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Search for heavy lepton partners of neutrinos in proton–proton collisions in the context of the type III seesaw mechanism ☆

CMS Collaboration ⋆

CERN, Switzerland

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ABSTRACT

A search is presented in proton–proton collisions at $\sqrt{s} = 7$ TeV for fermionic triplet states expected in type III seesaw models. The search is performed using final states with three isolated charged leptons and an imbalance in transverse momentum. The data, collected with the CMS detector at the LHC, correspond to an integrated luminosity of 4.9 fb^{-1}. No excess of events is observed above the background predicted by the standard model, and the results are interpreted in terms of limits on production cross sections and masses of the heavy partners of the neutrinos in type III seesaw models. Depending on the considered scenarios, lower limits are obtained on the mass of the heavy partner of the neutrino that range from 180 to 210 GeV. These are the first limits on the production of type III seesaw fermionic triplet states reported by an experiment at the LHC.

1. Introduction

Experiments on neutrino oscillations [1–4] indicate that neutrinos have mass and their masses are much smaller than those of the charged leptons. However, the origin of neutrino mass is still unknown. An interesting possibility is provided by the seesaw mechanism, in which a small Majorana mass can be generated for each of the known neutrinos by introducing massive states with Yukawa couplings to leptons and to the Higgs field. Seesaw models called type I [5,6], type II [7–11], and type III [12,13] introduce heavy states of mass M, that involve, respectively, weak-isospin singlets, scalar triplets, and fermion triplets. The neutrino masses are generically reduced relative to charged fermion masses by a factor v/M, where v is the vacuum expectation value of the Higgs field. For sufficiently large M (of the order of 10^{14} GeV), small neutrino masses are generated even for Yukawa couplings of ≈1. On the other hand, either smaller Yukawa couplings or extended seesaw mechanisms, such as those of the inverse seesaw models [14], are required to obtain small neutrino masses while keeping M close to a few hundreds of GeV. At the Large Hadron Collider (LHC), type II and III states can be produced through gauge interactions, so that the possible smallness of the Yukawa couplings does not affect the production cross section of the heavy states. In particular, the possibility of discovering a type III fermion at a proton–proton centre-of-mass energy of $\sqrt{s} = 14$ TeV is discussed in Refs. [15–17]. Recently, a leading-order (LO) computation of the signal expected at $\sqrt{s} = 7$ TeV has become available as a computer program for simulating such final states [18].

Given the electric charges of the lepton triplet, hereafter referred to as Σ^+, Σ^0, and Σ^-, the most promising signature for finding a Σ state with a mass M_Σ of the order of a few hundreds of GeV is in production through quark–antiquark annihilation $q\bar{q}' \to \Sigma^0\Sigma^+$, followed by the decays $\Sigma^0 \to \ell^\mp W^\pm$ and $\Sigma^+ \to W^+\nu$. The mass differences among the three electric charge states are assumed to be negligible. The mass range relevant for this analysis is bounded by the present lower limits (≈100 GeV) from the L3 experiment [19] and by the CMS loss of sensitivity near ≈200 GeV because of the very steep decrease of the expected cross section with mass. Since there are twice as many u as d valence quarks in the proton, the production of $\Sigma^+\Sigma^0$ via virtual W^+ bosons in the s-channel (Fig. 1) has the highest cross section of all the Σ charge combinations. (The cross section for the charge conjugate intermediary W^- is expected to be about a factor two smaller.) Selecting $W^\pm \to \ell^\pm\nu$ decays (where ℓ is an electron or muon) as the final states for the search, offers a very clean signature of three charged, isolated leptons. The decay $\Sigma^+ \to \ell^+ Z$, with $Z \to \nu\bar{\nu}$ or $Z \to q\bar{q}$, can also contribute significantly to the three-lepton final state, especially since its relative yield grows with M_Σ. The τ lepton also contributes to the three-lepton final states through $\tau \to \ell\nu_\ell\nu_\tau$ decays. Details of the phenomenology and the different contributions to the final state of interest can be found in Ref. [18].

The total width of the Σ states and their decay branching fractions to SM leptons depend on the mixing matrix element for the

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

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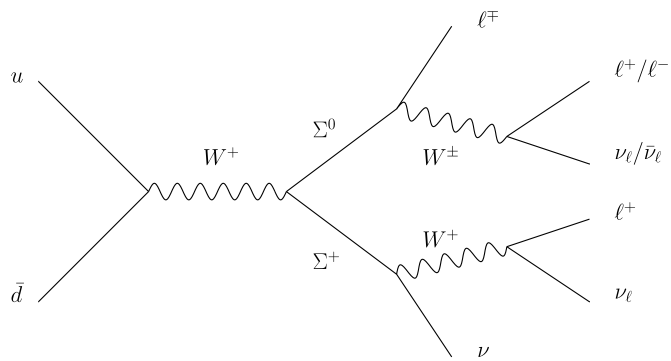

Fig. 1. Feynman diagram for the dominant contribution to three-charged-leptons final states in pair production of Σ in the type III seesaw models. The production cross section for the charged-conjugate intermediary W^- is expected to be about a factor of two smaller.

leptons V_α, where α labels each of the e, μ, and τ generations of leptons. Constraints on the mixing parameters and their products are available in Refs. [18,20].

The $\Sigma\Sigma$ production cross section does not depend on the matrix elements V_α, which enter only in the Σ decays. The fraction of Σ decays to the lepton α is proportional to:

$$b_\alpha = \frac{|V_\alpha|^2}{|V_e|^2 + |V_\mu|^2 + |V_\tau|^2}. \qquad (1)$$

If all three V_α values are less than $\approx 10^{-6}$, the Σ states can have sufficiently long lifetimes to produce leptons at secondary vertices, a possibility not considered in this analysis.

