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Search for heavy Majorana neutrinos in $\mu^{\pm}\mu^{\pm}$ + jets and $e^{\pm}e^{\pm}$ + jets events in pp collisions at $\sqrt{s} = 7\,\text{TeV}$

The CMS Collaboration*

Abstract

A search is performed for heavy Majorana neutrinos (N) using an event signature defined by two same-sign charged leptons of the same flavour and two jets. The data correspond to an integrated luminosity of $4.98\,\text{fb}^{-1}$ of pp collisions at a centre-of-mass energy of 7 TeV collected with the CMS detector at the Large Hadron Collider. No excess of events is observed beyond the expected standard model background and therefore upper limits are set on the square of the mixing parameter, $|V_{\ell \text{N}}|^2$, for $\ell = \text{e}, \mu$, as a function of heavy Majorana-neutrino mass. These are the first direct upper limits on the heavy Majorana-neutrino mixing for $m_{\text{N}} > 90\,\text{GeV}$.

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*See Appendix A for the list of collaboration members

1 Introduction

The non-zero masses of neutrinos, confirmed from studies of their oscillations among three species, provide the first evidence for physics beyond the standard model (SM) [1]. The smallness of neutrino masses underscore the lack of a coherent formulation for the generation of mass of elementary particles. The leading theoretical candidate for accommodating neutrino masses is the so-called "seesaw" mechanism [2–5], where the smallness of the observed neutrino masses (m_ν) is attributed to the largeness of a mass (m_{N}) of a new massive neutrino state N, with $m_\nu \approx y_\nu^2 v^2/m_{\mathrm{N}}$, where y_ν is a Yukawa coupling of ν to the Higgs field, and v is the Higgs vacuum expectation value in the SM. In this model the SM neutrinos would also be Majorana particles. Owing to the new heavy neutrino's Majorana nature, it is its own antiparticle, which allows processes that violate lepton-number conservation by two units. Consequently, searches for heavy Majorana neutrinos are of fundamental interest.

The phenomenology of searches for heavy Majorana neutrinos at hadron colliders has been considered by many authors [6–13]. Our search follows the studies in Ref. [11, 12] that use a model-independent phenomenological approach, with m_{N} and $V_{\ell\mathrm{N}}$ as free parameters, where $V_{\ell N}$ is a mixing parameter describing the mixing between the heavy Majorana neutrino and the SM neutrino ν_ℓ of flavour ℓ. Previous direct searches for heavy Majorana neutrinos based on this model have been reported by the L3 [14] and DELPHI [15] Collaborations at the Large Electron-Positron Collider. They have searched for $\mathrm{Z} \to \nu_\ell \mathrm{N}$ decays and set limits on $|V_{\ell\mathrm{N}}|^2$ as a function of m_{N} for heavy Majorana-neutrino masses up to approximately 90 GeV. The ATLAS Collaboration at the Large Hadron Collider (LHC) has also reported limits on heavy Majorana neutrino production [16, 17] in the context of an effective Lagrangian approach [18] and the Left-Right Symmetric Model [19, 20]. Indirect limits on $|V_{\mathrm{eN}}|^2$ have been obtained from the non-observation of neutrinoless double beta decay [21], resulting in 90% confidence level (CL) limits of $|V_{\mathrm{eN}}|^2/m_{\mathrm{N}} < 7 \times 10^{-5}\,\mathrm{TeV}^{-1}$. Precision electroweak measurements have been used to constrain the mixing parameters resulting in indirect 90% CL limits of $|V_{\mathrm{eN}}|^2 < 0.0066$, $|V_{\mu\mathrm{N}}|^2 < 0.0060$, and $|V_{\tau\mathrm{N}}|^2 < 0.016$ [22].

We report on a search for the production of a heavy Majorana neutrino in proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 7\,\mathrm{TeV}$ at the LHC using a set of data of integrated luminosity $4.98 \pm 0.11\,\mathrm{fb}^{-1}$ collected with the Compact Muon Solenoid (CMS) detector. The principal Feynman diagram for this process is shown in Fig. 1. The heavy Majorana neutrino can decay to a lepton with positive or negative charge, leading to events containing two leptons with the same or opposite sign. Same-sign events have much lower backgrounds from SM processes and therefore provide an accessible signature of heavy Majorana neutrino production. We search for events with two isolated leptons of same sign and flavour ($\mu^\pm\mu^\pm$ or $\mathrm{e}^\pm\mathrm{e}^\pm$) and at least two accompanying jets. Contributions from SM processes to such dilepton final states are very small and the background is dominated by processes such as multijet production, in which leptons from b-quark decays or from jets are misidentified as isolated prompt leptons.

