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Search for New Physics with a Mono-Jet and Missing Transverse Energy in pp Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration^{*}

Abstract

A study of events with missing transverse energy and an energetic jet is performed using pp collision data at a centre-of-mass energy of 7 TeV. The data were collected by the CMS detector at the LHC, and correspond to an integrated luminosity of 36 pb^{-1} . An excess of these events over standard model contributions is a signature of new physics such as large extra dimensions and unparticles. The number of observed events is in good agreement with the prediction of the standard model, and significant extension of the current limits on parameters of new physics benchmark models is achieved.

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^{*}See Appendix A for the list of collaboration members

This Letter describes a search for new physics in the missing transverse energy (E_T^{miss}) and jet final state using data collected with the Compact Muon Solenoid (CMS) experiment in pp collisions at a centre-of-mass energy of 7 TeV provided by the Large Hadron Collider (LHC). Events containing a single energetic jet (mono-jet) are selected, although a second less energetic jet is allowed. This event signature is predicted in models such as large extra dimensions, based on the scenario by Arkani-Hamed, Dimopoulos, and Dvali (ADD) [1–4], or unparticles [5]. The data used in this search were collected in 2010 and correspond to an integrated luminosity of 36 pb^{-1} . This study focuses on the search for direct production of a graviton G (or unparticle U) balanced by a hadronic jet via the processes $q\bar{q} \rightarrow gG$ (gU), $qg \rightarrow qG$ (qU) and $gg \rightarrow gG$ (gU). The primary backgrounds for this search are from Z+jet and W+jet production, and are estimated from the data.

The ADD model aims at explaining the large difference between the electroweak and Planck scales by introducing a number δ of extra spatial dimensions which in the simplest scenario are compactified over a torus of common radius R . The fundamental scale M_D is related to the effective four-dimensional Planck scale M_{Pl} according to the formula $M_{\text{Pl}}^2 \approx M_D^{\delta+2} R^\delta$. Gravitons are assumed to propagate in the extra dimensions with nonzero momentum. Graviton production is expected to be greatly enhanced due to the kinematically available phase space in the extra dimensions. Once produced, the gravitons are very weakly coupled and their presence can only be inferred from E_T^{miss} . Searches in both the jet plus E_T^{miss} and the γ plus E_T^{miss} channels were performed previously [6–11], without any evidence of new physics observed. The current lower limits on M_D range from $1.6 \text{ TeV}/c^2$ for $\delta = 2$ [6–9] to $0.95 \text{ TeV}/c^2$ for $\delta = 6$ [10].

More recently, interest in unparticle models has increased. These models relate to physics originating from a new scale-invariant (conformal) sector, which is coupled to the standard model (SM) through a connector sector at a high mass scale. An operator with a general non-integer scale dimension d_U in a conformal sector induces a spectrum of invisible, massless, and weakly interacting particles. If the mass scale Λ_U is assumed to be roughly $1 \text{ TeV}/c^2$, then by using an effective field theory below that scale one should be able to study the effects of unparticles at the LHC. While there have been no direct searches for unparticles, a recent interpretation of CDF results suggests lower limits on Λ_U between 2.11 and $9.19 \text{ TeV}/c^2$ for $1.05 < d_U < 1.35$ [12, 13].

The CMS apparatus has pixel and silicon-strip detectors for pseudorapidity of $|\eta| < 2.5$, where $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle relative to the beam direction. Contained in a 3.8 T magnetic solenoid, the tracking detectors provide momentum reconstruction down to about $100 \text{ MeV}/c$ with a resolution of about 1% at $100 \text{ GeV}/c$. A highly granular crystal electromagnetic calorimeter (ECAL) extends to $|\eta| < 3.0$, and has an energy resolution of better than 0.5% for photons with a transverse energy above 100 GeV . A hermetic hadronic calorimeter (HCAL) extends to $|\eta| < 5.0$ with a transverse hadronic energy resolution of about $100\%/\sqrt{E_T [\text{GeV}]} \oplus 5\%$. A muon detector system reconstructs and identifies muons to $|\eta| < 2.4$. A full description of the CMS detector can be found in Ref. [14].