This Letter reports on a search for fermionic triplet states expected in type III seesaw models, in final states with three charged leptons and an imbalance in transverse momentum (E_T^{miss}). The data sample corresponds to an integrated luminosity of 4.9 fb^{-1}, collected in proton–proton collisions at $\sqrt{s} = 7$ TeV with the Compact Muon Solenoid (CMS) detector at the LHC in 2011. The analysis is based on the model described in Ref. [15], using the implementation of Ref. [18]. Three possibilities are considered for the ratios b_α, defined in Eq. (1): first, $b_e = b_\mu = b_\tau = 1/3$, hereafter referred to as the flavor-democratic scenario (FDS), second, $b_e = 0$, $b_\mu = 1$, $b_\tau = 0$, and third, $b_e = 1$ and $b_\mu = b_\tau = 0$, hereafter referred to as the muon scenario (μS) and the electron scenario (eS), respectively.

2. The CMS detector

A detailed description of the CMS detector can be found in Ref. [21]. The central feature of the CMS apparatus is a superconducting solenoid that provides an axial magnetic field of 3.8 T. A silicon tracker, a lead-tungstate crystal electromagnetic calorimeter (ECAL), and a brass/scintillator hadron calorimeter (HCAL) reside within the magnetic field volume. Muons are identified using the central tracker and a muon system consisting of gas-ionization detectors embedded in the steel return yoke outside of the solenoid.

The directions of particles in the CMS detector are described using the azimuthal angle ϕ and the pseudorapidity η, defined as $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle relative to the anticlockwise proton beam. All objects are reconstructed using a particle-flow (PF) algorithm [22–24]. The PF algorithm combines information from all subdetectors to identify and reconstruct particles detected in the collision, namely charged hadrons, photons, neutral hadrons, muons, and electrons. Jets are reconstructed using the anti-k_T jet clustering algorithm with a distance parameter of 0.5 [25]. Jet energies are corrected for non-uniformity in calorimeter response and for differences found between jets in simulation and in data [26]. An imbalance in transverse momentum (E_T^{miss}) is defined by the magnitude of the vectorial sum of the transverse momenta (p_T) of all particles reconstructed through the PF algorithm.

3. Simulation of signal and background

To estimate signal efficiency, $\Sigma^+\Sigma^0$ events are generated using the FeynRules and MadGraph computer programs described in Ref. [18], while parton showers and hadronization are implemented using the pythia generator (v6.420) [27]. The detector simulation is based on the Geant4 program [28]. Given the number of M_Σ mass points to be generated, part of the detector simulation is performed using the CMS Fast Simulation framework [29,30]. Several background sources are considered in this analysis, the most relevant one being WZ production with both bosons decaying into leptons. A smaller contribution to the background comes from ZZ production, where the Z bosons decay leptonically, and one of the leptons is either outside of the detector acceptance or is misreconstructed. These two-boson events, calculated at next-to-LO with MCFM [31], are generated with pythia. Backgrounds from the production of three EW bosons are generated with MadGraph 5 [32]. Backgrounds from jets and photons that are misidentified as leptons are also taken into account, including events from Drell–Yan $\ell^+\ell^- +$ jets sources [33], W + jets, Z + jets, $t\bar{t}$, and Drell–Yan $\ell^+\ell^- + \gamma$ conversions to $\ell^+\ell^-$. (The Drell–Yan process consists of $q\bar{q} \to \gamma^*/Z \to \ell^+\ell^-$ production, with γ^* and Z intermediaries representing virtual γ or Z bosons.)

The presence of additional simultaneous pp interactions (pileup) is incorporated by simulating and mixing additional interactions with a multiplicity matching that observed in data.

4. Event selection criteria

The online trigger and the offline selection criteria are analogous to those used in other multi-lepton analyses performed by the CMS Collaboration [34,35]. Events are selected through two-lepton triggers in which two muons, two electrons, or one electron and one muon are required to be present. Because of the steady increase in instantaneous luminosity in 2011, some of the lepton p_T thresholds were increased over time to keep the trigger rates within the capabilities of the data acquisition system. For the two-muon trigger, the p_T requirements evolved from 7 GeV for each muon to asymmetric requirements of 17 GeV for the highest-p_T (leading) muon and 8 GeV for the second-highest p_T muon. For the two-electron trigger, the requirement is asymmetric, with a threshold applied to the energy of an ECAL cluster projected onto the plane transverse to the beam line ($E_T = E\sin\theta$). The cluster of the leading electron is required to have $E_T > 17$ GeV, and that of the next-to-leading electron to have $E_T > 8$ GeV. For the electron–muon trigger, the thresholds are either $E_T > 17$ GeV for the electron and $p_T > 8$ GeV for the muon, or $E_T > 8$ GeV for the electron and $p_T > 17$ GeV for the muon. The selected events must contain at least two lepton candidates with trajectories that have a transverse impact parameter of less than 0.2 mm relative to the principal interaction vertex. The chosen vertex is defined as the one with the largest value for the sum of the p_T^2 of the emanating tracks.

Muon candidates are reconstructed from a fit performed to hits in both the silicon tracker and the outer muon detectors, thereby defining a "global muon". The specific selection requirements for a muon are: (i) $p_T > 10$ GeV, (ii) $|\eta| < 2.4$, (iii) more than 10 hits in the silicon tracker, and (iv) a global-muon fit with $\chi^2/\text{dof} < 10$, where dof is the number of degrees of freedom.

Electron candidates are reconstructed using clusters of energy depositions in the ECAL that match the extrapolation of a reconstructed track. The electron track is fitted using a Gaussian-sum filter [36], with the algorithm taking into account the emission of bremsstrahlung photons in the silicon tracker. The specific requirements for a reconstructed electron are: (i) $p_T > 10$ GeV, (ii) $|\eta| < 1.44$, within the fully instrumented part of the central barrel, or $1.57 < |\eta| < 2.5$ for the endcap regions, (iii) not being a candidate for photon conversion, and (iv) the tracks reconstructed using three independent algorithms [23] to give the same sign for the electric charge.

