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Search for three-jet resonances in pp collisions at $\sqrt{s} = 7$ TeV ☆

CMS Collaboration *

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ABSTRACT

Results are reported from a search for the production of three-jet resonances in pp collisions at a center-of-mass energy $\sqrt{s} = 7$ TeV. The study uses the data sample collected by the CMS experiment at the LHC in 2011, corresponding to an integrated luminosity of 5.0 fb^{-1}. Events with high jet multiplicity and a large scalar sum of jet transverse momenta are analyzed for the presence of resonances in the three-jet invariant mass spectrum. No evidence for a narrow resonance is found in the data, and limits are set on the cross section for gluino pair production in an R-parity-violating supersymmetry model, for gluino masses greater than 280 GeV. Assuming a branching fraction for gluino decay into three jets of 100%, gluino masses below 460 GeV are excluded at 95% confidence level. These results significantly extend the range of previous limits.

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Many extensions of the standard model (SM) predict the existence of new, strongly interacting particles that lead to final states with high jet multiplicities. Examples of such particles include gluinos in R-parity-violating (RPV) SUSY models [1,2], or more generally any colored fermion resonance that transforms as an octet under $SU(3)_C$ [3–6]. Despite large production cross sections predicted by many of these models, the vast majority of current experimental searches are insensitive to them because they use signal selection criteria based on low jet multiplicities, such as dijet resonances, or require the presence of large missing transverse energy. While this strategy has proved effective in establishing cross section limits for many models of physics beyond the SM up to TeV mass scales [7,8], the currently published limits for models predicting high jet multiplicity final states [9–11] are much less stringent. Specifically, there are only two published results from searches involving six-jet final states at hadron colliders, one from the Tevatron [12] and the other from the Large Hadron Collider (LHC) [13], which exclude RPV gluinos with masses below 144 GeV and between 200 and 280 GeV, respectively.

This Letter presents the results of a search for three-jet resonances in multijet events in proton–proton (pp) collisions at $\sqrt{s} = 7$ TeV. The event sample was collected using the Compact Muon Solenoid (CMS) detector [14] at the LHC. The integrated luminosity is 4.98 ± 0.11 fb^{-1} [15], corresponding to the CMS data sample recorded in 2011. In this extension of previous CMS results [13] using 35 pb^{-1} of data, events with at least six high-transverse-momentum (p_T) jets are investigated for evidence of three-jet resonances using the jet-ensemble technique [12,13].

The CMS detector is a multi-purpose apparatus described in detail in Ref. [14]. A high-resolution silicon pixel and strip tracker, immersed in the 3.8 T magnetic field of the superconducting solenoid, provides charged particle tracking coverage for $|\eta| < 2.5$, where $\eta = -\ln[\tan(\theta/2)]$ is the pseudorapidity, and θ is the polar angle measured with respect to the counterclockwise proton beam direction. Jet energy deposits are measured using electromagnetic (ECAL) and hadronic (HCAL) calorimeters. The finely-segmented lead-tungstate crystal ECAL consists of a barrel and two endcap regions. The ECAL barrel covers the pseudorapidity range $|\eta| < 1.4$ with a granularity of $\Delta\eta \times \Delta\phi = 0.0174 \times 0.0174$, where ϕ is the azimuthal angle, measured in radians, and the endcaps cover $1.4 < |\eta| < 3.0$. The HCAL extends out to an $|\eta|$ of about 5.0. Its central and endcap regions consist of brass/scintillator sampling calorimeters that cover $|\eta| < 3.0$ with a granularity of $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ for central rapidities. Further coverage is provided by a steel/quartz-fiber Cherenkov calorimeter. Muons are measured in gas detectors embedded in the steel return yoke outside the solenoid.

Events are recorded using a two-tiered trigger system [14]. Objects satisfying the requirements at the first level are passed to the high-level trigger (HLT) which further reduces the total recorded rate. Triggers based on the scalar sum of all transverse energy from jets (H_T), reconstructed using only calorimeter information, are used to select events. To reduce the effects of multiple pp interactions in the same bunch crossings (pileup), which produce

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

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a large number of low-p_T particles, jets considered in the HLT selection are required to have $p_T > 40$ GeV. The HLT threshold for H_T ranged from 350 to 750 GeV over the course of the 2011 data collection period, depending on the instantaneous luminosity.

A further set of criteria is imposed on events passing the trigger. Events are required to contain at least one well-reconstructed primary event vertex [16]. Jets are required to have $p_T > 70$ GeV and $|\eta| < 3.0$, which suppresses background and minimizes pileup effects. Events with pair-produced gluinos are expected to have high jet multiplicity and large values of H_T. We therefore require events to contain at least six jets, and to have a total scalar sum of jet p_T exceeding 900 GeV. The latter requirement ensures that the trigger is fully efficient for these events.

Individual objects reconstructed using the CMS particle-flow algorithm [17] serve as input for jet reconstruction. The particle-flow algorithm [17] combines calorimeter information with reconstructed tracks to identify individual particles such as photons, leptons, and both neutral and charged hadrons within jets. The energy of photons is obtained directly from the calibrated ECAL measurement. The determination of the energy of electrons comes from a combination of the track momentum at the main interaction vertex, the corresponding ECAL cluster energy, and the sum of all energy from bremsstrahlung photons associated to the track. The energy of muons is obtained from the corresponding track momentum. Charged hadron energy is determined from a combination of the track momentum and the corresponding ECAL and HCAL energies, corrected for hardware zero-suppression effects, and calibrated for the non-linear response of the HCAL. Finally, the energy of neutral hadrons is obtained from the corresponding calibrated ECAL and HCAL energies.