Both ADD and unparticle signal events are generated with the PYTHIA 8.130 Monte Carlo generator [15, 16] with Tune 1 and passed through the CMS full simulation via the GEANT4 package [17]. The CTEQ 6.6M parton distribution functions (PDFs) [18] are used throughout. In order to scan the sensitivity in the relevant ADD parameter space, different samples with $M_D = 1, 2, 3 \text{ TeV}/c^2$ and $\delta = 2, 3, 4, 5, 6$ are produced. The models are effective theories and hold only for energies well below $M_D (\Lambda_U)$, we therefore follow the convention to suppress the simulated cross section of the graviton (unparticle) by a factor M_D^2/\hat{s} (Λ_U^2/\hat{s}) above M_D

(Λ_U) . A transverse momentum (p_T) cutoff on the parton recoiling against the graviton (unparticle) is introduced by requiring $\hat{p}_T > 50 \text{ GeV}/c$ at parton level, where \hat{p}_T is the transverse momentum of the outgoing parton (gluon or quark) from the initial hard scatter. In this analysis, unparticles are assumed sufficiently long-lived that they do not decay in the detector. The next-to-leading-order (NLO) QCD corrections to the direct graviton plus jet production in ADD are sizable and dependent on the p_T of the recoiling parton [19]. K factors ($\sigma_{\text{NLO}}/\sigma_{\text{LO}}$) are chosen for a graviton transverse momentum of several hundred GeV/c , corresponding to 1.5 for $\delta = 2, 3$ and 1.4 for $\delta = 4, 5, 6$. The background samples of vector boson plus jets and top quark pairs are produced with MADGRAPH [20] and simulated using PYTHIA (v6.420) [21] with tune D6T [22] for showering, based on a leading-order (LO) calculation of the matrix element with the shower matching prescription [23], and interfaced with TAUOLA [24]. The QCD multijet background sample is generated with MADGRAPH and also interfaced to PYTHIA with tune D6T for showering [21, 22].

Several jet and E_T^{miss} triggers are used for data collection, and all trigger paths are fully efficient for events with a value of $E_T^{\text{miss}} > 120 \text{ GeV}$ reconstructed offline. Events are required to have at least one primary vertex, where the vertex is reconstructed within a 24 cm window along the beam axis, has a transverse distance from the beam spot no more than 2 cm, and be of good quality [25]. Beam halo and other beam-induced background events are rejected by requiring at least 25% of the tracks in events with ten or more tracks to be well reconstructed [26].

Jets and E_T^{miss} are reconstructed using a particle flow technique [27]. The algorithm produces a unique list of particles in each event, using the combined information from all CMS subdetectors. This list is then used as input to the jet clustering, which reconstructs jets using the anti- k_T algorithm [28] with a distance parameter of 0.5. The missing transverse energy vector is computed as the negative vector sum of the transverse momenta of all particles reconstructed in the event, and has a magnitude denoted by E_T^{miss} .

Jet energies are corrected to establish a uniform calorimeter response in η and an absolute response in p_T calibrated at the particle level. Jet-energy-scale corrections are derived from Monte Carlo simulation (MC), and a residual correction is derived by measuring the p_T balance in di-jet events [29]. Jets are required to have $p_T > 30 \text{ GeV}/c$. To remove any artificial signals in the calorimeter, criteria based on energy sharing between neighbouring channels are applied [30]. Signals in HCAL or ECAL towers identified to be unphysical are removed from the reconstruction. Beam halo and cosmic muons are removed, but some of these events leave energy in both the ECAL and HCAL with no charged track associated with the energy cluster in the calorimeter. The fraction of jet energy carried by charged hadrons is therefore required to be above 15%. To reject high- p_T photons and electrons misidentified as hadronic jets, the energies assigned to neutral hadrons in the HCAL and neutral and charged hadrons in the ECAL must sum to less than 80% of the total jet energy. The combined effect of all data cleanup is to reject 1.5% of the events in the signal sample defined below.

