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Measurement of the Inclusive Jet Cross Section in pp Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration*

Abstract

The inclusive jet cross section is measured in pp collisions with a center-of-mass energy of 7 TeV at the LHC using the CMS experiment. The data sample corresponds to an integrated luminosity of 34 pb^{-1} . The measurement is made for jet transverse momenta in the range 18–1100 GeV and for absolute values of rapidity less than 3. The measured cross section extends to the highest values of jet p_T ever observed and, within the experimental and theoretical uncertainties, is generally in agreement with next-to-leading-order perturbative QCD predictions.

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*See Appendix A for the list of collaboration members

The measurement of the inclusive jet cross section is a benchmark of the standard model (SM) at hadron colliders [1, 2]. At the Large Hadron Collider (LHC), jets produced in the high center-of-mass energy collisions test the SM at the smallest distance scales presently possible, can constrain parton momentum distributions in the proton, and are sensitive to the strong coupling constant. Significant deviations from predictions of the inclusive jet cross section at high transverse momentum p_T could also be an indication of new phenomena beyond the SM. Results from the Tevatron $p\bar{p}$ collider demonstrate agreement with next-to-leading-order (NLO) theoretical predictions from perturbative Quantum Chromodynamics (pQCD) for jets in the p_T range of 50–650 GeV, using approximately 1 fb^{-1} of data at a center-of-mass energy $\sqrt{s} = 1.96 \text{ TeV}$ [3–5]. Early results from the ATLAS Collaboration for jets in the p_T range 60–600 GeV, based on a 17 nb^{-1} data sample of pp collisions at $\sqrt{s} = 7 \text{ TeV}$ at the LHC, also indicate agreement with theoretical predictions [6]. Using a data sample corresponding to 34 pb^{-1} of integrated luminosity from pp collisions recorded by the CMS detector at the LHC with $\sqrt{s} = 7 \text{ TeV}$, we significantly extend the p_T range from previous measurements of the inclusive jet p_T spectrum to 18–1100 GeV and for rapidities $|y| < 3.0$. The rapidity y is defined as $y = \frac{1}{2} \ln[(E + p_z)/(E - p_z)]$, where E is the jet energy and p_z is the component of the jet momentum along the beam axis. In this Letter, the inclusive jet cross section, differential in p_T and y , is compared with theoretical predictions at NLO in pQCD.

The CMS detector has silicon pixel and microstrip trackers covering pseudorapidities up to $|\eta| = 2.5$, where $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle relative to the counterclockwise proton beam direction. Together with a 3.8 T solenoid, the trackers provide track reconstruction down to transverse momenta of about 100 MeV and a resolution of about 1% at 100 GeV. A high-granularity electromagnetic crystal calorimeter (ECAL) extends up to $|\eta| = 3.0$, and has an energy resolution of better than 0.5% for unconverted photons with transverse energies above 100 GeV. A hermetic hadronic calorimeter (HCAL) extends up to $|\eta| = 5.0$ with a transverse hadronic energy resolution of about $100\%/\sqrt{E_T [\text{GeV}]} \oplus 5\%$. The calorimeter components relevant to this work may be described in terms of a cylindrical barrel region, extending up to $|\eta| = 1.5$, and two endcaps, covering $1.5 < |\eta| < 3.0$. An efficient muon system reconstructs and identifies muons up to $|\eta| = 2.4$. Events are collected using a two-level trigger system, consisting of a hardware Level-1 and a software high level trigger. Jets formed online by the trigger system use the energies measured in the ECAL and HCAL, and are uncorrected for the jet energy response of the calorimeters. This study uses inclusive single-jet triggers corresponding to p_T thresholds of 6, 15, 30, 50, 70, 100, and 140 GeV. Finally, a minimum-bias trigger is defined as a signal from at least one of two beam scintillator counters in coincidence with a signal from one of two beam pick-up timing devices. The CMS coordinate system is right-handed, with the origin centered at the nominal collision point, the x axis pointing radially toward the center of the LHC, the y axis pointing vertically upward, and the z axis pointing along the beam direction. More details about the CMS detector can be found in Ref. [7].

This measurement uses the infrared- and collinear-safe anti- k_T jet clustering algorithm [8], as implemented in Ref. [9]. A distance parameter of $R = 0.5$ is chosen. The CMS particle-flow (PF) algorithm reconstructs individual particles (leptons, photons, charged and neutral hadrons) by linking tracks, ECAL clusters, and HCAL clusters. The momentum or energy of each particle is measured based on information from all subdetectors. Broadly speaking, electrons are reconstructed from tracks and calibrated ECAL clusters; muons are reconstructed using tracks; charged hadrons are reconstructed from tracks and calibrated ECAL and HCAL clusters; photons and neutral hadrons are reconstructed from calibrated ECAL and HCAL clusters, respectively. A detailed description of the PF algorithm and performance can be found in Ref. [10] and references therein. Jets are reconstructed by clustering particles, including leptons. Because the

energy response of each reconstructed particle is close to unity, the jet momentum response is also close to unity and only small corrections (at the level of 5–10%) are needed [11, 12]. The bulk of these corrections are derived from simulation [13] with residual corrections determined from data. First, using an exclusive dijet sample containing back-to-back jets in azimuth, a residual relative correction of up to 8% removes any remaining pseudorapidity dependence of the jet momentum response. Second, using an exclusive data sample containing a single hadronic jet recoiling back-to-back in azimuth against a well measured photon [12], a small residual absolute correction of about 1% restores the response to unity. Jet momenta are further corrected for the pile-up of multiple proton-proton collisions [14], which ranged from nearly zero additional collisions at the very early period of LHC data taking in 2010 to an average of about three near the end of the 2010 running period. Finally, the jet momentum resolution is determined as a function of the jet p_T and y from simulation. Comparing the p_T balance in dijet events between data and simulation, the jet p_T resolution from simulation is scaled to be about 10% larger in the barrel and about 20% larger in the endcaps to match that from data [11, 12].

The efficiency of a given inclusive single-jet trigger is determined as the ratio of its trigger rate to either the minimum-bias trigger rate or the rate of the lower- p_T trigger preceding it. The minimum jet p_T is chosen so that the trigger efficiency exceeds 99% for each dataset. All events are required to have a primary vertex (PV) satisfying the following selection: the fit for the PV must include at least three associated tracks, the PV must lie within 0.15 cm of the beam axis, and the z coordinate of the PV must lie within the luminous collision region $|z_{PV}| < 24$ cm. This selection rejects noncollision and beam-related backgrounds. Loose jet identification criteria [15] are applied requiring that each jet within the tracker acceptance have at least two particles, of which at least one must be a charged hadron. Further, at most 90% of the jet energy is allowed to be from photons or neutral hadrons. Beyond the tracker acceptance, each jet is required to have both electromagnetic and hadronic energy. To remove effects from anomalous calorimeter noise, beam halo, or cosmic-ray backgrounds, events are rejected if the missing transverse momentum is both larger than 50% of the total visible transverse energy and larger than 100 GeV. The missing transverse momentum is defined as the modulus of the negative transverse vector sum over the momenta of all reconstructed particles in the event. Any inefficiency in selecting jets, due to the above criteria, is estimated from simulation to be negligible.