Jet reconstruction is performed using the anti-k_t algorithm [18] with a distance parameter of 0.5 in η–ϕ space. Jet energy scale corrections [19] derived from data and Monte Carlo (MC) simulation are applied to account for the non-linear and non-uniform response of the HCAL. A small residual correction factor is included to correct for differences in jet response between the detector and its simulation. The combined corrections are on the order of 5–10%, and their corresponding uncertainties range from 1 to 6%, depending on the jet pseudorapidity and p_T. Jet quality criteria [20] are applied to remove misidentified jets, which arise primarily from calorimeter noise. For both data and simulated signal events, more than 99.8% of all selected jets satisfy these criteria. After imposing all selection requirements, 114 599 events remain.

The benchmark signal model for the analysis features pair-produced gluinos, whose production and decay are simulated using the PYTHIA [21] v6.424 event simulation program with the CTEQ6L1 parton distribution function (PDF) set [22]. The gluino decay is modeled as an effective RPV coupling between the gluino and three light quarks, with a branching fraction of 100%. All superpartners except the gluino are decoupled, such that the mass of the squark is assumed to be much larger than that of the gluino [23]. The natural width of the gluino resonance is taken to be much smaller than the resolution of the detector, and no intermediate particles are produced in the gluino decay. The gluino mass is varied between 250 and 500 GeV in steps of 50 GeV, and additional mass points are generated at 750, 1000, 1250, and 1500 GeV. The leading-order (LO) cross section from PYTHIA is 92 pb for a gluino mass of 250 GeV and 2.1 pb for a gluino mass of 450 GeV, falling to about 1.3×10^{-5} pb for a gluino mass of 1500 GeV. Next-to-leading-order (NLO) correction factors (K-factors) are calculated using the PROSPINO [24] program and are applied to the LO cross sections. These values rise from 1.8 for a gluino mass of 250 GeV to 2.1 for a gluino mass of 450 GeV, and to 4.6 for a gluino mass of 1500 GeV, with corresponding uncertainties on the NLO cross sections of 15.1, 15.9, and 27.9%, respectively. Simulation of the CMS detector response is performed using GEANT4 [25].

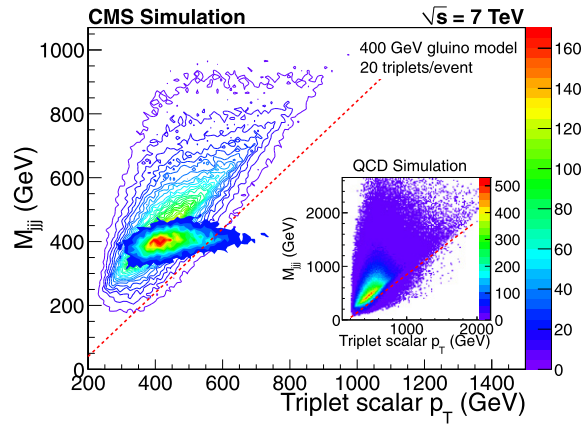

Fig. 1. Simulated triplet jet mass M_{jjj} versus the triplet scalar p_T of all 20 triplets for a gluino mass of 400 GeV, shown as a contoured distribution, with that of the triplets whose jets all originate from the same gluino parent overlaid. The overlaid "correct" triplets are shown to lie along a horizontal line corresponding to the generated gluino mass, while the behavior of all other triplets resembles the expectation for the QCD background, which is shown in the inset. All triplets falling to the right of the dashed line pass the requirement of Eq. (1) for a value of $\Delta = 160$ GeV.

The principal background arises from multijet events produced in strong interaction (QCD) processes. All other SM processes, such as fully-hadronic decays of top quark pairs, are predicted to make a negligible contribution. The QCD background arises primarily from events with two high-p_T jets from a hard interaction, combined with gluon jets from initial- or final-state radiation. We use the jet-ensemble technique to reconstruct the gluino candidates and to suppress background. The six highest-p_T jets in each event are combined in all possible three-jet combinations (triplets), resulting in 20 unique triplets per event. For signal events, at most two of the triplets correspond to a parent gluino, while the other triplets constitute a combinatorial background. Thus, background arises not only from QCD multijet events, but also from the signal events themselves. To improve sensitivity to the presence of a three-jet resonance, a requirement that exploits the observed linear correlation between the triplet mass and the scalar sum of the three jets' p_T values in background triplet combinations is imposed. We require

$$M_{jjj} < \sum_{i=1}^{3} p_T^i - \Delta, \tag{1}$$

where M_{jjj} is the triplet mass, $\sum_{i=1}^{3} p_T^i$ is the sum of the magnitudes of the transverse momenta of the jets within the triplet, and Δ is an offset adjusted to optimize signal sensitivity. Note that for signal triplets, M_{jjj} is fixed by the gluino mass and thus independent of its three jets' scalar p_T sum. Fig. 1 shows the simulated triplet mass versus the triplet scalar p_T for a gluino mass of 400 GeV. The value of Δ is determined by maximizing the ratio of the number of signal triplets to the sum of the number of signal and background triplets in a two-standard-deviation (σ) interval about the mean of a Gaussian function that describes the gluino mass peak. A common value $\Delta = 160$ GeV, which maximizes sensitivity to signal, is used for all gluino masses considered, and typically at most one triplet per event survives the requirement from Eq. (1). The fraction of signal triplets, whose jets all originate from the same parent gluino, that pass this requirement ranges from 2 to 13% depending on the gluino mass, while the efficiency to select all other triplet combinations in a signal event is below 1%.

After the final selection, residual background remains from both QCD multijet events and the combinatorial background triplets in possible gluino signal events. The latter contribute only minimally, and the shape of their mass distribution is found to be similar to that of the dominant QCD multijet background. We therefore consider the two background components together and parameterize their shape using the smoothly falling distribution [26] given by:

$$\frac{d\sigma}{dM_{jjj}} = \frac{P_0(1 - M_{jjj}/\sqrt{s})^{P_1}}{(M_{jjj}/\sqrt{s})^{P_2+P_3\ln(M_{jjj}/\sqrt{s})}}. \quad (2)$$

The parameters P_0, P_1, P_2, and P_3 have values of $(61.0 \pm 1.8) \times 10^3$ GeV^{-1}, 53.8 ± 0.7, -1.90 ± 0.04, and -0.13 ± 0.01, respectively, as determined by fitting this function to the data sample in the range from 260 to 1625 GeV using a χ^2 minimization technique. Thus, any potential signal would manifest itself as a localized positive deviation from the expectation of the background fit.