In order to reduce the background from W-boson decays, events with isolated leptons are rejected. A separate W boson enriched sample is also created by requiring isolated leptons, and is used to estimate the size of the primary background. Lepton candidates (electron and muon) are required to have $p_T > 20 \text{ GeV}/c$, to originate within 2 mm of the beam axis in the transverse plane, and to be spatially separated from jets by at least $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.5$ in order to avoid rejecting events where there are leptons from jets. Here $\Delta\eta$ and $\Delta\phi$ are the pseudorapidity and azimuthal angle (in radians) differences, respectively. Muon candidates within $|\eta| < 2.1$ are reconstructed by requiring both that compatible tracks in the silicon tracking detectors are found, and that these signals are consistent with a global fit to both silicon

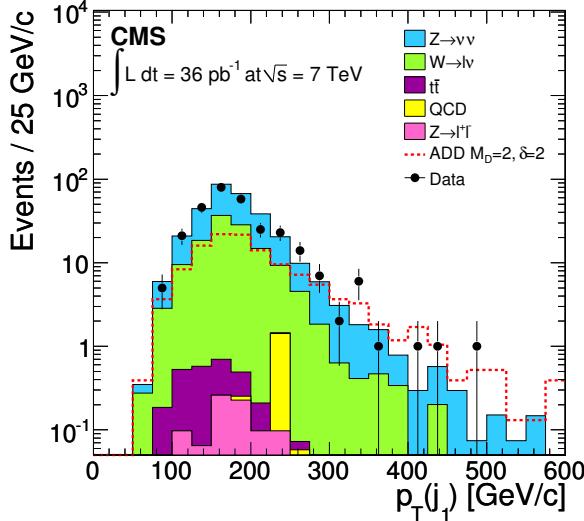


Figure 1: Distribution of $p_T(j_1)$, requiring $E_T^{\text{miss}} > 150 \text{ GeV}$, $N_{\text{jets}} \leq 2$, $|\eta(j_1)| < 2.4$, and $\Delta\phi(j_1, j_2) < 2$. A representative ADD signal (with $M_D = 2 \text{ TeV}/c^2$, $\delta = 2$) is shown as a dashed red line. The background is normalised to the measured rate in data.

tracker and muon detector hit locations [31]. Electron candidates are reconstructed starting from a cluster of energy deposits in the ECAL, which is then matched to hits in the silicon tracker. Electron candidates are required to have $|\eta| < 1.44$ or $1.56 < |\eta| < 2.5$ to avoid poorly-instrumented regions, and candidates with significant mismeasurement in the ECAL or consistent with a photon conversion are rejected [32]. For lepton candidates a cone of $\Delta R < 0.3$ is constructed around the track direction. An isolation parameter is defined as the scalar sum of the transverse momenta of tracks and transverse energies in the ECAL and HCAL in the cone, excluding the contribution from the muon (electron) candidate, divided by the muon p_T (electron E_T). Candidates with isolation values below 0.15 for muons or 0.09 (0.04) for electrons in the central (forward) regions are considered isolated.

The signal sample is selected by requiring $E_T^{\text{miss}} > 150 \text{ GeV}$, the most energetic jet (j_1) to have $p_T(j_1) > 110 \text{ GeV}/c$ and $|\eta(j_1)| < 2.4$. Events with more than two jets ($N_{\text{jets}} > 2$) with p_T above $30 \text{ GeV}/c$ are discarded. To increase the signal efficiency a second jet (j_2) is allowed provided that the angular separation with the highest- p_T jet satisfies $\Delta\phi(j_1, j_2) < 2.0$ radians, a selection that suppresses QCD dijet events. The $p_T(j_1)$ distribution of the signal sample is shown in Fig. 1. Remaining events with an isolated track are eliminated, as they come primarily from τ decays. A hollow cone $0.02 < \Delta R < 0.3$ is defined around each track with $p_T > 10 \text{ GeV}/c$. The scalar sum of the p_T of all tracks with $p_T > 1 \text{ GeV}/c$ inside the cone is calculated and the event is vetoed if this sum is smaller than 10% of the p_T of the original track.

