger⁹, 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. Mahrous¹⁰, 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. Dejjardin, 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. Agram¹⁴, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E. C. Chabert, N. Chanon, C. Collard, E. Conte¹⁴, X. Coubez, J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, J. A. Merlin², 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. Toriashvili¹⁵

Tbilisi State University, Tbilisi, Georgia

Z. Tsamalaidze⁹

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. Zhukov⁵

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. Nehr Korn, 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. Borras¹⁶, 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. Gallo¹⁷, J. Garay Garcia, A. Geiser, A. Gizhko, P. Gunnellini, J. Hauk, M. Hempel¹⁸, H. Jung, A. Kalogeropoulos, O. Karacheban¹⁸, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann¹⁸, 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. Pantaleo², 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. Hartmann², S. M. Heindl, U. Husemann, I. Katkov⁵, A. Kornmayer², 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. Gerasim, 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. Horvath¹⁹, F. Sikler, V. Veszpremi, G. Vesztergombi²⁰, A. J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²¹, J. Molnar, Z. Szillasi²

University of Debrecen, Debrecen, Hungary

M. Bartók²², A. Makovec, P. Raics, Z. L. Trocsanyi, B. Ujvari

National Institute of Science Education and Research, Bhubaneswar, India

S. Choudhury²³, 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. Mohanty², L. M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research, Mumbai, India

T. Aziz, S. Banerjee, S. Bhowmik²⁴, R. M. Chatterjee, R. K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu²⁵, Sa. Jain, G. Kole, S. Kumar, B. Mahakud, M. Maity²⁴, G. Majumder, K. Mazumdar, S. Mitra, G. B. Mohanty, B. Parida, T. Sarkar²⁴, N. Sur, B. Sutar, N. Wickramage²⁶

Indian Institute of Science Education and Research (IISER), Pune, India

S. Chauhan, S. Dube, A. Kapoor, K. Kotheekar, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

H. Bakhshiansohi, H. Behnamian, S. M. Etesami²⁷, A. Fahim²⁸, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh²⁹, 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. Battilana², 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. Primavera²

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. Candellise^{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 Ali³², F. Mohamad Idris³³, 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 Cruz³⁴, 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. Byszk³⁵, 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. Vadrucio, 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. Moisezenz, 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. Kim³⁸, 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. Azarkin³⁷, I. Dremin³⁷, M. Kirakosyan, A. Leonidov³⁷, 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. Kaminskiy³⁹, 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. Krychkin, 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. Adzic⁴⁰, 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 Marco⁴¹, 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. Orfanelli⁴², L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, A. Racz, T. Reis, G. Rolandi⁴³, M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, M. Simon, P. Sphicas⁴⁴, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Triossi, A. Tsirou, G. I. Veres²⁰, N. Wardle, H. K. Wöhri, A. Zagozdinska³⁵, 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. Starodumov⁴⁵, M. Takahashi, V. R. Tavolaro, K. Theofilatos, R. Wallny

Universität Zürich, Zurich, Switzerland

T. K. Aarrestad, C. Amsler⁴⁶, 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. Damarsekin, Z. S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E. E. Kangal⁴⁷, A. Kayis Topaksu, G. Onengut⁴⁸, K. Ozdemir⁴⁹, S. Ozturk⁵⁰, D. Sunar Cerci⁵¹, B. Tali⁵¹, H. Topakli⁵⁰, C. Zorbilmez

Physics Department, Middle East Technical University, Ankara, Turkey

B. Bilin, S. Bilmis, B. Isildak⁵², G. Karapinar⁵³, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, M. Kaya⁵⁴, O. Kaya⁵⁵, E. A. Yetkin⁵⁶, T. Yetkin⁵⁷

Istanbul Technical University, Istanbul, Turkey

A. Cakir, K. Cankocak, S. Sen⁵⁸, F. I. Vardarli

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. Newbold⁵⁹, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, D. Smith, V. J. Smith

Rutherford Appleton Laboratory, Didcot, UK

A. Belyaev⁶⁰, 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. Lucas⁵⁹, L. Lyons, A.-M. Magnan, S. Malik, J. Nash, A. Nikitenko⁴⁵, J. Pela, M. Pesaresi, D. M. Raymond, A. Richards, A. Rose, C. Seez, A. Tapper, K. Uchida, M. Vazquez Acosta⁶¹, 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. Iova 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. Wasserbaech⁶², 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. Bauerick, 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. Milenovic⁶³, G. Mitselmakher, D. Rank, R. Rossin, L. Shchutka, 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. Colafranceschi⁶⁴, 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. Bilki⁶⁵, W. Clarida, K. Dilsiz, S. Durgut, R. P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁶⁶, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok⁶⁷, 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. Musienko³⁶, 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. Bouhali⁶⁸, A. Castaneda Hernandez⁶⁸, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁶⁹, V. Krutelyov, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, A. Rose, A. Safonov, A. Tatarinov, K. A. Ulmer²

Texas Tech University, Lubbock, USA

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P. R. Duerdo, 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