All accepted lepton candidates are required to be isolated from other particles. In particular, selected muons must have $(\sum p_T)/p_T^{\mu} < 0.15$, where the sum over scalar p_T includes all other PF objects within a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ of the muon track, where $\Delta\eta$ and $\Delta\phi$ are the differences in pseudorapidity and azimuthal angle between the lepton axis and the positions of other particles. Similarly, an electron candidate is accepted if $(\sum p_T)/p_T^{e} < 0.20$ within a cone of $\Delta R = 0.3$.

The candidate events used for the search are required to have: (i) three isolated charged leptons originating from the same primary vertex, as defined above, (ii) sum of the lepton charges equal to +1, (iii) $E_T^{miss} > 30$ GeV, (iv) $p_T > 18, 15, 10$ GeV for the lepton of highest, next-to-highest, and lowest p_T, and (v) $H_T < 100$ GeV, where H_T is the scalar sum of the transverse momenta of jets with $p_T > 30$ GeV and $|\eta| < 2.4$, which reduces the background from $t\bar{t}$ events.

The selected events are classified into six categories that depend on lepton flavour and electric charge: $\mu^-e^+e^+$, $\mu^-e^+\mu^+$, $\mu^-\mu^+\mu^+$, $e^-\mu^+\mu^+$, $e^-e^+\mu^+$, and $e^-e^+e^+$. Except for the first and fourth categories, such configurations can also result from W^+Z events. Fig. 2 shows the distributions of the $\mu^-\mu^+$ invariant mass for $\mu^-e^+\mu^+$ and $\mu^-\mu^+\mu^+$ events in data, before applying any requirement on the $\mu^-\mu^+$ mass, compared to the sum of SM background contributions. A peak in the $\mu^+\mu^-$ effective mass close to that of the Z boson is evident in both simulated events and in data. To reduce the background from W^+Z events, a Z veto is added to the selection requirements for the corresponding categories as follows. Events with at least one $\ell^+\ell^-$ mass combination in the range $82 < m_{\ell^+\ell^-} < 102$ GeV are rejected. To reject lepton pairs from decays of heavy-flavour quarks, events with $m_{\ell^+\ell^-} < 12$ GeV are also discarded.

Other sources of background in final states with three leptons arise from conversions of photons into additional $\ell^+\ell^-$ pairs through the process $Z \to \ell^+\ell^-\gamma \to \ell^+\ell^-\ell'^+\ell'^-$. If one of these additional leptons carries most of the momentum of the photon, the final state can appear as a three-lepton event. In such cases, the invariant mass of the $\ell^+\ell^-\ell'$ state peaks close to the mass of the Z boson [34]. Since the probability of a photon conversion to electrons is higher than to muons, an additional Z veto of $82 < m_{\ell^+\ell^-e^+} < 102$ GeV is applied to the $\mu^-e^+\mu^+$ and $e^-e^+e^+$ categories to reject such events. This is discussed further in the next section.

5. Background estimation

Three types of SM processes can produce a three-lepton final state: (i) events containing three or more prompt leptons from production and leptonic decays of two or three EW bosons. This is referred to as irreducible background, since it corresponds to the same final states as the signal from Σ production, (ii) $V+\gamma$ and $V+\gamma^*$ events, where V represents any EW boson, with the accompanying photons converting to $\ell^+\ell^-$, and (iii) events with one or two prompt leptons and additional non-prompt leptons that arise from leptonic decays of hadrons within jets, called "misidentified jets".

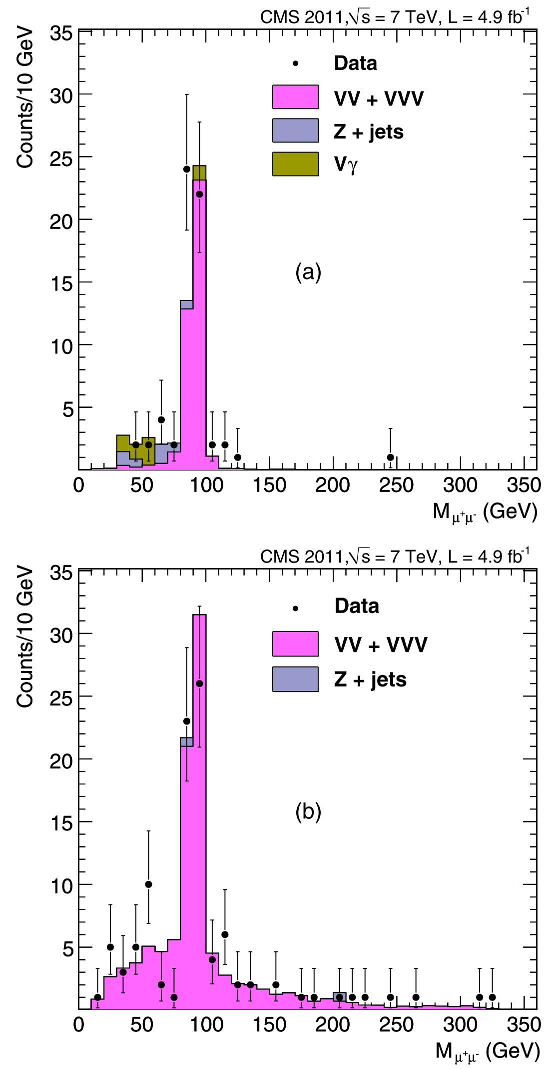

Fig. 2. Distributions of the $\mu^-\mu^+$ invariant mass for (a) $\mu^-e^+\mu^+$ and (b) $\mu^-\mu^+\mu^+$ events in data (black points), before applying any requirement on the $\mu^-\mu^+$ mass to reject Z bosons, compared to the sum of all major SM background contributions.

