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A.M. Sirunyan, M. Besançon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, et al.

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Measurement of the inclusive energy spectrum in the very forward direction in proton-proton collisions at $\sqrt{s} = 13$ TeV



The CMS collaboration

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

ABSTRACT: The differential cross section for inclusive particle production as a function of energy in proton-proton collisions at a center-of-mass energy of 13 TeV is measured in the very forward region of the CMS detector. The measurement is based on data collected with the CMS apparatus at the LHC, and corresponds to an integrated luminosity of $0.34 \mu\text{b}^{-1}$. The energy is measured in the CASTOR calorimeter, which covers the pseudorapidity region $-6.6 < \eta < -5.2$. The results are given as a function of the total energy deposited in CASTOR, as well as of its electromagnetic and hadronic components. The spectra are sensitive to the modeling of multiparton interactions in pp collisions, and provide new constraints for hadronic interaction models used in collider and in high energy cosmic ray physics.

KEYWORDS: Forward physics, Hadron-Hadron scattering (experiments)

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1 Introduction

Particle production at very forward rapidities ($|\eta| > 5$) in high energy hadronic collisions receives contributions from multiparton interactions (MPI), initial- and final-state radiation (from the hardest parton scattering), fragmentation of the so-called “beam remnants”, plus diffraction [1]. The sum of all these particle production mechanisms, typically referred to as the “underlying event” [2], is modeled phenomenologically in hadronic Monte Carlo event generators with parameters tuned from the data [3–5]. A good understanding of forward particle production is important for a complete description of the final states in proton-proton (pp) interactions at colliders, as well as to accurately simulate extensive air showers induced in the earth atmosphere by very high energy cosmic rays [6]. In particular, forward charged hadron production has direct impact on the total number of air-shower muons at the ground, whose measurement shows unexplained excesses compared to model predictions [7]. The rapidities covered in the presented measurement ($-6.6 < \eta < -5.2$, still well separated from the beam rapidity $y \approx 9.5$) are mostly sensitive to the MPI activity [8].

Previous studies of very forward particle production in pp collisions have been carried out at center-of-mass energies of 0.9, 2.76, 7 and 8 TeV by CMS [8, 9], at 7 and 8 TeV by TOTEM [9–11], and at 7 TeV by LHCf [12, 13]. The present paper reports new measurements of inclusive energy spectra at a center-of-mass energy of 13 TeV. The data are discussed in terms of the production of electrons and photons (mostly from π^0 decays), as well as hadrons (mostly π^\pm) in the very forward direction covered by the CASTOR calorimeter of the CMS experiment at the CERN LHC. CASTOR [14] covers the pseudorapidity region $-6.6 < \eta < -5.2$, and can distinguish between electromagnetic and hadronic energy depositions. CASTOR is only installed on the negative z -side of CMS, and hence has acceptance at negative pseudorapidities. Because of CASTOR’s very forward location, the data are sensitive to parton interactions at very small and large fractional momenta in the proton, $x < 10^{-4}$ and $x \rightarrow 1$.

2 Experimental setup and Monte Carlo simulation

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T [15]. Within the field volume in the central region are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yoke.

The central detectors of CMS are complemented by calorimeters in the forward direction, which all rely on the detection of Cherenkov photons produced when charged particles pass through their active quartz components. The “hadron forward” (HF) calorimeters cover the pseudorapidity interval $3.0 < |\eta| < 5.2$ and use quartz fibers embedded in a steel absorber. The CASTOR calorimeter is a sampling calorimeter composed of layers of fused silica quartz plates and tungsten absorbers, segmented in 16 azimuthal towers, each with 14 longitudinal channels. The two front channels have a combined depth of 20 radiation lengths and form the electromagnetic section of each tower. The remaining 12 channels constitute the hadronic section. The full depth of a tower amounts to 10 hadronic interaction lengths. A more detailed description of the CMS detector, together with a definition of the coordinate system used and all relevant kinematic variables, can be found in ref. [15]. For triggering purposes, the Beam Pickup Timing for the eXperiment device was used [16].

The corrections to the level of stable particles with $c\tau > 1$ cm are determined by means of a Monte Carlo (MC) simulation of the CMS apparatus based on GEANT4 [17], including all known information about the CASTOR detector.

The data are compared to model predictions from PYTHIA 8 [18] (version 8.212) with tune CUETP8M1 [19], which is based on measurements of the underlying event in $p\bar{p}$ and pp collisions at $\sqrt{s} = 1.96$ and 7 TeV, and tune 4C [4] combined with the MBR [20] model to describe diffractive processes. The PYTHIA 8 CUETP8M1 tunes use the NNPDF2.3LO [21] parton distribution functions (PDF), whereas tune 4C uses the CTEQ6L1 PDF [22]. Hadronic interaction event generators mostly developed for cosmic ray physics are also used: EPOS LHC [23] and its previous version EPOS 1.99 [24], QGSJETII [25] version II.3 and II.4, as well as SIBYLL 2.1 [26] and the recently released SIBYLL 2.3 [27]. The latest versions of all these models are tuned to LHC data up to $\sqrt{s} = 8$ TeV, while the earlier versions are tuned to Tevatron results [28].

3 Event selection and data analysis

The present analysis is based on data that were recorded during the low luminosity LHC Run in 2015, when CASTOR was operational and the CMS solenoid was off. The data correspond to an integrated luminosity of $0.34 \mu\text{b}^{-1}$, with an average pp interaction probability of 5% per bunch crossing. Data were recorded with an unbiased trigger requiring only the presence of two colliding bunches. Electronic noise and beam-induced backgrounds are studied with data taken without colliding bunches. Events are selected offline by requiring hadronic activity in the HF calorimeters on either side of CMS. At least one reconstructed calorimeter tower with energy larger than 5 GeV is required. With these selection criteria the residual contribution of electronic noise and beam background is well below 1%.

Beam halo muons are used to determine the calibration of each CASTOR channel relative to the others. This inter-calibration procedure cannot be applied to the last two longitudinal channels, which have detector noise levels very close to the muon ionization peak and are not included in the dedicated halo-muon trigger. These channels are therefore excluded from the analysis.

