Search for Neutral MSSM Higgs Bosons Decaying to Tau Pairs in pp Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration

Abstract

A search for neutral MSSM Higgs bosons in pp collisions at the LHC at a center-of-mass energy of 7 TeV is presented. The results are based on a data sample corresponding to an integrated luminosity of 36 pb$^{-1}$ recorded by the CMS experiment. The search uses decays of the Higgs bosons to tau pairs. No excess is observed in the tau-pair invariant-mass spectrum. The resulting upper limits on the Higgs boson production cross section times branching fraction to tau pairs, as a function of the pseudoscalar Higgs boson mass, yield stringent new bounds in the MSSM parameter space.

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*See Appendix A for the list of collaboration members*
The standard model (SM) has been extremely successful in describing a wide range of phenomena in particle physics, and has survived some four decades of experimental testing. However, the only remaining undiscovered particle predicted by the SM, the Higgs boson \([1–5]\), suffers from quadratically divergent self-energy corrections at high energies \([6]\). Numerous extensions to the SM have been proposed to address these divergences. One such model, supersymmetry \([7]\), a symmetry between fundamental bosons and fermions, results in cancellation of the divergences at tree level. The minimal supersymmetric extension to the standard model (MSSM) requires the presence of two Higgs doublets. This leads to a more complicated Higgs boson sector, with five massive Higgs bosons: a light neutral scalar \((h)\), two charged scalars \((H^\pm)\), a heavy neutral CP-even state \((H)\) and a neutral CP-odd state \((A)\).

The masses of the MSSM Higgs boson states are specified up to radiative corrections mainly by two parameters, usually taken to be the mass of the pseudoscalar state, \(m_A\), and the ratio of the vacuum expectation values of the two Higgs doublets, \(\tan \beta\). At large \(\tan \beta\) (greater than about 20–30), the couplings of the Higgs bosons to down-type quarks are proportional to \(\tan \beta\). As a result, the production cross section for two of the three neutral Higgs bosons can be nearly as large as that for the electroweak gauge bosons \(W\) and \(Z\) at a proton-proton collider such as the Large Hadron Collider (LHC). Two main production processes contribute to \(pp \rightarrow \phi + X\), where \(\phi = h, H,\) or \(A\): gluon fusion through a \(b\) quark loop and direct \(b\bar{b}\) annihilation from the \(b\) parton density in the beam protons.

The mass relations among the neutral MSSM Higgs bosons are such that if \(m_A \lesssim 130\) GeV/\(c^2\), at large \(\tan \beta\) the masses of the \(h\) and \(A\) are nearly degenerate, while that of the \(H\) is approximately 130 GeV/\(c^2\). If \(m_A \gtrsim 130\) GeV/\(c^2\), then the masses of the \(A\) and \(H\) are nearly degenerate, while that of the \(h\) remains near 130 GeV/\(c^2\). The precise value of the crossover point depends predominantly on the nature of the mass mixing in the top-squark states.

This Letter reports a search for MSSM neutral Higgs bosons in \(pp\) collisions at \(\sqrt{s} = 7\) TeV at the LHC, using a data sample collected in 2010 corresponding to 36 pb\(^{-1}\) of integrated luminosity recorded by the Compact Muon Solenoid (CMS) experiment. This search is similar to those performed at the Tevatron \([8]\) and complementary to the MSSM Higgs search at LEP \([9]\).

The tau-pair decays of the neutral Higgs bosons, having a branching fraction of about 10%, serve as the best experimental signature for this search. The \(b\bar{b}\) mode, though it has a much larger branching fraction, suffers from an overwhelming background from QCD processes. Three final states where one or both taus decay leptonically are used: \(e\tau_h\), \(\mu\tau_h\), and \(e\mu\), where we use the symbol \(\tau_h\) to indicate a reconstructed hadronic decay of a \(\tau\).

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 and the brass/scintillator hadron calorimeter. 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. Details of the CMS detector and its performance can be found elsewhere \([10]\).

CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the \(x\) axis pointing to the center of the LHC, the \(y\) axis pointing up (perpendicular to the LHC plane), and the \(z\) axis along the anticlockwise-beam direction. The polar angle \(\theta\) is measured from the positive \(z\) axis and the azimuthal angle \(\phi\) is measured in the \(xy\) plane. We measure the pseudorapidity \(\eta\) of outgoing particles based on their polar angle according to \(\eta \equiv -\ln(\tan(\frac{\theta}{2}))\).

The triggers used to select the events for this analysis are based on the presence of an electron and/or a muon trigger object \([11, 12]\). With increasing instantaneous luminosity, in order to
keep the online transverse momentum thresholds on electrons lower than those used in offline selections, special triggers requiring the presence of both a lepton and a charged track with an accompanying calorimeter pattern consistent with a \( \tau \) decaying hadronically were adopted for the \( e_{\tau_h} \) and \( \mu_{\tau_h} \) channels.