2 Signal simulation and data selection

The production and decay process is simulated using the event generator described in Ref. [12] and implemented in ALPGEN [23]. We use the CTEQ5M parton distribution functions [24]. Parton showering and hadronization are simulated using PYTHIA [25]. The Monte Carlo generated events are interfaced with CMS software, where GEANT4 [26] detector simulation, digitization of simulated electronic signals, and event reconstruction are performed. Monte Carlo simulated events are mixed with multiple minimum bias events with weights chosen using the

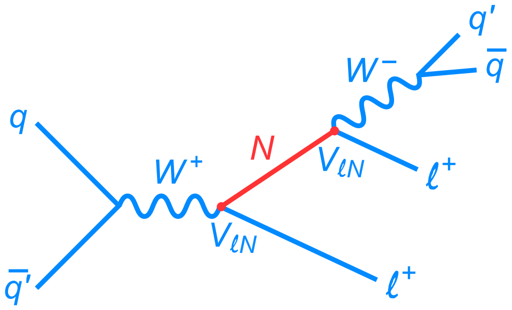

Figure 1: The lowest-order Feynman diagram for production of a heavy Majorana neutrino N. The charge-conjugate diagram also contributes and results in a $\ell^- \ell^- q\bar{q}'$ final state.

distribution of the number of reconstructed primary vertices observed in data to ensure correct simulation of the number of interactions per bunch crossing (pileup). The average number of interactions per crossing in the data used in this analysis is approximately 9. The cross section for the process shown in Fig. 1 for $|V_{\ell N}|^2 = 1$ has a value of 866 pb for $m_{\mathrm{N}} = 50$ GeV, which drops to 2.8 pb for $m_{\mathrm{N}} = 100$ GeV, and to 83 fb for $m_{\mathrm{N}} = 210$ GeV [12].

The CMS detector is described in detail in Ref. [27]. Its central feature is a superconducting solenoid, which provides a magnetic field of 3.8 T along the direction of the counterclockwise rotating beam (as viewed from above the plane of the accelerator), taken as the z axis of the detector coordinate system, with the centre of the detector defined to be $z = 0$. The azimuthal angle ϕ is measured in the plane perpendicular to the z axis, while the polar angle θ is measured with respect to this axis. Muons are measured in four layers of gaseous ionization detectors embedded in the steel return yoke of the magnet, while all other particle detection systems are located inside the bore of the solenoid. Charged particle trajectories are measured in a silicon pixel and strip tracker covering $0 \leq \phi \leq 2\pi$ in azimuth and $|\eta| < 2.5$, where η is the pseudorapidity, defined as $\eta = -\ln[\tan(\theta/2)]$. The tracker is surrounded by a lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass/scintillator hadron calorimeter that are used to measure the energy of electrons, photons, and hadronic jets. A two-level trigger system selects the most interesting events for analysis.

Dilepton triggers are used to select the signal sample. Depending on the average instantaneous luminosity of the LHC, dimuon events are recorded using a trigger requiring the presence of two muons, with transverse momenta (p_{T}) above 7 GeV for both muons in early data-taking runs, above 13 GeV for one muon and above 8 GeV for the second in later runs, or above 17 GeV for one muon and above 8 GeV for the second muon in most recent data. Trigger efficiencies are measured using $\mathrm{Z} \to \mu^+\mu^-$ and $\mathrm{Z} \to \mathrm{e}^+\mathrm{e}^-$ events selected in data, and are found to be $(96.0 \pm 2.0)\%$ for muons and $(98.5 \pm 1.0)\%$ for electrons.

Additional selections are performed offline to ensure the presence of well-identified muons, electrons, and jets. Events are first required to have a well-reconstructed primary vertex based on charged tracks reconstructed in the tracking detectors.

Muon and electron candidates are required to have $|\eta| < 2.4$ and to be consistent with originating from the primary interaction vertex. Muon candidates are reconstructed by matching tracks in the silicon tracker to hits in the outer muon system, and are also required to satisfy specific track-quality and calorimeter-deposition requirements. Electron candidates are reconstructed from energy depositions in the ECAL. These are matched to tracks in the silicon tracker and are required to satisfy shower distribution and cluster-track matching criteria.

Electron candidates within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$ of a muon candidate are rejected to remove spurious electron candidates formed from the track of a muon that has an associated photon from bremsstrahlung. Electron candidates from photon conversions are suppressed by looking for a partner track and requiring that this track has no missing hits in the inner layers of the silicon tracker.

Electron and muon candidates must be isolated from other activity in the event by requiring their relative isolation (I_{rel}) to be less than 0.1. Here I_{rel} is defined as the scalar sum of transverse track momenta and transverse calorimeter energy depositions present within $\Delta R < 0.3$ of the candidate's direction, excluding the candidate itself, divided by its transverse momentum.

Jets and the missing transverse energy in the event are reconstructed using the objects defined in the particle-flow method [28, 29]. Jets are formed from clusters based on the anti-k_{T} algorithm [30], with a distance parameter of 0.5 and are required to be within the pseudorapidity range $|\eta| < 2.5$ and to have transverse momentum $p_{\mathrm{T}} > 30\,\mathrm{GeV}$. At least two jets are required. The missing transverse energy is defined as the modulus of the negative of the vector sum of the transverse momenta of all reconstructed objects identified through the particle-flow algorithm. The missing transverse energy is required to be less than 50 GeV.

Events in the muon channel are required to contain two same-sign muons, one with p_{T} greater than 20 GeV and the other with p_{T} greater than 10 GeV. Events with an opposite-sign third muon that combines with one of the other candidate muons to give a $\mu^+\mu^-$ invariant mass within the window for a Z boson of 76–106 GeV are excluded. In the electron channel, events are required to contain two same-sign electrons, one with p_{T} greater than 20 GeV and one with p_{T} greater than 10 GeV. Events containing any third electron candidate are rejected. Overall signal acceptance includes trigger efficiency, geometrical acceptance, and all selection criteria. In the muon channel, the overall acceptance for heavy Majorana neutrino events ranges between 0.43% for $m_{\mathrm{N}} = 50\,\mathrm{GeV}$ to 29% for $m_{\mathrm{N}} = 210\,\mathrm{GeV}$. For the electron channel, the corresponding efficiency changes from 0.40% to 21% for these masses. The lower acceptance at low m_{N} is due to the smaller average p_{T} of the jets and leptons in these events.