Due to resolution effects, a jet may fall into a different p_T bin than the one corresponding to the true underlying jet (unaltered by experimental effects). Such bin-to-bin migrations distort the rapidly falling p_T spectrum. Each p_T bin width is chosen to be larger than the reconstructed jet p_T resolution in the bin to minimize the migration effects and large enough to ensure that statistical fluctuations do not dominate the measurement. The jet p_T spectra are corrected for resolution effects where the true jet p_T spectrum is modeled by a power-law *ansatz* motivated by the parton model, modified by a kinematic cutoff term at high p_T : $f(p_T; \alpha, \beta, \gamma) = N_0 [p_T]^{-\alpha} [1 - \frac{1}{\sqrt{s}} 2p_T \cosh(y_{\min})]^\beta \exp[-\gamma/p_T]$, where N_0 is a normalization factor, α, β, γ are fit parameters, and y_{\min} is the low-edge of the rapidity bin y under consideration. Similar parameterizations have been previously used by other experiments [4, 6, 16]. The function is then smeared using the jet p_T resolutions in bins of p_T and y . The parameters of the model are extracted by fitting the smeared transverse momentum spectrum to the experimental data. The data points are placed at the bin center, defined as the point where the value of the predicted function is equal to its mean value over the bin width. The p_T resolution corrections for each bin in p_T and y , determined by taking the ratio of the function to the smeared function, range from 5 to 10% as a function of p_T in the central rapidity bin and range from about 10% to 50% in the most-forward rapidity bin. Jet migrations across y bins due to y resolution are

found to be negligible within the tracker acceptance. Using simulation, migrations of up to 5% are observed and corrected across bins whose boundaries lie near the tracker acceptance.

The primary sources of systematic uncertainties in the cross section measurement arise from the jet momentum scale and resolution, as well as the integrated luminosity. The jet transverse momentum scale is sensitive to several effects including (a) the photon energy scale (known to 1.0% [17] and used to derive the residual absolute response corrections), (b) the relative response across detector regions (known to within 2.6% [12]), (c) pile-up effects (known to within 0.2% for very low pile-up conditions with low- p_T jet triggers or for intermediate pile-up conditions with high- p_T jet triggers), and (d) the calibration extrapolation to transverse momenta above available photon energies (dominated by uncertainties in jet fragmentation and estimated to be within 4% at 1100 GeV [12]). With those considerations, the total uncertainty in the jet transverse momentum scale is determined to be between 3% and 4% in the ranges $18 < p_T < 1100$ GeV and $|\eta| < 3.0$. The jet momentum resolutions for different y bins are known to within 10% at $|y| < 1.5$, increasing to 15% for $1.5 < |y| < 2.0$, 25% for $2.0 < |y| < 2.5$, and 30% for $2.5 < |y| < 3.0$ [11]. The integrated luminosity of the proton-proton collisions is known with a precision of 4% [18] and directly translates into a 4% normalization uncertainty on the inclusive jet cross section.

The next-to-leading-order perturbative QCD theoretical predictions are derived using NLO-JET++ 2.0.1 [19, 20] within the framework of FASTNLO 1.4 [21]. The FASTNLO framework is used for propagating uncertainties due to different parton distribution function (PDF) sets, α_s values, and scale choices. Non-perturbative (NP) corrections for hadronization and multiple parton interactions are estimated using PYTHIA 6.422 [22] and HERWIG++ 2.4.2 [23], which are applied to the NLO pQCD prediction. The correction is defined as the average of the models, and the associated theoretical uncertainty is assumed to be half of the difference between the two predictions. For low- p_T jets, the NP correction can be as large as 30%, with a relative uncertainty of 100%. Uncertainties from any residual dependence on the choice of renormalization scale μ_r and factorization scale μ_f are determined by varying the scales according to the following combinations [24]: $(\frac{1}{2}\mu_r, \frac{1}{2}\mu_f)$, $(\frac{1}{2}\mu_r, \mu_f)$, $(\mu_r, \frac{1}{2}\mu_f)$, $(\mu_r, 2\mu_f)$, $(2\mu_r, \mu_f)$, and $(2\mu_r, 2\mu_f)$. The default choice is $\mu_r = \mu_f = p_T$. These scale variations modify the prediction of the inclusive jet cross section by about 5% to 10%. Following the PDF4LHC recommendation [25], PDF uncertainties are evaluated via a prescribed envelope, defined as the maximum variation between different PDF sets constructed from CT10 [26], MSTW2008NLO [27], and NNPDF2.0 [28], including their respective uncertainties and using their respective default values of the strong coupling constant $\alpha_s(m_Z) = 0.1180, 0.1190, \text{ and } 0.1202$. The middle of the envelope is taken as the central prediction. The uncertainties are on the order of 10% up to a p_T of 800 GeV, except when approaching the kinematic limit where they can be as large as 40%. Finally, an additional uncertainty from the current knowledge of the strong coupling constant is calculated from the CT10as PDF set [26] with values of $\alpha_s(m_Z)$ varied conservatively by ± 0.002 and added in quadrature to the PDF uncertainty. The uncertainties due to these variations in $\alpha_s(m_Z)$ are between 2.5 to 5.0%. The PDF uncertainties are dominated by differences between PDF sets in the PDF4LHC recommendation for $50 < p_T < 500$ GeV, and by uncertainties within a single PDF set for $p_T > 500$ GeV.

The fully-corrected inclusive jet cross section is shown in Figs. 1 and 2. Figure 1 shows the jet p_T spectra between 18 and 1100 GeV, falling over 10 orders of magnitude in rate, and for six different rapidity bins. The comparison with the theoretical NLO prediction, corrected for NP effects, is more easily discerned in Fig. 2, which provides the ratio of the jet p_T spectra from data to the theoretical prediction for each of the six rapidity bins. The total theoretical systematic uncertainty from the prediction is superimposed as solid lines above and below unity, and