The analysis presented here makes use of particle flow techniques which combine the information from all CMS subdetectors to identify and reconstruct individual particles in the event, namely muons, electrons, photons, and charged and neutral hadrons. The detailed description of the algorithm and its commissioning can be found elsewhere \[13\] \[14\]. The particle list is given as input to the jet, tau, and missing transverse energy reconstruction.

The main challenge in the identification of hadronic tau decays is overcoming the large background due to hadronic jets from QCD processes. Hadronic tau decays almost always yield one or three charged pions, plus zero to several neutral pions, depending on the decay mode. The algorithm used here starts with a high-transverse-momentum (\( p_T \)) reconstructed charged hadron, and combines it with other nearby reconstructed charged hadron and neutral pion candidates. The algorithm considers all possible combinations of these objects and determines which are consistent with the kinematics of tau decay. Among those, it chooses the most isolated in terms of the presence of nearby reconstructed particles. Requirements on the isolation variables determine an operating point in the space of tau identification efficiency versus the jet-to-tau misidentification rate. We optimize the full analysis for best sensitivity by choosing the “loose” operating point of the HPS algorithm \[15\].

For the \( \mu_{\tau_h} \) and \( e_{\tau_h} \) final states, we select events with an isolated muon or electron with \( p_T > 15 \text{ GeV/c} \) and \( |\eta| < 2.1 \), and an oppositely charged \( \tau_h \) with \( p_T > 20 \text{ GeV/c} \) and \( |\eta| < 2.3 \). The transverse mass of the \( \ell = e, \mu \) with the missing transverse energy \( E_T \), obtained using all reconstructed particles in the event, is defined as \( M_T = \sqrt{2p_T^\ell E_T (1 - \cos \Delta \phi)} \), where \( \Delta \phi \) is the difference in azimuth between the \( e \) or \( \mu \) and the \( E_T \) vector. We require \( M_T < 40 \text{ GeV/c}^2 \), in order to reduce the background from \( W+\text{jets} \) events. For the \( e\mu \) final state, we select events with an isolated electron with \( |\eta| < 2.5 \) and an oppositely charged isolated muon, both with \( p_T > 15 \text{ GeV/c} \) and \( M_T < 50 \text{ GeV/c}^2 \), calculated for each lepton separately. We reject events in which there are more than one \( e \) or \( \mu \).

The observed number of events in each channel appears in Table 1. The largest source of events selected with these requirements comes from \( Z \rightarrow \ell\ell \). We estimate the contribution from this process using a detailed \textsc{geant4} simulation of the CMS detector, with the events modeled by the \textsc{powheg} Monte Carlo generator \[16\] \[19\]. We determine the normalization for this process based on the number of observed \( Z \rightarrow \ell\ell \) events \[20\].

A significant source of background arises from QCD multijet events and \( W+\text{jets} \) events in which a jet is misidentified as \( \tau_h \), and there is a real or misidentified \( e \) or \( \mu \). The rates for these processes are estimated using the number of observed same-charge events, and cross-checked using the jet-to-tau misidentification rate measured in multijet events. Other backgrounds include \( t\bar{t} \) production and \( Z \rightarrow e\mu \) events, particularly in the \( e\tau_h \) channel, due to the 2–3\% probability for electrons to be misidentified as \( \tau_h \) \[15\]. The small fake-lepton background from \( W+\text{jets} \) and QCD for the \( e\mu \) channel is estimated using data. Table 1 shows the expected number of events for each of the background processes. The event generator \textsc{pythia6} \[21\] is used to model the Higgs boson signal and other backgrounds. The \textsc{tauola} \[22\] package is used for tau decays in all cases.

To distinguish the Higgs boson signal from the background, we reconstruct the tau-pair mass using a likelihood technique. The algorithm estimates the original tau three-momenta by max-
Table 1: Number of estimated background events in the selected sample, observed number of events, and overall signal efficiency for $m_A = 200 \text{ GeV}/c^2$ (including all branching fractions) for each search channel. Uncertainties do not include those on integrated luminosity or energy scales. The QCD multijet background for the $e\tau_h$ final state is the sum of the QCD multijet and $\gamma$+jet backgrounds.

