EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

FERMILAB-PUB-10-618-CMS

CERN-PH-EP/2010-054
2013/02/27

CMS-EXO-10-007

Search for Pair Production of Second-Generation Scalar Leptoquarks in pp Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration*

arXiv:1012.4033v1 [hep-ex] 17 Dec 2010

Abstract

A search for pair production of second-generation scalar leptoquarks in the final state with two muons and two jets is performed using proton-proton collision data at $\sqrt{s} =$ 7 TeV collected by the CMS detector at the LHC. The data sample used corresponds to an integrated luminosity of 34 pb^{-1}. The number of observed events is in good agreement with the predictions from the standard model processes. An upper limit is set on the second-generation leptoquark cross section times β^2 as a function of the leptoquark mass, and leptoquarks with masses below 394 GeV are excluded at a 95% confidence level for $\beta = 1$, where β is the leptoquark branching fraction into a muon and a quark. These limits are the most stringent to date.

Submitted to Physical Review Letters

*See Appendix A for the list of collaboration members

Several extensions of the standard model [1–5] predict the existence of leptoquarks (LQ), hypothetical particles that carry both lepton and baryon numbers and couple to both leptons and quarks. Leptoquarks are fractionally charged and can be either scalar or vector particles. In order to satisfy constraints from flavour-changing neutral currents and rare pion and kaon decays [6, 7], leptoquarks are restricted to couple to a single lepton-quark generation.

In proton-proton collisions at the CERN Large Hadron Collider (LHC) the dominant mechanisms for pair production of scalar leptoquarks are gluon-gluon fusion and $q\bar{q}$-annihilation. The cross section depends on the strong coupling constant and the LQ mass and has been calculated at Next-to-Leading-Order (NLO) [8]; the dependence on the Yukawa coupling λ is negligible [8]. Leptoquarks decay to a quark and a charged lepton of the same generation with unknown branching fraction β and to a quark and a neutrino with branching fraction $(1-\beta)$. In this analysis, we consider the decay of a second-generation leptoquark to a muon and a quark.

Several experiments have searched for leptoquarks, but so far no evidence has been observed. A review of LQ phenomenology and searches can be found in [9, 10]. The most recent limits from the DØ experiment at the Fermilab Tevatron collider exclude second-generation scalar leptoquarks with masses below 316 GeV for $\beta = 1$, based on proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV [11] .

This Letter describes a search for pair production of second-generation scalar leptoquarks with the CMS experiment using LHC proton-proton collisions at $\sqrt{s} = 7$ TeV. The data sample used corresponds to an integrated luminosity of $34.0 \pm 3.7\,\mathrm{pb}^{-1}$.

The CMS detector, described in detail elsewhere [12], uses a cylindrical coordinate system with the z axis along the counterclockwise beam direction The angles θ and ϕ are the polar and azimuthal angles, respectively. Pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$, where θ is measured with respect to the $+z$-axis. The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadron calorimeter (HCAL). Muons are measured in gas-ionization detectors embedded in the steel return yoke. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. The inner tracking system consists of a silicon pixel and strip tracker, providing the required granularity and precision for the reconstruction of vertices of charged particles having pseudorapidities $|\eta| < 2.5$. The ECAL and HCAL are used to measure the energies of photons, electrons, and hadrons within a region of $|\eta| < 3.0$. The three muon systems surrounding the solenoid cover a region $|\eta| < 2.4$ and are composed of drift tubes in the barrel region ($|\eta| < 1.2$), of cathode strip chambers in the endcaps ($0.9 < |\eta| < 2.4$), and of resistive plate chambers in both the barrel region and the endcaps ($|\eta| < 1.6$). Events are recorded based on a first-level trigger decision coming from either the calorimeter or muon systems. The final trigger decision is based on the information from all subsystems, which is passed on to the High Level Trigger (HLT), consisting of a farm of computers running a version of the reconstruction software optimized for fast processing. The signature of the decay of pair-produced second-generation leptoquarks studied here consists of two muons and two jets with high transverse momentum (p_T). Events are selected by a single muon trigger without isolation requirements and with lower p_T thresholds dependent upon the instantaneous luminosity. The HLT efficiency for events with two high p_T muons is always greater than 99%.

The Monte Carlo (MC) signal events are generated using the PYTHIA [13] generator (version 6.422) in the LQ mass range 250-600 GeV. The CTEQ6.6 [14] Parton Distribution Function (PDF) sets are used. The main background processes that can mimic the signature of the LQ signal

are $Z/\gamma^* +$ jets, $t\bar{t}$, VV (WW, ZZ, WZ), $W +$ jets, and multijet events. The $t\bar{t}$, VV, and muon-enriched multi-jets events are generated with MADGRAPH [15, 16]; $Z/\gamma^* +$ jets and $W +$ jets events are generated with ALPGEN. In MADGRAPH and ALPGEN samples, parton showering and hadronization is performed with PYTHIA.

Muons are reconstructed as tracks in the muon system that are matched to the tracks reconstructed in the inner tracking system. Muons are required to have $p_T > 30$ GeV, $|\eta| < 2.4$. The muon relative isolation paramter is defined as the scalar sum of the p_T of all tracks in the tracker and the transverse energies of hits in the ECAL and HCAL in a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the muon track, excluding the contribution from the muon itself, divided by the muon p_T. Muons are required to have a relative isolation parameter less than 0.05. $\Delta\eta$ and $\Delta\phi$ are the pseudorapidity and azimuthal angle differences between the muon track and other reconstructed tracks or hits in the calorimeter. To have a precise measurement of the transverse impact parameter of the muon relative to the beam-spot position, only muons with tracks containing more than 10 hits in the silicon tracker are considered. To reject muons from cosmic rays, the transverse impact parameter is required to be less than 2 mm. In addition, the two muon candidates are required to be separated from each other by at least $\Delta R = 0.3$ and at least one muon must be in the pseudorapidity region $|\eta| < 2.1$. The efficiency of selecting dimuon events is 61-70% for the LQ mass range of 200-500 GeV.