To estimate the number of signal events expected after all selection criteria are applied, the sum of a Gaussian function that represents the signal and the four-parameter function (Eq. (2)) that models the background are fitted to the simulated gluino M_{jjj} distribution, for $M_{jjj} > 260$ GeV. Below 260 GeV, the triplet mass distribution falls off rapidly due to restrictions imposed by the H_T threshold in the HLT. The width of the Gaussian function modeling the signal varies according to the detector resolution from 17 GeV for a gluino mass of 250 GeV, to 100 GeV for a gluino mass of 1500 GeV, as determined from simulation. The integral of the Gaussian component provides the estimate for the expected number of signal triplets reconstructed, and the value of this integral, divided by the number of signal events generated, determines the signal acceptance for each gluino mass. The signal acceptance per event includes all selection criteria and is parameterized with a second-order polynomial as a function of gluino mass. The event acceptance is 0.25% for a gluino of mass 250 GeV, 1.5% for a gluino of mass 450 GeV, and rises to 2.6% for a gluino of mass 1500 GeV.

The systematic uncertainty on the signal acceptance is evaluated as follows. The uncertainty related to the jet energy scale [19] is evaluated by varying the jet energy scale correction within its uncertainties, then recalculating the acceptance for different gluino mass values. The largest difference with respect to the nominal acceptance is taken as the systematic uncertainty and ranges from 9 to 18%. The difference between the calculated gluino acceptance at each mass point and the parameterized acceptance is taken as an uncertainty for each mass value and varies from 1 to 18%. The level of initial- and final-state radiation is varied following a prescription used in many other results [27], where the relative amount of each is separately increased and decreased with respect to the nominal value. The associated uncertainty is evaluated in a similar manner to that described for the jet energy scale uncertainties. The difference of 3 to 5% with respect to the nominal acceptance is taken as the systematic uncertainty. To determine the effect of pileup on the signal acceptance, the MC signal samples are reweighted such that the distribution of reconstructed primary vertices is shifted high and then low by one standard deviation compared to the nominal analysis (in the nominal analysis, the MC distribution is reweighted to correspond to the measured distribution). The acceptance procedure is repeated at both points and the largest difference with respect to the nominal acceptance is taken as the systematic uncertainty, which varies from 1 to 3%. The uncertainty corresponding to the choice of PDF set is evaluated by reweighting the events to correspond to each of its associated eigenvector sets and repeating the acceptance calculation. The difference, added in quadrature from all sets, is 4% and is taken as the systematic uncertainty. To estimate the uncertainty due to the choice of background parameterizations, alternate functions were fit to the data and compared

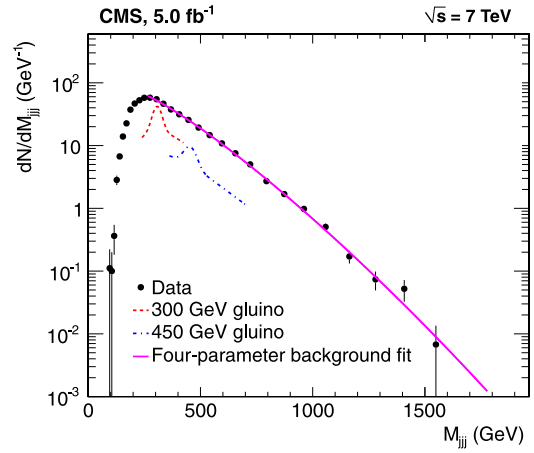

Fig. 2. Mass distribution for selected jet triplets. The four-parameter background fit is shown by the solid line. The NLO expectation for a 300 GeV gluino signal is shown by the dotted line, and that of a 450 GeV gluino signal by the dash-dotted line. Each of the two is normalized to the integrated luminosity of the data sample.

to the default fit. The results of each of these fits agree within statistical uncertainties, and the largest deviation from any of the alternate fits to the default fit is taken as the systematic uncertainty, ranging from 1.3% at a mass of 300 GeV to 2.9% at a mass of 500 GeV. These contributions, combined with those from the luminosity measurement (2.2%), yield a total systematic uncertainty on the signal acceptance between 14 and 26%, depending on the gluino mass.

The measured mass distribution for the selected jet triplets is shown in Fig. 2, where the four-parameter background fit is represented by the solid line. The expectation for a 300 GeV and a 450 GeV gluino signal are also included as a dotted and dash-dotted line, respectively, and each is normalized to the integrated luminosity of the data sample. We choose the width of bins to equal 10% of the mass value. This yields bin widths in general correspondence with the expected instrumental mass resolution.

To search for an excess in the number of triplets with respect to the expected background, we compute the difference between the measured number of triplets observed in each mass bin and the number of triplets predicted in this bin by the background fit. Fig. 3 shows this difference, normalized to the background prediction (Fig. 3a) and to the uncertainty in the background prediction (Fig. 3b). In both cases, the predicted background is in agreement with the data over the full mass range.