The E_T^{miss} distribution from data and the expected backgrounds after all selection criteria are shown in Fig. 2, together with a distribution of the integrated number of E_T^{miss} events above a given threshold. The only significant remaining backgrounds after all requirements stem from electroweak processes with genuine missing transverse energy in the final state. Table 1 lists the number of events selected at each step of the analysis from data and simulation.

Rather than using the background estimates from MC shown in Table 1, the $Z + \text{jets}$ with $Z \rightarrow \nu\nu$ (denoted $Z(\nu\nu) + \text{jets}$) and $W + \text{jets}$ backgrounds are estimated from $\mu + \text{jet}$ events derived from the data sample. The selection defining this control sample has the same initial requirements as for the signal region, except that one or more muons are explicitly required. Well-reconstructed

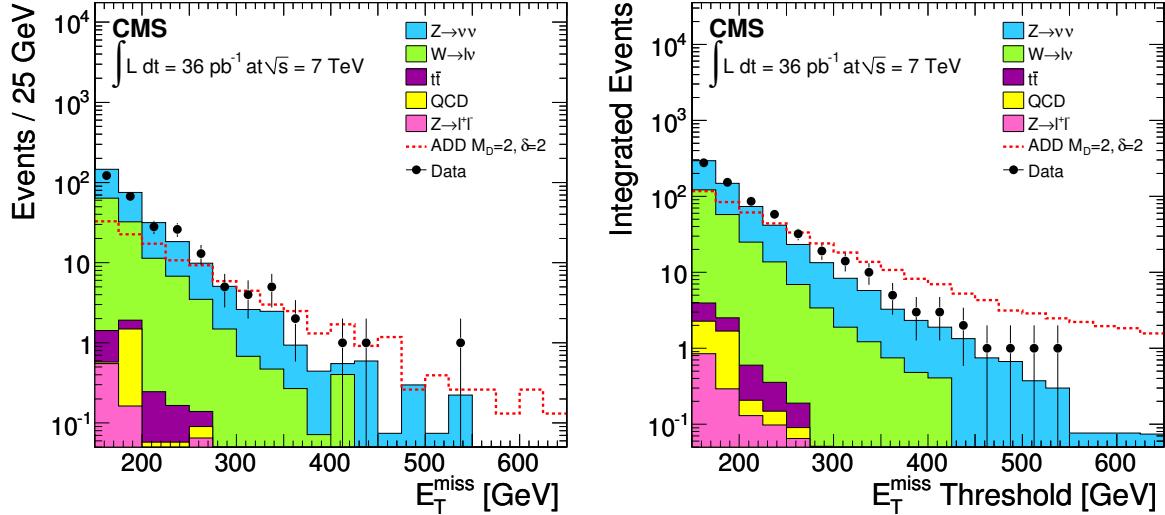


Figure 2: Missing transverse energy E_T^{miss} after all selection cuts for data, SM background, and an example of ADD signal ($M_D=2 \text{ TeV}/c^2$, $\delta=2$). The figure at right shows the integrated number of events above a given threshold. The background is normalised to the measured rate in data.

Table 1: Mono-jet data sample and analysis cuts, with luminosity-normalised leading-order MC. Lepton removal eliminates isolated muons or tracks for $p_T(e, \mu) > 10 \text{ GeV}/c$.

Requirement	W+jets	Z($\nu\nu$)+jets	Z($\ell\ell$)+jets	t <bar>t</bar>	QCD	Total MC	Data
$E_T^{\text{miss}} > 150 \text{ GeV}$, jet cleaning	622	259	46.7	90.4	202	1220	1298
$p_T(j_1) > 110 \text{ GeV}/c$, $ \eta(j_1) < 2.4$	583	245	43.4	76.9	201	1149	1193
$N_{\text{jets}} \leq 2$	446	201	34.3	11.3	74.3	767	778
$\Delta\phi(j_1, j_2) < 2$	370	182	29.5	9.1	6.3	597	596
Lepton Removal	107	173	0.8	1.7	1.4	284	275