The response of CASTOR to pions and electrons was measured in a test beam in 2008 [29]. However, the configuration of CASTOR changed since then. Because of this, an independent method based on 7 TeV collision data is used to determine the absolute energy scale calibration of CASTOR. The average energy measured by the HF calorimeters in the region $3 < |\eta| < 5$ is fully corrected to the particle level [30] and extrapolated to the region covered by CASTOR, using various hadronic interaction models. The result of the extrapolation is used to calibrate CASTOR. The detector response is found to be consistent with the test beam results. Such a data-driven method facilitates the assignment of a realistic uncertainty on the calorimeters energy scale.

In order to reconstruct the total energy deposited in CASTOR, the energies of all calorimeter towers above the noise threshold are summed up. This threshold is determined independently for every calorimeter tower and varies between 2 and 2.5 GeV. The electromagnetic and hadronic contributions to the total energy can be determined by using the corresponding sections of CASTOR. The measured detector-level spectra are shown in figure 1. Differences among model predictions are apparent.

The correction to the particle level is carried out through an unfolding technique by means of the ROOUNFOLD package [31] with the iterative algorithm proposed by D’Agostini [32]. The procedure is stopped after 4 (6, 5) iterations for the total (electromagnetic, hadronic) spectrum, when the change with respect to the previous step is less than one percent. Figure 2 shows the distributions of reconstructed energy in CASTOR as a function of the true energy at particle level for PYTHIA 8 CUETP8M1. The fact that the slope of the correlation for the hadronic energy is not unity reflects the noncompensating nature of the calorimeter.

The event selection at particle level is based on the Lorentz-invariant fractional momentum loss of the proton, ξ . All final-state particles are divided into two systems, X and Y , based on their rapidity with respect to the pair of particles with the largest separation in rapidity. All particles on the negative side of this gap are assigned to the system X , while the particles on the positive side are assigned to the system Y [8]. The invariant masses, M_X and M_Y , of each system are calculated using the four-momenta of the individual particles, and the variable ξ is defined as the maximum of their squared ratios to the center-of-mass energy:

$$\begin{aligned} \xi_X &= M_X^2/s, & \xi_Y &= M_Y^2/s, & \text{and} \\ \xi &= \max(\xi_X, \xi_Y). \end{aligned} \tag{3.1}$$

The variable ξ , commonly used to describe diffractive processes, is well defined for any pp final-state and provides a particularly economical particle-level description of the phase space acceptance at forward rapidities, independent of the underlying particle production mechanism. Events with $\xi > 10^{-6}$ at particle level are selected, with an efficiency of about

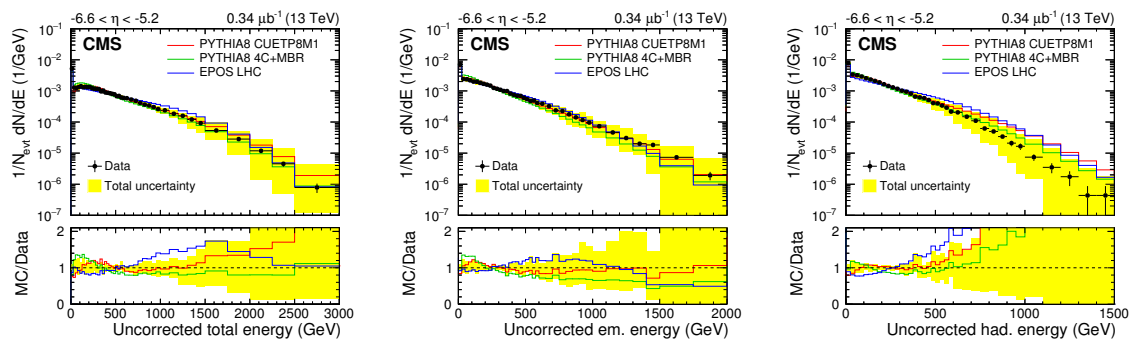


Figure 1. Spectra of the energy reconstructed in CASTOR, normalized to the number of events that pass the offline event selection, compared to the detector-level predictions of various event generators. The total energy spectrum is shown in the left panel, the electromagnetic in the middle, and the hadronic in the right. Statistical (systematic) uncertainties are shown with error bars (yellow band, discussed in section 4).

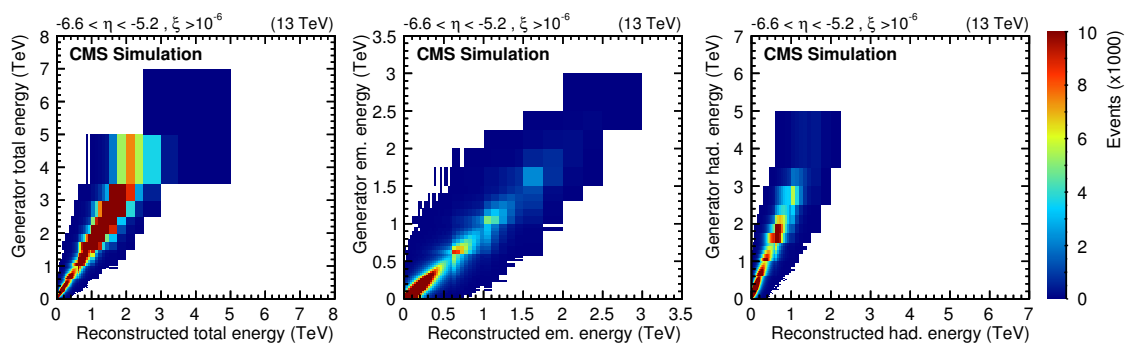


Figure 2. Distributions of reconstructed energy as a function of the particle-level energy for PYTHIA 8 CUETP8M1 for the total (left), electromagnetic (middle), and hadronic (right) energy in CASTOR. The color indicates the number of events. The selection $\xi > 10^{-6}$ is explained in the text.

97.3% and a purity of about 99.5% with respect to the detector-level event selection. The total energy at particle level is calculated by summing up the energies of all particles, except muons and neutrinos, within the acceptance of CASTOR. Muons and neutrinos are excluded since they do not deposit relevant energies in the detector. For the electromagnetic spectrum, only electrons and photons are used; the latter are excluded for the hadronic energy spectrum. The decay photons of neutral pions constitute the dominant contribution to the electromagnetic spectrum.