Because no excess of events is observed in the measured mass distribution, we proceed to place upper limits on the cross section times the branching fraction for the production of three-jet resonances in the data. Both observed and expected limits are calculated using a modified frequentest CL_s method with a one-sided profile likelihood test statistic [28]. The background model parameters and their corresponding uncertainties are taken from the fit of the four-parameter background function (Eq. (2)) to the data. The uncertainties on the parameters that describe the background shape are included as log-normal constraints, and they are 1.3% for P_1, 2.2% for P_2, 8.6% for P_3, with a normalization uncertainty on P_0 of 3%. The central value of each parameter is set to the best fit value and the width to one standard deviation. The range is truncated at $\pm 3\sigma$. In addition to the background parameters, log-normal constraints are included for the acceptance and integrated luminosity. These systematic uncertainties are treated as global constraints in the likelihood.

The observed and expected 95% confidence level (CL) upper limits on the gluino pair production cross section times branch-

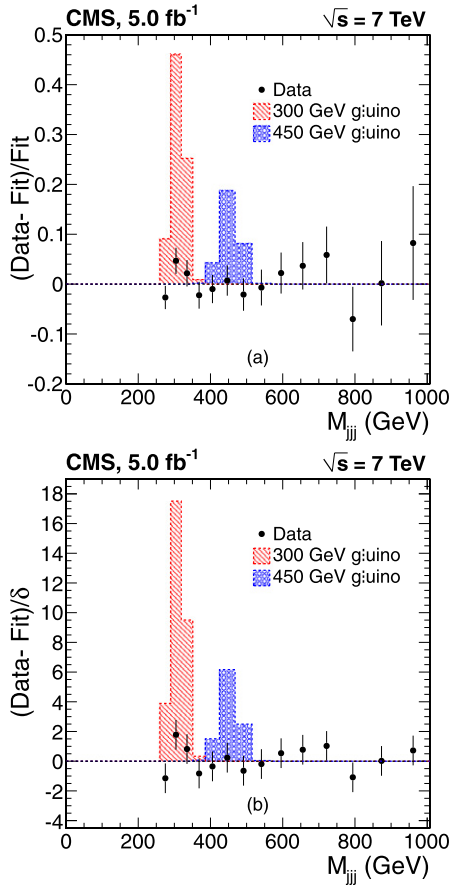

Fig. 3. Difference between the measured triplet mass distribution and the fitted background parametrization, divided by the fitted value (a) or by the statistical uncertainty δ on the fitted value (b), shown for both data and the NLO expectation of two gluino models, one with a gluino mass of 300 GeV and the other with a gluino mass of 450 GeV.

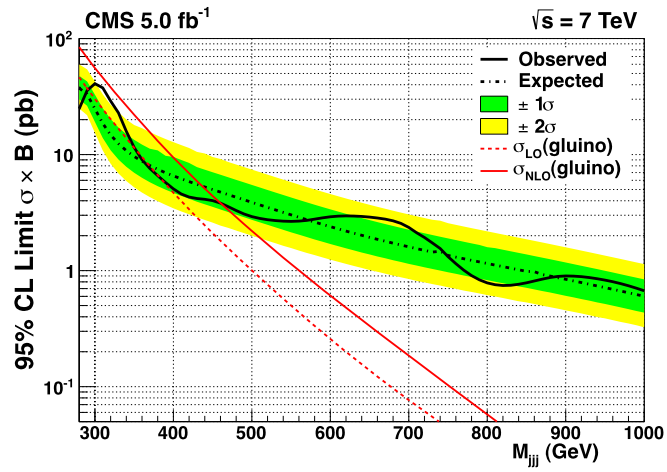

Fig. 4. Observed and expected 95% CL upper limits on the cross section times branching fraction for gluino pair production followed by RPV decay of each gluino to three light-flavored quark jets. Also shown are the $\pm 1\sigma$ and $\pm 2\sigma$ bands on the expected limit, as well as the theoretical LO and NLO cross sections for gluino production, assuming a branching fraction of a gluino decay into three jets of 100%.

ing fraction as a function of gluino mass are presented in Fig. 4. The corresponding 95% CL lower limit on the gluino mass is determined by finding the mass value at which the limit line crosses that of the NLO gluino cross section, assuming a branching fraction for the signal model of 100%. We perform the search in the region of M_{jjj} above 280 GeV and exclude masses below 460 GeV at 95% CL.

In summary, a search has been performed for three-jet resonance production in pp collisions at a center-of-mass energy of 7 TeV, using a data sample corresponding to an integrated luminosity of 5.0 fb^{-1}. Events having the properties of high jet multiplicity and large scalar sum of jet p_{T}, which are expected signatures of high-mass hadronic resonances, were analyzed for the presence of signal events, and no evidence for a narrow resonance was found. For a mass range above 280 GeV, the production of gluinos, modeled as an effective RPV coupling between the gluino and three light quarks with a branching fraction of 100%, has been excluded for masses below 460 GeV at 95% CL. These are the most stringent limits to date.

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CMS Collaboration

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

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, E. Aguilo, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan [1], M. Friedl, R. Frühwirth [1], V.M. Ghete, J. Hammer, N. Hörmann, J. Hrubec, M. Jeitler [1], W. Kiesenhofer, V. Knünz, M. Krammer [1], I. Krätschmer, D. Liko, I. Mikulec, M. Pernicka [†], B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz [1]

Institut für Hochenergiephysik der OeAW, Wien, Austria

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

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

S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, S. Luyckx, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, Z. Staykova, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, Belgium

B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, T. Hreus, A. Léonard, P.E. Marage, T. Reis, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang

Université Libre de Bruxelles, Bruxelles, Belgium

V. Adler, K. Beernaert, A. Cimmino, S. Costantini, G. Garcia, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. Mccartin, A.A. Ocampo Rios, D. Ryckbosch, N. Strobbe, F. Thyssen, M. Tytgat, P. Verwilligen, S. Walsh, E. Yazgan, N. Zaganidis

Ghent University, Ghent, Belgium

S. Basegmez, G. Bruno, R. Castello, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco [2], J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrzkowski, N. Schul, J.M. Vizan Garcia