3 Background estimation

There are three potential sources of same-sign dilepton backgrounds. The first and most important originates from events containing leptons from b-quark decays or generic jets that are misidentified as leptons. Examples of this background include: (i) multijet production in which two jets are misidentified as leptons; (ii) $\mathrm{W}(\to \ell\nu)$ + jets events in which one of the jets is misidentified as a lepton; and (iii) $\mathrm{t\bar{t}}$ decays in which one of the top quarks decays giving a prompt isolated lepton ($\mathrm{t} \to \mathrm{Wb} \to \ell\nu_\ell\mathrm{b}$), and the other lepton of same charge arises from a b-quark decay. From Monte Carlo studies we find that the dominant contribution to this background is from multijet production, with the sum of $\mathrm{W}(\to \ell\nu)$ + jets and $\mathrm{t\bar{t}}$ events comprising approximately 15–35% of the total misidentified lepton background. These backgrounds are estimated using control samples in collision data as described below.

To estimate the misidentified lepton background, an independent data sample enriched in multijet events is used to calculate the probability for a jet that passes minimal lepton selection requirements to also pass the more stringent requirements used to define selected leptons. The lepton candidates passing the less stringent requirements are referred to as "loose leptons" and their misidentification probability is calculated as a function of transverse momentum and pseudorapidity. This probability is used as a weight in the calculation of the background in events that pass all the signal selections except that one or both leptons fail the tight criteria (used to select the leptons in signal events). This sample is referred to as the "orthogonal" sample.

The misidentification probability is applied to the orthogonal sample by counting the number of events in which one lepton passes the tight criteria, while the other lepton fails the tight selection but passes the loose selection ($N_{n\overline{n}}$), and the number of events in which both leptons fail the tight selection, but pass the loose criteria ($N_{\overline{nn}}$). The total contribution to the signal sample (i.e. the number of events when both leptons pass the tight selection, N_{nn}), is then obtained by weighting events of type $n\overline{n}$ and $\overline{nn}$ by the appropriate misidentification probability factors. To account for double counting we correct for $\overline{nn}$ events that can also be $n\overline{n}$.

In the muon channel, loose muons are defined by relaxing the muon isolation requirement from $I_{\mathrm{rel}} < 0.1$ (used to select signal events) to $I_{\mathrm{rel}} < 0.8$. In the electron channel, loose electrons are defined by relaxing the isolation from 0.1 to 0.6, and by removing a requirement on transverse impact parameter normally used for tight electrons.

We evaluate the method used to estimate the background from misidentified leptons by checking the procedure using Monte Carlo simulated event samples in which the true background is known. The misidentification probabilities are obtained from multijet events and are used to estimate the misidentified lepton backgrounds in $\mathrm{t\bar{t}}$, W + jets, and multijet events by applying the background estimation method described above. The differences between the estimated backgrounds and the true number of events in the Monte Carlo samples is used as input to the overall systematic uncertainty.

The overall systematic uncertainty on the misidentified lepton background is determined from the variation of the background estimate with the loose lepton definition and the variation with the leading jet p_{T} requirement in the data samples used to measure the misidentification probability, as well as from the independent Monte Carlo validation studies described above. The overall uncertainty is found to be 35%.

The second contribution to the background is from $\ell^+\ell^-$ events in which the charge of one of the leptons is mismeasured. Since the charge mismeasurement probability is very small for muons, this background is significant only in the electron channel. The background from mismeasurement of electron charge is estimated through probabilities calculated in Monte Carlo studies of $\mathrm{e^+e^-}$ events that pass all selections for signal, except the same-sign requirement. The average electron mismeasurement probability is found to be $(3.3 \pm 0.2) \times 10^{-4}$ in the ECAL barrel region ($|\eta| < 1.5$) and $(2.9 \pm 0.1) \times 10^{-3}$ in the ECAL endcap region ($1.5 < |\eta| < 2.5$). To validate the charge mismeasurement probability, we select a control sample of $\mathrm{Z} \to \mathrm{e^+e^-}$ events in data, requiring an $\mathrm{e^+e^-}$ invariant mass between 76 and 106 GeV. We use the difference between the predicted and the observed number of $\mathrm{e^{\pm}e^{\pm}}$ events, including uncertainties, to set a systematic uncertainty of 25% on the background from charge mismeasurement.

The third background source is the irreducible background from SM production of two genuine isolated leptons of the same sign, which can originate from sources such as ZZ, WZ, and $\mathrm{W}\gamma$ diboson production, $\mathrm{t\bar{t}W}$, double W-strahlung $\mathrm{W^{\pm}W^{\pm}qq}$ processes, and double-parton scattering (two $\mathrm{qq'} \to \mathrm{W}$). These have relatively small cross sections, and are consequently estimated using Monte Carlo simulations. We use PYTHIA to simulate ZZ and WZ production and MADGRAPH [31] for the remaining processes.

4 Systematic uncertainties

The sources of systematic uncertainty associated with signal efficiency and background estimates can be summarized as follows.

(1) The systematic uncertainty on the integrated luminosity is 2.2% [32].

(2) The systematic uncertainty from choice of parton distribution functions is estimated from Monte Carlo simulations following the PDF4LHC recommendations [33] and is found to be 6% of the signal yield.