Jets are reconstructed using the anti-k_T [17] algorithm with a distance parameter $R = 0.5$ and are required to have $p_T > 30$ GeV and $|\eta| < 3.0$. Jet-energy-scale corrections derived from MC simulated events are applied to establish a relative uniform response in η and an absolute uniform response in p_T. A residual jet energy correction is derived from data by looking at the balance in p_T in dijet events, and it is applied to jets in data.

Additional selection requirements are placed on two variables, which are effective at discriminating the LQ signal from the major sources of background. The first is the dimuon invariant mass, $M_{\mu\mu}$. The second variable, S_T, is defined as the sum of the magnitudes of the p_T of the two highest p_T muons and the two highest p_T jets. The two muons in the signal events come from the decays of two high-mass particles, and they tend to form a large invariant mass. Thus, events are selected if $M_{\mu\mu} > 115$ GeV. This helps to reduce the contribution from $Z/\gamma^* +$ jets processes, which is one of the largest backgrounds. In addition, the LQ pair is expected to have a large S_T. The lower threshold on S_T is optimized for different LQ mass hypotheses by using a Bayesian approach [18, 19] to minimize the expected upper limit on the LQ cross section in the absence of an observed signal. The S_T cut helps to further reduce background sources, most noticeably $t\bar{t}$. The optimal S_T threshold values for each mass hypothesis are given in Table 1. While the LQ signal is expected to peak in the mass distribution of the μ-jet pairs, we find that the S_T variable gives sufficient power of discrimination in the range of LQ masses considered. The μ-jet mass distribution would nevertheless be important to establish the signal in case an excess is observed.

The contribution from $t\bar{t}$ is estimated with the MC sample, using uncertainties determined from data [20]. The contribution from $W +$ jets is negligible once the full event selection is applied. The small contribution from VV is estimated from MC. The multijet background is found to be negligible using a control data sample of same-sign dimuon events. The background from $Z/\gamma^* +$ jets is determined by comparing $Z/\gamma^* +$ jets events from data and MC samples in two different regions: at the Z boson peak, $80 < M_{\mu\mu} < 100$ GeV, and in the high-mass region, $M_{\mu\mu} > 115$ GeV. In the low-mass region, the ratio of data to MC events (R_L) is determined to be $R_L = 1.28 \pm 0.14$ after selecting two muons and two jets with $p_T > 30$ GeV, and a preliminary requirement of $S_T >$250 GeV. This rescaling factor is applied to the number of $Z/\gamma^* +$ jets MC

events in the high-mass region after the full selection.

Reasonable agreement between data and MC predictions is observed at all selection levels. The dimuon invariant mass is shown in Fig. 1 (left) after the initial selection of muons and jets with $p_T > 30$ GeV and a preliminary requirement of $S_T > 250$ GeV. The $M_{\mu\mu}$ distribution in data is consistent with the expected SM background prediction. The S_T distribution is also shown in Fig. 1 (right) after the initial selection of muons and jets with $p_T > 30$ GeV and the additional requirement of $M_{\mu\mu} > 115$ GeV.

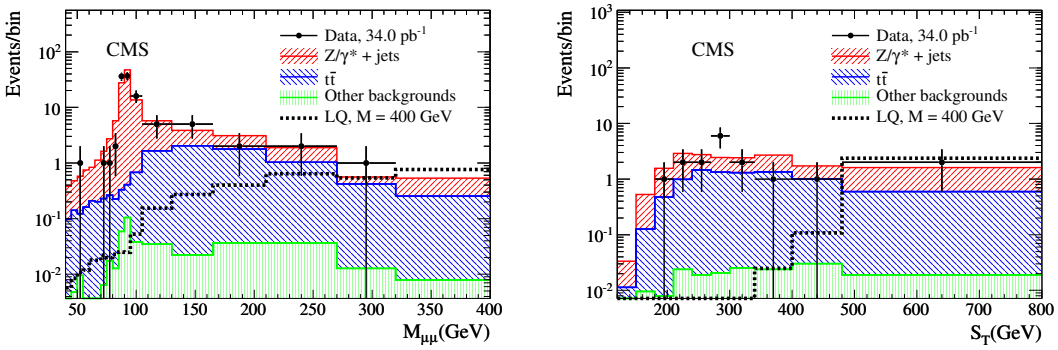

Figure 1: The distribution of $M_{\mu\mu}$ (left) after requiring at least two muons and at least two jets with $p_T > 30$ GeV and $S_T > 250$ GeV, and the distribution of S_T (right) after requiring at least two muons and at least two jets with $p_T > 30$ GeV and $M_{\mu\mu} > 115$ GeV. The $Z/\gamma^* \to \mu\mu +$ jets contribution is rescaled by the factor $R_L = 1.28$. Other backgrounds correspond to VV, W + jets, and multijet processes. Uncertainties are statistical.

The event yields from data, expected LQ signal (for several mass hypotheses), signal selection efficiency times acceptance, and expected standard model backgrounds are summarized in Table 1.