The irreducible background from more than two leptons is dominated by SM WZ production, but also includes ZZ and three-boson events. The two-boson contribution, which is reduced substantially by the Z mass veto, and the three-boson contribution, which is dominated by the WWW channel, are both evaluated using MC simulation. The contribution from three-boson production is small relative to the other sources, as shown in Table 1.

As mentioned in Section 4, photon conversions in the presence of W or Z bosons can produce isolated leptons that constitute another source of background. External conversions of photons, namely of produced photons that interact with the material in the detector to yield primarily e^+e^- pairs, are evaluated from simulation ($V\gamma$ in Table 1). Internal conversions, involving the direct materialisation of virtual photons into $\mu^+\mu^-$ or e^+e^- pairs, can also provide a similar source of background. Both external and internal conversions can become problematic when one of the two final-state leptons carries off most of the photon energy, and the second lepton is not detected. The contribution of conversions to electrons is reduced by the additional three-lepton-mass rejection applied to the $\mu^-e^+\mu^+$ and $e^-e^+e^+$ categories as discussed above. The

Table 1
Summary of the mean number of SM background events expected in each event category, after final selections. V represents a Z or a W bosons and Vγ is the contribution from external photon conversions. The column labelled "Misidentified jets" includes backgrounds with non-prompt leptons, the column $\gamma^* \to \mu^+\mu^-$ shows background expectation from internal photon conversions, where a virtual photon converts to a muon pair, and one muon is lost. The contribution of $\gamma^* \to e^+e^-$ is removed by the rejection criteria on three-lepton masses. Statistical uncertainties are included for the six categories, and systematic uncertainties on normalizations are listed in the last row.

	VV	VVV	Vγ	Misidentified jets	$\gamma^* \to \mu^+\mu^-$
$\mu^-e^+e^+$	0.3 ± 0.1	0.09 ± 0.01	–	0.4 ± 0.4	–
$\mu^-e^+\mu^+$	4.0 ± 0.3	0.19 ± 0.01	–	3.1 ± 1.2	–
$\mu^-\mu^+\mu^+$	4.9 ± 0.3	0.11 ± 0.01	–	5.7 ± 1.9	0.7 ± 0.2
$e^-\mu^+\mu^+$	0.3 ± 0.1	0.09 ± 0.01	–	0.8 ± 0.5	–
$e^-e^+\mu^+$	4.9 ± 0.3	0.21 ± 0.02	–	3.0 ± 1.2	0.4 ± 0.1
$e^-e^+e^+$	2.5 ± 0.2	0.06 ± 0.01	1.4 ± 1.0	1.1 ± 0.6	–
Normalization uncertainties	17% (WZ) 7.5% (ZZ)	50%	13%	50%	50%

contribution from internal photon conversions to muons $\gamma^* \to \mu^+\mu^-$ is evaluated according to the method described in Ref. [34], where the ratio of $\ell^+\ell^-\mu^\pm$ to $\ell^+\ell^-\gamma$ events, in which the mass is close to that of a Z boson, defines a conversion factor C_μ for muons. The background is estimated from C_μ and from the number of $\ell^+\ell^-\gamma$ events in data that pass all selections, except the three-lepton requirements. An alternative evaluation is obtained from events in an independent Z-enriched control region, by reversing the E_T^{miss} requirement to $E_T^{miss} < 20$ GeV. As mentioned before, events from Z decays into two muons or two electrons that contain an additional muon from internal photon conversion, produce a peak in the three-lepton invariant mass distribution close to the Z mass. The number of events expected in the final sample is estimated from the ratio of simulated events for Z production with $E_T^{miss} > 30$ GeV to that with $E_T^{miss} < 20$ GeV. This estimate agrees with that of the previous method. The $\gamma^* \to \mu^+\mu^-$ background contribution is small, as can be seen in Table 1. An overall uncertainty of $\pm 50\%$ is assumed for this source of background, which is limited by the statistical precision of both estimates (30%), and has an additional contribution from the choice of normalization criteria (40%).

The largest background, aside from the irreducible backgrounds, arises from the Z + jets process (including the Drell–Yan contribution), in which the Z boson decays leptonically, and a jet in the event is misidentified as a third lepton. Processes with non-prompt leptons from heavy-flavour decays are not simulated with sufficient accuracy with the MC generators and we therefore use a method based on data to estimate this contribution. The yield of such background in data is estimated using a sample of leptons that pass less restrictive selection criteria than the ones described previously. The lepton candidates passing all selection criteria are called "tight leptons", while those passing all but the isolation requirements are called "loose leptons". The probability for a non-prompt lepton to pass tight selection is called the misidentification rate, and it is measured in samples of multijet events where a negligible fraction of the lepton candidates is expected to be due to prompt leptons. The contribution to the background is obtained from the lepton misidentification rate and the events that pass full selection of the analysis, based on loose lepton identification. The misidentification rate depends on p_T and η of the lepton. However, only the average value is used, and an uncertainty of 50% is assigned to this background estimate. Several cross checks of the method used to evaluate this background contribution have been performed using data and simulation. They show agreement between the number of observed leptons and the number of leptons predicted on the basis of the lepton misidentification rate.

Events from $t\bar{t}$ production with two leptonic W decays and an additional coincident lepton, are reduced through the PF isolation requirements for leptons and by the selection on H_T. Simulations show that the remaining $t\bar{t}$ background is negligible, and its contribution is included in the estimate of non-prompt leptons.

SM background contributions expected in each of the six analyzed event categories are summarized in Table 1.

6. Systematic uncertainties

Systematic uncertainties can be divided in two categories: those related to the extraction of the signal and those relevant to the sources of background. The first group includes efficiencies of trigger selections, particle reconstruction, and lepton identification. In the kinematic region defined by the analysis, the trigger efficiency for the signal is very high because it is based on a combination of three separate two-lepton triggers, each of which is found to be 92% to 100% efficient, and the estimated overall efficiency is $(99 \pm 1)\%$.