(3) The hard-scattering scale in the ALPGEN Monte Carlo generator is varied from the nominal value of Q^2 to $4Q^2$ and $Q^2/4$. The resulting uncertainty on the signal yield is 1%.

(4) The jet energy scale is changed by its estimated uncertainty [34] resulting in a systematic uncertainty of between 3.3% for high heavy Majorana-neutrino mass ($m_{\mathrm{N}} = 210\,\mathrm{GeV}$) and 14.2% at low mass ($m_{\mathrm{N}} = 50\,\mathrm{GeV}$). For low mass events the jets from the heavy Majorana neutrino decay have lower average p_{T}, leading to larger uncertainties.

(5) The systematic uncertainty due to the uncertainty on the jet energy resolution [34] is determined to be 0.2%–1%, depending on m_{N}.

(6) The uncertainty in modeling event pileup is studied in the Monte Carlo simulations and found to be 1%.

(7) The systematic uncertainty on the estimate of misidentified lepton background is 35%.

(8) The systematic uncertainty on the background from mismeasurement of electron charge is 25%.

(9) The systematic uncertainties on normalizations of irreducible SM backgrounds are: 6% for WZ and ZZ [35]; 10% for Wγ [35]; and 50% for the other processes, determined by varying the Q^2 scale and parton distribution functions in Monte Carlo simulations.

In the muon channel the systematic uncertainty due to the muon trigger, as indicated above, is based on studies of $\mathrm{Z} \rightarrow \mu^+\mu^-$ events in collision data, and is determined to be 2% per muon. The offline muon selection efficiency is taken from Monte Carlo simulation, and cross-checked with data using studies of $\mathrm{Z} \rightarrow \mu^+\mu^-$ events. The efficiencies measured in data and Monte Carlo simulation are found to be in agreement within uncertainties; the systematic uncertainty associated with the small differences is 2%. The overall systematic uncertainty due to the muon trigger and selection is 4%. In the electron channel the systematic uncertainty from the trigger and electron selections is determined in a similar way, and found to be 10%.

5 Results and discussion

After applying all the final selections we observe 65 events in data in the muon channel and expect a total SM background of $70 \pm 4\,(\mathrm{stat.}) \pm 22\,(\mathrm{syst.})$ events, with the dominant contribution of $63 \pm 4\,(\mathrm{stat.}) \pm 22\,(\mathrm{syst.})$ events arising from the misidentified muon background. The data are in agreement with the estimated background. In the electron channel we observe 201 events in data, and estimate the total SM background as $219 \pm 6\,(\mathrm{stat.}) \pm 62\,(\mathrm{syst.})$ events, with the dominant contribution of $177 \pm 5\,(\mathrm{stat.}) \pm 62\,(\mathrm{syst.})$ events arising from the misidentified electron background. The data are again in agreement with the estimated background. The final estimates for the two channels are given in Table 1.

Table 1: Observed event yields and estimated backgrounds in the muon and electron channel. Also shown are the expected number of signal events for two heavy Majorana-neutrino masses of 130 and 210 GeV/c^2, for a mixing parameter $|V_{\ell N}|^2 = 0.1$. The sets of first and second uncertainties on the background and signal estimates correspond, respectively, to statistical and systematic contributions. For the irreducible SM backgrounds and the expected signals, the first uncertainty is due to the statistical error associated with the finite size of the Monte Carlo event samples used.

Source	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$
Irreducible SM backgrounds:		
WZ	$3.2 \pm 0.3 \pm 0.2$	$4.9 \pm 0.3 \pm 0.3$
ZZ	$1.0 \pm 0.1 \pm 0.1$	$2.1 \pm 0.1 \pm 0.1$
Wγ	$0.75 \pm 0.27 \pm 0.07$	$1.7 \pm 0.4 \pm 0.2$
$t\bar{t}W$	$1.06 \pm 0.05 \pm 0.53$	$0.62 \pm 0.04 \pm 0.31$
W^+W^+qq	$0.76 \pm 0.06 \pm 0.38$	$0.73 \pm 0.07 \pm 0.37$
W^-W^-qq	$0.45 \pm 0.03 \pm 0.23$	$0.27 \pm 0.02 \pm 0.13$
Double-parton $W^{\pm}W^{\pm}$	$0.07 \pm 0.02 \pm 0.04$	$0.19 \pm 0.03 \pm 0.10$
Total irreducible SM background	$7.3 \pm 0.4 \pm 0.7$	$10.6 \pm 0.6 \pm 0.6$
Charge mismeasurement background	$0^{+0.2}_{-0}$	$31.9 \pm 2.7 \pm 8.0$
Misidentified lepton background	$63.1 \pm 4.2 \pm 22.1$	$176.8 \pm 4.7 \pm 61.9$
Total background	$70 \pm 4 \pm 22$	$219 \pm 6 \pm 62$
Data	65	201
Expected signal:		
$m_N = 130\,\text{GeV}/c^2$, $|V_{\ell N}|^2 = 0.1$	$58 \pm 1 \pm 4$	$39 \pm 1 \pm 3$
$m_N = 210\,\text{GeV}/c^2$, $|V_{\ell N}|^2 = 0.1$	$12.0 \pm 0.1 \pm 0.8$	$8.5 \pm 0.1 \pm 0.6$

Figure 2 shows the distributions of invariant mass of the second highest p_T lepton and the two leading jets in the event for data, standard model backgrounds, and three choices for the Majorana neutrino signal: $m_N = 80\,\text{GeV}/c^2$, $|V_{\ell N}|^2 = 0.025$, $m_N = 130\,\text{GeV}/c^2$, $|V_{\ell N}|^2 = 0.025$, and $m_N = 210\,\text{GeV}/c^2$, $|V_{\ell N}|^2 = 0.25$. From Monte Carlo studies, the choice of second highest p_T lepton is found to give better performance for reconstruction of the Majorana neutrino mass compared with taking either the leading p_T lepton or randomly picking one of the leptons.