| Process                        | $\mu\tau_h$ | $e\tau_h$ | $e\mu$ |
|--------------------------------|-------------|-----------|--------|
| $Z \rightarrow \tau\tau$      | 329 ± 77    | 190 ± 44  | 88 ± 5 |
| $t\bar{t}$                     | 6 ± 3       | 2.6 ± 1.3 | 7.1 ± 1.3 |
| $Z \rightarrow \ell\ell$, jet $\rightarrow \tau_h$ | 6.4 ± 2.4  | 15 ± 6.2 | - |
| $Z \rightarrow \ell\ell$      | 12.9 ± 3.5  | 109 ± 28  | 2.4 ± 0.3 |
| $W \rightarrow \ell\nu$       | 54.9 ± 4.8  | 30.6 ± 3.1 | |
| $W \rightarrow \tau\nu, \tau \rightarrow \ell\nu$ | 14.7 ± 1.3 | 7.0 ± 0.7 | 1.5 ± 0.5 |
| QCD multijet and $\gamma$+jet | 132 ± 14    | 181 ± 23  | |
| $WW/WZ/ZZ$                     | 1.6 ± 0.8   | 0.8 ± 0.4 | 3.0 ± 0.4 |
| Total                          | 557 ± 79    | 536 ± 57  | 102 ± 5 |
| Observed                       | 517         | 540       | 101    |
| Signal Efficiency              | 0.0391      | 0.0245    | 0.00582 |

imizing a likelihood with respect to free parameters corresponding to the missing tau-neutrino momenta, and subject to all applicable kinematic constraints. Other terms in the likelihood take into account the tau-decay phase space and the probability density in the tau transverse momentum, parametrized as a function of the tau-pair mass. This algorithm yields a tau-pair mass with a mean consistent with the true value, and a distribution with a nearly Gaussian shape. The mass resolution is $\sim$21% at a Higgs boson mass of 130 GeV/$c^2$, to be compared with $\sim$24% for the (non-Gaussian) distribution of the invariant mass reconstructed from the visible tau-decay products. The observed reconstructed tau-pair mass distribution for all three channels is shown in Fig. 1.

Various imperfectly known or imperfectly simulated effects can alter the shape and normalization of the reconstructed tau-pair invariant-mass spectrum. The main sources of normalization uncertainties include the total integrated luminosity (11%) [23], background normalizations (Table 1), Z production cross section (4%), and lepton identification and isolation efficiency (0.2–2.0% depending on lepton type). The tau identification efficiency uncertainty is estimated to be 23% from an independent study [15]. Uncertainties that contribute to mass spectrum shape variations include the tau (3%), muon (1%), and electron (2%) energy scales, and uncertainties on the $E_T^\tau$ scale that is used for the tau-pair invariant-mass reconstruction [24]. The $E_T^\tau$ scale uncertainties contribute via the jet-energy scale (3%) and unclustered energy scale (10%), where the unclustered energy is defined as the energy remaining after vectorially subtracting leptons and objects clustered in jets with $p_T > 10 \text{ GeV}/c$.

To search for the presence of a Higgs boson signal in the selected events, we perform a maximum likelihood fit to the tau-pair invariant-mass spectrum. Systematic uncertainties are represented by nuisance parameters, which we remove by marginalization, assuming a log normal prior for normalization parameters, and Gaussian priors for mass-spectrum shape uncertainties. The uncertainties that affect the shape of the mass spectrum, mainly those corresponding to the energy scales, are represented by nuisance parameters whose variation results in a continuous modification of the spectrum shape [25].

The parameter representing the tau identification uncertainty affects taus from the Higgs boson
signal and the main background, \( Z \to \tau\tau \), equally. This effectively allows the observed \( Z \to \tau\tau \) events to provide an in situ calibration of this efficiency, except for Higgs boson masses near that of the Z. Near the Z mass, the tau identification efficiency uncertainty dominates in the e\(\tau_h \) and \( \mu\tau_h \) channels, and the e\(\mu \) channel thus provides the greatest sensitivity.

The mass spectra show no evidence for the presence of a Higgs boson signal, and we set 95% CL (confidence level) upper bounds on the Higgs boson cross section times the tau-pair branching fraction (denoted by \( \sigma \cdot B_{\tau\tau} \)) using a Bayesian method assuming a uniform prior in \( \sigma \cdot B_{\tau\tau} \).

Figure 2 shows the observed upper bound on \( \sigma \cdot B_{\tau\tau} \) as a function of \( m_A \), where we use as the signal acceptance model the combined mass spectra from the gg and b\(\bar{b} \) production processes for \( h \), \( A \), and \( H \), and assuming \( \tan \beta = 30 \) [26]. The plot also shows the one- and two-standard-deviation range of expected upper limits for various potential experimental outcomes. The observed limits are well within the expected range assuming no signal. The observed and expected upper limits are shown in Table 2.