Uncertainties on lepton selection efficiencies are determined using a "tag-and-probe" method [37], both in data and through MC simulations, and the differences between these are taken as systematic uncertainties on the efficiencies. Additional contributions include uncertainties on the energy scales and on resolutions for leptons and for E_T^{miss}, as well as uncertainties in the modeling of pileup, all of which are obtained from a full GEANT4 simulation. As mentioned in Section 3, GEANT4 simulation of the signal is restricted to a limited number of M_Σ masses. In fact, the largest available value for this simulation is $M_\Sigma = 140$ GeV. The efficiencies are therefore extrapolated to higher mass points using fast detector simulation. The difference between the efficiencies evaluated with the full and fast simulation at 140 GeV is taken as an additional contribution to the overall uncertainty. The largest difference is for the channel with three muons. Statistical uncertainties of the extrapolation are also taken into account. The uncertainties attributed to the expected signal efficiencies are summarized in Table 2 for $M_\Sigma = 180$ GeV, and are expected not to differ significantly for higher mass points [18].

As mentioned above, the uncertainties on backgrounds are estimated using MC simulations or control samples in data. For the dominant irreducible background of WZ production, we apply a 17% uncertainty on the measured cross section [38]. Uncertainties of 7.5% for ZZ [39], and 13% for Vγ [40] cross sections are also taken into account. For very small backgrounds, such as WWW, we assume a normalization uncertainty of 50%.

Uncertainties on background estimates from methods based on data were discussed in Section 5, and those statistical and systematic uncertainties are summarized in Table 1.

The overall uncertainty on integrated luminosity is 2.2% [41]. For backgrounds determined from simulation, the systematic uncertainties on efficiency and luminosity are common to all signals.

Table 2
Uncertainties on signal efficiency for each event category for $M_\Sigma = 180$ GeV. Total systematic and total systematic + statistical (fourth and sixth columns) are calculated in quadrature.

	Source of uncertainty					
	Trigger	Signal efficiency (Full simulation)	(Fullsim/Fastsim) systematic	Total systematic	(Fullsim/Fastsim) statistical	Total syst. + stat.
$\mu^- e^+ e^+$	1.0%	6.3%	2.9%	7.0%	3.0%	7.6%
$\mu^- e^+ \mu^+$	1.0%	4.5%	6.8%	8.2%	2.3%	8.5%
$\mu^- \mu^+ \mu^+$	1.0%	3.9%	11.1%	11.8%	3.3%	12.2%
$e^- \mu^+ \mu^+$	1.0%	4.5%	8.5%	9.7%	2.9%	10.1%
$e^- e^+ \mu^+$	1.0%	6.3%	4.1%	7.6%	2.4%	7.9%
$e^- e^+ e^+$	1.0%	7.6%	2.8%	8.0%	4.2%	9.1%

Table 3
Summary of the expected mean number of events for signal as a function of M_Σ, for the expected SM background, and the observed number of events in data, after implementing all analysis selections. Each of the three possibilities for mixing (FDS, μS, eS) described in Section 1 are considered separately in the analysis.

Category	Expected signal for M_Σ (GeV)									Expected background	Observed in data
	FDS					μS		eS			
	120	130	140	180	200	180	200	180	200		
$\mu^- e^+ e^+$	7.9	6.0	4.5	1.7	1.1	1.6	1.0	3.6	2.4	0.8 ± 0.4	2
$\mu^- e^+ \mu^+$	12.3	9.0	7.0	3.0	2.0	6.0	4.0	1.4	0.92	7.3 ± 2.1	9
$\mu^- \mu^+ \mu^+$	7.8	5.2	3.6	1.4	0.93	6.1	4.0	–	–	11.5 ± 3.6	7
$e^- \mu^+ \mu^+$	8.3	6.2	4.8	1.8	1.2	3.7	2.5	1.6	1.0	1.1 ± 0.7	0
$e^- e^+ \mu^+$	13.2	9.5	6.9	2.7	1.8	1.1	0.75	5.7	3.8	8.6 ± 2.2	7
$e^- e^+ e^+$	3.9	2.8	2.0	1.0	0.63	–	–	4.16	2.8	5.0 ± 1.4	4

7. Results

Table 3 presents the results of our search for the fermionic Σ triplet states in terms of the expected number of signal events, the expected number of events from SM background, and the number of observed events in each of the analyzed event categories. Each of the three possibilities for mixing (FDS, μS, eS) described in Section 1 is considered in the analysis.

No significant excess of events is observed relative to the SM expectations in any of the six analysis channels. Combining all channels, we set upper limits at the 95% confidence level (CL) on $\sigma \times \mathcal{B}$, on the product of the production cross section of $\Sigma^+\Sigma^0$ and its branching fraction ($\mathcal{B}$) to the three-lepton final states, where the lepton can be an electron, muon or τ (contributing through $\tau \to \ell \nu_\ell \nu_\tau$). The branching fraction to three-lepton final states depends on M_Σ [18], and is predicted to be about 9% for $M_\Sigma \approx 200$ GeV, where we extrapolate signal yields to $M_\Sigma > 180$ GeV using the results of Ref. [18].