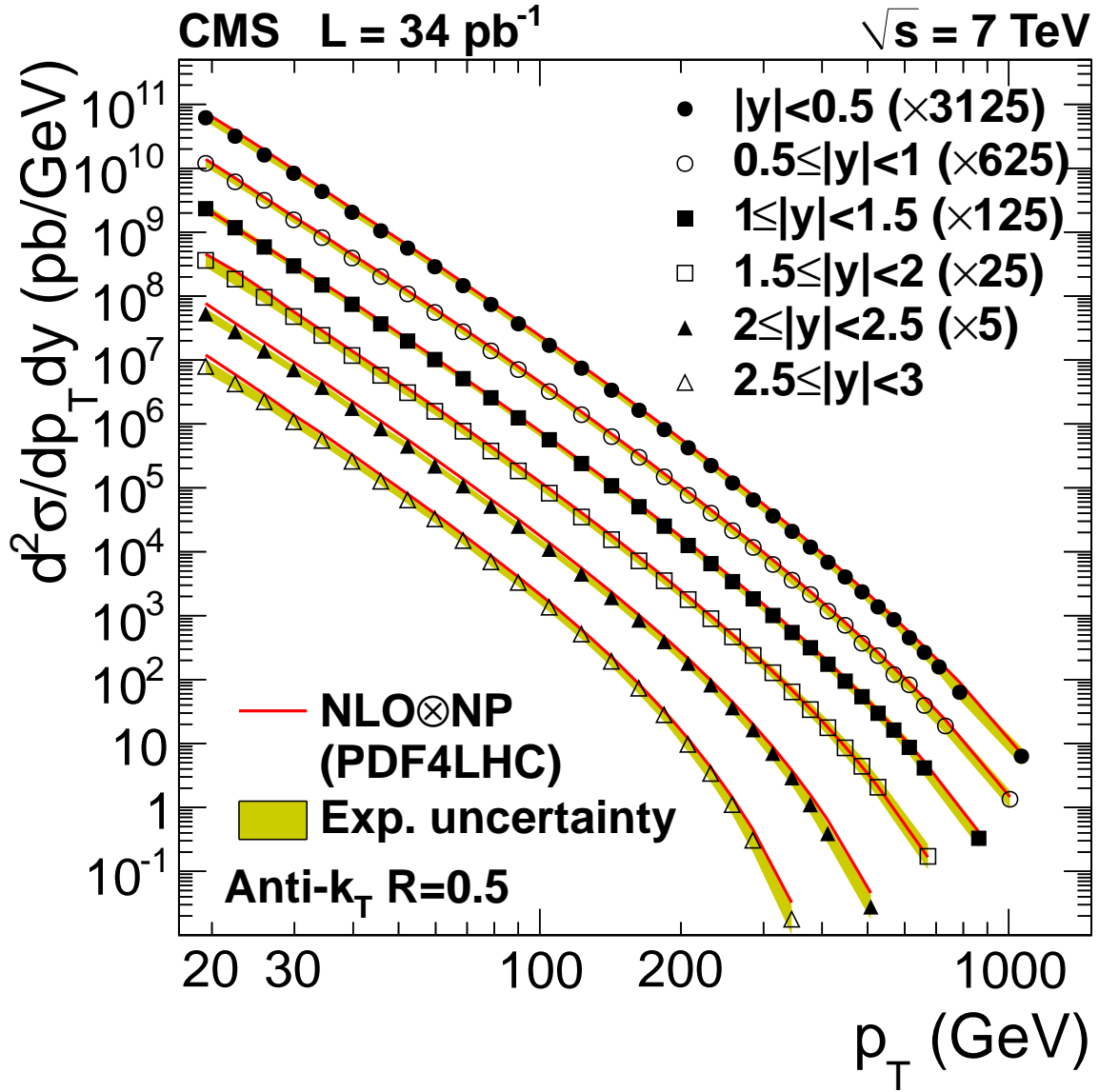


Figure 1: Fully-corrected inclusive jet differential cross sections as a function of p_T for six different rapidity intervals, scaled by the factors shown in the legend for easier viewing. The next-to-leading-order (NLO) theoretical predictions, corrected for non-perturbative (NP) effects via multiplicative factors, are superimposed.

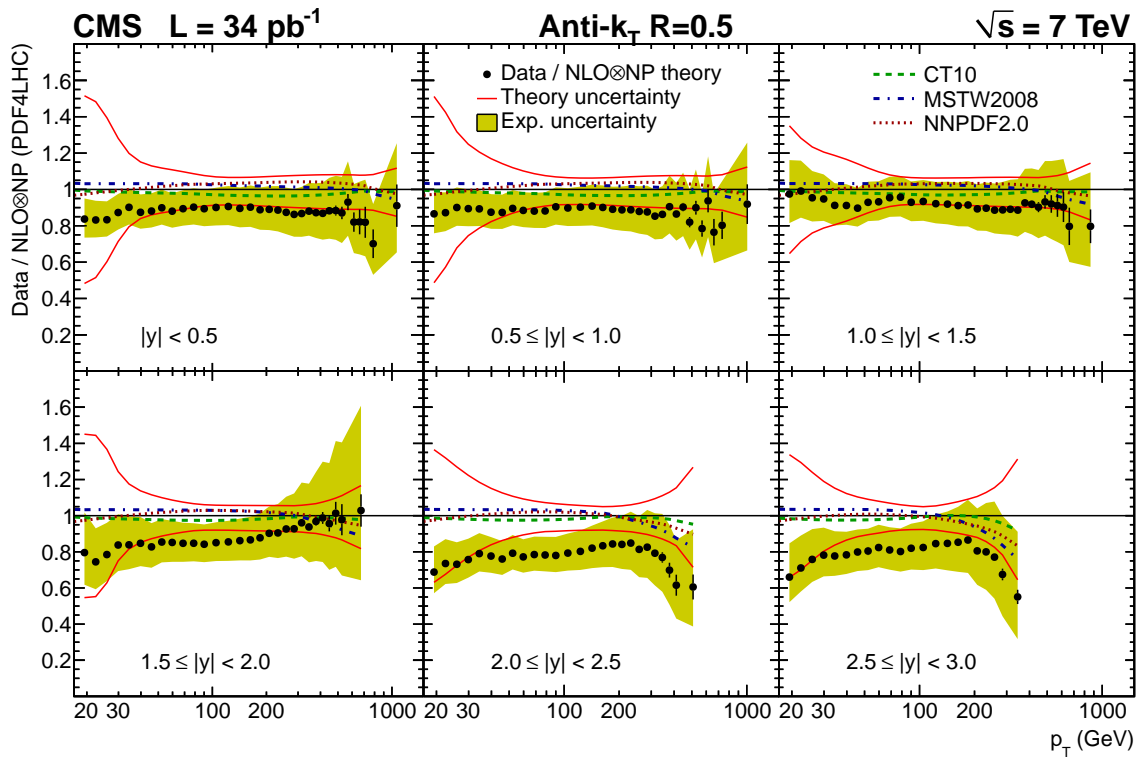


Figure 2: Ratios of the fully-corrected measured jet p_T differential cross sections to the theoretical prediction as a function of p_T . The error bars show the experimental statistical uncertainties. The shaded band about the data points represent the total experimental systematic uncertainty. The solid lines represent the total theoretical systematic uncertainty. The central predictions for the CT10 (dashed line), MSTW2008NLO (dash-dotted line), and NNPDF2.0 (dotted line) PDF sets are also shown.

the total systematic uncertainty due to experimental effects is centered on the data points as a shaded band. The central predictions for the CT10, MSTW2008NLO, and NNPDF2.0 PDF sets are also overlaid. The PDF uncertainties are large and asymmetric at high jet p_T , dominating the theoretical uncertainty band. Nevertheless, compared to the PDF4LHC recommendation, similar trends between data and the central prediction of each PDF set are observed. Within the experimental and theoretical uncertainties, the predictions are seen to be consistent with the data across a wide range of jet p_T and rapidities, although the predictions are systematically above the data.