and isolated muons are selected following the criteria outlined above. To ensure a pure W+jets sample, a single isolated muon is required to form, with the E_T^{miss} , a transverse mass M_T between 50 and 100 GeV/ c^2 . The transverse mass is defined as $M_T = \sqrt{2p_T E_T^{\text{miss}} (1 - \cos(\Delta\phi))}$, where $\Delta\phi$ is the angle in the transverse plane between the p_T the E_T^{miss} vectors. Within the M_T window there are 113 single-muon events in the data, compared to 103 estimated from MC (95.3 W+jets, 2.9 W($\tau\nu$)+jets, 2.4 Z+jets, 2.4 t \bar{t} , and 0.08 from QCD multijets). The shape and yield of the muon distributions observed in the data are consistent with the expectation from SM sources. We estimate the number of W+jets background events to be 117 ± 16 . This estimate is obtained by scaling the surviving W+jets MC events in the signal sample by the ratio of observed and predicted W+jets events in the muon sample.

To estimate the number of Z($\nu\nu$)+jets background events, the number of muon events in the M_T window is rescaled by several factors, including: (i) the ratio between the W($\mu\nu$)+jets and Z($\nu\nu$)+jets production cross sections, obtained by combining the branching fractions of the decays [33] (0.553 ± 0.021), (ii) the reciprocal of the kinematic and geometric acceptance of the simulated sample (2.40 ± 0.12), (iii) the efficiency of the lepton veto in the signal region taken from simulation (0.95 ± 0.02), (iv) the spectral shape differences in W+jets and Z+jets for $p_T(W, Z) > 150$ GeV/ c (1.33 ± 0.03), and (v) the correction for contributions other than W($\mu\nu$)+jets, extracted from LO MC (0.923 ± 0.071). All uncertainties include both statistical and systematic effects. The number of Z($\nu\nu$)+jets events in the signal region predicted from W+jets events is 176 ± 30 , which agrees with the MC. A crosscheck is made using two opposite-sign muons from Z($\nu\nu$)+jets, where the 13 events with an invariant mass consistent with that of a Z boson gives a prediction of 162 ± 45 background events. The estimated number of events from all background sources is 297 ± 45 . The uncertainty includes both statistical and systematic sources, with correlations taken into account.

The most important uncertainties related to theoretical signal modeling and experimental mis-measurement are (i) the jet energy scale, simulated by shifting the jet four-vectors by an η - and p_T -dependent factor related to the response, yielding a variation of 3–7% (7.5–11.5%) for the ADD (unparticle) signal efficiency [29], (ii) the jet energy resolution, estimated from a γ +jet sample and resulting in a 0.3–2.2% (0.6–2.9%) uncertainty on the ADD (unparticle) signal acceptance [34], (iii) uncertainties on the PDFs, evaluated using a reweighting technique with the CTEQ6M parameterisation [18] and resulting in a systematic uncertainty of 1–2% (3–7%) for the ADD (unparticle) signal, and (iv) a 4% uncertainty on the luminosity measurement [35]. The total systematic uncertainties range from 6% to 13%, with the jet energy scale uncertainty being the dominant one.

To interpret the consistency of the observed number of events with the background expectation in the context of a model, and also to facilitate comparison with previous results, we set exclusion limits for both the ADD model and the unparticle scenario. The upper limit on the number of non-SM events consistent with the measurements is set using a Bayesian method [33, 36] with a flat signal prior. A log-normal density function is assigned to the background estimate with the uncertainty derived from data. The total uncertainty incorporates the individual uncertainties on each background process and takes correlations into account.

Exclusion limits for the ADD model are given in Table 2 and significantly improve the previous limits for this model. For unparticles with spin = 0, production cross sections above 54 pb are excluded at 95% confidence level (CL) for $d_U = 1.7$ and $\Lambda_U = 1$ TeV/ c^2 . The limits for other d_U and Λ_U are comparable and are shown in Fig. 3; for $d_U = (1.35, 1.40, 1.45, 1.50, 1.60, 1.70)$, unparticles are excluded at 95% CL for $\Lambda_U < (18.9, 8.07, 4.57, 2.90, 1.62, 1.07)$ TeV/ c^2 , compared to the expected limits of $(13.4, 6.43, 3.75, 2.38, 1.46, 1.00)$ TeV/ c^2 . From the ADD model with