4 Experimental uncertainties and results

The experimental uncertainties of the present results are mainly of systematic nature, with the CASTOR energy scale uncertainty being the most significant contribution. In the data-driven calibration method, uncertainties on the energy scale arise from the HF energy scale uncertainty, the extrapolation uncertainty, and the noncompensating calorimetric response of CASTOR. Furthermore, the energy measured by CASTOR depends on its exact location

with respect to the interaction point. This is because the energy flow $dE/d\eta$ rises sharply with η in the very forward region. For the present data, the position of CASTOR is known to within 1 mm, leading to a 7.5% energy scale uncertainty. This is determined by means of Monte Carlo studies in which CASTOR is moved within the measurement uncertainties. All contributions to the energy scale uncertainty add up to 17% at detector level.

An additional systematic uncertainty comes from the inter-calibration of the channels with respect to each other. This affects the separation of the electromagnetic and hadronic energies by up to 16%.

The sensitivity of the result to the event selection based on activity in HF is quantified by varying by 10% the 5 GeV selection threshold, which corresponds to the energy scale uncertainty of the HF calorimeters. The effect is below 6.2% for the total energy, and less for the electromagnetic and hadronic energies. Other sources of uncertainties, such as noise, beam background, or pileup are found to be negligible.

The detector-level spectra are varied within each of the above uncertainties, and then unfolded. The spread of the unfolded spectra is then taken as a measure of the systematic uncertainty associated to each distribution. Since the unfolding relies on Monte Carlo simulation, three models are used to unfold the detector-level spectra: PYTHIA 8 4C+MBR, PYTHIA 8 CUETP8M1, and EPOS LHC. The average of the resulting spectra is used as the nominal result and half their spread as an additional model-dependent systematic uncertainty. This uncertainty is below 20% for the total and electromagnetic spectra. The model dependence for the hadronic energy is higher and reaches 63% in some energy bins. These uncertainties increase with energy. The luminosity recorded by CMS is determined with a precision of 2.3% for data taken with full magnetic field [33]. The luminosity at zero magnetic field can be recalibrated by comparing full and zero field data directly; the corresponding uncertainty is 2.6%.

All contributions to the systematic uncertainties are added in quadrature. Example values are given for two bins of total, hadronic, and electromagnetic energies in table 1. The statistical uncertainties are calculated with the full covariance matrices of the unfolded results and therefore include correlations induced by the unfolding procedure. The full covariance matrices are available in the HEPDATA record of this paper; the differential cross section measurements with uncertainties are also tabulated therein [34]. In the figures, the total uncertainties are shown as yellow bands; they include the statistical uncertainties, which in most bins are not visible. The uncertainty assigned to the model dependence of the unfolding procedure is shown as an orange band.

The total, electromagnetic, and hadronic energy spectra are measured in the region $-6.6 < \eta < -5.2$ and corrected to the particle level for $\xi > 10^{-6}$. They are shown in figures 3–5 and compared to the predictions of EPOS, QGSJETII and SIBYLL (left plots) and various PYTHIA 8 tunes (right plots). All spectra feature a sharp peak at zero reflecting the presence of diffractive events with forward rapidity gap(s). The total and hadronic energy spectra exhibit peaks at about 300 and 100 GeV respectively, followed by a long tail towards higher energies. Such a peak is not observed in the electromagnetic spectrum.

In figure 3, the distribution of the total energy is shown. Different parts of the spectrum are reproduced by different models. None of the models reproduce all features of the data,

	Total		Electromagnetic		Hadronic	
	300 GeV	3000 GeV	300 GeV	1200 GeV	300 GeV	2000 GeV
Energy Scale	+17% -14%	+94% -77%	+5.9% -2.1%	+93% -65%	+11% -10%	+169% -80%
Unfolding	±5.8%	±6.4%	±5.2%	±4.1%	±6.9%	±17%
Event selection	±0.5%	<0.01%	±0.14%	<0.01%	±0.06%	<0.01%
Luminosity	±2.6%					
Statistical	±1.2%	±4.3%	±1.5%	±5.9%	±1.0%	±4.2%

Table 1. Uncertainties on the differential cross sections at a few selected values of the total, electromagnetic, and hadronic energies.

but the bump at about 300 GeV is visible in all of them. The spectrum is best described by EPOS LHC and QGSJETII.4. The PYTHIA 8 tunes tend to overestimate the contribution of the soft part of the spectrum and so does SIBYLL 2.3. The high energy tail is well described by PYTHIA 8 and SIBYLL, whereas EPOS LHC and QGSJETII.4 overestimate the region between 1 and 2.5 TeV. The predictions are also very sensitive to the scaling parameter $p_{T,0}^{\text{ref}}$ of PYTHIA 8, which parameterizes the dampening of the partonic cross sections for $p_T \rightarrow 0$ at the nominal reference energy of 7 TeV [18]. Large deviations from the CUETP8M1 $p_{T,0}^{\text{ref}}$ default value of 2.4024 GeV modify the simulation of MPI and lead to predictions inconsistent with the data; the PDF choice (NNPDF2.3 in CUETP8M1 versus CTEQ6L1 in 4C) and/or the diffraction model used (MBR or default PYTHIA 8 model) also play a role in some regions of phase space.

The electromagnetic spectrum is shown in figure 4; it is relatively well described by most of the models within uncertainties. Only PYTHIA 8 4C+MBR and SIBYLL 2.3 do not correctly model the shape of the soft part of the spectrum up to about 500 GeV. The comparison of the data to the predictions of various PYTHIA 8 tunes indicates that the electromagnetic energy distribution is also very sensitive to the underlying modeling of MPI.

Figure 5 shows the hadronic energy distribution. While EPOS LHC and QGSJETII perform well at lower energies, they predict too large a cross section in the range of 600 to 1800 GeV. This feature is also observed in the total energy spectrum, suggesting that the excess originates from the production of hadrons. SIBYLL 2.3 reproduces the slope of the spectrum over a larger energy range, but significantly overestimates the cross section at very low energy, while SIBYLL 2.1 shows a large excess at around 500 GeV, similar to that observed in the total energy spectrum.