In conclusion, using a data sample corresponding to 34 pb^{-1} of integrated luminosity from pp collisions recorded by the CMS detector at the LHC with a center-of-mass energy of 7 TeV, the jet transverse momentum spectrum has been measured for $18 < p_T < 1100 \text{ GeV}$ and for six rapidity bins up to $|y| = 3.0$. The dominant systematic uncertainties arise from the absolute jet momentum scale and resolution, as well as the integrated luminosity measurement. The NLO pQCD predictions for the inclusive jet cross section, corrected for non-perturbative effects and using the PDF4LHC recommendations, are generally in agreement with the data. This measurement extends to the highest values of jet p_T ever observed.

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doi:10.1016/j.nuclphysb.2010.05.008.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan, M. Friedl, R. Frühwirth, V.M. Ghete, J. Hammer¹, S. Häsnel, M. Hoch, N. Hörmann, J. Hrubec, M. Jeitler, W. Kiesenhofer, M. Krammer, D. Liko, I. Mikulec, M. Pernicka, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, F. Teischinger, P. Wagner, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz

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

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

S. Bansal, L. Benucci, E.A. De Wolf, X. Janssen, J. Maes, T. Maes, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, O. Devroede, R. Gonzalez Suarez, A. Kalogeropoulos, M. Maes, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Université Libre de Bruxelles, Bruxelles, Belgium

O. Charaf, B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, G.H. Hammad, T. Hreus, P.E. Marage, L. Thomas, C. Vander Velde, P. Vanlaer

Ghent University, Ghent, Belgium

V. Adler, A. Cimmino, S. Costantini, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. McCartin, D. Ryckbosch, F. Thyssen, M. Tytgat, L. Vanelderen, P. Verwilligen, S. Walsh, N. Zaganidis

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

S. Basegmez, G. Bruno, J. Caudron, L. Ceard, E. Cortina Gil, J. De Favereau De Jeneret, C. Delaere¹, D. Favart, A. Giammanco, G. Grégoire, J. Hollar, V. Lemaître, J. Liao, O. Militaru, S. Oryn, D. Pagano, A. Pin, K. Piotrkowski, N. Schul

Université de Mons, Mons, Belgium

N. Bely, T. Caeberts, E. Daubie

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves, D. De Jesus Damiao, M.E. Pol, M.H.G. Souza

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

W. Carvalho, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, S.M. Silva Do Amaral, A. Sznajder

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil

C.A. Bernardes², F.A. Dias, T.R. Fernandez Perez Tomei, E. M. Gregores², C. Lagana, F. Marinho, P.G. Mercadante², S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

N. Darmenov¹, L. Dimitrov, V. Genchev¹, P. Iaydjiev¹, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, I. Vankov

University of Sofia, Sofia, Bulgaria

A. Dimitrov, R. Hadjiiska, A. Karadzhinova, V. Kozhuharov, L. Litov, M. Mateev, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China

J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China

Y. Ban, S. Guo, Y. Guo, W. Li, Y. Mao, S.J. Qian, H. Teng, L. Zhang, B. Zhu, W. Zou

Universidad de Los Andes, Bogota, Colombia

A. Cabrera, B. Gomez Moreno, A.A. Ocampo Rios, A.F. Osorio Oliveros, J.C. Sanabria

Technical University of Split, Split, Croatia

N. Godinovic, D. Lelas, K. Lelas, R. Plestina³, D. Polic, I. Puljak

University of Split, Split, Croatia

Z. Antunovic, M. Dzelalija

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, S. Duric, K. Kadija, S. Morovic

University of Cyprus, Nicosia, Cyprus

A. Attikis, M. Galanti, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

Charles University, Prague, Czech Republic

M. Finger, M. Finger Jr.

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

Y. Assran⁴, S. Khalil⁵, M.A. Mahmoud⁶

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

A. Hektor, M. Kadastik, M. Müntel, M. Raidal, L. Rebane

Department of Physics, University of Helsinki, Helsinki, Finland

V. Azzolini, P. Eerola, G. Fedi

Helsinki Institute of Physics, Helsinki, Finland

S. Czellar, J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland

K. Banzuzi, A. Korpela, T. Tuuva

Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France

D. Sillou

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, F.X. Gentit, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, M. Marionneau, L. Millischer, J. Rander, A. Rosowsky, I. Shreyber, M. Titov, P. Verrecchia

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj⁷, C. Broutin, P. Busson, C. Charlot, T. Dahms, L. Dobrzynski, S. Elgammal, R. Granier de Cassagnac, M. Haguenaer, P. Miné, C. Mironov, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Thiebaut, B. Wyslouch⁸, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

J.-L. Agram⁹, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte⁹, F. Drouhin⁹, C. Ferro, J.-C. Fontaine⁹, D. Gelé, U. Goerlach, S. Greder, P. Juillot, M. Karim⁹, A.-C. Le Bihan, Y. Mikami, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France

F. Fassi, D. Mercier

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

C. Baty, S. Beauceron, N. Beaupere, M. Bedjidian, O. Bondu, G. Boudoul, D. Boumediene, H. Brun, J. Chasserat, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, B. Ille, T. Kurca, T. Le Grand, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia

D. Lomidze

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

G. Anagnostou, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, N. Mohr, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, M. Weber, B. Wittmer

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

M. Ata, W. Bender, E. Dietz-Laursonn, M. Erdmann, J. Frangenheim, T. Hebbeker, A. Hinzmann, K. Hoepfner, T. Klimkovich, D. Klingebiel, P. Kreuzer, D. Lanske[†], C. Magass, M. Merschmeyer, A. Meyer, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier

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

M. Bontenackels, M. Davids, M. Duda, G. Flügge, H. Geenen, M. Giffels, W. Haj Ahmad, D. Heydhausen, T. Kress, Y. Kuessel, A. Linn, A. Nowack, L. Perchalla, O. Pooth, J. Rennefeld, P. Sauerland, A. Stahl, M. Thomas, D. Tornier, M.H. Zoeller

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, W. Behrenhoff, U. Behrens, M. Bergholz¹⁰, A. Bethani, K. Borrás, A. Cakir, A. Campbell, E. Castro, D. Dammann, G. Eckerlin, D. Eckstein, A. Flossdorf, G. Flucke, A. Geiser, J. Hauk, H. Jung¹, M. Kasemann, I. Katkov¹¹, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann¹⁰, R. Mankel, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, J. Olzem, D. Pitzl, A. Raspereza, A. Raval, M. Rosin, R. Schmidt¹⁰, T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, J. Tomaszewska, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany

C. Autermann, V. Blobel, S. Bobrovskiy, J. Draeger, H. Enderle, U. Gebbert, K. Kaschube,

G. Kaussen, R. Klanner, J. Lange, B. Mura, S. Naumann-Emme, F. Nowak, N. Pietsch, C. Sander, H. Schettler, P. Schleper, M. Schröder, T. Schum, J. Schwandt, H. Stadie, G. Steinbrück, J. Thomsen

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

C. Barth, J. Bauer, V. Buege, T. Chwalek, W. De Boer, A. Dierlamm, G. Dirkes, M. Feindt, J. Gruschke, C. Hackstein, F. Hartmann, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, J.R. Komaragiri, T. Kuhr, D. Martschei, S. Mueller, Th. Müller, M. Niegel, O. Oberst, A. Oehler, J. Ott, T. Peiffer, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, M. Renz, C. Saout, A. Scheurer, P. Schieferdecker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, J. Wagner-Kuhr, T. Weiler, M. Zeise, V. Zhukov¹¹, E.B. Ziebarth

Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece

G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari, E. Petrakou

University of Athens, Athens, Greece

L. Gouskos, T.J. Mertzimekis, A. Panagiotou, E. Stiliaris

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras, F.A. Triantis

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

A. Aranyi, G. Bencze, L. Boldizsar, C. Hajdu¹, P. Hidas, D. Horvath¹², A. Kapusi, K. Krajczar¹³, F. Sikler¹, G.I. Veres¹³, G. Vesztergombi¹³

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, J. Molnar, J. Palinkas, Z. Szillasi, V. Veszpremi

University of Debrecen, Debrecen, Hungary

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

Panjab University, Chandigarh, India

S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Jindal, M. Kaur, J.M. Kohli, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, A.P. Singh, J.B. Singh, S.P. Singh

University of Delhi, Delhi, India

S. Ahuja, S. Bhattacharya, B.C. Choudhary, B. Gomber, P. Gupta, S. Jain, S. Jain, R. Khurana, A. Kumar, M. Naimuddin, K. Ranjan, R.K. Shivpuri

Bhabha Atomic Research Centre, Mumbai, India

R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, P. Mehta, A.K. Mohanty¹, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India

T. Aziz, M. Guchait¹⁴, A. Gurtu, M. Maity¹⁵, D. Majumder, G. Majumder, K. Mazumdar, G.B. Mohanty, A. Saha, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India

S. Banerjee, S. Dugad, N.K. Mondal

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

H. Arfaei, H. Bakhshiansohi¹⁶, S.M. Etesami, A. Fahim¹⁶, M. Hashemi, A. Jafari¹⁶, M. Khakzad, A. Mohammadi¹⁷, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh, M. Zeinali¹⁸

INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy

M. Abbrescia^{a,b}, L. Barbone^{a,b}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, N. De Filippis^{a,c,1}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, L. Lusito^{a,b}, G. Maggi^{a,c}, M. Maggi^a, N. Manna^{a,b}, B. Marangelli^{a,b}, S. My^{a,c}, S. Nuzzo^{a,b}, N. Pacifico^{a,b}, G.A. Pierro^a, A. Pompili^{a,b}, G. Pugliese^{a,c}, F. Romano^{a,c}, G. Roselli^{a,b}, G. Selvaggi^{a,b}, L. Silvestris^a, R. Trentadue^a, S. Tuppiti^{a,b}, G. Zito^a

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

G. Abbiendi^a, A.C. Benvenuti^a, D. Bonacorsi^a, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^a, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^a, P. Giacomelli^a, M. Giunta^a, C. Grandi^a, S. Marcellini^a, G. Masetti^b, M. Meneghelli^{a,b}, A. Montanari^a, F.L. Navarra^{a,b}, F. Odorici^a, A. Perrotta^a, F. Primavera^a, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G. Siroli^{a,b}, R. Travaglini^{a,b}

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

S. Albergo^{a,b}, G. Cappello^{a,b}, M. Chiorboli^{a,b,1}, S. Costa^{a,b}, A. Tricomi^{a,b}, C. Tuve^a

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}, S. Frosali^{a,b}, E. Gallo^a, S. Gonzi^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^{a,1}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, S. Colafranceschi¹⁹, F. Fabbri, D. Piccolo

INFN Sezione di Genova, Genova, Italy

P. Fabbri, R. Musenich

INFN Sezione di Milano-Bicocca ^a, Università di Milano-Bicocca ^b, Milano, Italy

A. Benaglia^{a,b}, F. De Guio^{a,b,1}, L. Di Matteo^{a,b}, S. Gennai¹, A. Ghezzi^{a,b}, S. Malvezzi^a, A. Martelli^{a,b}, A. Massironi^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, S. Sala^a, T. Tabarelli de Fatis^{a,b}

INFN Sezione di Napoli ^a, Università di Napoli "Federico II" ^b, Napoli, Italy

S. Buontempo^a, C.A. Carrillo Montoya^{a,1}, N. Cavallo^{a,20}, A. De Cosa^{a,b}, F. Fabozzi^{a,20}, A.O.M. Iorio^{a,1}, L. Lista^a, M. Merola^{a,b}, P. Paolucci^a

INFN Sezione di Padova ^a, Università di Padova ^b, Università di Trento (Trento) ^c, Padova, Italy

P. Azzi^a, N. Bacchetta^a, P. Bellan^{a,b}, D. Bisello^{a,b}, A. Branca^a, R. Carlin^{a,b}, P. Checchia^a, M. De Mattia^{a,b}, T. Dorigo^a, U. Dosselli^a, F. Fanzago^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino, S. Lacaprara^{a,21}, I. Lazzizzera^{a,c}, M. Margoni^{a,b}, M. Mazzucato^a, A.T. Meneguzzo^{a,b}, M. Nespolo^{a,1}, L. Perrozzi^{a,1}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b}, S. Vanini^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}

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

P. Baesso^{a,b}, U. Berzano^a, S.P. Ratti^{a,b}, C. Riccardi^{a,b}, P. Torre^{a,b}, P. Vitulo^{a,b}, C. Viviani^{a,b}

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

M. Biasini^{a,b}, G.M. Bilei^a, B. Caponeri^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, A. Lucaroni^{a,b,1}, G. Mantovani^{a,b}, M. Menichelli^a, A. Nappi^{a,b}, F. Romeo^{a,b}, A. Santocchia^{a,b}, S. Taroni^{a,b,1}, M. Valdata^{a,b}

INFN Sezione di Pisa ^a, Università di Pisa ^b, Scuola Normale Superiore di Pisa ^c, Pisa, Italy

P. Azzurri^{a,c}, G. Bagliesi^a, J. Bernardini^{a,b}, T. Boccali^{a,1}, G. Broccolo^{a,c}, R. Castaldi^a, R.T. D'Agnolo^{a,c}, R. Dell'Orso^a, F. Fiori^{a,b}, L. Foà^{a,c}, A. Giassi^a, A. Kraan^a, F. Ligabue^{a,c},