The upper limits on $\sigma\mathcal{B}$ as a function of fermion mass M_Σ, combining for all channels by multiplying the corresponding likelihood functions, are shown in Fig. 3, 4, and 5, for FDS, μS, and eS possibilities, respectively. The dashed lines correspond to the expected limits obtained from MC pseudo-experiments, and are based on the CLs criterion [42,43]. The observed limits on data are computed following both a Bayesian approach [33, Ch. 33], and a frequentist method also based on the CLs criterion. In the former, the assumed prior is a constant. In both calculations, the uncertainties on efficiencies for detecting signal, the uncertainty on integrated luminosity and on the expected SM background, are treated as uninteresting "nuisance" parameters with Gaussian or log-normal densities. Upper limits are computed at 95% CL using the RooStats software [44], and the package developed to combine results from searches for the Higgs boson [45]. The two results are similar, as shown in Figs. 3, 4, and 5. The results are stable relative to variations of ±20% on the systematic uncertainties. Finally, we extract lower limits on M_Σ using the theoretical dependence of the cross section on M_Σ, as represented by the solid blue lines of Fig. 3, 4, and 5, for the three possibilities for the type III seesaw model for signal. The expected and observed 95% CL limits obtained with the Bayesian method are given in Table 4.

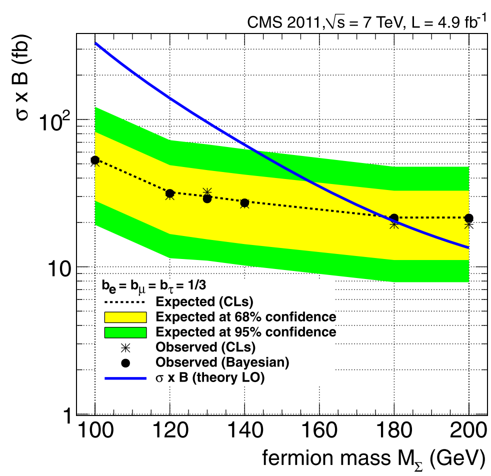

Fig. 3. The expected (dashed line) and observed (asterisks and black points) exclusion limits at 95% confidence level on $\sigma\mathcal{B}$ as a function of the fermion mass M_Σ, assuming $b_e = b_\mu = b_\tau = 1/3$ (FDS) for the signal. The solid (blue) curve represents the predictions of the LO type III seesaw models. The light (yellow) and dark (green) shaded areas represent, respectively, the 1 standard deviation (68% CL) and 2 standard deviations (95% CL) limits on the expected results obtained from MC pseudo-experiments, which reflect the combined statistical and systematic uncertainties of the SM contributions. The asterisks and the black points show, respectively, the observed limits computed following a frequentist method based on the CLs criterion and a Bayesian approach.

The reported limits are valid only for short Σ lifetimes, which hold for values of the matrix elements V_α greater than $\approx 10^{-6}$. For smaller values, the analysis requires a different approach, since the leptons can originate from displaced vertices in an environment that, as indicated previously, is not considered in this analysis.

8. Summary

A search has been presented for fermionic triplet states expected in type III seesaw models. The search was performed in events with three isolated leptons (muons or electrons), whose charges sum to +1, and contain jets and an imbalance in transverse

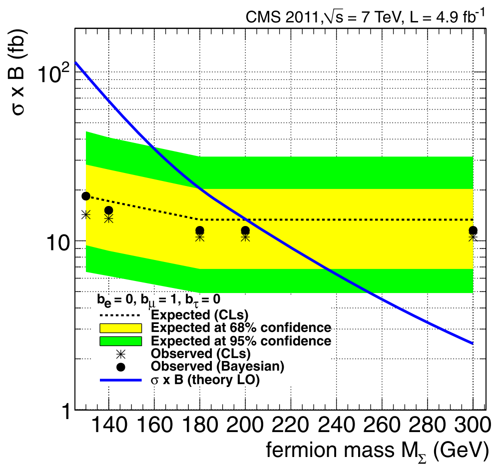

Fig. 4. The expected (dashed line) and observed (asterisks and black points) exclusion limits at 95% confidence level on $\sigma\mathcal{B}$ as a function of the fermion mass M_Σ, assuming $b_e = 0$, $b_\mu = 1$, $b_\tau = 0$ (μS) for the signal. The solid (blue) curve represents the predictions of the LO type III seesaw models. The light (yellow) and dark (green) shaded areas represent, respectively, the 1 standard deviation (68% CL) and 2 standard deviations (95% CL) limits on the expected results obtained from MC pseudo-experiments, which reflect the combined statistical and systematic uncertainties of the SM contributions. The asterisks and the black points show, respectively, the observed limits computed following a frequentist method based on the CLs criterion and a Bayesian approach.

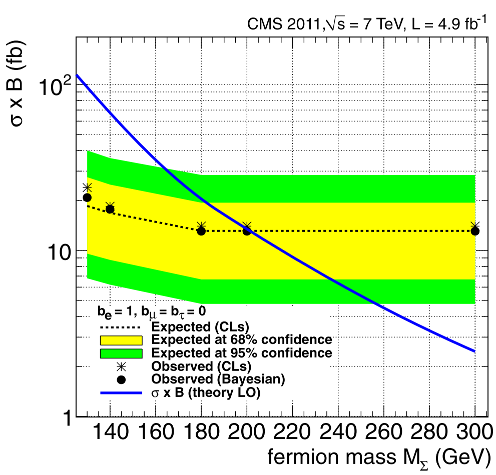

Fig. 5. The expected (dashed line) and observed (black points) exclusion limits at 95% confidence level on $\sigma\mathcal{B}$ as a function of the fermion mass M_Σ, assuming $b_e = 1$, $b_\mu = 0$, $b_\tau = 0$ (eS) for the signal. The solid (blue) curve represents the predictions of the LO type III seesaw models. The light (yellow) and dark (green) shaded areas represent, respectively, the 1 standard deviation (68% CL) and 2 standard deviations (95% CL) limits on the expected results obtained from MC pseudo-experiments, which reflect the combined statistical and systematic uncertainties of the SM contributions. The asterisks and the black points show, respectively, the observed limits computed following a frequentist method based on the CLs criterion and a Bayesian approach.

Table 4
The expected and observed limits on M_Σ and on $\sigma\mathcal{B}$ at the given mass are obtained using the Bayesian method, specified at a 95% confidence level, for the three assumed sets of branching fractions b_α defined in Eq. (1).