5 Summary

The electromagnetic, hadronic, and total energy spectra of particles produced at very forward pseudorapidities ($-6.6 < \eta < -5.2$) have been measured with the CASTOR calorimeter of the CMS experiment in proton-proton collisions at a center-of-mass energy of 13 TeV. The experimental distributions, fully corrected for detector effects, are compared

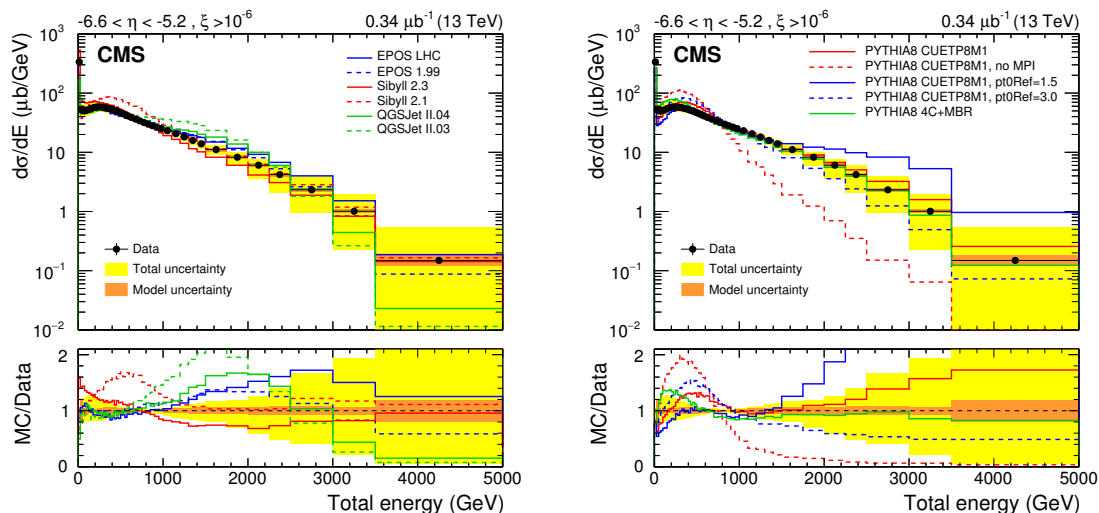


Figure 3. Differential cross section as a function of the total energy in the region $-6.6 < \eta < -5.2$ for events with $\xi > 10^{-6}$. The left panel shows the data compared to MC event generators mostly developed for cosmic ray induced air showers, and the right panel to different PYTHIA 8 tunes.

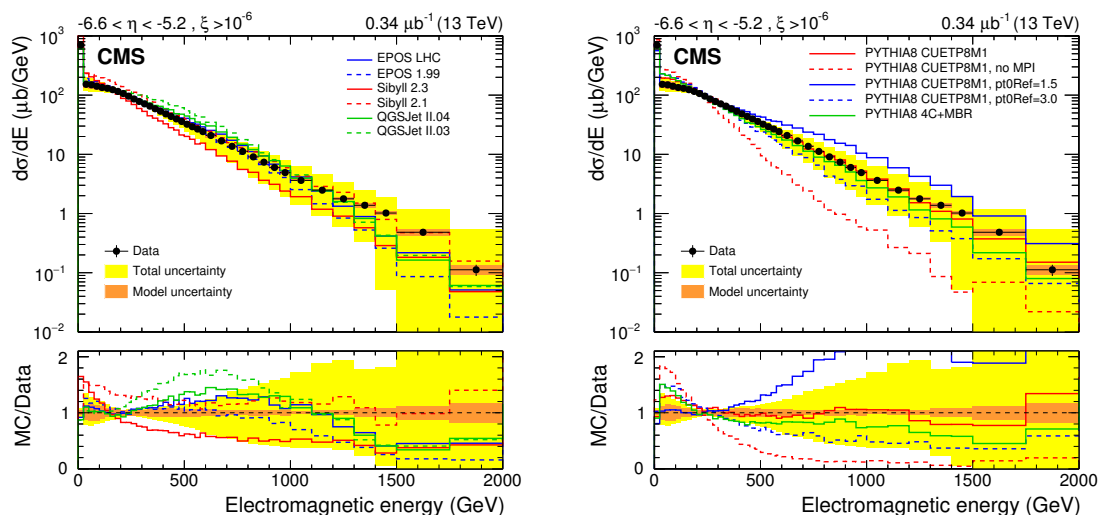


Figure 4. Differential cross section as a function of the electromagnetic energy in the region $-6.6 < \eta < -5.2$ for events with $\xi > 10^{-6}$. The left panel shows the data compared to MC event generators mostly developed for cosmic ray induced air showers, and the right panel to different PYTHIA 8 tunes.

to the predictions of various Monte Carlo event generators commonly used in high energy cosmic ray physics (EPOS, QGSJETII, and SIBYLL), and those of different tunes of PYTHIA 8. None of the generators considered describe all features seen in the data.

The present measurements are particularly sensitive to the modeling of multiparton interactions (MPI) that dominate particle production in the underlying event at forward rapidities in pp collisions. PYTHIA 8 CUETP8M1 without MPI is ruled out by the data, which exhibit much harder spectra than predicted by the model. The shape of the spectra are significantly influenced by the MPI-related settings in PYTHIA 8. The present results can therefore contribute to improvements in future Monte Carlo parameter tunes.

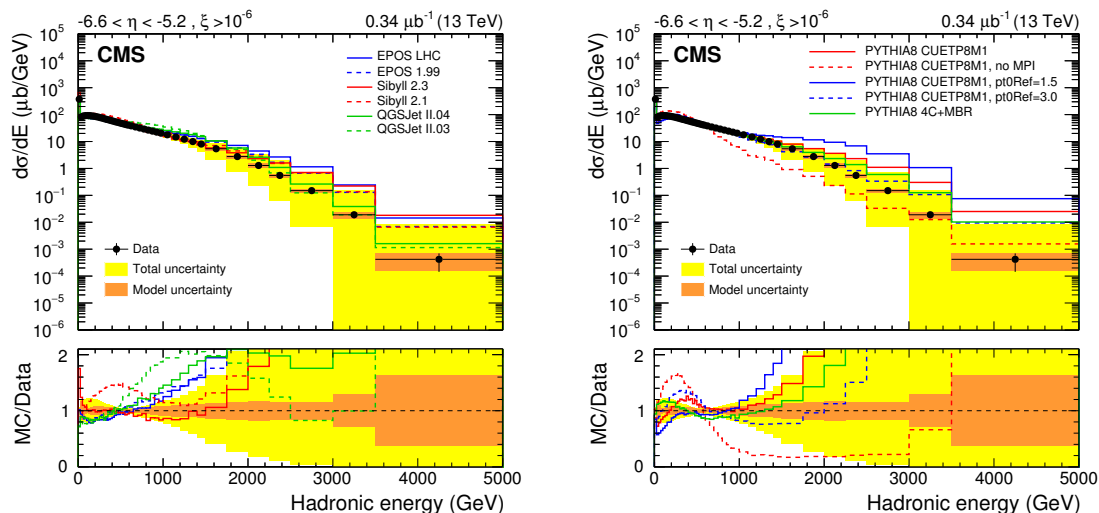


Figure 5. Differential cross section as a function of the hadronic energy in the region $-6.6 < \eta < -5.2$ for events with $\xi > 10^{-6}$. The left panel shows the data compared to MC event generators mostly developed for cosmic ray induced air showers, and the right panel to different PYTHIA 8 tunes.