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

N. Beliy, T. Caebergs, E. Daubie, G.H. Hammad

Université de Mons, Mons, Belgium

G.A. Alves, M. Correa Martins Junior, D. De Jesus Damiao, T. Martins, M.E. Pol, M.H.G. Souza

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, W. Carvalho, A. Custódio, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, D. Matos Figueiredo, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, L. Soares Jorge, A. Sznajder

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

T.S. Anjos [3], C.A. Bernardes [3], F.A. Dias [4], T.R. Fernandez Perez Tomei, E.M. Gregores [3], C. Lagana, F. Marinho, P.G. Mercadante [3], S.F. Novaes, Sandra S. Padula

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

V. Genchev [5], P. Iaydjiev [5], S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

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

University of Sofia, Sofia, Bulgaria

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

Institute of High Energy Physics, Beijing, China

C. Asawatangtrakuldee, Y. Ban, S. Guo, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, D. Wang, L. Zhang, B. Zhu, W. Zou

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

C. Avila, J.P. Gomez, B. Gomez Moreno, A.F. Osorio Oliveros, J.C. Sanabria

Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, R. Plestina [6], D. Polic, I. Puljak [5]

Technical University of Split, Split, Croatia

Z. Antunovic, M. Kovac

University of Split, Split, Croatia

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

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M. Finger, M. Finger Jr.

Charles University, Prague, Czech Republic

Y. Assran [7], S. Elgammal [8], A. Ellithi Kamel [9], S. Khalil [8], M.A. Mahmoud [10], A. Radi [11,12]

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

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

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, G. Fedi, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

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

Helsinki Institute of Physics, Helsinki, Finland

K. Banzuzi, A. Karjalainen, A. Korpela, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

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

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

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj [13], C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenauer, P. Miné, C. Mironov, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

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

J.-L. Agram [14], J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte [14], F. Drouhin [14], C. Ferro, J.-C. Fontaine [14], D. Gelé, U. Goerlach, P. Juillot, A.-C. Le Bihan, P. Van Hove

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

F. Fassi, D. Mercier

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

S. Beauceron, N. Beaupere, O. Bondu, G. Boudoul, J. Chasserat, R. Chierici [5], D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, Y. Tschudi, P. Verdier, S. Viret

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

Z. Tsamalaidze [15]

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

G. Anagnostou, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov [16]

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

M. Ata, J. Caudron, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, P. Kreuzer, C. Magass, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, M. Weber

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

M. Bontenackels, V. Cherepanov, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Nowack, L. Perchalla, O. Pooth, P. Sauerland, A. Stahl

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

M. Aldaya Martin, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz [17], A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, F. Costanza, D. Dammann, C. Diez Pardos, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann [17], B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, M. Rosin, J. Salfeld-Nebgen, R. Schmidt [17], T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

C. Autermann, V. Blobel, J. Draeger, H. Enderle, J. Erfle, U. Gebbert, M. Görner, T. Hermanns, R.S. Höing, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, F. Nowak, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, J. Thomsen, L. Vanelderen

University of Hamburg, Hamburg, Germany

C. Barth, J. Berger, C. Böser, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff [5], C. Hackstein, F. Hartmann, T. Hauth [5], M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, I. Katkov [16], J.R. Komaragiri, P. Lobelle Pardo, D. Martschei, S. Mueller, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, A. Oehler, J. Ott, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, S. Röcker, A. Scheurer, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

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

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

L. Gouskos, T.J. Mertzimekis, A. Panagiotou, N. Saoulidou

University of Athens, Athens, Greece

I. Evangelou, C. Foudas [5], P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras

University of Ioánnina, Ioánnina, Greece

G. Bencze, C. Hajdu [5], P. Hidas, D. Horvath [18], F. Sikler, V. Veszpremi, G. Vesztergombi [19]

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

N. Beni, S. Czellar, J. Molnar, J. Palinkas, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

University of Debrecen, Debrecen, Hungary

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

Panjab University, Chandigarh, India

Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, S. Malhotra, M. Naimuddin, K. Ranjan, V. Sharma, R.K. Shivpuri

University of Delhi, Delhi, India

S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, S. Sarkar, M. Sharan

Saha Institute of Nuclear Physics, Kolkata, India

A. Abdulsalam, R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, P. Mehta, A.K. Mohanty [5], L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Ganguly, M. Guchait [20], M. Maity [21], G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research – EHEP, Mumbai, India

S. Banerjee, S. Dugad

Tata Institute of Fundamental Research – HECR, Mumbai, India

H. Arfaei, H. Bakhshiansohi [22], S.M. Etesami [23], A. Fahim [22], M. Hashemi, H. Hesari, A. Jafari [22], M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh [24], M. Zeinali [23]

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

M. Abbrescia [a,b], L. Barbone [a,b], C. Calabria [a,b,5], S.S. Chhibra [a,b], A. Colaleo [a], D. Creanza [a,c], N. De Filippis [a,c,5], M. De Palma [a,b], L. Fiore [a], G. Iaselli [a,c], L. Lusito [a,b], G. Maggi [a,c], M. Maggi [a], B. Marangelli [a,b], S. My [a,c], S. Nuzzo [a,b], N. Pacifico [a,b], A. Pompili [a,b], G. Pugliese [a,c], G. Selvaggi [a,b], L. Silvestris [a], G. Singh [a,b], R. Venditti, G. Zito [a]

[a] *INFN Sezione di Bari, Bari, Italy*
[b] *Università di Bari, Bari, Italy*
[c] *Politecnico di Bari, Bari, Italy*

G. Abbiendi [a], A.C. Benvenuti [a], D. Bonacorsi [a,b], S. Braibant-Giacomelli [a,b], L. Brigliadori [a,b], 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,b,5], P. Giacomelli [a], C. Grandi [a], L. Guiducci [a,b], S. Marcellini [a], G. Masetti [a], M. Meneghelli [a,b,5], A. Montanari [a], F.L. Navarria [a,b], F. Odorici [a], A. Perrotta [a], F. Primavera [a,b], A.M. Rossi [a,b], T. Rovelli [a,b], G. Siroli [a,b], R. Travaglini [a,b]