Scenario	95% CL: $\sigma\mathcal{B}$ (fb)		95% CL: M_Σ (GeV)	
	Exp.	Obs.	Exp.	Obs.
FDS	22	20	177	179
μS	13	11	201	211
eS	13	13	202	204

momentum. The data are from proton–proton collisions at $\sqrt{s} = 7$ TeV, recorded during 2011 by the CMS experiment at the CERN LHC, and correspond to an integrated luminosity of 4.9 fb^{-1}.

No evidence for pair production of $\Sigma^+\Sigma^0$ states has been found, and 95% confidence upper limits are set on the product of the production cross section of $\Sigma^+\Sigma^0$ and its branching fraction to the examined three-lepton final states. Comparing the results with predictions from type III seesaw models, lower bounds are established at 95% confidence on the mass of the Σ states. Limits are reported for three choices of mixing possibilities between the Σ states and the three lepton generations. Depending on the considered scenarios, lower limits are obtained on the mass of the heavy partner of the neutrino that range from 180 to 210 GeV. The results are valid only if at least one of the mixing matrix elements is larger than $\approx 10^{-6}$. These are the first limits on the production of type III seesaw fermionic triplet states reported by an experiment at the LHC.

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CMS Collaboration

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

Yerevan Physics Institute, Yerevan, Armenia

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

Institut für Hochenergiephysik der OeAW, Wien, Austria

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

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

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

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, Belgium

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

Université Libre de Bruxelles, Bruxelles, Belgium

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

Ghent University, Ghent, Belgium

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

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

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

Université de Mons, Mons, Belgium

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

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

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

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

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

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

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

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

University of Sofia, Sofia, Bulgaria

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

Institute of High Energy Physics, Beijing, China

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

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

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

Universidad de Los Andes, Bogota, Colombia

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

Technical University of Split, Split, Croatia

Z. Antunovic, M. Kovac

University of Split, Split, Croatia

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

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M. Finger, M. Finger Jr.

Charles University, Prague, Czech Republic

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

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

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

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, G. Fedi, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

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

Helsinki Institute of Physics, Helsinki, Finland

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

Lappeenranta University of Technology, Lappeenranta, Finland

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

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

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj [13], C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, M. Dalchenko, 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

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

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

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

F. Fassi, D. Mercier

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

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

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

Z. Tsamalaidze [15]

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

G. Anagnostou, 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, I. Physikalisches Institut, Aachen, Germany

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

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

M. Bontenackels, V. Cherepanov, 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

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

M. Aldaya Martin, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz [17], A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, F. Costanza, D. Dammann, C. Diez Pardos, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann [17], B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, 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

Deutsches Elektronen-Synchrotron, 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

University of Hamburg, Hamburg, Germany

C. Barth, J. Berger, C. Böser, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff [5], C. Hackstein, F. Hartmann, T. Hauth [5], M. Heinrich, H. Held, K.H. Hoffmann, 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

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

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

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

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

University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

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

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

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

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

University of Debrecen, Debrecen, Hungary

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

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

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

Saha Institute of Nuclear Physics, Kolkata, India

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

Bhabha Atomic Research Centre, Mumbai, India

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

Tata Institute of Fundamental Research - EHEP, Mumbai, India

S. Banerjee, S. Dugad

Tata Institute of Fundamental Research - HECR, Mumbai, India

H. Arfaei [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

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

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

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

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

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

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

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

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

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

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

INFN Laboratori Nazionali di Frascati, Frascati, Italy

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

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

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

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

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

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

P. Azzi [a], N. Bacchetta [a,5], P. Bellan [a,b], C. Biggio [a,b,28], D. Bisello [a,b], F. Bonnet [a], A. Branca [a,b,5], R. Carlin [a,b], P. Checchia [a], T. Dorigo [a], F. 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], N. Pozzobon [a,b], P. Ronchese [a,b], F. Simonetto [a,b], E. Torassa [a], M. Tosi [a,b], S. Vanini [a,b], P. Zotto [a,b], G. Zumerle [a,b]

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

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

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

M. Biasini [a,b], G.M. Bilei [a], L. Fanò [a,b], P. Lariccia [a,b], 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]

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

P. Azzurri [a,c], G. Bagliesi [a], J. Bernardini [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,29], A. Messineo [a,b], F. Palla [a], A. Rizzi [a,b], A.T. Serban [a,30], P. Spagnolo [a], P. Squillacioti [a,5], R. Tenchini [a], G. Tonelli [a,b], A. Venturi [a], P.G. Verdini [a]

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

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

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

N. Amapane [a,b], R. Arcidiacono [a,c], S. Argiro [a,b], M. Arneodo [a,c], C. Biino [a], N. Cartiglia [a], M. Costa [a,b], 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]

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

S. Belforte [a], V. Candelise [a,b], 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]

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

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

Kangwon National University, Chunchon, Republic of Korea

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

Kyungpook National University, Daegu, Republic of Korea

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

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

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

Korea University, Seoul, Republic of Korea

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

University of Seoul, Seoul, Republic of Korea

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

Sungkyunkwan University, Suwon, Republic of Korea

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

Vilnius University, Vilnius, Lithuania

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

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

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

H.A. Salazar Ibarguen

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

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

D. Krofcheck

University of Auckland, Auckland, New Zealand

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

University of Canterbury, Christchurch, New Zealand

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

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

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

National Centre for Nuclear Research, Swierk, Poland

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

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

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

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

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

Joint Institute for Nuclear Research, Dubna, Russia

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

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

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

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

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

Moscow State University, Moscow, Russia

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

P.N. Lebedev Physical Institute, Moscow, Russia

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

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

P. Adzic [31], M. Djordjevic, M. Ekmedzic, D. Krpic [31], J. Milosevic

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

M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

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

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

Universidad Autónoma de Madrid, Madrid, Spain

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

Universidad de Oviedo, Oviedo, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini [32], 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