T. Lomtadze^a, L. Martini^{a,22}, A. Messineo^{a,b}, F. Palla^a, G. Segneri^a, A.T. Serban^a, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b,1}, A. Venturi^{a,1}, P.G. Verdini^a

INFN Sezione di Roma ^a, Università di Roma "La Sapienza" ^b, Roma, Italy

L. Barone^{a,b}, F. Cavallari^a, D. Del Re^{a,b}, E. Di Marco^{a,b}, M. Diemoz^a, D. Franci^{a,b}, M. Grassi^{a,1}, E. Longo^{a,b}, S. Nourbakhsh^a, G. Organtini^{a,b}, F. Pandolfi^{a,b,1}, R. Paramatti^a, S. Rahatlou^{a,b}, C. Rovelli¹

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

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, C. Biino^a, C. Botta^{a,b,1}, N. Cartiglia^a, R. Castello^{a,b}, M. Costa^{a,b}, N. Demaria^a, A. Graziano^{a,b,1}, C. Mariotti^a, M. Marone^{a,b}, S. Maselli^a, E. Migliore^{a,b}, G. Mila^{a,b}, V. Monaco^{a,b}, M. Musich^{a,b}, M.M. Obertino^{a,c}, N. Pastrone^a, M. Pelliccioni^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, V. Sola^{a,b}, A. Solano^{a,b}, A. Staiano^a, A. Vilela Pereira^a

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

S. Belforte^a, F. Cossutti^a, G. Della Ricca^{a,b}, B. Gobbo^a, D. Montanino^{a,b}, A. Penzo^a

Kangwon National University, Chunchon, Korea

S.G. Heo, S.K. Nam

Kyungpook National University, Daegu, Korea

S. Chang, J. Chung, D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, H. Park, S.R. Ro, D. Son, D.C. Son, T. Son

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

Zero Kim, J.Y. Kim, S. Song

Korea University, Seoul, Korea

S. Choi, B. Hong, M.S. Jeong, M. Jo, H. Kim, J.H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park, H.B. Rhee, E. Seo, S. Shin, K.S. Sim

University of Seoul, Seoul, Korea

M. Choi, S. Kang, H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea

Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, E. Kwon, J. Lee, S. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania

M.J. Bilinskas, I. Grigelionis, M. Janulis, D. Martisiute, P. Petrov, T. Sabonis

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

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez, R. Magaña Villalba, A. Sánchez-Hernández, L.M. Villasenor-Cendejas

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

University of Auckland, Auckland, New Zealand

D. Krofcheck, J. Tam, C.H. Yiu

University of Canterbury, Christchurch, New Zealand

P.H. Butler, R. Doesburg, H. Silverwood

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

M. Ahmad, I. Ahmed, M.I. Asghar, H.R. Hoorani, W.A. Khan, T. Khurshid, S. Qazi

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

G. Brona, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Soltan Institute for Nuclear Studies, Warsaw, Poland

T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

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

N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, P. Musella, A. Nayak, P.Q. Ribeiro, J. Seixas, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia

I. Belotelov, P. Bunin, I. Golutvin, A. Kamenev, V. Karjavin, V. Konoplyanikov, G. Kozlov, A. Lanev, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

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

V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, A. Toropin, S. Troitsky

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, V. Gavrilov, V. Kaftanov[†], M. Kossov¹, A. Krokhotin, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia

E. Boos, M. Dubinin²³, L. Dudko, A. Ershov, A. Gribushin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, L. Sarycheva, V. Savrin, A. Snigirev

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, S.V. Rusakov, A. Vinogradov

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

I. Azhgirey, S. Bitioukov, V. Grishin¹, V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkine, V. Petrov, R. Ryutin, S. Slabospitsky, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

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

P. Adzic²⁴, M. Djordjevic, D. Krpic²⁴, J. Milosevic

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

M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cepeda, M. Cerrada,

M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, C. Diez Pardos, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J.M. Vizan Garcia

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

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini²⁵, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, C. Jorda, P. Lobelle Pardo, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez²⁶, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, 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, A.J. Bell²⁷, D. Benedetti, C. Bernet³, W. Bialas, P. Bloch, A. Bocci, S. Bolognesi, M. Bona, H. Breuker, K. Bunkowski, T. Camporesi, G. Cerminara, J.A. Coarasa Perez, B. Curé, D. D'Enterria, A. De Roeck, S. Di Guida, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, A. Gaddi, G. Georgiou, H. Gerwig, D. Gigi, K. Gill, D. Giordano, F. Glege, R. Gomez-Reino Garrido, M. Gouzevitch, P. Govoni, S. Gowdy, L. Guiducci, M. Hansen, C. Hartl, J. Harvey, J. Hegeman, B. Hegner, H.F. Hoffmann, A. Honma, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, P. Lecoq, C. Lourenço, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, A. Maurisset, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, E. Nesvold¹, M. Nguyen, T. Orimoto, L. Orsini, E. Perez, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, A. Racz, J. Rodrigues Antunes, G. Rolandi²⁸, T. Rommerskirchen, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, I. Segoni, A. Sharma, P. Siegrist, M. Simon, P. Sphicas²⁹, M. Spiropulu²³, M. Stoye, M. Tadel, P. Tropea, A. Tsiros, P. Vichoudis, M. Voutilainen, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille³⁰, A. Starodumov³¹

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

P. Bortignon, L. Caminada³², N. Chanon, Z. Chen, S. Cittolin, G. Dissertori, M. Dittmar, J. Eugster, K. Freudenreich, C. Grab, A. Hervé, W. Hintz, P. Lecomte, W. Luster, C. Marchica³², P. Martinez Ruiz del Arbol, P. Meridiani, P. Milenov³³, F. Moortgat, C. Nägeli³², P. Nef, F. Nessi-Tedaldi, L. Pape, F. Pauss, T. Punz, A. Rizzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, M.-C. Sawley, B. Stieger, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, M. Weber, L. Wehrli, J. Weng

Universität Zürich, Zurich, Switzerland

E. Aguiló, C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, C. Regenfus, P. Robmann, A. Schmidt, H. Snoek

National Central University, Chung-Li, Taiwan

Y.H. Chang, K.H. Chen, S. Dutta, C.M. Kuo, S.W. Li, W. Lin, Z.K. Liu, Y.J. Lu, D. Mekterovic, R. Volpe, J.H. Wu, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, J.G. Shiu, Y.M. Tzeng, M. Wang

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci³⁴, S. Cerci³⁵, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, I. Hos, E.E. Kangal, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk, A. Polatoz, K. Sogut³⁶, D. Sunar Cerci³⁵, B. Tali³⁵, H. Topakli³⁴, D. Uzun, L.N. Vergili, M. Vergili, S. Yilmaz