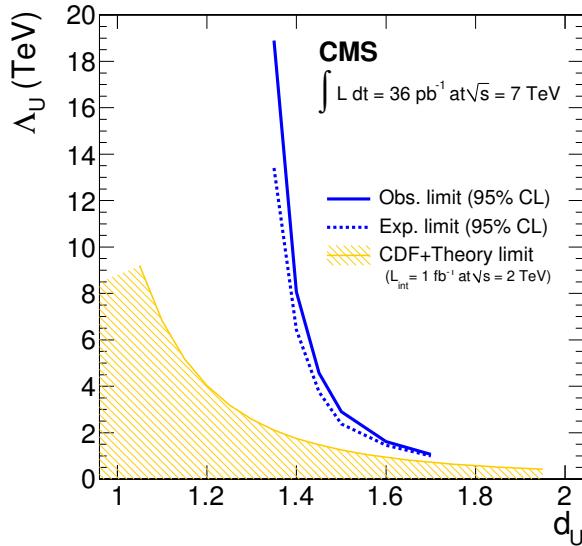


Figure 3: Observed and expected 95% CL lower limits on the allowed region of unparticle model parameters d_U and Λ_U , compared to those derived from CDF results [12, 13].

Table 2: Observed and expected 95% CL lower limits on the ADD model parameter M_D (in TeV/c^2) as functions of δ , with and without NLO K factors applied.

δ	K factor	LO Exp.	LO Obs.	NLO Exp.	NLO Obs.
2	1.5	2.17	2.29	2.41	2.56
3	1.5	1.82	1.92	1.99	2.07
4	1.4	1.67	1.74	1.78	1.86
5	1.4	1.59	1.65	1.68	1.74
6	1.4	1.54	1.59	1.62	1.68

$M_D = 3 \text{ TeV}/c^2$ and $\delta = 3$, which gives the largest signal acceptance of 9.9%, we evaluate a cross-section upper limit for our selection of 18.7 pb and exclude new processes at 95% CL above this value that result in mono-jet events.

In summary, a search is performed for signatures from the ADD and unparticle models in events collected by the CMS experiment from pp collisions at $\sqrt{s} = 7 \text{ TeV}$. A final state with an energetic jet and a significant amount of missing transverse energy is analyzed with the first CMS data, corresponding to an integrated luminosity of 36 pb^{-1} . The QCD multijet background is reduced by several orders of magnitude to a negligible level using topological cuts. A measurement of the electroweak background from $W(\mu\nu)$ -enriched data is used to derive a background estimate for the $W+\text{jets}$ and $Z(\nu\nu)+\text{jets}$ remaining in the signal region. The data are found to be in agreement with the expected contributions from SM processes. Limits on model parameters are derived and constitute a significant improvement of those set by previous experiments for ADD and unparticles.

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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. Hänsel, 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. Lemaitre, J. Liao, O. Militaru, C. Nuttens, S. Ovyn, D. Pagano, A. Pin, K. Piotrzkowski, N. Schul

Université de Mons, Mons, Belgium

N. Beliy, T. Caebergs, E. Daubie

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

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

W.L. Aldá Júnior, 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, V. Genchev¹, P. Iaydjiev¹, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov

University of Sofia, Sofia, Bulgaria

A. Dimitrov, R. Hadjiiska, A. Karadzhinova, V. Kozuharov, 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, 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

A. Awad, S. Khalil⁴, A. Radi⁵

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

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

Department of Physics, University of Helsinki, Helsinki, Finland

V. Azzolini, P. Eerola, G. Fedi

Helsinki Institute of Physics, Helsinki, Finland

S. Czellar, J. Hätkönen, 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. Karjalainen, A. Korppela, 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. Bluj⁶, C. Broutin, P. Busson, C. Charlot, T. Dahms, L. Dobrzynski, S. Elgammal, R. Granier de Cassagnac, M. Haguenauer, P. Miné, C. Mironov, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Thiebaux, B. Wyslouch⁷, A. Zabi