Table 1: The data event yields in 34.0 pb^{-1} for different leptoquark mass hypotheses, together with the optimized S_T threshold values (in GeV) for each mass, background predictions, number of expected LQ signal events (S), and signal selection efficiency times acceptance (ϵ_S). M_{LQ} and S_T values are listed in GeV. The $Z/\gamma^* \to \mu\mu +$ jets contribution is rescaled by the factor $R_L = 1.28$. Other backgrounds correspond to VV, W + jets, and multijet processes. Uncertainties are statistical.

M_{LQ} (S_T Cut) [GeV]	MC Signal Samples Selected Events	Acceptance × Efficiency	Monte Carlo Background Samples Selected Events in $t\bar{t}$ + jets	Z/γ^* + jets	Others	All	Events in Data	Obs./Exp. 95% C.L. u.l. on σ [pb]
200 ($S_T > 310$)	160±20	0.388±0.003	3.9±0.1	4.08±0.07	0.1±0.01	8.1±0.1	5	0.661/0.444
225 ($S_T > 350$)	89±9	0.421±0.003	2.7±0.1	2.99±0.05	0.07±0.01	5.8±0.1	3	0.525/0.342
250 ($S_T > 400$)	51±5	0.437±0.003	1.6±0.08	1.92±0.04	0.051±0.009	3.57±0.09	3	0.422/0.370
280 ($S_T > 440$)	28±3	0.467±0.003	0.98±0.06	1.53±0.03	0.038±0.008	2.55±0.07	3	0.352/0.375
300 ($S_T > 440$)	21±2	0.518±0.004	0.98±0.06	1.53±0.03	0.038±0.008	2.55±0.07	3	0.318/0.339
320 ($S_T > 490$)	14±1	0.509±0.004	0.55±0.04	1.12±0.02	0.019±0.005	1.69±0.05	2	0.287/0.302
340 ($S_T > 530$)	9±1	0.508±0.003	0.34±0.04	0.79±0.01	0.01±0.004	1.14±0.04	1	0.261/0.246
400 ($S_T > 560$)	4.0±0.4	0.578±0.004	0.27±0.03	0.67±0.01	0.01±0.004	0.95±0.03	0	0.220/0.219
450 ($S_T > 620$)	1.9±0.2	0.600±0.004	0.16±0.03	0.49±0.01	0.006±0.003	0.66±0.03	0	0.198/0.153
500 ($S_T > 700$)	0.9±0.1	0.602±0.004	0.08±0.02	0.277±0.006	0.003±0.002	0.36±0.02	0	0.179/0.152

Several sources of systematic uncertainties are considered in this analysis. The uncertainty on the integrated luminosity is taken as 11% [21]. A 5% systematic uncertainty is assigned to the

jet-energy-scale (JES) [22] of each jet. A smaller, $\sim 1\%$ systematic uncertainty comes from the muon momentum scale. The 300 GeV LQ signal efficiency changes by 2% and 1% due to JES and muon momentum scale uncertainties, respectively. The effect of the muon momentum scale uncertainty on the total background is estimated to be $< 0.5\%$. The JES contributes 2% to the estimate of the $Z/\gamma^* +$jets background described above and 15% to the estimate of the VV background from MC. The statistical uncertainty on the value of R_L after a preselection requirement ($S_T > 250$ GeV), 11%, is used as an uncertainty on the estimated $Z/\gamma^* +$jets background. A 41% systematic uncertainty is taken from the CMS measurement of the $t\bar{t}$ production cross section [20] and assigned to the estimate of the $t\bar{t}$ background; it includes the effect of JES on the estimate of the $t\bar{t}$ background. The effect of jet energy and muon momentum resolution on expected signal and backgrounds is found to be negligible. A 5% systematic uncertainty per muon is assigned due to differences in reconstruction, identification, trigger, and isolation efficiencies between data and MC [23], resulting in a 10% uncertainty on the efficiency of selecting events with two muons both for the signal and background processes. A theoretical uncertainty on the LQ signal production cross sections due to the choice of renormalization/factorization scales has been calculated by varying the scales between half and twice the LQ mass, and is found to 14-15% for LQ masses between 200 and 500 GeV. The 90% C.L. PDF uncertainties on LQ cross section have been obtained using the CTEQ6.6 [14] PDF error set following a standard prescription and have been found to vary from 8 to 22 % for leptoquarks in the mass range of 200 - 500 GeV [8]. The effect of PDF uncertainties is less than 0.5% on signal acceptance. The PDF uncertainties are not considered for background sources with uncertainties determined from data. The systematic uncertainties, their magnitude, and the relative impact on the number of signal and background events are summarized in Table 2.

Table 2: Systematic uncertainties and their effects on number of signal and background events

Systematic Uncertainty	Magnitude	Effect on Signal	Effect on Background
JES	5%	2%	–
JES & Data Backgr. Est.	–	–	25%
Muon Momentum Scale	1%	1%	$< 0.5\%$
Muon Pair Reco/ID/Iso	10%	10%	$< 0.05\%$
Integrated Luminosity	11%	11%	–
Total		15%	25%

One candidate event survives the full selection criteria corresponding to a leptoquark mass hypothesis of 340 GeV, and no candidates survive for criteria corresponding to masses greater than 450 GeV. An upper limit on the LQ cross section is set using a Bayesian method [18, 19] with a flat signal prior. A log-normal probability density function is used to integrate over the systematic uncertainties. Using Poisson statistics, a 95% confidence level (C.L.) upper limit is obtained on $\sigma \times \beta^2$. This is shown in Fig. 2 together with the NLO predictions for the scalar LQ pair production cross section. The 95% C.L. exclusion on β as a function of LQ mass is also shown in Fig. 2. The systematic uncertainties reported in Table 2 are included in the calculation as nuisance parameters. With the assumption that $\beta = 1$, second-generation scalar leptoquarks with masses less than 394 GeV are excluded at 95% C.L., 78 GeV higher than the limit set at the DØ Experiment at the Tevatron [11]. This is in agreement with the expected limit of 394 GeV. The corresponding observed limit on cross section is 0.223 pb. If the lower edge of the theoretical $\sigma \times \beta^2$ curve is used, the observed (expected) limit on LQ mass is 380 (378) GeV and

the observed limit on cross section is 0.225 pb.