[a] *INFN Sezione di Bologna, Bologna, Italy*
[b] *Università di Bologna, Bologna, Italy*

S. Albergo [a,b], G. Cappello [a,b], M. Chiorboli [a,b], S. Costa [a,b], R. Potenza [a,b], A. Tricomi [a,b], C. Tuve [a,b]

[a] *INFN Sezione di Catania, Catania, Italy*
[b] *Università di Catania, Catania, 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], M. Meschini [a], S. Paoletti [a], G. Sguazzoni [a], A. Tropiano [a,5]

[a] *INFN Sezione di Firenze, Firenze, Italy*
[b] *Università di Firenze, Firenze, Italy*

L. Benussi, S. Bianco, S. Colafranceschi [25], F. Fabbri, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

P. Fabbricatore [a], R. Musenich [a], S. Tosi [a,b]

[a] INFN Sezione di Genova, Genova, Italy
[b] Università di Genova, Genova, Italy

A. Benaglia [a,b,5], F. De Guio [a,b], L. Di Matteo [a,b,5], S. Fiorendi [a,b], S. Gennai [a,5], A. Ghezzi [a,b], S. Malvezzi [a], R.A. Manzoni [a,b], A. Martelli [a,b], A. Massironi [a,b,5], 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]

[a] INFN Sezione di Milano-Bicocca, Milano, Italy
[b] Università di Milano-Bicocca, Milano, Italy

S. Buontempo [a], C.A. Carrillo Montoya [a], N. Cavallo [a,26], A. De Cosa [a,b,5], O. Dogangun [a,b], F. Fabozzi [a,26], A.O.M. Iorio [a], L. Lista [a], S. Meola [a,27], M. Merola [a,b], P. Paolucci [a,5]

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

P. Azzi [a], N. Bacchetta [a,5], M. Bellato [a], D. Bisello [a,b], A. Branca [a,b,5], R. Carlin [a,b], P. Checchia [a], T. Dorigo [a], F. Gasparini [a,b], U. Gasparini [a,b], A. Gozzelino [a], K. Kanishchev [a,c], S. Lacaprara [a], I. Lazzizzera [a,c], M. Margoni [a,b], A.T. Meneguzzo [a,b], J. Pazzini [a,b], N. Pozzobon [a,b], P. Ronchese [a,b], F. Simonetto [a,b], E. Torassa [a], M. Tosi [a,b,5], S. Vanini [a,b], P. Zotto [a,b], G. Zumerle [a,b]

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

M. Gabusi [a,b], S.P. Ratti [a,b], C. Riccardi [a,b], P. Torre [a,b], P. Vitulo [a,b]

[a] INFN Sezione di Pavia, Pavia, Italy
[b] Università di Pavia, Pavia, Italy

M. Biasini [a,b], G.M. Bilei [a], L. Fanò [a,b], P. Lariccia [a,b], A. Lucaroni [a,b,5], G. Mantovani [a,b], M. Menichelli [a], A. Nappi [a,b], F. Romeo [a,b], A. Saha [a], A. Santocchia [a,b], A. Spiezia [a,b], S. Taroni [a,b,5]

[a] INFN Sezione di Perugia, Perugia, Italy
[b] Università di Perugia, Perugia, Italy

P. Azzurri [a,c], G. Bagliesi [a], T. Boccali [a], G. Broccolo [a,c], R. Castaldi [a], R.T. D'Agnolo [a,c], R. Dell'Orso [a], F. Fiori [a,b,5], L. Foà [a,c], A. Giassi [a], A. Kraan [a], F. Ligabue [a,c], T. Lomtadze [a], L. Martini [a,28], A. Messineo [a,b], F. Palla [a], A. Rizzi [a,b], A.T. Serban [a,29], P. Spagnolo [a], P. Squillacioti [a,5], R. Tenchini [a], G. Tonelli [a,b,5], A. Venturi [a,5], P.G. Verdini [a]

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

L. Barone [a,b], F. Cavallari [a], D. Del Re [a,b,5], M. Diemoz [a], C. Fanelli, M. Grassi [a,b,5], E. Longo [a,b], P. Meridiani [a,5], F. Micheli [a,b], S. Nourbakhsh [a,b], G. Organtini [a,b], R. Paramatti [a], S. Rahatlou [a,b], M. Sigamani [a], L. Soffi [a,b]

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

N. Amapane [a,b], R. Arcidiacono [a,c], S. Argiro [a,b], M. Arneodo [a,c], C. Biino [a], N. Cartiglia [a], M. Costa [a,b], D. Dattola [a], N. Demaria [a], C. Mariotti [a,5], S. Maselli [a], E. Migliore [a,b], V. Monaco [a,b], M. Musich [a,5], M.M. Obertino [a,c], N. Pastrone [a], M. Pelliccioni [a], A. Potenza [a,b], A. Romero [a,b], R. Sacchi [a,b], A. Solano [a,b], A. Staiano [a], A. Vilela Pereira [a]

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

S. Belforte [a], V. Candelise [a,b], F. Cossutti [a], G. Della Ricca [a,b], B. Gobbo [a], M. Marone [a,b,5], D. Montanino [a,b,5], A. Penzo [a], A. Schizzi [a,b]

[a] INFN Sezione di Trieste, Trieste, Italy
[b] Università di Trieste, Trieste, Italy