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

J.-L. Agram⁸, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte⁸, F. Drouhin⁸, C. Ferro, J.-C. Fontaine⁸, D. Gelé, U. Goerlach, S. Greder, P. Juillot, M. Karim⁸, A.-C. Le Bihan, Y. Mikami, P. Van Hove

Centre de Calcul de l’Institut National de Physique Nucléaire 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, S. Beranek, 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, E. Dietz-Laursonn, M. Erdmann, T. Hebbeker, A. Hinzmann, K. Hoepfner, T. Klimkovich, D. Klingebiel, P. Kreuzer, D. Lanske[†], J. Lingemann, 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, F. Hoehle, B. Kargoll, 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. Bergholz⁹, A. Bethani, K. Borras, 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. Katkov¹⁰, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann⁹, R. Mankel, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, J. Olzem, A. Petrukhin, D. Pitzl, A. Raspereza, A. Raval, M. Rosin, R. Schmidt⁹, T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, J. Tomaszevska, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany

C. Autermann, V. Blobel, S. Bobrovskyi, J. Draeger, H. Enderle, U. Gebbert, M. Görner,

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

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

C. Barth, J. Bauer, J. Berger, 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. Zhukov¹⁰, 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. Horvath¹¹, A. Kapusi, K. Krajczar¹², F. Sikler¹, G.I. Veres¹², G. Vesztregombi¹²

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. Singh, S.P. Singh

University of Delhi, Delhi, India

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

Saha Institute of Nuclear Physics, Kolkata, India

S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, R. Khurana, S. Sarkar

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. Guchait¹³, A. Gurtu, M. Maity¹⁴, D. Majumder, G. Majumder, K. Mazumdar, G.B. Mohanty, A. Saha, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HEGR, Mumbai, India

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

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

H. Arfaei, H. Bakhshiansohi¹⁵, S.M. Etesami, A. Fahim¹⁵, M. Hashemi, A. Jafari¹⁵, M. Khakzad,

A. Mohammadi¹⁶, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh, M. Zeinali¹⁷

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. Tupputi^{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. Navarria^{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,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}, 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. Colafranceschi¹⁸, F. Fabbri, D. Piccolo

INFN Sezione di Genova, Genova, Italy

P. Fabbricatore, 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,19}, A. De Cosa^{a,b}, F. Fabozzi^{a,19}, 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}, M. Biasotto^{a,20}, D. Bisello^{a,b}, A. Branca^a, R. Carlin^{a,b}, P. Checchia^a, T. Dorigo^a, F. Gasparini^{a,b}, A. Gozzelino, M. Gulmini^{a,20}, S. Lacaprara^{a,20}, I. Lazzizzera^{a,c}, M. Margoni^{a,b}, G. Maron^{a,20}, 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}, A. Triossi^a, 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. Biasinia^{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,21}, 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}, P. Meridiani, 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. Potenza^{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. Jo, H. Kim, J.H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park, 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, 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. Kofcheck, J. Tam

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. Górska, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, PortugalN. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, P. Musella, A. Nayak, J. Pela¹, P.Q. Ribeiro, J. Seixas, J. Varela**Joint Institute for Nuclear Research, Dubna, Russia**

S. Afanasiev, I. Belotelov, P. Bunin, I. Golutvin, V. Karjavin, G. Kozlov, A. Lanev, P. Moisenz, V. Palichik, V. Perelygin, M. Savina, 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, An. 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, RussiaV. 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. Dubinin²², L. Dudko, A. Ershov, A. Gribushin, O. Kodolova, I. Loktin, 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, RussiaI. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin¹, V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkine, V. Petrov, R. Ryutin, 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. Adzic²³, M. Djordjevic, D. Krpic²³, 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. Felcini²⁴, 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 Gomez²⁵, 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. Bell²⁶, D. Benedetti, C. Bernet³, W. Bialas, P. Bloch, A. Bocci, S. Bolognesi, M. Bona, H. Breuker, K. Bunkowski, T. Camporesi, G. Cerminara, T. Christiansen, 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. Rolandi²⁷, T. Rommerskirchen, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, I. Segoni, A. Sharma, P. Siegrist, M. Simon, P. Sphicas²⁸, M. Spiropulu²², M. Stoye, P. Tropea, A. Tsirou, 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. Sibille²⁹, A. Starodumov³⁰