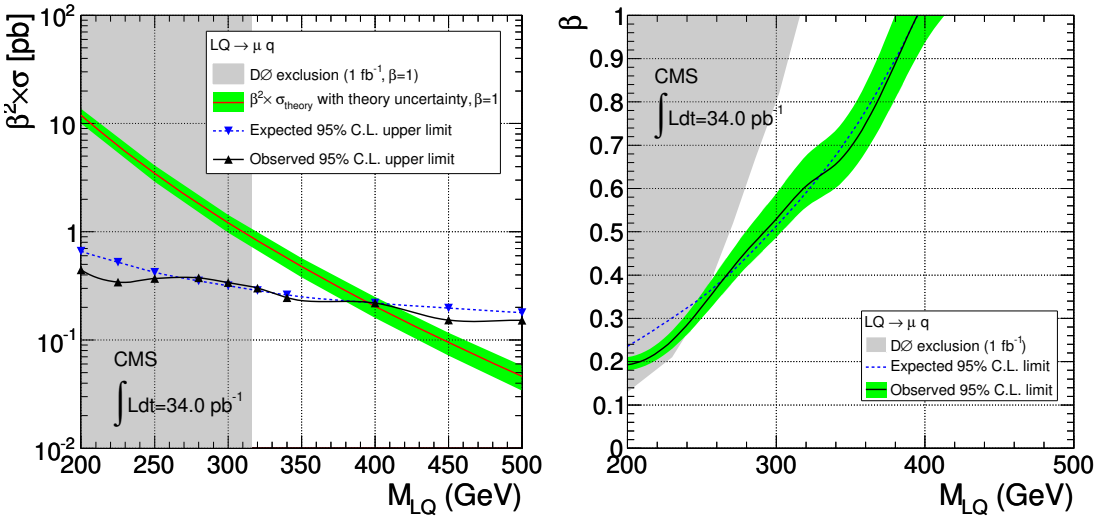

Figure 2: (Left) The expected and observed 95% C.L. upper limit on the scalar leptoquark pair production cross section multiplied by β^2 as a function of the LQ mass, together with the NLO theoretical cross section curve. The shaded band on the theoretical values includes CTEQ6.6 PDF uncertainties and the error on the leptoquark production cross section due to renormalization and factorization scale variation by a factor of two. The shaded region is excluded by the current DØ limits [11]. (Right) The minimum β for 95% C.L. exclusion of the leptoquark hypothesis as a function of leptoquark mass. The observed limit and corresponding uncertainty band is obtained by considering the observed upper limit and theoretical branching ratio and its uncertainty in the left-hand figure. Note: The shaded area excluded by the DØ experiment was determined with combined information from the decay channel with two muons and two jets and the decay channel with one muon, missing transverse energy, and two jets.

In summary, a search for pair production of second-generation scalar leptoquarks decaying to two muons and two jets has been performed using 7 TeV pp collision data corresponding to an integrated luminosity of 34.0 pb^{-1}. The number of observed candidate events agrees well with the number of expected standard model background events. A Bayesian approach that includes the treatment of systematic uncertainties as nuisance parameters is used to set limits on the LQ cross section times β^2 as a function of LQ mass. At 95% C.L., the pair production of second-generation scalar leptoquarks with masses below 394 GeV is excluded for $\beta = 1$, where β is the leptoquark branching fraction into a muon and a quark. This is the most stringent limit to date on the existence of second-generation scalar leptoquarks.

We extend our thanks to Michael Krämer for providing the tools for calculation of the leptoquark theoretical cross section and PDF uncertainty. We wish to congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from: FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); Academy of Sciences and NICPB (Estonia); Academy of Finland, ME, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); PAEC (Pakistan); SCSR (Poland); FCT (Portu-

gal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MST and MAE (Russia); MSTD (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA).

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
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. Hammer[1], S. Hänsel, C. Hartl, M. Hoch, N. Hörmann, J. Hrubec, M. Jeitler, G. Kasieczka, W. Kiesenhofer, M. Krammer, D. Liko, I. Mikulec, M. Pernicka, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, F. Teischinger, 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
L. Benucci, L. Ceard, K. Cerny, E.A. De Wolf, X. Janssen, 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
V. Adler, S. Beauceron, F. Blekman, S. Blyweert, J. D'Hondt, O. Devroede, R. Gonzalez Suarez, A. Kalogeropoulos, J. Maes, M. Maes, S. Tavernier, 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, J. Wickens

Ghent University, Ghent, Belgium
S. Costantini, M. Grunewald, B. Klein, 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, J. De Favereau De Jeneret, C. Delaere, P. Demin, D. Favart, A. Giammanco, G. Grégoire, J. Hollar, V. Lemaitre, J. Liao, O. Militaru, S. Ovyn, D. Pagano, A. Pin, K. Piotrzkowski, L. Quertenmont, 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, D. De Jesus Damiao, M.E. Pol, M.H.G. Souza

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W. Carvalho, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, F. Torres Da Silva De Araujo