We see no evidence for a significant excess in the data beyond the backgrounds predicted from the SM and set 95% CL exclusion limits on the square of the heavy Majorana-neutrino mixing parameter as a function of m_N, using the CL_s method [36–38] based on the event yields shown in Table 1. In the muon channel analysis we set limits on $|V_{\mu N}|^2$ as a function of m_N, under the assumption $|V_{eN}|^2 = |V_{\tau N}|^2 = 0$. In the electron channel analysis we set limits on $|V_{eN}|^2$ as a function of m_N under the assumption $|V_{\mu N}|^2 = |V_{\tau N}|^2 = 0$. Figure 3(a) shows the resulting upper limits in the muon channel ($|V_{\mu N}|^2$ vs. m_N), while Fig. 3(b) shows the upper limits in the electron channel ($|V_{eN}|^2$ vs. m_N). These are the first direct upper limits on the heavy Majorana-neutrino mixing for $m_N > 90\,\text{GeV}$.

For low m_N the limits in both channels are less stringent than the existing limits from DELPHI and L3 shown in Figs. 3(a) and 3(b), due to the higher backgrounds at the LHC. However, the DELPHI and L3 limits are derived from $Z \to \nu_\ell N$ and are restricted to masses below approximately 90 GeV. The limits reported here extend well beyond this mass. For $m_N = 90\,\text{GeV}$ we

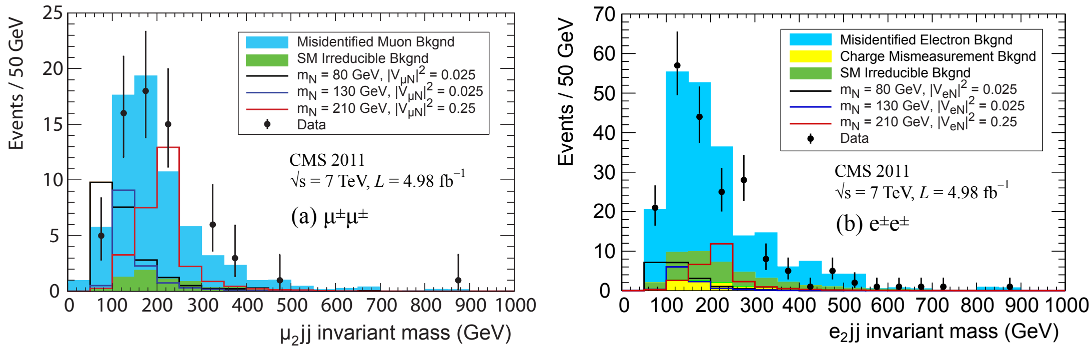

Figure 2: Invariant mass of the second leading p_T lepton and the two leading jets for events passing the signal selection. The plots show the data, standard model backgrounds, and three choices for the heavy Majorana-neutrino signal: $m_N = 80\,\text{GeV}/c^2$, $|V_{\ell N}|^2 = 0.025$, $m_N = 130\,\text{GeV}/c^2$, $|V_{\ell N}|^2 = 0.025$, and $m_N = 210\,\text{GeV}/c^2$, $|V_{\ell N}|^2 = 0.25$. (a) Distributions for $\mu^{\pm}\mu^{\pm}$ events; (b) distributions for $e^{\pm}e^{\pm}$ events.

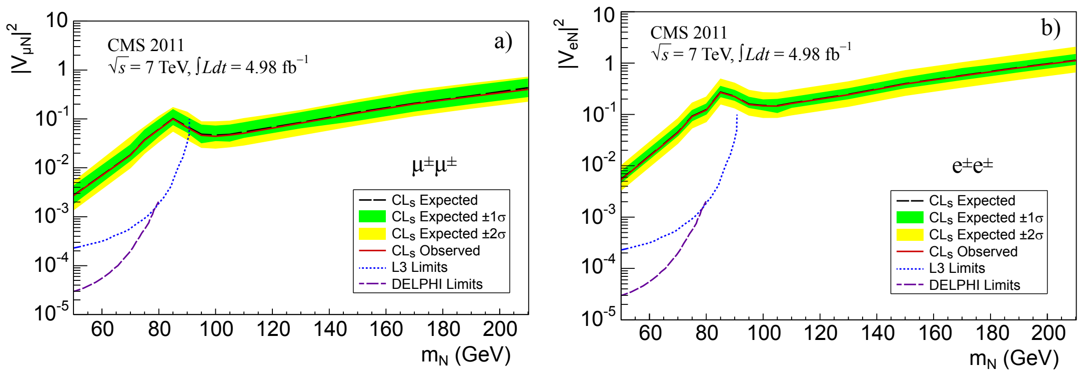

Figure 3: Exclusion region at 95% CL in the square of the heavy Majorana-neutrino mixing parameter as a function of the heavy Majorana-neutrino mass: (a) $|V_{\mu \text{N}}|^2$ vs m_{N}; (b) $|V_{\text{eN}}|^2$ vs. m_{N}. The long-dashed black line is the expected upper limit, with one and two standard-deviation bands shown in dark green and light yellow, respectively. The solid red line is the observed upper limit, and is very close to the expected limit such that the two curves almost overlap. Also shown are the upper limits from L3 [14] and DELPHI [15]. The regions above the exclusion lines are ruled out at 95% CL.

find $|V_{\mu \text{N}}|^2 < 0.07$ and $|V_{\text{eN}}|^2 < 0.22$. At $m_{\text{N}} = 210\,\text{GeV}$ we find $|V_{\mu \text{N}}|^2 < 0.43$, while for $|V_{\text{eN}}|^2$ the limit reaches 1.0 at a mass of 203 GeV.