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

L. Bäni, P. Bortignon, L. Caminada³¹, N. Chanon, Z. Chen, S. Cittolin, G. Dissertori, M. Dittmar, J. Eugster, K. Freudenreich, C. Grab, W. Hintz, P. Lecomte, W. Lustermann, C. Marchica³¹, P. Martinez Ruiz del Arbol, P. Milenovic³², F. Moortgat, C. Nägeli³¹, 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. Aguiro, 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, 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. Bakirci³³, S. Cerci³⁴, C. Dozen, I. Dumanoglu, E. Eskut, S. Gergis, G. Gokbulut, I. Hos, E.E. Kangal, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk³⁵, A. Polatoz, K. Sogut³⁶, D. Sunar Cerci³⁴, B. Tali³⁴, H. Topakli³³, D. Uzun, L.N. Vergili, M. Vergili

Middle East Technical University, Physics Department, Ankara, Turkey

I.V. Akin, T. Aliev, B. Bilin, 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. Gülmез, B. Isildak, M. Kaya³⁸, O. Kaya³⁸, M. Özbek, 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. Nikitenko³⁰, 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

The University of Alabama, Tuscaloosa, USA

C. Henderson

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, G. Breto, 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, 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, E. Sudano, M. Tadel, 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, L.A.T. Bauerick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, F. Borcherding, 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. Khatiwada, 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. 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. Hohlmann, H. Kalakhety, R. Ralich, I. Vodopiyanov

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, D.J. Hofman, S. Khalatyan, G.J. Kunde⁴⁶, F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, 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. Giurgiu, 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. Stephanos, F. Stöckli, K. Sumorok, K. Sung, E.A. Wenger, R. Wolf, 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. Dudero, G. Franzoni, J. Haupt, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, V. Rekovic, R. Rusack, M. Saserville, A. Singovsky, N. Tambe

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, J. Zennamo

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, A. Brinkerhoff, 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, M. De Mattia, A. Everett, A.F. Garfinkel, L. Gutay, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, C. Liu, V. Marousov, 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, 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, W. Sakumoto, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, USA

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulian, 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, 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, W. Flanagan, 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, T. Libeiro, 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, A. Hervé, P. Klabbers, 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 British University, Cairo, Egypt
- 5: Also at Ain Shams University, Cairo, Egypt
- 6: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland
- 7: Also at Massachusetts Institute of Technology, Cambridge, USA
- 8: Also at Université de Haute-Alsace, Mulhouse, France
- 9: Also at Brandenburg University of Technology, Cottbus, Germany
- 10: Also at Moscow State University, Moscow, Russia
- 11: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 12: Also at Eötvös Loránd University, Budapest, Hungary
- 13: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
- 14: Also at University of Visva-Bharati, Santiniketan, India
- 15: Also at Sharif University of Technology, Tehran, Iran
- 16: Also at Shiraz University, Shiraz, Iran
- 17: Also at Isfahan University of Technology, Isfahan, Iran
- 18: Also at Facoltà Ingegneria Università di Roma "La Sapienza", Roma, Italy
- 19: Also at Università della Basilicata, Potenza, Italy
- 20: Also at Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy
- 21: Also at Università degli studi di Siena, Siena, Italy
- 22: Also at California Institute of Technology, Pasadena, USA
- 23: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
- 24: Also at University of California, Los Angeles, Los Angeles, USA
- 25: Also at University of Florida, Gainesville, USA
- 26: Also at Université de Genève, Geneva, Switzerland
- 27: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
- 28: Also at University of Athens, Athens, Greece
- 29: Also at The University of Kansas, Lawrence, USA
- 30: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 31: Also at Paul Scherrer Institut, Villigen, Switzerland
- 32: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 33: Also at Gaziosmanpasa University, Tokat, Turkey
- 34: Also at Adiyaman University, Adiyaman, Turkey
- 35: Also at The University of Iowa, Iowa City, USA
- 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