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil
F.A. Dias, M.A.F. Dias, T.R. Fernandez Perez Tomei, E. M. Gregores[2], F. Marinho, S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
N. Darmenov[1], L. Dimitrov, V. Genchev[1], P. Iaydjiev[1], S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, I. Vankov

University of Sofia, Sofia, Bulgaria
M. Dyulendarova, R. Hadjiiska, V. Kozhuharov, L. Litov, E. Marinova, 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, J. Wang, J. Wang, X. Wang, Z. Wang, M. Xu, M. Yang, J. Zang, Z. Zhang

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China
Y. Ban, S. Guo, W. Li, Y. Mao, S.J. Qian, H. Teng, B. Zhu

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. Plestina[3], 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, H. Rykaczewski

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran[4], M.A. Mahmoud[5]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
A. Hektor, M. Kadastik, K. Kannike, M. Müntel, M. Raidal, L. Rebane

Department of Physics, University of Helsinki, Helsinki, Finland
V. Azzolini, P. Eerola

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

Lappeenranta University of Technology, Lappeenranta, Finland
K. Banzuzi, A. Korpela, T. Tuuva

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

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, 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. Bianchini, M. Bluj[6], C. Broutin, P. Busson, C. Charlot, T. Dahms, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenauer, P. Miné, C. Mironov, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Thiebaux, B. Wyslouch[7], A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram[8], J. Andrea, A. Besson, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte[8], F. Drouhin[8], C. Ferro, J.-C. Fontaine[8], D. Gelé, U. Goerlach, S. Greder, P. Juillot, M. Karim[8], A.-C. Le Bihan, Y. Mikami, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France
F. Fassi, D. Mercier

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
C. Baty, N. Beaupere, M. Bedjidian, O. Bondu, G. Boudoul, D. Boumediene, H. Brun, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, A. Falkiewicz, 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, H. Xiao

E. Andronikashvili Institute of Physics, Academy of Science, Tbilisi, Georgia
V. Roinishvili

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

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
M. Ata, W. Bender, M. Erdmann, J. Frangenheim, T. Hebbeker, A. Hinzmann, K. Hoepfner, C. Hof, T. Klimkovich, D. Klingebiel, P. Kreuzer, D. Lanske†, C. Magass, G. Masetti, M. Merschmeyer, A. Meyer, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier

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

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, W. Behrenhoff, U. Behrens, M. Bergholz[9], K. Borras, A. Cakir, A. Campbell, E. Castro, D. Dammann, G. Eckerlin, D. Eckstein, A. Flossdorf, G. Flucke, A. Geiser, I. Glushkov, J. Hauk, H. Jung, M. Kasemann, I. Katkov, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann[9], R. Mankel, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, J. Olzem, A. Parenti, A. Raspereza, A. Raval, R. Schmidt[9], T. Schoerner-Sadenius, N. Sen, M. Stein, J. Tomaszewska, D. Volyanskyy, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany
C. Autermann, S. Bobrovskyi, J. Draeger, H. Enderle, U. Gebbert, K. Kaschube, G. Kaussen, R. Klanner, J. Lange, B. Mura, S. Naumann-Emme, F. Nowak, N. Pietsch, C. Sander, H. Schettler, P. Schleper, M. Schröder, T. Schum, J. Schwandt, A.K. Srivastava, H. Stadie, G. Steinbrück, J. Thomsen, R. Wolf

Institut für Experimentelle Kernphysik, Karlsruhe, Germany
J. Bauer, V. Buege, T. Chwalek, W. De Boer, A. Dierlamm, G. Dirkes, M. Feindt, J. Gruschke, C. Hackstein, F. Hartmann, S.M. Heindl, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc,

T. Kuhr, D. Martschei, S. Mueller, Th. Müller, M. Niegel, O. Oberst, A. Oehler, J. Ott, T. Peiffer, D. Piparo, G. Quast, K. Rabbertz, F. Ratnikov, M. Renz, C. Saout, A. Scheurer, P. Schieferdecker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, J. Wagner-Kuhr, M. Zeise, V. Zhukov[10], 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. Petrakou

University of Athens, Athens, Greece
L. Gouskos, T.J. Mertzimekis, A. Panagiotou[1]

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, G. Debreczeni, C. Hajdu[1], D. Horvath[11], A. Kapusi, K. Krajczar[12], A. Laszlo, F. Sikler, G. Vesztergombi[12]

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

University of Delhi, Delhi, India
S. Ahuja, S. Bhattacharya, B.C. Choudhary, P. Gupta, S. Jain, S. Jain, A. Kumar, R.K. Shivpuri

Bhabha Atomic Research Centre, Mumbai, India
R.K. Choudhury, D. Dutta, S. Kailas, S.K. Kataria, A.K. Mohanty[1], L.M. Pant, P. Shukla, P. Suggisetti

Tata Institute of Fundamental Research - EHEP, Mumbai, India
T. Aziz, M. Guchait[13], A. Gurtu, M. Maity[14], D. Majumder, G. Majumder, K. Mazumdar, G.B. Mohanty, A. Saha, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India
S. Banerjee, S. Dugad, N.K. Mondal

Institute for Studies in Theoretical Physics & Mathematics (IPM), Tehran, Iran
H. Arfaei, H. Bakhshiansohi, S.M. Etesami, A. Fahim, M. Hashemi, A. Jafari, M. Khakzad, A. Mohammadi, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh, M. Zeinali

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], M. De Palma[a,b], A. Dimitrov[a], L. Fiore[a], G. Iaselli[a,c], L. Lusito[a,b,1], 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], 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], 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]

INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy
S. Albergo[a,b], G. Cappello[a,b], M. Chiorboli[a,b,1], S. Costa[a,b], A. Tricomi[a,b], C. Tuve[a]

INFN Sezione di Firenze [a], Università di Firenze [b], Firenze, Italy
G. Barbagli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], S. Frosali[a,b], E. Gallo[a], C. Genta[a], 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. Colafranceschi[15], F. Fabbri, D. Piccolo

INFN Sezione di Genova, Genova, Italy
P. Fabbricatore, R. Musenich

INFN Sezione di Milano-Biccoca [a], Università di Milano-Bicocca [b], Milano, Italy
A. Benaglia[a,b], F. De Guio[a,b,1], L. Di Matteo[a,b], A. Ghezzi[a,b,1], M. Malberti[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], V. Tancini[a,b]

INFN Sezione di Napoli [a], Università di Napoli "Federico II" [b], Napoli, Italy
S. Buontempo[a], C.A. Carrillo Montoya[a], A. Cimmino[a,b], A. De Cosa[a,b], M. De Gruttola[a,b], F. Fabozzi[a,16], A.O.M. Iorio[a], L. Lista[a], M. Merola[a,b], P. Noli[a,b], P. Paolucci[a]

INFN Sezione di Padova [a], Università di Padova [b], Università di Trento (Trento) [c], Padova, Italy
P. Azzi[a], N. Bacchetta[a], P. Bellan[a,b], D. Bisello[a,b], A. Branca[a], R. Carlin[a,b], P. Checchia[a], E. Conti[a], M. De Mattia[a,b], T. Dorigo[a], U. Dosselli[a], F. Fanzago[a], F. Gasparini[a,b], U. Gasparini[a,b], P. Giubilato[a,b], A. Gresele[a,c], S. Lacaprara[a,17], I. Lazzizzera[a,c], M. Margoni[a,b], M. Mazzucato[a], A.T. Meneguzzo[a,b], L. Perrozzi[a,1], N. Pozzobon[a,b], P. Ronchese[a,b], F. Simonetto[a,b], E. Torassa[a], M. Tosi[a,b], S. Vanini[a,b], P. Zotto[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
P. Baesso[a,b], U. Berzano[a], C. Riccardi[a,b], P. Torre[a,b], P. Vitulo[a,b], C. Viviani[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
M. Biasini[a,b], G.M. Bilei[a], B. Caponeri[a,b], L. Fanò[a,b], P. Lariccia[a,b], A. Lucaroni[a,b,1], G. Mantovani[a,b], M. Menichelli[a], A. Nappi[a,b], A. Santocchia[a,b], L. Servoli[a], S. Taroni[a,b], M. Valdata[a,b], R. Volpe[a,b,1]

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], A. Messineo[a,b], F. Palla[a], F. Palmonari[a], S. Sarkar[a,c], 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], E. Longo[a,b], G. Organtini[a,b], A. Palma[a,b], F. Pandolfi[a,b,1], R. Paramatti[a], S. Rahatlou[a,b]

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,1], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], V. Sola[a,b], A. Solano[a,b], A. Staiano[a], D. Trocino[a,b], A. Vilela Pereira[a,b,1]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
F. Ambroglini[a,b], 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

Kyungpook National University, Daegu, Korea
S. Chang, J. Chung, D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, H. Park, D. Son, D.C. 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, H.B. Rhee, E. Seo, S. Shin, K.S. Sim

University of Seoul, Seoul, Korea
M. Choi, S. Kang, H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea
Y. Choi, Y.K. Choi, J. Goh, 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, R. Lopez-Fernandez, 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
P. Allfrey, D. Krofcheck

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

Soltan Institute for Nuclear Studies, Warsaw, Poland
T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
N. Almeida, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, P. Martins, P. Musella, A. Nayak, P.Q. Ribeiro, J. Seixas, P. Silva, J. Varela[1], H.K. Wöhri

Joint Institute for Nuclear Research, Dubna, Russia
I. Belotelov, P. Bunin, M. Finger, M. Finger Jr., I. Golutvin, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St Petersburg), Russia
N. Bondar, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, A. Toropin, S. Troitsky

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, V. Gavrilov, V. Kaftanov†, M. Kossov[1], A. Krokhotin, N. Lychkovskaya, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia
E. Boos, M. Dubinin[18], L. Dudko, A. Ershov, A. Gribushin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, L. Sarycheva, V. Savrin, A. Snigirev

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, S.V. Rusakov, A. Vinogradov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, S. Bitioukov, V. Grishin[1], V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkine, V. Petrov, R. Ryutin, S. Slabospitsky, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[19], M. Djordjevic, D. Krpic[19], 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, N. Colino, B. De La Cruz, C. Diez Pardos, 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, 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, M. Chamizo Llatas, S.H. Chuang, J. Duarte Campderros, M. Felcini[20], 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 Gomez[21], T. Rodrigo, 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. Bell[22], D. Benedetti, C. Bernet[3], W. Bialas, P. Bloch, A. Bocci, S. Bolognesi, H. Breuker, G. Brona, K. Bunkowski, T. Camporesi, E. Cano, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, B. Curé, D. D'Enterria, A. De Roeck, F. Duarte Ramos, A. Elliott-Peisert, B. Frisch, W. Funk, A. Gaddi, S. Gennai, 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, J. Harvey, J. Hegeman, B. Hegner, C. Henderson, G. Hesketh, H.F. Hoffmann, A. Honma, V. Innocente, P. Janot, E. Karavakis, P. Lecoq, C. Leonidopoulos, C. Lourenço, A. Macpherson, T. Mäki, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, E. Nesvold[1], M. Nguyen, T. Orimoto, L. Orsini, E. Perez, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, G. Polese, A. Racz, G. Rolandi[23], T. Rommerskirchen, C. Rovelli[24], M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, I. Segoni, A. Sharma, P. Siegrist, M. Simon, P. Sphicas[25], D. Spiga, M. Spiropulu[18], F. Stöckli, M. Stoye, P. Tropea, A. Tsirou, A. Tsyganov, G.I. Veres[12], 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. Sibille[26], A. Starodumov[27]