We can interpret the upper limits on \( \sigma \cdot B_{\tau\tau} \) in the MSSM parameter space of \( \tan \beta \) versus \( m_A \) for an example scenario. We use here the \( m_{\max}^1 \) benchmark scenario in which \( M_{\text{SUSY}} = 1 \text{ TeV}/c^2 \); \( X_I = 2M_{\text{SUSY}} \); \( \mu = 200 \text{ GeV}/c^2 \); \( M_\chi = 800 \text{ GeV}/c^2 \); \( M_2 = 200 \text{ GeV}/c^2 \); and \( A_b = A_t \), where \( M_{\text{SUSY}} \) denotes the common soft-SUSY-breaking squark mass of the third generation; \( X_I \) is the stop mixing parameter; \( A_t \) and \( A_b \) the stop and sbottom trilinear couplings, respectively; \( \mu \) the Higgsino mass parameter; \( M_\chi \) the gluino mass; and \( M_2 \) the \( SU(2) \)-gaugino mass parameter. The value of \( M_1 \) is fixed via the GUT relation \( M_1 = (5/3)M_2 \sin \theta_W / \cos \theta_W \). In determining these bounds on \( \tan \beta \), shown in Table 2 and in Fig. 3, we have used the central values of the Higgs boson cross sections as a function of \( \tan \beta \) reported.
Observed 95% CL upper bounds

\begin{align*}
\sigma(pp \to \phi X)B(\phi \to \tau\tau) & \quad (pb) \\
CMS & \\
36 \text{ pb}^{-1} & 7 \text{ TeV} \\
\end{align*}

Median expected

1σ expected range

2σ expected range

Figure 2: The expected one- and two-standard-deviation ranges and observed 95% CL upper limits on $\sigma_\phi \cdot B_{\tau\tau}$ as a function of $m_A$.

Table 2: Expected range and observed 95% CL upper limits for $\sigma_\phi \cdot B_{\tau\tau}$ as functions of $m_A$, and 95% CL upper bound on $\tan \beta$ in the $m_{h_{\text{max}}}$ scenario described in the text. No bounds on $\tan \beta$ above 60 are quoted.

| $m_A$ (GeV/c²) | Expected $\sigma_\phi \cdot B_{\tau\tau}$ (pb) | Observed $\sigma_\phi \cdot B_{\tau\tau}$ (pb) | 95% CL Upper Limit | 95% CL Upper Limit |
|----------------|-----------------------------------------------|-----------------------------------------------|-------------------|-------------------|
| 90             | 107.75                                        | 153.30                                        | 227.10            | 147.74            |
| 100            | 88.61                                         | 127.09                                        | 184.17            | 112.30            |
| 120            | 42.72                                         | 62.48                                         | 90.24             | 39.61             |
| 130            | 31.97                                         | 45.96                                         | 67.11             | 25.40             |
| 140            | 22.14                                         | 32.81                                         | 47.30             | 18.20             |
| 160            | 13.83                                         | 19.70                                         | 29.27             | 11.37             |
| 180            | 9.95                                          | 14.16                                         | 23.13             | 9.78              |
| 200            | 7.90                                          | 11.36                                         | 17.61             | 8.71              |
| 250            | 5.01                                          | 7.54                                          | 11.15             | 5.77              |
| 300            | 3.77                                          | 5.71                                          | 8.58              | 4.36              |
| 350            | 3.09                                          | 4.64                                          | 7.04              | 3.60              |
| 400            | 2.57                                          | 3.79                                          | 5.39              | 2.86              |
| 450            | 2.21                                          | 3.34                                          | 4.77              | 2.41              |
| 500            | 2.00                                          | 2.95                                          | 4.18              | 2.10              |
by the LHC Higgs Cross Section Working Group [26]. The cross sections have been obtained from the GGH@NNLO [28, 29] and HIGLU [30] programs for the gluon-fusion process and from the BBH@NNLO [31] program for the $b\bar{b} \to \phi$ process in the 5-flavor scheme, rescaling the corresponding Yukawa couplings by the MSSM factors calculated with FeynHiggs [32]. The $gg \to \phi$ cross-section calculations combine the full quark mass-dependent NLO QCD corrections [33] and NNLO corrections in the heavy-top-quark limit [28, 34, 35]. The effect of the theoretical uncertainties is illustrated in Fig. 3. We do not quote limits above $\tan \beta = 60$ as the theoretical relation between cross section and $\tan \beta$ becomes unreliable.

The present results exclude a region in $\tan \beta$ down to values smaller than those excluded by the Tevatron experiments [8] for $m_A \lesssim 140$ GeV/$c^2$, and significantly extend the excluded region of MSSM parameter space at larger values of $m_A$. Figure 3 also shows the region excluded by the LEP experiments [9].