Middle East Technical University, Physics Department, Ankara, Turkey

I.V. Akin, T. Aliev, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, E. Yildirim, M. Zeyrek

Bogazici University, Istanbul, Turkey

M. Deliomeroglu, D. Demir³⁷, E. Gülmez, B. Isildak, M. Kaya³⁸, O. Kaya³⁸, S. Ozkorucuklu³⁹, N. Sonmez⁴⁰

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

L. Levchuk

University of Bristol, Bristol, United Kingdom

F. Bostock, J.J. Brooke, T.L. Cheng, E. Clement, D. Cussans, R. Frazier, J. Goldstein, M. Grimes, M. Hansen, D. Hartley, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold⁴¹, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, S. Ward

Rutherford Appleton Laboratory, Didcot, United Kingdom

L. Basso⁴², K.W. Bell, A. Belyaev⁴², C. Brew, R.M. Brown, B. Camanzi, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley, S.D. Worm

Imperial College, London, United Kingdom

R. Bainbridge, G. Ball, J. Ballin, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, B.C. MacEvoy, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko³¹, A. Papageorgiou, M. Pesaresi, K. Petridis, M. Pioppi⁴³, D.M. Raymond, S. Rogerson, N. Rompotis, A. Rose, M.J. Ryan, C. Seez, P. Sharp, A. Sparrow, A. Tapper, S. Tourneur, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, D. Wardrope, T. Whyntie

Brunel University, Uxbridge, United Kingdom

M. Barrett, M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leslie, W. Martin, I.D. Reid, L. Teodorescu

Baylor University, Waco, USA

K. Hatakeyama, H. Liu

Boston University, Boston, USA

T. Bose, E. Carrera Jarrin, C. Fantasia, A. Heister, J. St. John, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, L. Sulak

Brown University, Providence, USA

A. Avetisyan, S. Bhattacharya, J.P. Chou, D. Cutts, A. Ferapontov, U. Heintz, S. Jabeen, G. Kukartsev, G. Landsberg, M. Luk, M. Narain, D. Nguyen, M. Segala, T. Sinthuprasith, T. Speer, K.V. Tsang

University of California, Davis, Davis, USA

R. Breedon, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, P.T. Cox, J. Dolen, R. Erbacher, E. Friis, W. Ko, A. Kopecky, R. Lander, H. Liu, S. Maruyama, T. Miceli, M. Nikolic, D. Pellett, J. Robles, S. Salur, T. Schwarz, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra, C. Veelken

University of California, Los Angeles, Los Angeles, USA

V. Andreev, K. Arisaka, D. Cline, R. Cousins, A. Deisher, J. Duris, S. Erhan, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein[†], J. Tucker, V. Valuev

University of California, Riverside, Riverside, USA

J. Babb, A. Chandra, R. Clare, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng, S.C. Kao, F. Liu, H. Liu, O.R. Long, A. Luthra, H. Nguyen, B.C. Shen[†], R. Stringer, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, San Diego, La Jolla, USA

W. Andrews, J.G. Branson, G.B. Cerati, E. Dusinger, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, H. Pi, M. Pieri, R. Ranieri, M. Sani, V. Sharma, S. Simon, Y. Tu, A. Vartak, S. Wasserbaech⁴⁴, F. Würthwein, A. Yagil, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, J.R. Vlimant

California Institute of Technology, Pasadena, USA

A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, K. Shin, V. Timciuc, P. Traczyk, J. Veverka, R. Wilkinson, Y. Yang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

B. Akgun, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, S.Y. Jun, Y.F. Liu, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, USA

J.P. Cumalat, M.E. Dinardo, B.R. Drell, C.J. Edelmaier, W.T. Ford, A. Gaz, B. Heyburn, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner, S.L. Zang

Cornell University, Ithaca, USA

L. Agostino, J. Alexander, D. Cassel, A. Chatterjee, S. Das, N. Eggert, L.K. Gibbons, B. Heltsley, W. Hopkins, A. Khukhunaishvili, B. Kreis, G. Nicolas Kaufman, J.R. Patterson, D. Puigh, A. Ryd, E. Salvati, X. Shi, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, USA

A. Biselli, G. Cirino, D. Winn

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, M. Atac, J.A. Bakken, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, F. Borchering, K. Burkett,

J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, S. Cihangir, W. Cooper, D.P. Eartly, V.D. Elvira, S. Esen, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, D. Green, K. Gunthoti, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, H. Jensen, M. Johnson, U. Joshi, R. Khaliwada, B. Klima, K. Kousouris, S. Kunori, S. Kwan, C. Leonidopoulos, P. Limon, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, T. Miao, K. Mishra, S. Mrenna, Y. Musienko⁴⁵, C. Newman-Holmes, V. O'Dell, R. Pordes, O. Prokofyev, N. Saoulidou, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

University of Florida, Gainesville, USA

D. Acosta, P. Avery, D. Bourilkov, M. Chen, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, K. Matchev, G. Mitselmakher, L. Muniz, C. Prescott, R. Remington, M. Schmitt, B. Scurlock, P. Sellers, N. Skhirtladze, M. Snowball, D. Wang, J. Yelton, M. Zakaria

Florida International University, Miami, USA

C. Ceron, V. Gaultney, L. Kramer, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, D. Mesa, J.L. Rodriguez

Florida State University, Tallahassee, USA

T. Adams, A. Askew, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, L. Quertenmont, S. Sekmen, V. Veeraraghavan

Florida Institute of Technology, Melbourne, USA

M.M. Baarmand, B. Dorney, S. Guragain, M. Hohmann, H. Kalakhety, R. Ralich, I. Vodopiyarov

University of Illinois at Chicago (UIC), Chicago, USA

M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, J. Callner, R. Cavanaugh, C. Dragoiu, L. Gauthier, C.E. Gerber, S. Hamdan, D.J. Hofman, S. Khalatyan, G.J. Kunde⁴⁶, F. Lacroix, M. Malek, C. O'Brien, C. Silvestre, A. Smoron, D. Strom, N. Varelas

The University of Iowa, Iowa City, USA

U. Akgun, E.A. Albayrak, B. Bilki, W. Clarida, F. Duru, C.K. Lae, E. McCliment, J.-P. Merlo, H. Mermerkaya⁴⁷, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, J. Olson, Y. Onel, F. Ozok, S. Sen, J. Wetzel, T. Yetkin, K. Yi

Johns Hopkins University, Baltimore, USA

B.A. Barnett, B. Blumenfeld, A. Bonato, C. Eskew, D. Fehling, G. Giurciu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, N.V. Tran, A. Whitbeck

The University of Kansas, Lawrence, USA

P. Baringer, A. Bean, G. Benelli, O. Grachov, R.P. Kenny Iii, M. Murray, D. Noonan, S. Sanders, J.S. Wood, V. Zhukova

Kansas State University, Manhattan, USA

A.f. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze, Z. Wan

Lawrence Livermore National Laboratory, Livermore, USA

J. Gronberg, D. Lange, D. Wright

University of Maryland, College Park, USA

A. Baden, M. Boutemeur, S.C. Eno, D. Ferencek, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn, Y. Lu, A.C. Mignerey, K. Rossato, P. Rumerio, F. Santanastasio, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