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
P. Bortignon, L. Caminada[28], Z. Chen, S. Cittolin, G. Dissertori, M. Dittmar, J. Eugster, K. Freudenreich, C. Grab, A. Hervé, W. Hintz, P. Lecomte, W. Lustermann, C. Marchica[28], P. Martinez Ruiz del Arbol, P. Meridiani, P. Milenovic[29], F. Moortgat, 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[20], M. Weber, L. Wehrli, J. Weng

Universität Zürich, Zurich, Switzerland
E. Aguiló, C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, C. Regenfus, P. Robmann, A. Schmidt, H. Snoek, L. Wilke

National Central University, Chung-Li, Taiwan
Y.H. Chang, K.H. Chen, W.T. Chen, S. Dutta, A. Go, C.M. Kuo, S.W. Li, W. Lin, M.H. Liu, Z.K. Liu, Y.J. Lu, 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. Bakirci, S. Cerci[30], Z. Demir, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, A. Kayis Topaksu, A. Nart, G. Onengut, K. Ozdemir, S. Ozturk, A. Polatoz, K. Sogut[31], B. Tali, H. Topakli, D. Uzun, L.N. Vergili, M. Vergili, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
I.V. Akin, T. Aliev, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, E. Yildirim, M. Zeyrek

Bogazici University, Istanbul, Turkey
M. Deliomeroglu, D. Demir[32], E. Gülmez, A. Halu, B. Isildak, M. Kaya[33], O. Kaya[33], S. Ozkorucuklu[34], N. Sonmez[35]

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
P. Bell, 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, B. Huckvale, J. Jackson, L. Kreczko, S. Metson, D.M. Newbold[36], K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, S. Ward

Rutherford Appleton Laboratory, Didcot, United Kingdom
L. Basso, K.W. Bell, A. Belyaev, C. Brew, R.M. Brown, B. Camanzi, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, 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, J. Fulcher, D. Futyan, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, R. Nandi, J. Nash, A. Nikitenko[27], A. Papageorgiou, M. Pesaresi, K. Petridis, M. Pioppi[37], D.M. Raymond, N. Rompotis, A. Rose, M.J. Ryan, C. Seez, P. Sharp, A. Sparrow, A. Tapper, S. Tourneur, M. Vazquez Acosta, T. Virdee, S. Wakefield, 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

Boston University, Boston, USA
T. Bose, E. Carrera Jarrin, A. Clough, 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. Narain, D. Nguyen, M. Segala, T. Speer, K.V. Tsang

University of California, Davis, Davis, USA
M.A. Borgia, R. Breedon, M. Calderon De La Barca Sanchez, D. Cebra, 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, 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, R. Clare, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng, S.C. Kao, F. Liu, H. Liu, A. Luthra, H. Nguyen, G. Pasztor[38], A. Satpathy, B.C. Shen†, R. Stringer, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, San Diego, La Jolla, USA
W. Andrews, J.G. Branson, G.B. Cerati, E. Dusinberre, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, B. Mangano, J. Muelmenstaedt, S. Padhi, C. Palmer, G. Petrucciani, H. Pi, M. Pieri, R. Ranieri, M. Sani, V. Sharma[1], S. Simon, Y. Tu, A. Vartak, F. Würthwein, A. Yagil

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. Bornheim, J. Bunn, Y. Chen, M. Gataullin, D. Kcira, V. Litvine, Y. Ma, A. Mott, H.B. Newman, C. Rogan, 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, N. Terentyev, 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, 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, A. Chatterjee, S. Das, N. Eggert, L.J. Fields, L.K. Gibbons, B. Heltsley, W. Hopkins, A. Khukhunaishvili, B. Kreis, V. Kuznetsov, G. Nicolas Kaufman, J.R. Patterson, D. Puigh, D. Riley, A. Ryd, X. Shi, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, USA
A. Biselli, G. Cirino, D. Winn

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, M. Atac, J.A. Bakken, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, F. Borcherding, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, S. Cihangir, M. Demarteau, D.P. Eartly, V.D. Elvira, S. Esen, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, D. Green, K. Gunthoti, O. Gutsche, A. Hahn, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, E. James, H. Jensen, M. Johnson, U. Joshi, R. Khatiwada, B. Kilminster, B. Klima, K. Kousouris, S. Kunori, S. Kwan, P. Limon, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, T. McCauley, T. Miao, K. Mishra, S. Mrenna, Y. Musienko[39], C. Newman-Holmes, V. O'Dell, S. Popescu[40], R. Pordes, O. Prokofyev, N. Saoulidou, E. Sexton-Kennedy, S. Sharma, A. Soha, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

University of Florida, Gainesville, USA
D. Acosta, P. Avery, D. Bourilkov, M. Chen, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, S. Goldberg, B. Kim, S. Klimenko, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, K. Matchev, G. Mitselmakher, L. Muniz, Y. Pakhotin, C. Prescott, R. Remington, M. Schmitt, B. Scurlock, P. Sellers, N. Skhirtladze, 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, J.L. Rodriguez