In conclusion, we have performed a search for neutral MSSM Higgs bosons, using the first sample of CMS data from proton-proton collisions at a center-of-mass energy of 7 TeV at the LHC, corresponding to an integrated luminosity of 36 pb$^{-1}$. The tau-pair decay mode in final states with one $e$ or $\mu$ plus a hadronic decay of a tau, and the $e\mu$ final state were used. The observed tau-pair mass spectrum reveals no evidence for neutral Higgs boson production, and we determine an upper bound on the product of the Higgs boson cross section and tau-pair branching fraction as a function of $m_A$. These results, interpreted in the MSSM parameter space of $\tan \beta$ versus $m_A$, in the $m_A^{\text{max}}$ scenario, exclude a previously unexplored region reaching as low as $\tan \beta = 23$ at $m_A = 130$ GeV/$c^2$.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria
W. Adam, T. Bergauer, M. Dragicevic, J. Erò, C. Fabjan, M. Friedl, R. Frühwirth, V.M. Ghete, J. Hammer1, S. Hänsel, M. Hoch, N. Hörmann, J. Hrubec, M. Jeitler, G. Kasieczka, W. Kiesenhofer, M. Krammer, D. Liko, I. Mikulec, M. Pernicka, H. Rohringer, R. Schönbeck, J. Strauss, F. Teischinger, P. Wagner, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz

National Centre for Particle and High Energy Physics, Minsk, Belarus
V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universität Antwerpen, Antwerpen, Belgium
L. Benucci, 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
F. Blekman, S. Blyweert, J. D’Hondt, O. Devroede, R. Gonzalez Suarez, A. Kalogeropoulos, J. Maes, M. Maes, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

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

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

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, G. Bruno, J. Caudron, L. Cearer, E. Cortina Gil, J. De Favereau De Jeneret, C. Delaere1, D. Favart, A. Giammanco, G. Grégoire, J. Hollar, V. Lemaitre, J. Liao, O. Militaru, S. Ovyn, D. Pagano, A. Pin, K. Piotrzkowski, N. Schul

Université de Mons, Mons, Belgium
N. Beliy, T. Caebergs, E. Daubie

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, 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, T.R. Fernandez Perez Tomei, E. M. Gregores2, C. Laguna, F. Marinho, P.G. Mercadante2, S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
N. Darmenov1, L. Dimitrov, V. Genchev1, P. Iaydjiev1, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, I. Vankov
University of Sofia, Sofia, Bulgaria
A. Dimitrov, R. Hadjiiska, A. Karadzhinova, V. Kozhuharov, L. Litov, M. Mateev, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China
J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

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

Universidad de Los Andes, Bogota, Colombia
A. Cabrera, B. Gomez Moreno, A.A. Ocampo Rios, A.F. Osorio Oliveros, J.C. Sanabria

Technical University of Split, Split, Croatia
N. Godinovic, D. Lelas, K. Lelas, R. Plestina³, D. Polic, I. Puljak

University of Split, Split, Croatia
Z. Antunovic, M. Dzelalija

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, S. Duric, K. Kadija, S. Morovic

University of Cyprus, Nicosia, Cyprus
A. Attikis, M. Galanti, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr.

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran⁴, S. Khalil⁵, M.A. Mahmoud⁶

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

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

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

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

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

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, F.X. Gentit, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, M. Marionneau, L. Millischer, J. Rander, A. Rosowsky, I. Shreyber, M. Titov, P. Verrecchia
H. Schettler, P. Schleper, M. Schröder, T. Schum, J. Schwanrt, H. Stadie, G. Steinbrück, J. Thomsen

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

Institute of Nuclear Physics “Demokritos”, Aghia Paraskevi, Greece
G. Daskalakis, T. Geralis, K. Karafasoulis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari, E. Petrakou

University of Athens, Athens, Greece
L. Gouskos, T.J. Mertzimekis, A. Panagiotou, E. Stiliaris

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

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
A. Aranyi, G. Bencze, L. Boldizsar, C. Hajdu, P. Hidas, D. Horvath, A. Kapusi, K. Krajczar, F. Sikler, G.I. Veres, G. Vesztergombi

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

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

Bhabha Atomic Research Centre, Mumbai, India
R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty, L.M. Pant, P. Shukla

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

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

Institute for Research and Fundamental Sciences (IPM), Tehran, Iran
H. Arfaei, H. Bakhshiansohi, S.M. Etesami, A. Fahimi, M. Hashemi, A. Jafari, M. Khakzad, A. Mohammad, M. Mohammad Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh, M. Zeinali

INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
M. Abbrescia, L. Barbone, C. Calabria, A. Colaleo, D. Creanza, N. De Filippis,
M. De Palma\textsuperscript{a,b}, L. Fiore\textsuperscript{a}, G. Iaselli\textsuperscript{a,c}, L. Lusito\textsuperscript{a,b}, G. Maggi\textsuperscript{a,c}, M. Maggi\textsuperscript{a}, N. Manna\textsuperscript{a,b}, B. Marangelli\textsuperscript{a,b}, S. My\textsuperscript{a,c}, S. Nuzzo\textsuperscript{a,b}, N. Pacifico\textsuperscript{a,b}, G.A. Pierro\textsuperscript{a}, A. Pomplii\textsuperscript{a,b}, G. Pugliese\textsuperscript{a,c}, F. Romano\textsuperscript{a,c}, G. Roselli\textsuperscript{a,b}, G. Selvaggi\textsuperscript{a,b}, L. Silvestris\textsuperscript{a}, R. Trentadue\textsuperscript{a}, S. Tupputi\textsuperscript{a,b}, G. Zito\textsuperscript{a}