S.G. Heo, T.Y. Kim, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

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

Kyungpook National University, Daegu, Republic of Korea

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

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

S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park

Korea University, Seoul, Republic of Korea

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

University of Seoul, Seoul, Republic of Korea

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

Sungkyunkwan University, Suwon, Republic of Korea

M.J. Bilinskas, I. Grigelionis, M. Janulis, A. Juodagalvis

Vilnius University, Vilnius, Lithuania

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

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

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

H.A. Salazar Ibarguen

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

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

D. Krofcheck

University of Auckland, Auckland, New Zealand

A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

University of Canterbury, Christchurch, New Zealand

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

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

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

National Centre for Nuclear Research, Swierk, Poland

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

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

N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Seixas, J. Varela, P. Vischia

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

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

Joint Institute for Nuclear Research, Dubna, Russia

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

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

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

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, M. Erofeeva, V. Gavrilov, M. Kossov [5], N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

A. Belyaev, E. Boos, M. Dubinin [4], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, A. Popov, L. Sarycheva [†], V. Savrin, A. Snigirev

Moscow State University, Moscow, Russia

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

P.N. Lebedev Physical Institute, Moscow, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin [5], V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

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

P. Adzic [30], M. Djordjevic, M. Ekmedzic, D. Krpic [30], J. Milosevic

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

M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, 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, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

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

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

Universidad Autónoma de Madrid, Madrid, Spain

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J. Piedra Gomez

Universidad de Oviedo, Oviedo, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini [31], M. Fernandez, G. Gomez, J. Gonzalez Sanchez, A. Graziano, C. Jorda, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, J.F. Benitez, C. Bernet [6], G. Bianchi, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, D. D'Enterria, A. Dabrowski, A. De Roeck, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, K. Kousouris, P. Lecoq, Y.-J. Lee, P. Lenzi, C. Lourenço, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, P. Musella, E. Nesvold, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzi, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi [32], T. Rommerskirchen, C. Rovelli [33], M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas [*,34], D. Spiga, A. Tsirou, G.I. Veres [19], J.R. Vlimant, H.K. Wöhri, S.D. Worm [35], W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, 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. Sibille [36]

Paul Scherrer Institut, Villigen, Switzerland

L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, J. Eugster, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Lustermann, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli [37], P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov [38], B. Stieger, M. Takahashi, L. Tauscher [†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Tupputi, M. Verzetti

Universität Zürich, Zurich, Switzerland

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

National Central University, Chung-Li, Taiwan

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J.G. Shiu, Y.M. Tzeng, X. Wan, M. Wang

National Taiwan University (NTU), Taipei, Taiwan

A. Adiguzel, M.N. Bakirci [39], S. Cerci [40], C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, G. Karapinar [41], A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk [42], A. Polatoz, K. Sogut [43], D. Sunar Cerci [40], B. Tali [40], H. Topakli [39], L.N. Vergili, M. Vergili

Cukurova University, Adana, 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, M. Yalvac, E. Yildirim, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, B. Isildak [44], M. Kaya [45], O. Kaya [45], S. Ozkorucuklu [46], N. Sonmez [47]

Bogazici University, Istanbul, Turkey

K. Cankocak

Istanbul Technical University, Istanbul, Turkey

L. Levchuk

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

F. Bostock, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold [35], K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

University of Bristol, Bristol, United Kingdom

L. Basso [48], K.W. Bell, A. Belyaev [48], C. Brew, R.M. Brown, 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

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, G. Ball, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, 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, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko [38], A. Papageorgiou, J. Pela [5], M. Pesaresi, K. Petridis, M. Pioppi [49], D.M. Raymond, S. Rogerson, A. Rose, M.J. Ryan, C. Seez, P. Sharp [†], A. Sparrow, M. Stoye, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie

Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

K. Hatakeyama, H. Liu, T. Scarborough

Baylor University, Waco, USA

O. Charaf, C. Henderson, P. Rumerio

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, USA

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

Brown University, Providence, USA

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, J. Dolen, R. Erbacher, M. Gardner, R. Houtz, W. Ko, A. Kopecky, R. Lander, T. Miceli, D. Pellett,

F. Ricci-tam, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra

University of California, Davis, Davis, USA

V. Andreev, D. Cline, R. Cousins, J. Duris, S. Erhan, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein [†], P. Traczyk, V. Valuev, M. Weber

University of California, Los Angeles, Los Angeles, USA

J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng [50], H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, Riverside, Riverside, USA

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech [51], F. Würthwein, A. Yagil, J. Yoo

University of California, San Diego, La Jolla, 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, C. West

University of California, Santa Barbara, Santa Barbara, USA

A. Apresyan, A. Bornheim, Y. Chen, E. Di Marco, J. Duarte, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, M. Spiropulu [4], V. Timciuc, J. Veverka, R. Wilkinson, Y. Yang, R.Y. Zhu

California Institute of Technology, Pasadena, USA

B. Akgun, V. Azzolini, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, Y.F. Liu, M. Paulini, H. Vogel, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado at Boulder, Boulder, USA

J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, B. Heltsley, A. Khukhunaishvili, B. Kreis, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Tucker, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Cornell University, Ithaca, USA

D. Winn

Fairfield University, Fairfield, USA

S. Abdullin, M. Albrow, J. Anderson, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, D. Green, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Kilminster, B. Klima, S. Kunori, S. Kwan, C. Leonidopoulos, J. Linacre, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko [52], C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, D. Bourilkov, M. Chen, T. Cheng, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic [53], G. Mitselmakher, L. Muniz, R. Remington, A. Rinkevicius, P. Sellers, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

University of Florida, Gainesville, USA

V. Gaultney, S. Hewamanage, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida International University, Miami, 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, V. Veeraraghavan, M. Weinberg

Florida State University, Tallahassee, USA

M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, I. Vodopiyanov

Florida Institute of Technology, Melbourne, USA

M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, I. Bucinskaite, J. Callner, R. Cavanaugh, C. Dragoiu, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, D. Strom, N. Varelas