Florida State University, Tallahassee, USA
T. Adams, A. Askew, D. Bandurin, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, 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, E.J. Garcia-Solis, C.E. Gerber, D.J. Hofman, S. Khalatyan, F. Lacroix, C. O'Brien, C. Silvestre, A. Smoron, D. Strom, N. Varelas

The University of Iowa, Iowa City, USA
U. Akgun, E.A. Albayrak, B. Bilki, K. Cankocak[41], W. Clarida, F. Duru, C.K. Lae, E. McCliment, J.-P. Merlo, H. Mermerkaya, 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, M. Murray, D. Noonan, V. Radicci, S. Sanders, J.S. Wood, V. Zhukova

Kansas State University, Manhattan, USA
T. Bolton, I. Chakaberia, A. Ivanov, 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. Stephans, K. Sumorok, K. Sung, E.A. Wenger, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

University of Minnesota, Minneapolis, USA
P. Cole, S.I. Cooper, P. Cushman, B. Dahmes, A. De Benedetti, P.R. Dudero, G. Franzoni, J. Haupt, K. Klapoetke, Y. Kubota, J. Mans, V. Rekovic, R. Rusack, M. Sasseville, A. Singovsky

University of Mississippi, University, USA
L.M. Cremaldi, R. Godang, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders, D. Summers

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

State University of New York at Buffalo, Buffalo, USA
U. Baur, A. Godshalk, I. Iashvili, A. Kharchilava, A. Kumar, S.P. Shipkowski, K. Smith

Northeastern University, Boston, USA
G. Alverson, E. Barberis, D. Baumgartel, O. Boeriu, M. Chasco, K. Kaadze, S. Reucroft, J. Swain, D. Wood, J. Zhang

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

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

The Ohio State University, Columbus, USA
B. Bylsma, L.S. Durkin, J. Gu, C. Hill, P. Killewald, K. Kotov, T.Y. Ling, M. Rodenburg, G. Williams

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

University of Puerto Rico, Mayaguez, USA
J.G. Acosta, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, A. Zatserklyaniy

Purdue University, West Lafayette, USA
E. Alagoz, V.E. Barnes, G. Bolla, L. Borrello, D. Bortoletto, A. Everett, A.F. Garfinkel, Z. Gecse, L. Gutay, Z. Hu, M. Jones, O. Koybasi, A.T. Laasanen, N. Leonardo, C. Liu, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, K. Potamianos, I. Shipsey, D. Silvers, A. Svyatkovskiy, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, USA
P. Jindal, N. Parashar

Rice University, Houston, USA
C. Boulahouache, V. Cuplov, K.M. Ecklund, F.J.M. Geurts, J.H. Liu, J. Morales, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, USA
B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, H. Flacher,

A. Garcia-Bellido, P. Goldenzweig, Y. Gotra, J. Han, A. Harel, D.C. Miner, D. Orbaker, G. Petrillo, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, USA
A. Bhatti, L. Demortier, K. Goulianos, G. Lungu, C. Mesropian, M. Yan

Rutgers, the State University of New Jersey, Piscataway, USA
O. Atramentov, A. Barker, D. Duggan, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, D. Hits, A. Lath, S. Panwalkar, R. Patel, A. Richards, K. Rose, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas

University of Tennessee, Knoxville, USA
G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

Texas A&M University, College Station, USA
J. Asaadi, R. Eusebi, J. Gilmore, A. Gurrola, T. Kamon, V. Khotilovich, R. Montalvo, C.N. Nguyen, J. Pivarski, A. Safonov, S. Sengupta, A. Tatarinov, D. Toback, M. Weinberger

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

Vanderbilt University, Nashville, USA
E. Appelt, E. Brownson, D. Engh, C. Florez, W. Gabella, W. Johns, P. Kurt, C. Maguire, A. Melo, P. Sheldon, J. Velkovska

University of Virginia, Charlottesville, USA
M.W. Arenton, M. Balazs, S. Boutle, M. Buehler, S. Conetti, 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, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton[1], M. Herndon, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, D. Lomidze, R. Loveless, A. Mohapatra, D. Reeder, I. Ross, A. Savin, W.H. Smith, J. Swanson, M. Weinberg

†: Deceased
1: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
2: Also at Universidade Federal do ABC, Santo Andre, Brazil
3: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
4: Also at Suez Canal University, Suez, Egypt
5: Also at Fayoum University, El-Fayoum, 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 Facoltà Ingegneria Università di Roma "La Sapienza", Roma, Italy
16: Also at Università della Basilicata, Potenza, Italy
17: Also at Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy
18: Also at California Institute of Technology, Pasadena, USA
19: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
20: Also at University of California, Los Angeles, Los Angeles, USA
21: Also at University of Florida, Gainesville, USA
22: Also at Université de Genève, Geneva, Switzerland
23: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
24: Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy
25: Also at University of Athens, Athens, Greece
26: Also at The University of Kansas, Lawrence, USA
27: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
28: Also at Paul Scherrer Institut, Villigen, Switzerland
29: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
30: Also at Adiyaman University, Adiyaman, Turkey
31: Also at Mersin University, Mersin, Turkey
32: Also at Izmir Institute of Technology, Izmir, Turkey
33: Also at Kafkas University, Kars, Turkey
34: Also at Suleyman Demirel University, Isparta, Turkey
35: Also at Ege University, Izmir, Turkey
36: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
37: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
38: Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
39: Also at Institute for Nuclear Research, Moscow, Russia
40: Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
41: Also at Istanbul Technical University, Istanbul, Turkey