Event generators developed for modeling high energy cosmic ray air showers, tuned to LHC measurements at 0.9, 7, and 8 TeV, agree better with the present data than those tuned to Tevatron results alone. This is especially true for QGSJETII and SIBYLL. However, all these models underestimate the muon production rate in extensive air showers because of their inaccurate description of the hadronic shower component [35]. The present results provide new constraints for improving the modeling of hadron production in event generators commonly used in high energy particle and cosmic ray physics.

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The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, 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, A. König, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabadý, N. Rad, B. Rahbaran, H. Rohringer, J. Schieck¹, J. Strauss, W. Waltenberger, C.-E. Wulz¹

Institute for Nuclear Problems, Minsk, Belarus

O. Dvornikov, V. Makarenko, V. Mossolov, J. Suarez Gonzalez, V. Zykunov

National Centre for Particle and High Energy Physics, Minsk, Belarus

N. Shumeiko

Universiteit Antwerpen, Antwerpen, Belgium

S. Alderweireldt, E.A. De Wolf, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussel, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, S. Lowette, S. Moortgat, L. Moreels, A. Olbrechts, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium

H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni, F. Zhang²

Ghent University, Ghent, Belgium

A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov, D. Poyraz, S. Salva, R. Schöfbeck, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

H. Bakhshiansohi, C. Beluffi³, O. Bondu, S. Brochet, G. Bruno, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, A. Jafari, M. Komm, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrkowski, L. Quertenmont, M. Selvaggi, M. Vidal Marono, S. Wertz

Université de Mons, Mons, Belgium

N. Bely

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, 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. Chinellato⁴, A. Custódio, E.M. Da Costa, G.G. Da Silveira⁵, 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 Manganote⁴, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista ^a, Universidade Federal do ABC ^b, São Paulo, Brazil

S. Ahuja^a, C.A. Bernardes^a, S. Dogra^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, C.S. Moon^a, S.F. Novaes^a, Sandra S. Padula^a, D. Romero Abad^b, J.C. Ruiz Vargas^a

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

Beihang University, Beijing, China

W. Fang⁶

Institute of High Energy Physics, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen⁷, T. Cheng, C.H. Jiang, D. Leggat, Z. Liu, F. Romeo, M. Ruan, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Universidad de Los Andes, Bogota, Colombia

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, C.F. González Hernández, J.D. Ruiz Alvarez, J.C. Sanabria

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano, T. Sculac

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, T. Susa

University of Cyprus, Nicosia, Cyprus

A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, D. Tsiakkouri

Charles University, Prague, Czech Republic

M. Finger⁸, M. Finger Jr.⁸

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin

**Academy of Scientific Research and Technology of the Arab Republic of Egypt,
Egyptian Network of High Energy Physics, Cairo, Egypt**

A.A. Abdelalim^{9,10}, Y. Mohammed¹¹, E. Salama^{12,13}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

M. Kadastik, L. Perrini, 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, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini,
S. Lehti, T. Lindén, P. Luukka, J. Tuominiemi, E. Tuovinen, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland

J. Talvitie, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro,
F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry,
I. Kucher, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov

**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, R. Granier de Cassagnac, M. Jo, S. Lisniak, P. Miné,
M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno,
Y. Sirois, A.G. Stahl Leitner, T. Strebler, Y. Yilmaz, A. Zabi, A. Zghiche

**Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg,
CNRS-IN2P3**

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,
A.-C. Le Bihan, P. Van Hove

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

S. Gadrat

**Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut
de Physique Nucléaire de Lyon, Villeurbanne, France**

S. Beauceron, C. Bernet, G. Boudoul, C.A. Carrillo Montoya, R. Chierici, D. Contardo,
B. Courbon, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, G. Grenier,

B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov¹⁵, D. Sabes, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret

Georgian Technical University, Tbilisi, Georgia

T. Toriashvili¹⁶

Tbilisi State University, Tbilisi, Georgia

Z. Tsamalaidze⁸

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

C. Autermann, S. Beranek, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, T. Verlage

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

A. Albert, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teysier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

V. Cherepanov, G. Flügge, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, A. Stahl¹⁷

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A.A. Bin Anuar, K. Borras¹⁸, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Dolinska, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo¹⁹, J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, A. Harb, J. Hauk, M. Hempel²⁰, H. Jung, A. Kalogeropoulos, O. Karacheban²⁰, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann²⁰, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M.Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany

V. Blobel, M. Centis Vignali, A.R. Draeger, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, M. Hoffmann, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, T. Lapsien, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo¹⁷, T. Peiffer, A. Perieanu, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

M. Akbiyik, C. Barth, S. Baur, C. Baus, J. Berger, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, S. Fink, B. Freund, R. Friese, M. Giffels, A. Gilbert,

P. Goldenzweig, D. Haitz, F. Hartmann¹⁷, S.M. Heindl, U. Husemann, I. Katkov¹⁵, S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, 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. Gerasis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, I. Topsis-Giotis

National and Kapodistrian University of Athens, Athens, Greece

S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

University of Ioánnina, Ioánnina, Greece

I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Paradas

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

N. Filipovic, G. Pasztor

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath²¹, F. Sikler, V. Veszpremi, G. Vesztergombi²², A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²³, A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen

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

Indian Institute of Science (IISc)

J.R. Komaragiri

National Institute of Science Education and Research, Bhubaneswar, India

S. Bahinipati²⁴, S. Bhowmik²⁵, S. Choudhury²⁶, P. Mal, K. Mandal, A. Nayak²⁷, D.K. Sahoo²⁴, N. Sahoo, S.K. Swain

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, U.Bhawandeep, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, P. Kumari, 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. Keshri, S. Malhotra, M. Naimuddin, K. Ranjan, R. Sharma, V. Sharma