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

U. Akgun, E.A. Albayrak, B. Bilki [54], W. Clarida, F. Duru, S. Griffiths, J.-P. Merlo, H. Mermerkaya [55], A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, Y. Onel, F. Ozok, S. Sen, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

The University of Iowa, Iowa City, USA

B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, A. Whitbeck

Johns Hopkins University, Baltimore, USA

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

The University of Kansas, Lawrence, USA

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

Kansas State University, Manhattan, USA

J. Gronberg, D. Lange, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, M. Boutemeur, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn, T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, K. Pedro, A. Peterman, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

University of Maryland, College Park, USA

A. Apyan, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, Y. Kim, M. Klute, K. Krajczar [56], W. Li, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, E.A. Wenger, R. Wolf, B. Wyslouch, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

Massachusetts Institute of Technology, Cambridge, USA

S.I. Cooper, B. Dahmes, A. De Benedetti, G. Franzoni, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, R. Rusack, M. Sasseville, A. Singovsky, N. Tambe, J. Turkewitz

University of Minnesota, Minneapolis, USA

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

University of Mississippi, University, USA

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

University of Nebraska-Lincoln, Lincoln, USA

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

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, D. Nash, D. Trocino, D. Wood, J. Zhang

Northeastern University, Boston, USA

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

Northwestern University, Evanston, USA

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

University of Notre Dame, Notre Dame, USA

B. Bylsma, L.S. Durkin, C. Hill, R. Hughes, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, C. Vuosalo, G. Williams, B.L. Winer

The Ohio State University, Columbus, USA

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

Princeton University, Princeton, USA

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

University of Puerto Rico, Mayaguez, USA

E. Alagoz, V.E. Barnes, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, M. Vidal Marono, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University, West Lafayette, USA

S. Guragain, N. Parashar

Purdue University Calumet, Hammond, USA

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

Rice University, Houston, USA

B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, A. Garcia-Bellido,

P. Goldenzweig, J. Han, A. Harel, D.C. Miner, D. Vishnevskiy, M. Zielinski

University of Rochester, Rochester, USA

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, S. Malik, C. Mesropian

The Rockefeller University, New York, USA

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, A. Lath, S. Panwalkar, M. Park, R. Patel, V. Rekovic, J. Robles, K. Rose, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas

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

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

University of Tennessee, Knoxville, USA

R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon [57], V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, P.R. Dudero, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, Y. Roh, I. Volobouev

Texas Tech University, Lubbock, USA

E. Appelt, A.G. Delannoy, C. Florez, S. Greene, A. Gurrola, W. Johns, C. Johnston, P. Kurt, C. Maguire, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

Vanderbilt University, Nashville, USA

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

University of Virginia, Charlottesville, USA

S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

Wayne State University, Detroit, USA

M. Anderson, M. Bachtis, D. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, E. Friis, 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, I. Ojalvo, F. Palmonari, G.A. Pierro, I. Ross, A. Savin, W.H. Smith, J. Swanson

University of Wisconsin, Madison, USA

* Corresponding author.
† Deceased.
[1] Also at Vienna University of Technology, Vienna, Austria.
[2] Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.
[3] Also at Universidade Federal do ABC, Santo Andre, Brazil.
[4] Also at California Institute of Technology, Pasadena, USA.
[5] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[6] Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
[7] Also at Suez Canal University, Suez, Egypt.
[8] Also at Zewail City of Science and Technology, Zewail, Egypt.
[9] Also at Cairo University, Cairo, Egypt.
[10] Also at Fayoum University, El-Fayoum, Egypt.
[11] Also at British University, Cairo, Egypt.
[12] Now at Ain Shams University, Cairo, Egypt.
[13] Also at National Centre for Nuclear Research, Swierk, Poland.
[14] Also at Université de Haute-Alsace, Mulhouse, France.
[15] Now at Joint Institute for Nuclear Research, Dubna, Russia.
[16] Also at Moscow State University, Moscow, Russia.

[17] Also at Brandenburg University of Technology, Cottbus, Germany.
[18] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[19] Also at Eötvös Loránd University, Budapest, Hungary.
[20] Also at Tata Institute of Fundamental Research – HECR, Mumbai, India.
[21] Also at University of Visva-Bharati, Santiniketan, India.
[22] Also at Sharif University of Technology, Tehran, Iran.
[23] Also at Isfahan University of Technology, Isfahan, Iran.
[24] Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[25] Also at Facoltà Ingegneria Università di Roma, Roma, Italy.
[26] Also at Università della Basilicata, Potenza, Italy.
[27] Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
[28] Also at Università degli Studi di Siena, Siena, Italy.
[29] Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania.
[30] Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia.
[31] Also at University of California, Los Angeles, Los Angeles, USA.
[32] Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[33] Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy.
[34] Also at University of Athens, Athens, Greece.
[35] Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[36] Also at The University of Kansas, Lawrence, USA.
[37] Also at Paul Scherrer Institut, Villigen, Switzerland.
[38] Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[39] Also at Gaziosmanpasa University, Tokat, Turkey.
[40] Also at Adiyaman University, Adiyaman, Turkey.
[41] Also at Izmir Institute of Technology, Izmir, Turkey.
[42] Also at The University of Iowa, Iowa City, USA.
[43] Also at Mersin University, Mersin, Turkey.
[44] Also at Ozyegin University, Istanbul, Turkey.
[45] Also at Kafkas University, Kars, Turkey.
[46] Also at Suleyman Demirel University, Isparta, Turkey.
[47] Also at Ege University, Izmir, Turkey.
[48] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[49] Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy.
[50] Also at University of Sydney, Sydney, Australia.
[51] Also at Utah Valley University, Orem, USA.
[52] Also at Institute for Nuclear Research, Moscow, Russia.
[53] Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[54] Also at Argonne National Laboratory, Argonne, USA.
[55] Also at Erzincan University, Erzincan, Turkey.
[56] Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
[57] Also at Kyungpook National University, Daegu, Republic of Korea.