INFN Sezione di Bologna \textsuperscript{a}, Università di Bologna \textsuperscript{b}, Bologna, Italy

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

INFN Sezione di Catania \textsuperscript{a}, Università di Catania \textsuperscript{b}, Catania, Italy

S. Albergo\textsuperscript{a,b}, G. Cappello\textsuperscript{a,b}, M. Chiornola\textsuperscript{a,b}, 1, S. Costa\textsuperscript{a,b}, A. Tricomi\textsuperscript{a,b}, C. Tuve\textsuperscript{a}

INFN Sezione di Firenze \textsuperscript{a}, Università di Firenze \textsuperscript{b}, Firenze, Italy

G. Barbagli\textsuperscript{a}, V. Ciulli\textsuperscript{a,b}, C. Civinini\textsuperscript{a}, R. D’Alessandro\textsuperscript{a,b}, E. Focardi\textsuperscript{a,b}, S. Frosali\textsuperscript{a,b}, E. Gallo\textsuperscript{a}, S. Gonzi\textsuperscript{a,b}, P. Lenzi\textsuperscript{a,b}, M. Meschini\textsuperscript{a}, S. Paoletti\textsuperscript{a}, G. Sguazzoni\textsuperscript{a}, A. Tropiano\textsuperscript{a,1}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, S. Colafranceschi\textsuperscript{19}, F. Fabbrri, D. Piccolo

INFN Sezione di Genova, Genova, Italy

P. Fabbricatore, R. Musenich

INFN Sezione di Milano-Bicocca \textsuperscript{a}, Università di Milano-Bicocca \textsuperscript{b}, Milano, Italy

A. Benaglia\textsuperscript{a,b}, F. De Guio\textsuperscript{a,b,1}, L. Di Matteo\textsuperscript{a,b}, G. Ghezzi\textsuperscript{a,b}, S. Malvezzi\textsuperscript{a}, A. Martelli\textsuperscript{a,b}, A. Massironi\textsuperscript{a,b}, D. Menasco\textsuperscript{a}, L. Moroni\textsuperscript{a}, M. Paganoni\textsuperscript{a,b}, D. Pedrini\textsuperscript{a}, S. Ragazzi\textsuperscript{a,b}, N. Redaelli\textsuperscript{a}, S. Sala\textsuperscript{a}, T. Tabarelli de Fatis\textsuperscript{a,b}, V. Tancini\textsuperscript{a,b}

INFN Sezione di Napoli \textsuperscript{a}, Università di Napoli “Federico II” \textsuperscript{b}, Napoli, Italy

S. Buontempo\textsuperscript{a}, C.A. Carrillo Montoya\textsuperscript{a,1}, N. Cavalli\textsuperscript{a,20}, A. De Costa\textsuperscript{a,b}, F. Fabozzi\textsuperscript{a,20}, A.O.M. Iorio\textsuperscript{a,1}, L. Lista\textsuperscript{a}, M. Merola\textsuperscript{a,b}, P. Paolucci\textsuperscript{a}

INFN Sezione di Padova \textsuperscript{a}, Università di Padova \textsuperscript{b}, Università di Trento (Trento) \textsuperscript{c}, Padova, Italy

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

INFN Sezione di Pavia \textsuperscript{a}, Università di Pavia \textsuperscript{b}, Pavia, Italy

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

INFN Sezione di Perugia \textsuperscript{a}, Università di Perugia \textsuperscript{b}, Perugia, Italy

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

INFN Sezione di Pisa \textsuperscript{a}, Università di Pisa \textsuperscript{b}, Scuola Normale Superiore di Pisa \textsuperscript{c}, Pisa, Italy

P. Azzurri\textsuperscript{a,c}, G. Bagliesi\textsuperscript{a}, J. Bernardini\textsuperscript{a,b}, T. Boccali\textsuperscript{a,1}, G. Broccoli\textsuperscript{a,c}, R. Castaldi\textsuperscript{a}, R.T. D’Agnolo\textsuperscript{a,c}, R. Dell’Orso\textsuperscript{a}, F. Fiori\textsuperscript{a,b}, L. Foà\textsuperscript{a,c}, A. Giassi\textsuperscript{a}, A. Kraan\textsuperscript{a}, F. Ligabue\textsuperscript{a,c}, T. Lomtadze\textsuperscript{a}, L. Martin\textsuperscript{a,22}, A. Messineo\textsuperscript{a,b}, F. Palla\textsuperscript{a}, G. Segneri\textsuperscript{a}, A.T. Serban\textsuperscript{a}, P. Spagnolo\textsuperscript{a}, R. Tenchini\textsuperscript{a}, G. Tonelli\textsuperscript{a,b,1}, A. Venturi\textsuperscript{a,b}, P.G. Verdini\textsuperscript{a}
INFN Sezione di Roma $^a$, Università di Roma "La Sapienza" $^b$, Roma, Italy
L. Barone$^{a,b}$, F. Cavallari$^a$, D. Del Re$^{a,b}$, E. Di Marco$^{a,b}$, M. Diemoz$^a$, D. Franci$^{a,b}$, M. Grassi$^{a,1}$, E. Longo$^{a,b}$, S. Nourbakhsh$^a$, G. Organtini$^a,b$, F. Pandolfi$^{a,b,1}$, R. Paramatti$^a$, S. Rahatlou$^{a,b}$