Saha Institute of Nuclear Physics, Kolkata, India

R. Bhattacharya, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

Indian Institute of Technology Madras, Madras, India

P.K. Behera

Bhabha Atomic Research Centre, Mumbai, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty¹⁷, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, S. Dugad, G. Kole, B. Mahakud, S. Mitra, G.B. Mohanty, B. Parida, N. Sur, B. Sutar

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, R.K. Dewanjee, S. Ganguly, M. Guchait, Sa. Jain, S. Kumar, M. Maity²⁵, G. Majumder, K. Mazumdar, T. Sarkar²⁵, N. Wickramage²⁸

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

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

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

S. Chenarani²⁹, E. Eskandari Tadavani, S.M. Etesami²⁹, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi³⁰, F. Rezaei Hosseinabadi, B. Safarzadeh³¹, 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,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^{a,b}, A. Ranieri^a, G. Selvaggi^{a,b}, A. Sharma^a, L. Silvestris^{a,17}, R. Venditti^{a,b}, P. Verwilligen^a

INFN Sezione di Bologna ^a, Università di Bologna ^b, Bologna, Italy

G. Abbiendi^a, C. Battilana, 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,17}

INFN Sezione di Catania ^a, Università di Catania ^b, Catania, Italy

S. Albergo^{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, Firenze, Italy

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, L. Russo^{a,32}, G. Sguazzoni^a, D. Strom^a, L. Viliani^{a,b,17}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera¹⁷

INFN Sezione di Genova ^a, Università di Genova ^b, Genova, ItalyV. Calvelli^{a,b}, F. Ferro^a, M.R. Monge^{a,b}, E. Robutti^a, S. Tosi^{a,b}**INFN Sezione di Milano-Bicocca ^a, Università di Milano-Bicocca ^b, Milano, Italy**L. Brianza^{a,b,17}, F. Brivio^{a,b}, V. Ciriolo, M.E. Dinardo^{a,b}, S. Fiorendi^{a,b,17}, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, M. Malberti^{a,b}, S. Malvezzi^a, R.A. Manzoni^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Pigazzini^{a,b}, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}**INFN Sezione di Napoli ^a, Università di Napoli 'Federico II' ^b, Napoli, Italy, Università della Basilicata ^c, Potenza, Italy, Università G. Marconi ^d, Roma, Italy**S. Buontempo^a, N. Cavallo^{a,c}, G. De Nardo, S. Di Guida^{a,d,17}, M. Esposito^{a,b}, F. Fabozzi^{a,c}, F. Fienga^{a,b}, A.O.M. Iorio^{a,b}, G. Lanza^a, L. Lista^a, S. Meola^{a,d,17}, P. Paolucci^{a,17}, C. Sciacca^{a,b}, F. Thyssen^a**INFN Sezione di Padova ^a, Università di Padova ^b, Padova, Italy, Università di Trento ^c, Trento, Italy**P. Azzi^{a,17}, N. Bacchetta^a, L. Benato^{a,b}, D. Bisello^{a,b}, A. Boletti^{a,b}, R. Carlin^{a,b}, A. Carvalho Antunes De Oliveira^{a,b}, P. Checchia^a, M. Dall'Osso^{a,b}, P. De Castro Manzano^a, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, S. Lacaprara^a, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, J. Pazzini^{a,b}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Zanetti^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}**INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy**A. Braghieri^a, F. Fallavollita^{a,b}, 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}, L. Fanò^{a,b}, P. Lariccia^{a,b}, R. Leonardi^{a,b}, G. Mantovani^{a,b}, V. Mariani^{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,32}, P. Azzurri^{a,17}, G. Bagliesi^a, J. Bernardini^a, T. Boccali^a, R. Castaldi^a, M.A. Ciocci^{a,32}, R. Dell'Orso^a, S. Donato^{a,c}, G. Fedi, A. Giassi^a, M.T. Grippo^{a,32}, 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,33}, 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, Roma, Italy**L. Barone^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, D. Del Re^{a,b,17}, M. Diemoz^a, S. Gelli^{a,b}, E. Longo^{a,b}, F. Margaroli^{a,b}, B. Marzocchi^{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}

INFN Sezione di Torino ^a, Università di Torino ^b, Torino, Italy, Università del Piemonte Orientale ^c, Novara, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c,17}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, C. Biino^a, N. Cartiglia^a, F. Cenna^{a,b}, M. Costa^{a,b}, R. Covarelli^{a,b}, A. Degano^{a,b}, N. Demaria^a, L. Finco^{a,b}, B. Kiani^{a,b}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, E. Monteil^{a,b}, M. Monteno^a, M.M. Obertino^{a,b}, 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. Ruspà^{a,c}, R. Sacchi^{a,b}, K. Shchelina^{a,b}, V. Sola^a, A. Solano^{a,b}, A. Staiano^a, P. Traczyk^{a,b}

INFN Sezione di Trieste ^a, Università di Trieste ^b, Trieste, Italy

S. Belforte^a, M. Casarsa^a, F. Cossutti^a, G. Della Ricca^{a,b}, A. Zanetti^a

Kyungpook National University, Daegu, Korea

D.H. Kim, G.N. Kim, M.S. Kim, S. Lee, S.W. Lee, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

Chonbuk National University, Jeonju, Korea

A. Lee

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

H. Kim

Hanyang University, Seoul, Korea

J.A. Brochero Cifuentes, T.J. Kim

Korea University, Seoul, Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, Y. Kim, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Seoul National University, Seoul, Korea

J. Almond, J. Kim, H. Lee, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

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, C. Hwang, 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, M.A.B. Md Ali³⁴, F. Mohamad Idris³⁵, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz³⁶, A. Hernandez-Almada, R. Lopez-Fernandez, R. Magaña Villalba, J. Mejia Guisao, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

S. Carpinteyro, I. Pedraza, H.A. Salazar Ibarquen, C. Uribe Estrada

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, A. Saddique, M.A. Shah, 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

K. Bunkowski, A. Byszuk³⁷, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

P. Bargassa, C. Beirão Da Cruz E Silva, B. Calpas, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadrucio, J. Varela

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^{38,39}, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