Massachusetts Institute of Technology, Cambridge, USA

B. Alver, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, P. Everaerts, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, P. Harris, Y. Kim, M. Klute, Y.-J. Lee, W. Li, C. Loizides, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephens, F. Stöckli, K. Sumorok, K. Sung, E.A. Wenger, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

University of Minnesota, Minneapolis, USA

S.I. Cooper, P. Cushman, B. Dahmes, A. De Benedetti, P.R. Duderø, G. Franzoni, J. Haupt, K. Klappoetke, Y. Kubota, J. Mans, V. Rekovic, R. Rusack, M. Sasseville, A. Singovsky

University of Mississippi, University, USA

L.M. Cremaldi, R. Godang, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders, D. Summers

University of Nebraska-Lincoln, Lincoln, USA

K. Bloom, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, J. Keller, T. Kelly, I. Kravchenko, J. Lazo-Flores, H. Malbouisson, S. Malik, G.R. Snow

State University of New York at Buffalo, Buffalo, USA

U. Baur, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S.P. Shipkowski, K. Smith

Northeastern University, Boston, USA

G. Alverson, E. Barberis, D. Baumgartel, O. Boeriu, M. Chasco, S. Reucroft, J. Swain, D. Trocino, D. Wood, J. Zhang

Northwestern University, Evanston, USA

A. Anastassov, A. Kubik, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

University of Notre Dame, Notre Dame, USA

L. Antonelli, D. Berry, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, T. Kolberg, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, J. Ziegler

The Ohio State University, Columbus, USA

B. Bylsma, L.S. Durkin, J. Gu, C. Hill, P. Killewald, K. Kotov, T.Y. Ling, M. Rodenburg, G. Williams

Princeton University, Princeton, USA

N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, A. Hunt, J. Jones, E. Laird, D. Lopes Pegna, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

University of Puerto Rico, Mayaguez, USA

J.G. Acosta, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, A. Zatserklyaniy

Purdue University, West Lafayette, USA

E. Alagoz, V.E. Barnes, G. Bolla, L. Borrello, D. Bortoletto, A. Everett, A.F. Garfinkel, L. Gutay, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, C. Liu, V. Maroussov,

P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, USA

P. Jindal, N. Parashar

Rice University, Houston, USA

C. Boulahouache, V. Cuplov, K.M. Ecklund, F.J.M. Geurts, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, USA

B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, H. Flacher, A. Garcia-Bellido, P. Goldenzweig, Y. Gotra, J. Han, A. Harel, D.C. Miner, D. Orbaker, G. Petrillo, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, USA

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulios, G. Lungu, S. Malik, C. Mesropian, M. Yan

Rutgers, the State University of New Jersey, Piscataway, USA

O. Atramentov, A. Barker, D. Duggan, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, D. Hits, A. Lath, S. Panwalkar, R. Patel, A. Richards, K. Rose, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas

University of Tennessee, Knoxville, USA

G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

Texas A&M University, College Station, USA

R. Eusebi, J. Gilmore, A. Gurrola, T. Kamon, V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, J. Pivarski, A. Safonov, S. Sengupta, A. Tatarinov, D. Toback, M. Weinberger

Texas Tech University, Lubbock, USA

N. Akchurin, C. Bardak, J. Damgov, C. Jeong, K. Kovitanggoon, S.W. Lee, P. Mane, Y. Roh, A. Sill, I. Volobouev, R. Wigmans, E. Yazgan

Vanderbilt University, Nashville, USA

E. Appelt, E. Brownson, D. Engh, C. Florez, W. Gabella, M. Issah, W. Johns, P. Kurt, C. Maguire, A. Melo, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, USA

M.W. Arenton, M. Balazs, S. Boutle, B. Cox, B. Francis, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, R. Yohay

Wayne State University, Detroit, USA

S. Gollapinni, R. Harr, P.E. Karchin, P. Lamichhane, M. Mattson, C. Milstène, A. Sakharov

University of Wisconsin, Madison, USA

M. Anderson, M. Bachtis, J.N. Bellinger, D. Carlsmith, S. Dasu, J. Efron, K. Flood, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, P. Klabbbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, F. Palmonari, D. Reeder, I. Ross, A. Savin, W.H. Smith, J. Swanson, M. Weinberg

†: Deceased

1: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

2: Also at Universidade Federal do ABC, Santo Andre, Brazil

3: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

4: Also at Suez Canal University, Suez, Egypt

- 5: Also at British University, Cairo, Egypt
- 6: Also at Fayoum University, El-Fayoum, Egypt
- 7: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland
- 8: Also at Massachusetts Institute of Technology, Cambridge, USA
- 9: Also at Université de Haute-Alsace, Mulhouse, France
- 10: Also at Brandenburg University of Technology, Cottbus, Germany
- 11: Also at Moscow State University, Moscow, Russia
- 12: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 13: Also at Eötvös Loránd University, Budapest, Hungary
- 14: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
- 15: Also at University of Visva-Bharati, Santiniketan, India
- 16: Also at Sharif University of Technology, Tehran, Iran
- 17: Also at Shiraz University, Shiraz, Iran
- 18: Also at Isfahan University of Technology, Isfahan, Iran
- 19: Also at Facoltà Ingegneria Università di Roma "La Sapienza", Roma, Italy
- 20: Also at Università della Basilicata, Potenza, Italy
- 21: Also at Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy
- 22: Also at Università degli studi di Siena, Siena, Italy
- 23: Also at California Institute of Technology, Pasadena, USA
- 24: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
- 25: Also at University of California, Los Angeles, Los Angeles, USA
- 26: Also at University of Florida, Gainesville, USA
- 27: Also at Université de Genève, Geneva, Switzerland
- 28: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
- 29: Also at University of Athens, Athens, Greece
- 30: Also at The University of Kansas, Lawrence, USA
- 31: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 32: Also at Paul Scherrer Institut, Villigen, Switzerland
- 33: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 34: Also at Gaziosmanpasa University, Tokat, Turkey
- 35: Also at Adiyaman University, Adiyaman, Turkey
- 36: Also at Mersin University, Mersin, Turkey
- 37: Also at Izmir Institute of Technology, Izmir, Turkey
- 38: Also at Kafkas University, Kars, Turkey
- 39: Also at Suleyman Demirel University, Isparta, Turkey
- 40: Also at Ege University, Izmir, Turkey
- 41: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 42: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 43: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
- 44: Also at Utah Valley University, Orem, USA
- 45: Also at Institute for Nuclear Research, Moscow, Russia
- 46: Also at Los Alamos National Laboratory, Los Alamos, USA
- 47: Also at Erzincan University, Erzincan, Turkey