INFN Sezione di Torino $^a$, Università di Torino $^b$, Università del Piemonte Orientale (Novara) $^c$, Torino, Italy
N. Amapane$^{a,b}$, R. Arcidiacono$^{a,c}$, S. Argiro$^{a,b}$, M. Arneodo$^{a,c}$, C. Biino$^a$, C. Botta$^{a,b,1}$, N. Cartiglia$^a$, R. Castello$^{a,b}$, M. Costa$^{a,b}$, N. Demaria$^a$, A. Graziano$^{a,b,1}$, C. Mariotti$^a$, M. Marone$^{a,b}$, S. Maselli$^a$, E. Migliore$^{a,b}$, G. Mila$^{a,b}$, V. Monaco$^{a,b}$, M. Musich$^{a,b}$, M.M. Obertino$^{a,c}$, N. Pastrone$^a$, M. Pelliccioni$^{a,b}$, A. Romero$^{a,b}$, M. Ruspa$^{a,c}$, R. Sacchi$^{a,b}$, V. Sola$^{a,b}$, A. Solano$^{a,b}$, A. Staiano$^a$, A. Vilela Pereira$^{a,b}$

INFN Sezione di Trieste $^a$, Università di Trieste $^b$, Trieste, Italy
S. Belforte$^a$, F. Cossutti$^a$, G. Della Ricca$^{a,b}$, B. Gobbo$^a$, D. Montanino$^{a,b}$, A. Penzo$^a$

Kangwon National University, Chunchon, Korea
S.G. Heo, S.K. Nam

Kyungpook National University, Daegu, Korea
S. Chang, J. Chung, D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, H. Park, S.R. Ro, D. Son, D.C. Son, T. Son

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
Zero Kim, J.Y. Kim, S. Song

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

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

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

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

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castillo-Valdez, E. De La Cruz-Burelo, R. Lopez-Fernandez, R. Magaña Villalba, A. Sánchez-Hernández, L.M. Villasenor-Cendejas

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

University of Auckland, Auckland, New Zealand
D. Krofcheck, J. Tam

University of Canterbury, Christchurch, New Zealand
P.H. Butler, R. Doesburg, H. Silverwood
National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
M. Ahmad, I. Ahmed, M.I. Asghar, H.R. Hoorani, W.A. Khan, T. Khurshid, S. Qazi

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
G. Brona, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

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

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, P. Musella, A. Nayak, P.Q. Ribeiro, J. Seixas, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, I. Belotelov, P. Bunin, 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
V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, A. Vorobyev

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

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, V. Gavrilov, V. Kaftanov, M. Kossòv, A. Krokhotin, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

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

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

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, S. Bitioukov, V. Grishin, V. Kachanov, D. Konstantinov, A. Korabev, 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, M. Djordjevic, D. Krpic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cepeda, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, C. Diez Pardos, D. Dominguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott
Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, G. Codispoti, J.F. de Trocóniz

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

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini, 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, T. Rodrigo, A.Y. Rodriguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, A.J. Bell, D. Benedetti, C. Bernet, W. Bialas, P. Bloch, A. Bocci, S. Bolognesi, M. Bona, H. Breuker, K. Bunkowski, T. Camporesi, G. Cerminara, J.A. Coarasa Perez, B. Curé, D. D’Enterria, A. De Roeck, S. Di Guida, 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, C. Hartl, J. Harvey, J. Hegner, B. Hegner, H.F. Hoffmann, A. Honma, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, P. Lecomte, W. Lustermann, C. Marchica, P. Martinez Ruiz del Arbol, P. Meridiani, P. Milenovic, F. Moortgat, C. Nägeli, 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, C. Urscheler, R. Wallny, M. Weber, L. Wehrli, J. Weng

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, A. Starodumov

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
P. Bortignon, L. Caminada, N. Chanon, Z. Chen, S. Cittolin, G. Dissertori, M. Dittmar, J. Eugster, K. Freudenberg, C. Grab, A. Hervé, W. Hintz, P. Lecomte, W. Lustermann, C. Marchica, P. Martinez Ruiz del Arbol, P. Meridiani, P. Milenovic, F. Moortgat, C. Nägeli, 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, R. Wallny, M. Weber, L. Wehrli, J. Weng