L. Chtchipounov, V. Golovtsov, Y. Ivanov, V. Kim⁴⁰, E. Kuznetsova⁴¹, V. Murzin, V. Oreshkin, V. Sulimov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyev, 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, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia

T. Aushev, A. Bylinkin³⁹

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

M. Chadeeva⁴², R. Chistov⁴², S. Polikarpov, V. Rusinov, E. Zhemchugov

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin³⁹, I. Dremin³⁹, M. Kirakosyan, A. Leonidov³⁹, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, M. Dubinin⁴³, L. Dudko, A. Ershov, A. Gribushin, L. Kheyn, V. Klyukhin, O. Kodolova, I. Lokhtin, O. Lukina, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia

V. Blinov⁴⁴, Y. Skovpen⁴⁴, D. Shtol⁴⁴

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

I. Azhgirey, I. Bayshev, S. Bitiukov, D. Elumakhov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

P. Adzic⁴⁵, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

J. Alcaraz Maestre, M. Barrio Luna, 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

J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad de Oviedo, Oviedo, Spain

J. Cuevas, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, I. Suárez Andrés, P. Vischia, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

I.J. Cabrillo, A. Calderon, E. Curras, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, F. Matorras, J. Piedra Gomez, T. Rodrigo, 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, P. Baillon, A.H. Ball, D. Barney, P. Bloch, A. Bocci, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, Y. Chen, D. d’Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, E. Di Marco⁴⁶, M. Dobson, B. Dorney, T. du Pree, D. Duggan, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, S. Fartoukh, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, M. Girone, F. Glege, D. Gulhan, S. Gundacker, M. Guthoff, P. Harris, J. Hegeman, V. Innocente, P. Janot, J. Kieseler, H. Kirschenmann, V. Knünz, A. Kornmayer¹⁷, M.J. Kortelainen, K. Kousouris, M. Krammer¹, C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic⁴⁷, F. Moortgat, S. Morovic, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi⁴⁸, M. Rovere, H. Sakulin, J.B. Sauvan, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, P. Sphicas⁴⁹, J. Steggemann, M. Stoye, Y. Takahashi, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns⁵⁰, G.I. Veres²², M. Verweij, N. Wardle, H.K. Wöhri, A. Zagozdzińska³⁷, 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, S.A. Wiederkehr

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, 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. Paus, G. Perrin, L. Perrozzi, M. Quittnat, M. Rossini, M. Schönenberger, A. Starodumov⁵¹, V.R. Tavolaro, K. Theofilatos, R. Wallny

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. AMSler⁵², L. Caminada, M.F. Canelli, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, C. Seitz, Y. Yang, A. Zucchetta

National Central University, Chung-Li, Taiwan

V. Candelise, T.H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

Arun Kumar, P. Chang, Y.H. Chang, Y. Chao, K.F. Chen, P.H. Chen, F. Fiori, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Paganis, A. Psallidas, J.f. Tsai

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

B. Asavapibhop, G. Singh, N. Srimanobhas, N. Suwonjandee

Cukurova University - Physics Department, Science and Art Faculty

A. Adiguzel, S. Cerci⁵³, S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, I. Hos⁵⁴, E.E. Kangal⁵⁵, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut⁵⁶, K. Ozdemir⁵⁷, D. Sunar Cerci⁵³, B. Tali⁵³, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

B. Bilin, S. Bilmis, B. Isildak⁵⁸, G. Karapinar⁵⁹, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, M. Kaya⁶⁰, O. Kaya⁶¹, E.A. Yetkin⁶², T. Yetkin⁶³

Istanbul Technical University, Istanbul, Turkey

A. Cakir, K. Cankocak, S. Sen⁶⁴

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

B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom

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, D.M. Newbold⁶⁵, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁶⁶, 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

Imperial College, London, United Kingdom

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, R. Di Maria, P. Dunne, A. Elwood, D. Futyan, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, R. Lucas⁶⁵, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, J. Nash, A. Nikitenko⁵¹, J. Pela, B. Penning, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta⁶⁷, T. Virdee¹⁷, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, U.S.A.

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika

Catholic University of America

R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, U.S.A.

A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, U.S.A.

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

Brown University, Providence, U.S.A.

G. Benelli, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J.M. Hogan, O. Jesus, K.H.M. Kwok, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, E. Spencer, R. Syarif

University of California, Davis, Davis, U.S.A.

R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, J. Smith, M. Squires, D. Stolp, K. Tos, M. Tripathi

University of California, Los Angeles, U.S.A.

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, D. Saltzberg, C. Schnaible, V. Valuev, M. Weber

University of California, Riverside, Riverside, U.S.A.

E. Bouvier, K. Burt, R. Clare, J. Ellison, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, A. Shrinivas, W. Si, H. Wei, S. Wimpenny, B. R. Yates

University of California, San Diego, La Jolla, U.S.A.

J.G. Branson, G.B. Cerati, S. Cittolin, M. Derdzinski, R. Gerosa, A. Holzner, D. Klein, V. Krutelyov, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech⁶⁸, C. Welke, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara - Department of Physics, Santa Barbara, U.S.A.

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, M. Franco Sevilla, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, S.D. Mullin, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, J. Yoo

California Institute of Technology, Pasadena, U.S.A.

D. Anderson, J. Bendavid, A. Bornheim, J. Bunn, J. Duarte, J.M. Lawhorn, A. Mott, H.B. Newman, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, U.S.A.

M.B. Andrews, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, U.S.A.

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, T. Mulholland, K. Stenson, S.R. Wagner

Cornell University, Ithaca, U.S.A.

J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Fairfield University, Fairfield, U.S.A.

D. Winn

Fermi National Accelerator Laboratory, Batavia, U.S.A.

S. Abdullin, M. Albrow, G. Apollinari, A. Apresyan, 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[†], M. Cremonesi, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, 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. Linacre, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck, Y. Wu

University of Florida, Gainesville, U.S.A.

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, J.F. Low, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, D. Rank, L. Shchutska, D. Sperka, L. Thomas, J. Wang, S. Wang, J. Yelton

Florida International University, Miami, U.S.A.

S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, U.S.A.

A. Ackert, T. Adams, A. Askew, S. Bein, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, H. Prosper, A. Santra, R. Yohay

Florida Institute of Technology, Melbourne, U.S.A.

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, U.S.A.