6 Summary

A search for heavy Majorana neutrinos in $\mu^{\pm}\mu^{\pm}$ and $e^{\pm}e^{\pm}$ events has been performed using a set of data corresponding to $5.0\,\text{fb}^{-1}$ of pp collisions at a centre-of-mass energy of 7 TeV. No excess of events beyond the standard model background prediction is found. Upper limits at the 95% CL are set on the square of the heavy Majorana-neutrino mixing parameter, $|V_{\ell \text{N}}|^2$, for $\ell = \text{e}, \mu$, as a function of heavy Majorana-neutrino mass, as shown in Figs. 3(a) and 3(b). For $m_{\text{N}} = 90\,\text{GeV}$ the limits are $|V_{\mu \text{N}}|^2 < 0.07$ and $|V_{\text{eN}}|^2 < 0.22$. At $m_{\text{N}} = 210\,\text{GeV}$ the limits are $|V_{\mu \text{N}}|^2 < 0.43$, while for $|V_{\text{eN}}|^2$ the limit reaches 1.0 at a mass of 203 GeV. These are the first direct upper limits on the heavy Majorana-neutrino mixing for $m_{\mathrm{N}} > 90\,\mathrm{GeV}$.

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

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

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

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

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

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

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

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

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, M. Correa Martins Junior, D. De Jesus Damiao, T. Martins, M.E. Pol, M.H.G. Souza

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

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil
T.S. Anjos[3], C.A. Bernardes[3], F.A. Dias[4], T.R. Fernandez Perez Tomei, E. M. Gregores[3], C. Lagana, F. Marinho, P.G. Mercadante[3], S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
V. Genchev[5], P. Iaydjiev[5], S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

University of Sofia, Sofia, Bulgaria
A. Dimitrov, R. Hadjiiska, V. Kozhuharov, L. Litov, 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, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

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

Universidad de Los Andes, Bogota, Colombia
C. Avila, J.P. Gomez, B. Gomez Moreno, A.F. Osorio Oliveros, J.C. Sanabria

Technical University of Split, Split, Croatia
N. Godinovic, D. Lelas, R. Plestina[6], D. Polic, I. Puljak[5]

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

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

University of Cyprus, Nicosia, Cyprus
A. Attikis, M. Galanti, G. Mavromanolakis, 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. Assran[7], S. Elgammal[8], A. Ellithi Kamel[9], S. Khalil[8], M.A. Mahmoud[10], A. Radi[11,12]

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

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, G. Fedi, M. Voutilainen

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

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

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, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, L. Millischer, A. Nayak, J. Rander, A. Rosowsky, I. Shreyber, M. Titov

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj[13], C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenauer, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram[14], J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte[14], F. Drouhin[14], C. Ferro, J.-C. Fontaine[14], D. Gelé, U. Goerlach, P. Juillot, A.-C. Le Bihan, P. Van Hove

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

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, N. Beaupere, O. Bondu, G. Boudoul, J. Chasserat, R. Chierici[5], D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, L. Sgandurra, V. Sordini, Y. Tschudi, P. Verdier, S. Viret

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[15]

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

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

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
M. Bontenackels, V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, J. Lingemann[5], A. Nowack, L. Perchalla, O. Pooth, P. Sauerland, A. Stahl

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

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

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

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

University of Athens, Athens, Greece
L. Gouskos, T.J. Mertzimekis, A. Panagiotou, N. Saoulidou

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

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
G. Bencze, C. Hajdu, P. Hidas, D. Horvath[18], F. Sikler, V. Veszpremi, G. Vesztergombi[19]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Molnar, J. Palinkas, Z. Szillasi

University of Debrecen, Debrecen, Hungary
J. Karancsi, P. Raics, Z.L. Trocsanyi, B. Ujvari

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

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

Saha Institute of Nuclear Physics, Kolkata, India
S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India
A. Abdulsalam, R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, P. Mehta, A.K. Mohanty[5], L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India
T. Aziz, S. Ganguly, M. Guchait[20], M. Maity[21], G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage

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

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
H. Arfaei[22], H. Bakhshiansohi, S.M. Etesami[23], A. Fahim[22], M. Hashemi, H. Hesari, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh[24], 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,5], S.S. Chhibra[a,b], A. Colaleo[a], D. Creanza[a,c],