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

National Central University, Chung-Li, Taiwan
Y.H. Chang, K.H. Chen, C.M. Kuo, S.W. Li, W. Lin, Z.K. Liu, Y.J. Lu, D. Mekterovic, R. Volpe, J.H. Wu, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, W.-S. Hou, H. 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, S. 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, D. Sunar Cerci, 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, E. G"ulmez, B. Isildak, M. Kaya, O. Kaya, S. Ozkorucuklu, N. Sonmez

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

University of Bristol, Bristol, United Kingdom
F. Bostock, J.J. Brooke, T.L. Cheng, E. Clement, D. Cussans, R. Frazier, J. Goldstein, M. Grimes, M. Hansen, D. Hartley, G.P. Heath, H.F. Heath, J. Jackson, L. Kreczko, S. Metson, D.M. Newbold, 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. Olaya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley, S.D. Worm

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

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

Baylor University, Waco, USA
K. Hatakeyama

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

Brown University, Providence, USA
A. Avetisyan, S. Bhattacharya, J.P. Chou, D. Cutts, A. Feraudontov, U. Heintz, S. Jabeen, G. Kukartsev, G. Landsberg, M. Narain, D. Nguyen, M. Segala, T. Sinthuprasith, T. Speer, K.V. Tsang

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

**University of California, Los Angeles, Los Angeles, USA**
V. Andreev, K. Arisaka, D. Cline, R. Cousins, A. Deisher, J. Duris, S. Erhan, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein, J. Tucker, V. Valuev

**University of California, Riverside, Riverside, USA**
J. Babb, A. Chandra, R. Clare, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng, S.C. Kao, F. Liu, H. Liu, O.R. Long, A. Luthra, H. Nguyen, B.C. Shen, R. Stringer, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

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

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

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

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

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

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

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

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

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

Florida International University, Miami, USA
C. Ceron, V. Gaulinney, L. Kramer, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, D. Mesa, J.L. Rodriguez

Florida State University, Tallahassee, USA
T. Adams, A. Askew, D. Bandurin, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, L. Quertenmont, S. Sekmen, V. Veeraraghavan

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, B. Dorney, S. Guragain, M. Hohlmann, H. Kalakhety, R. Ralich, I. Vodopiyanov

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, J. Callner, R. Cavanaugh, C. Dragoiu, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, G.J. Kunde, F. Lacroix, M. Malek, C. O’Brien, C. Silvestre, A. Smoron, D. Strom, N. Varelas

The University of Iowa, Iowa City, USA
U. Akgun, E.A. Albayrak, B. Bilki, W. Clarida, F. Duru, C.K. Lae, E. McCliment, J.-P. Merlo, H. Mermakaya, 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. Grigsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, N.V. Tran, A. Whitbeck

The University of Kansas, Lawrence, USA
P. Baringer, A. Bean, G. Benelli, O. Grachov, R.P. Kenny Iii, M. Murray, D. Noonan, S. Sanders, J.S. Wood, V. Zhukova

Kansas State University, Manhattan, USA
A.f. Barfuss, T. Bolton, I. Chakabaria, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze, Z. Wan

Lawrence Livermore National Laboratory, Livermore, USA
J. Gronberg, D. Lange, D. Wright

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

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

University of Minnesota, Minneapolis, USA
S.I. Cooper, P. Cushman, B. Dahmes, A. De Benedetti, P.R. 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, H. Malbouisson, S. Malik, G.R. Snow

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

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

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

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

The Ohio State University, Columbus, USA
B. Bylsma, L.S. Durkin, J. Gu, C. Hill, P. Killewalde, 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. Zatserklyani

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

Purdue University Calumet, Hammond, USA
P. Jindal, N. Parashar
Rice University, Houston, USA  
C. Boulahouache, V. Cuplov, K.M. Ecklund, F.J.M. Geurts, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

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

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

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

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

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

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

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

University of Virginia, Charlottesville, USA  
M.W. Arenton, M. Balazs, S. Boutle, B. Cox, B. Francis, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, R. Yohay

Wayne State University, Detroit, USA  
S. Gollapinni, R. Harr, P.E. Karchin, P. Lamichhane, M. Mattson, C. Milstène, A. Sakharov

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

†: Deceased
1: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
2: Also at Universidade Federal do ABC, Santo Andre, Brazil
3: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
4: Also at Suez Canal University, Suez, Egypt
5: Also at British University, Cairo, Egypt
6: Also at Fayoum University, El-Fayoum, Egypt
7: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland
8: Also at Massachusetts Institute of Technology, Cambridge, USA
A The CMS Collaboration

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