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, K. Jung, I.D. Sandoval Gonzalez, N. Varelas, H. Wang, Z. Wu, M. Zakaria, J. Zhang

The University of Iowa, Iowa City, U.S.A.

B. Bilki⁶⁹, W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁷⁰, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok⁷¹, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, U.S.A.

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

The University of Kansas, Lawrence, U.S.A.

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, L. Forthomme, R.P. Kenny III, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, S. Sanders, R. Stringer, J.D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, U.S.A.

A. Ivanov, K. Kaadze, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Lawrence Livermore National Laboratory, Livermore, U.S.A.

F. Rebassoo, D. Wright

University of Maryland, College Park, U.S.A.

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, J.A. Gomez, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

Massachusetts Institute of Technology, Cambridge, U.S.A.

D. Abercrombie, B. Allen, A. Apyan, V. Azzolini, R. Barbieri, A. Baty, R. Bi, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, K. Krajczar, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, 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. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

University of Minnesota, Minneapolis, U.S.A.

A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, S. Kalafut, S.C. Kao, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

University of Mississippi, Oxford, U.S.A.

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, U.S.A.

E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, A. Malta Rodrigues, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, U.S.A.

M. Alyari, J. Dolen, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, U.S.A.

G. Alverson, E. Barberis, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Ori-moto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood

Northwestern University, Evanston, U.S.A.

S. Bhattacharya, O. Charaf, K.A. Hahn, A. Kumar, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, U.S.A.

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁸, M. Planer, A. Reinsvold, R. Ruchti, N. Rupprecht, G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, U.S.A.

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, R. Hughes, W. Ji, B. Liu, W. Luo, D. Puigh, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, U.S.A.

S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, D. Lange, J. Luo, D. Marlow, T. Medvedeva, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, A. Svyatkovskiy, C. Tully

University of Puerto Rico, Mayaguez, U.S.A.

S. Malik

Purdue University, West Lafayette, U.S.A.

A. Barker, V.E. Barnes, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, A. Khatiwada, D.H. Miller, N. Neumeister, J.F. Schulte, X. Shi, J. Sun, F. Wang, W. Xie

Purdue University Calumet, Hammond, U.S.A.

N. Parashar, J. Stupak

Rice University, Houston, U.S.A.

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

University of Rochester, Rochester, U.S.A.

B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, 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, U.S.A.

A. Agapitos, J.P. Chou, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, U.S.A.

A.G. Delannoy, M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

Texas A&M University, College Station, U.S.A.

O. Bouhali⁷², A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, E. Juska, T. Kamon⁷³, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov, K.A. Ulmer

Texas Tech University, Lubbock, U.S.A.

N. Akchurin, J. Damgov, F. De Guio, C. Dragoiu, P.R. Duderov, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Vanderbilt University, Nashville, U.S.A.

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, U.S.A.

M.W. Arenton, P. Barria, B. Cox, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, U.S.A.

C. Clarke, R. Harr, P.E. Karchin, J. Sturdy

University of Wisconsin - Madison, Madison, WI, U.S.A.

D.A. Belknap, J. Buchanan, C. Caillol, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, T. Perry, G.A. Pierro, G. Polese, T. Ruggles, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

†: Deceased

1: Also at Vienna University of Technology, Vienna, Austria

2: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

3: Also at Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS/IN2P3, Strasbourg, France

4: Also at Universidade Estadual de Campinas, Campinas, Brazil

5: Also at Universidade Federal de Pelotas, Pelotas, Brazil

6: Also at Université Libre de Bruxelles, Bruxelles, Belgium

7: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany

8: Also at Joint Institute for Nuclear Research, Dubna, Russia

- 9: Also at Helwan University, Cairo, Egypt
- 10: Now at Zewail City of Science and Technology, Zewail, Egypt
- 11: Now at Fayoum University, El-Fayoum, 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 Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 16: Also at Tbilisi State University, Tbilisi, Georgia
- 17: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 18: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- 19: Also at University of Hamburg, Hamburg, Germany
- 20: Also at Brandenburg University of Technology, Cottbus, Germany
- 21: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 22: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- 23: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- 24: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
- 25: Also at University of Visva-Bharati, Santiniketan, India
- 26: Also at Indian Institute of Science Education and Research, Bhopal, India
- 27: Also at Institute of Physics, Bhubaneswar, India
- 28: Also at University of Ruhuna, Matara, Sri Lanka
- 29: Also at Isfahan University of Technology, Isfahan, Iran
- 30: Also at Yazd University, Yazd, Iran
- 31: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 32: Also at Università degli Studi di Siena, Siena, Italy
- 33: Also at Purdue University, West Lafayette, U.S.A.
- 34: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
- 35: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 36: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
- 37: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 38: Also at Institute for Nuclear Research, Moscow, Russia
- 39: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 40: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 41: Also at University of Florida, Gainesville, U.S.A.
- 42: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 43: Also at California Institute of Technology, Pasadena, U.S.A.
- 44: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 45: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 46: Also at INFN Sezione di Roma; Università di Roma, Roma, Italy
- 47: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 48: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 49: Also at National and Kapodistrian University of Athens, Athens, Greece
- 50: Also at Riga Technical University, Riga, Latvia
- 51: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia

- 52: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
- 53: Also at Adiyaman University, Adiyaman, Turkey
- 54: Also at Istanbul Aydin University, Istanbul, Turkey
- 55: Also at Mersin University, Mersin, Turkey
- 56: Also at Cag University, Mersin, Turkey
- 57: Also at Piri Reis University, Istanbul, Turkey
- 58: Also at Ozyegin University, Istanbul, Turkey
- 59: Also at Izmir Institute of Technology, Izmir, Turkey
- 60: Also at Marmara University, Istanbul, Turkey
- 61: Also at Kafkas University, Kars, Turkey
- 62: Also at Istanbul Bilgi University, Istanbul, Turkey
- 63: Also at Yildiz Technical University, Istanbul, Turkey
- 64: Also at Hacettepe University, Ankara, Turkey
- 65: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 66: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 67: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
- 68: Also at Utah Valley University, Orem, U.S.A.
- 69: Also at Argonne National Laboratory, Argonne, U.S.A.
- 70: Also at Erzincan University, Erzincan, Turkey
- 71: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 72: Also at Texas A&M University at Qatar, Doha, Qatar
- 73: Also at Kyungpook National University, Daegu, Korea