N. De Filippis[a,c,5], M. De Palma[a,b], L. Fiore[a], G. Iaselli[a,c], L. Lusito[a,b], G. Maggi[a,c], M. Maggi[a], B. Marangelli[a,b], S. My[a,c], S. Nuzzo[a,b], N. Pacifico[a,b], A. Pompili[a,b], G. Pugliese[a,c], G. Selvaggi[a,b], L. Silvestris[a], G. Singh[a,b], R. Venditti[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,b], S. Braibant-Giacomelli[a,b], L. Brigliadori[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a,b,5], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], S. Marcellini[a], G. Masetti[a], M. Meneghelli[a,b,5], A. Montanari[a], F.L. Navarria[a,b], F. Odorici[a], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], T. Rovelli[a,b], G. Siroli[a,b], R. Travaglini[a,b]

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

INFN Sezione di Firenze [a], Università di Firenze [b], Firenze, Italy
G. Barbagli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], S. Frosali[a,b], E. Gallo[a], S. Gonzi[a,b], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], A. Tropiano[a]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, S. Colafranceschi[25], F. Fabbri, D. Piccolo

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

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
A. Benaglia[a,b], F. De Guio[a,b], L. Di Matteo[a,b,5], S. Fiorendi[a,b], S. Gennai[a,5], A. Ghezzi[a,b], S. Malvezzi[a], R.A. Manzoni[a,b], A. Martelli[a,b], A. Massironi[a,b,5], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], N. Redaelli[a], S. Sala[a], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli [a], Università di Napoli "Federico II" [b], Napoli, Italy
S. Buontempo[a], C.A. Carrillo Montoya[a], N. Cavallo[a,26], A. De Cosa[a,b,5], O. Dogangun[a,b], F. Fabozzi[a,26], A.O.M. Iorio[a], L. Lista[a], S. Meola[a,27], M. Merola[a,b], P. Paolucci[a,5]

INFN Sezione di Padova [a], Università di Padova [b], Università di Trento (Trento) [c], Padova, Italy
P. Azzi[a], N. Bacchetta[a,5], P. Bellan[a,b], D. Bisello[a,b], A. Branca[a,5], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], K. Kanishchev[a,c], S. Lacaprara[a], I. Lazzizzera[a,c], M. Margoni[a,b], A.T. Meneguzzo[a,b], M. Nespolo[a,5], J. Pazzini[a,b], P. Ronchese[a,b], F. Simonetto[a,b], E. Torassa[a], S. Vanini[a,b], P. Zotto[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
M. Gabusi[a,b], S.P. Ratti[a,b], C. Riccardi[a,b], P. Torre[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
M. Biasini[a,b], G.M. Bilei[a], L. Fanò[a,b], P. Lariccia[a,b], G. Mantovani[a,b], M. Menichelli[a], A. Nappi[a,b†], F. Romeo[a,b], A. Saha[a], A. Santocchia[a,b], A. Spiezia[a,b], S. Taroni[a,b]

INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa, Italy
P. Azzurri[a,c], G. Bagliesi[a], T. Boccali[a], G. Broccolo[a,c], R. Castaldi[a], R.T. D'Agnolo[a,c,5], R. Dell'Orso[a], F. Fiori[a,b,5], L. Foà[a,c], A. Giassi[a], A. Kraan[a], F. Ligabue[a,c], T. Lomtadze[a], L. Martini[a,28], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], A.T. Serban[a,29], P. Spagnolo[a], P. Squillacioti[a,5], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], 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], M. Diemoz[a], C. Fanelli, M. Grassi[a,b,5], E. Longo[a,b],

P. Meridiani[a,5], F. Micheli[a,b], S. Nourbakhsh[a,b], G. Organtini[a,b], R. Paramatti[a], S. Rahatlou[a,b], M. Sigamani[a], L. Soffi[a,b]

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

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], G. Della Ricca[a,b], B. Gobbo[a], M. Marone[a,b,5], D. Montanino[a,b,5], A. Penzo[a], A. Schizzi[a,b]

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

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

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

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

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

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

Vilnius University, Vilnius, Lithuania
M.J. Bilinskas, I. Grigelionis, M. Janulis, A. Juodagalvis

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez, R. Magaña Villalba, J. Martínez-Ortega, 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

University of Canterbury, Christchurch, New Zealand
A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
M. Ahmad, M.H. Ansari, M.I. Asghar, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

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

Soltan Institute for Nuclear Studies, Warsaw, Poland
H. Bialkowska, B. Boimska, 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, J. Seixas, J. Varela, P. Vischia

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

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

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

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

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

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

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin[5], V. Kachanov, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[30], M. Djordjevic, M. Ekmedzic, D. Krpic[30], 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. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, C. Fernandez

Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, G. Codispoti, J.F. de Trocóniz

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

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[31], M. Fernandez, G. Gomez, J. Gonzalez Sanchez, A. Graziano, C. Jorda, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

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

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[36]

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

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

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, A.P. Singh, R. Volpe, S.S. Yu

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

Chulalongkorn University, Bangkok, Thailand
B. Asavapibhop, N. Srimanobhas

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

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

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

Istanbul Technical University, Istanbul, Turkey
K. Cankocak

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

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

Rutherford Appleton Laboratory, Didcot, United Kingdom
L. Basso[48], K.W. Bell, A. Belyaev[48], C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

Imperial College, London, United Kingdom
R. Bainbridge, G. Ball, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko[38], A. Papageorgiou, J. Pela, M. Pesaresi, K. Petridis, M. Pioppi[49], D.M. Raymond, S. Rogerson, A. Rose, M.J. Ryan, C. Seez, P. Sharp[†], A. Sparrow, M. Stoye, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie

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

Baylor University, Waco, USA
K. Hatakeyama, H. Liu, T. Scarborough

The University of Alabama, Tuscaloosa, USA
O. Charaf, C. Henderson, P. Rumerio

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

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

University of California, Davis, Davis, USA
R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, J. Dolen, R. Erbacher, M. Gardner, R. Houtz, W. Ko, A. Kopecky, R. Lander, O. Mall, T. Miceli, D. Pellett, F. Ricci-tam, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra

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

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

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

University of California, 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, C. West

California Institute of Technology, Pasadena, USA
A. Apresyan, A. Bornheim, Y. Chen, E. Di Marco, J. Duarte, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, M. Spiropulu, V. Timciuc, J. Veverka, R. Wilkinson, S. Xie, Y. Yang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
B. Akgun, V. Azzolini, A. Calamba, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, Y.F. Liu, M. Paulini, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, USA
J.P. Cumalat, B.R. Drell, W.T. Ford, A. Gaz, E. Luiggi Lopez, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner

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

Fairfield University, Fairfield, USA
D. Winn

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

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

Florida International University, Miami, USA
V. Gaultney, S. Hewamanage, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

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

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, 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, I. Bucinskaite, J. Callner, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, D. Strom, P. Turner, N. Varelas

The University of Iowa, Iowa City, USA
U. Akgun, E.A. Albayrak, B. Bilki[54], W. Clarida, F. Duru, J.-P. Merlo, H. Mermerkaya[55], A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, Y. Onel, F. Ozok[56], S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

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

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

Kansas State University, Manhattan, USA
A.F. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze

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

University of Maryland, College Park, USA
A. Baden, M. Boutemeur, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn,

T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, K. Pedro, A. Peterman, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

Massachusetts Institute of Technology, Cambridge, USA
A. Apyan, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, Y. Kim, M. Klute, K. Krajczar[57], P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, E.A. Wenger, R. Wolf, B. Wyslouch, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

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

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

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

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, M. Chasco, J. Haley, D. Nash, D. Trocino, D. Wood, J. Zhang

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

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

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

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

University of Puerto Rico, Mayaguez, USA
E. Brownson, A. Lopez, H. Mendez, J.E. Ramirez Vargas

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

Purdue University Calumet, Hammond, USA
S. Guragain, N. Parashar

Rice University, Houston, USA
A. Adair, C. Boulahouache, K.M. Ecklund, F.J.M. Geurts, W. Li, 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, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, D.C. Miner, D. Vishnevskiy, M. Zielinski

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

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

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

Texas A&M University, College Station, USA
R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon[58], V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, C. Dragoiu, P.R. Dudero, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, Y. Roh, I. Volobouev

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

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

Wayne State University, Detroit, USA
S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

University of Wisconsin, Madison, USA
M. Anderson, D. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, E. Friis, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, I. Ojalvo, F. Palmonari, G.A. Pierro, I. Ross, A. Savin, W.H. Smith, J. Swanson

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
3: Also at Universidade Federal do ABC, Santo Andre, Brazil
4: Also at California Institute of Technology, Pasadena, USA

5: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
6: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
7: Also at Suez Canal University, Suez, Egypt
8: Also at Zewail City of Science and Technology, Zewail, Egypt
9: Also at Cairo University, Cairo, Egypt
10: Also at Fayoum University, El-Fayoum, Egypt
11: Also at British University, Cairo, Egypt
12: Now at Ain Shams University, Cairo, Egypt
13: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland
14: Also at Université de Haute-Alsace, Mulhouse, France
15: Now at Joint Institute for Nuclear Research, Dubna, Russia
16: Also at Moscow State University, Moscow, Russia
17: Also at Brandenburg University of Technology, Cottbus, Germany
18: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
19: Also at Eötvös Loránd University, Budapest, Hungary
20: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
21: Also at University of Visva-Bharati, Santiniketan, India
22: Also at Sharif University of Technology, Tehran, Iran
23: Also at Isfahan University of Technology, Isfahan, Iran
24: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Teheran, Iran
25: Also at Facoltà Ingegneria Università di Roma, Roma, Italy
26: Also at Università della Basilicata, Potenza, Italy
27: Also at Università degli Studi Guglielmo Marconi, Roma, Italy
28: Also at Università degli studi di Siena, Siena, Italy
29: Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania
30: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
31: Also at University of California, Los Angeles, Los Angeles, USA
32: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
33: Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy
34: Also at University of Athens, Athens, Greece
35: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
36: Also at The University of Kansas, Lawrence, USA
37: Also at Paul Scherrer Institut, Villigen, Switzerland
38: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
39: Also at Gaziosmanpasa University, Tokat, Turkey
40: Also at Adiyaman University, Adiyaman, Turkey
41: Also at Izmir Institute of Technology, Izmir, Turkey
42: Also at The University of Iowa, Iowa City, USA
43: Also at Mersin University, Mersin, Turkey
44: Also at Ozyegin University, Istanbul, Turkey
45: Also at Kafkas University, Kars, Turkey
46: Also at Suleyman Demirel University, Isparta, Turkey
47: Also at Ege University, Izmir, Turkey
48: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
49: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
50: Also at University of Sydney, Sydney, Australia
51: Also at Utah Valley University, Orem, USA

52: Also at Institute for Nuclear Research, Moscow, Russia
53: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
54: Also at Argonne National Laboratory, Argonne, USA
55: Also at Erzincan University, Erzincan, Turkey
56: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
57: Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
58: Also at Kyungpook National University, Daegu, Korea