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

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 [33], C. Rovelli [34], M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas [35,*], D. Spiga, A. Tsirou, G.I. Veres [19], J.R. Vlimant, H.K. Wöhri, S.D. Worm [36], W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille [37]

Paul Scherrer Institut, Villigen, Switzerland

L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, J. Eugster, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Lustermann, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli [38], 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 [39], B. Stieger, M. Takahashi, L. Tauscher [†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

C. Amsler [40], V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Tupputi, M. Verzetti

Universität Zürich, Zurich, Switzerland

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

National Central University, Chung-Li, Taiwan

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

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, N. Srimanobhas

Chulalongkorn University, Bangkok, Thailand

A. Adiguzel, M.N. Bakirci [41], S. Cerci [42], C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, G. Karapinar [43], A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk [44], A. Polatoz, K. Sogut [45], D. Sunar Cerci [42], B. Tali [42], H. Topakli [41], L.N. Vergili, M. Vergili

Cukurova University, Adana, Turkey

I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalvac, E. Yildirim, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, B. Isildak [46], M. Kaya [47], O. Kaya [47], S. Ozkorucuklu [48], N. Sonmez [49]

Bogazici University, Istanbul, Turkey

K. Cankocak

Istanbul Technical University, Istanbul, Turkey

L. Levchuk

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

F. Bostock, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold [36], K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

University of Bristol, Bristol, United Kingdom

L. Basso [50], K.W. Bell, A. Belyaev [50], C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, G. Ball, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko [39], A. Papageorgiou, J. Pela, M. Pesaresi, K. Petridis, M. Pioppi [51], D.M. Raymond, S. Rogerson, A. Rose, M.J. Ryan, C. Seez, P. Sharp [†], A. Sparrow, M. Stoye, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie

Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

K. Hatakeyama, H. Liu, T. Scarborough

Baylor University, Waco, USA

O. Charaf, C. Henderson, P. Rumerio

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, USA

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

Brown University, Providence, USA

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

University of California, Davis, Davis, USA

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

University of California, Los Angeles, Los Angeles, USA

J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng[52], H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, Riverside, Riverside, USA

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech[53], F. Würthwein, A. Yagil, J. Yoo

University of California, San Diego, La Jolla, USA

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, C. West

University of California, Santa Barbara, Santa Barbara, USA

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

California Institute of Technology, Pasadena, 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

Carnegie Mellon University, Pittsburgh, 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

University of Colorado at Boulder, Boulder, USA

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

Cornell University, Ithaca, USA

D. Winn

Fairfield University, Fairfield, USA

S. Abdullin, M. Albrow, J. Anderson, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, D. Green, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson,

U. Joshi, B. Kilminster, B. Klima, S. Kunori, S. Kwan, C. Leonidopoulos, J. Linacre, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko [54], 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

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, D. Bourilkov, M. Chen, T. Cheng, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic [55], G. Mitselmakher, L. Muniz, M. Park, R. Remington, A. Rinkevicius, P. Sellers, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

University of Florida, Gainesville, USA

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

Florida International University, Miami, USA

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

Florida State University, Tallahassee, USA

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

Florida Institute of Technology, Melbourne, USA

M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, I. Bucinskaite, J. Callner, R. Cavanaugh, 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

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

U. Akgun, E.A. Albayrak, B. Bilki [56], W. Clarida, F. Duru, J.-P. Merlo, H. Mermerkaya [57], A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, Y. Onel, F. Ozok [58], S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

The University of Iowa, Iowa City, USA

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

Johns Hopkins University, Baltimore, USA

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

The University of Kansas, Lawrence, USA

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

Kansas State University, Manhattan, USA

J. Gronberg, D. Lange, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

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

University of Maryland, College Park, USA

A. Apyan, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, Y. Kim, M. Klute, K. Krajczar [59], 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

Massachusetts Institute of Technology, Cambridge, USA

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

University of Minnesota, Minneapolis, USA

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

University of Mississippi, Oxford, USA

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

University of Nebraska-Lincoln, Lincoln, USA

A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar

State University of New York at Buffalo, Buffalo, USA

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

Northeastern University, Boston, USA

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

Northwestern University, Evanston, USA

L. Antonelli, D. Berry, A. Brinkerhoff, 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

University of Notre Dame, Notre Dame, 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

The Ohio State University, Columbus, USA

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

Princeton University, Princeton, USA

E. Brownson, A. Lopez, H. Mendez, J.E. Ramirez Vargas

University of Puerto Rico, Mayaguez, USA

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

Purdue University, West Lafayette, USA

S. Guragain, N. Parashar

Purdue University Calumet, Hammond, USA

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

Rice University, Houston, USA

B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, D.C. Miner, D. Vishnevskiy, M. Zielinski

University of Rochester, Rochester, USA

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

The Rockefeller University, New York, USA

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

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

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

University of Tennessee, Knoxville, USA

R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon [60], V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

Texas A&M University, College Station, USA

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

Texas Tech University, Lubbock, USA

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

Vanderbilt University, Nashville, USA

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

University of Virginia, Charlottesville, USA

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

Wayne State University, Detroit, USA

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

University of Wisconsin, Madison, USA

[*] Corresponding author.
[†] Deceased.
[1] Also at Vienna University of Technology, Vienna, Austria.
[2] Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.
[3] Also at Universidade Federal do ABC, Santo Andre, Brazil.
[4] Also at California Institute of Technology, Pasadena, USA.
[5] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[6] Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
[7] Also at Suez Canal University, Suez, Egypt.
[8] Also at Zewail City of Science and Technology, Zewail, Egypt.
[9] Also at Cairo University, Cairo, Egypt.
[10] Also at Fayoum University, El-Fayoum, Egypt.

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