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

CMS Collaboration*

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 \( \Sigma^+, \Sigma^0, \) and \( \Sigma^- \), the most promising signature for finding a \( \Sigma \) state with a mass \( M_{\Sigma} \) of the order of a few hundreds of GeV is in production through quark–antiquark annihilation \( q\bar{q} \rightarrow \Sigma^0 \Sigma^+ \), followed by the decays \( \Sigma^0 \rightarrow \ell^\mp W^\mp \) and \( \Sigma^+ \rightarrow W^+ \nu \). 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 quark annihilations 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 \( \Sigma \) charge combinations. (The cross section for the charge conjugate intermediary W is expected to be about a factor two smaller.) Selecting \( W^\pm \rightarrow \ell^\mp \nu \) decays (where \( \ell \) is an electron or muon) as the final states for the search, offers a very clean signature of three charged, isolated leptons. The decay \( \Sigma^+ \rightarrow \ell^+ Z \), with \( Z \rightarrow \nu\bar{\nu} \) or \( Z \rightarrow q\bar{q} \), can also contribute significantly to the three-lepton final state, especially since its relative yield grows with \( M_{\Sigma} \). The \( \tau \) lepton also contributes to the three-lepton final states through \( \tau \rightarrow \ell \nu \nu \) 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 \( \Sigma \) states and their decay branching fractions to SM leptons depend on the mixing matrix element for the...
leptons $V_\alpha$, where $\alpha$ labels each of the e, $\mu$, and $\tau$ 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 $V_\alpha$, which enter only in the $\Sigma$ decays. The fraction of $\Sigma$ decays to the lepton $\alpha$ is proportional to:

$$b_\alpha = \frac{|V_{\alpha e}|^2}{|V_{\alpha e}|^2 + |V_{\alpha \mu}|^2 + |V_{\alpha \tau}|^2}.$$  \hspace{1cm} (1)

If all three $V_{\alpha e}$ values are less than $10^{-6}$, the $\Sigma$ 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 ($E_T^{miss}$) 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 $M_\Sigma$ 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 ZZ 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 jets and photons that are misidentified as leptons are also taken into account, including events from Drell–Yan $\ell^+\ell^-$ + jets sources [32], W + jets, Z + jets, $t\bar{t}$, and Drell–Yan $\ell^+\ell^-$ + $\gamma$ conversions to $\ell^+\ell^-\gamma$. (The Drell–Yan process consists of $q\bar{q} \rightarrow \gamma^* / Z \rightarrow \ell^+\ell^-$ production, with $\gamma^*$ and $Z$ intermediaries representing virtual $\gamma$ 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 $\chi^2$/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: $e^-e^+e^+$, $\mu^- e^+\mu^+$, $\mu^- \mu^+\mu^+$, $e^- \mu^+\mu^+$, $e^- e^+\mu^+$, 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 $\ell^+ \ell^- \ell^-$ mass combination in the range $82 < m_{\ell^+\ell^-\ell^-} < 102$ 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 $\ell^+ \ell^- \ell^-$ pairs through the process $Z \rightarrow \ell^+ \ell^- \gamma \rightarrow \ell^+ \ell^- \ell^+ \ell^-$. 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 $82 < m_{\ell^+\ell^-\ell^-} < 102$ 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 $Z$ 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 lepton decays of hadrons within jets, called “misidentified jets”.

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
contribution from internal photon conversions to muons $\gamma^* \rightarrow \mu^+\mu^-$ is evaluated according to the method described in Ref. [34], where the ratio of $t^+t^\gamma$ to $t^+t\gamma'$ events, in which the mass is close to that of a $Z$ boson, defines a conversion factor $C_\mu$ for muons. The background is estimated from $C_\mu$ and from the number of $t^+t\gamma$ 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 $E_T^{\text{miss}}$ requirement to $E_T^{\text{miss}} < 20$ 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 $E_T^{\text{miss}} > 30$ GeV to that with $E_T^{\text{miss}} < 20$ GeV. This estimate agrees with that of the previous method. The $\gamma^* \rightarrow \mu^+\mu^-$ 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 $\eta$ 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 from internal photon conversions to muons $\gamma^* \rightarrow \mu^+\mu^-$ 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.

### 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 $V\gamma$ is the contribution from external photon conversions. The column labelled “Misidentified jets” includes backgrounds with non-prompt leptons, the column $\gamma^* \rightarrow \mu^+\mu^-$ shows background expectation from internal photon conversions, where a virtual photon converts to a muon pair, and one muon is lost. The contribution of $\gamma^* \rightarrow e^+e^-$ 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.

| $V\gamma$ | $VVV$ | $VV$ | $V\gamma$ | Misidentified jets | $\gamma^* \rightarrow \mu^+\mu^-$ |
|---|---|---|---|---|---|
| $\mu^-e^+e^+$ | 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 |
| $e^-e^+\mu^+$ | 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 |
| $e^-e^-\mu^+$ | 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%

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 ± 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 $E_T^{\text{miss}}$ as well as uncertainties in the modeling of pileup, all of which are obtained from a full $\text{GEANT}$ simulation. As mentioned in Section 3, $\text{GEANT}$ simulation of the signal is restricted to a limited number of $M_{\Sigma}$ 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 $V\gamma$ [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.
of the cross section on about 9% for of observed events in each of the analyzed event categories. Each expected number of events from SM background, and the number

Table 2

| Source of uncertainty | Trigger | Signal efficiency | (Fullsim/Fastsim) systematic | Total systematic | (Fullsim/Fastsim) statistical | Total syst. + stat. |
|-----------------------|---------|-------------------|-----------------------------|-----------------|-------------------------------|-------------------|
| \(\mu^-\mu^+e^-\)    | 1.0%    | 6.3%              | 2.9%                        | 7.0%            | 3.0%                          | 7.6%              |
| \(\mu^-\mu^+e^-\)    | 1.0%    | 6.5%              | 6.6%                        | 8.2%            | 2.3%                          | 8.5%              |
| \(\mu^-\mu^+\mu^-\)  | 1.0%    | 3.9%              | 11.1%                       | 11.8%           | 3.3%                          | 12.2%             |
| \(\mu^-\mu^+\mu^-\)  | 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%              |
| \(e^-e^+\mu^-\)      | 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 Table 3

| Category | Expected signal for \(M_\Sigma\) (GeV) | \(\mu S\) | eS | Expected background | Observed in data |
|----------|-------------------------------------|-----------|----|---------------------|-----------------|
| FDS      | 120 130 140 180 200 200             | 180 200   | 180 200 |                    |                 |
| \(\mu^-\mu^+e^-\) | 7.9 6.0 4.5 1.7 1.1 1.0 1.0 | 1.6 | 3.6 | 2.4 | 0.8 ± 0.4 | 2 |
| \(\mu^-\mu^+\mu^-\) | 12.3 9.0 7.0 3.0 2.0 6.0 4.0 | 1.4 | 1.4 | 0.92 | 7.3 ± 2.1 | 9 |
| \(\mu^-\mu^+\mu^-\) | 7.8 5.2 3.6 1.4 0.93 0.31 0.04 | 1.6 | 1.0 | 1.0 | 11.5 ± 3.6 | 7 |
| \(e^-\mu^-\mu^-\) | 3.0 6.2 4.8 1.8 1.2 3.7 2.5 | 1.6 | 0.75 | 3.8 | 8.6 ± 2.2 | 7 |
| \(e^-e^+\mu^-\) | 13.2 9.5 6.9 2.7 1.8 1.1 0.63 | - | - | 4.16 | 2.8 | 5.0 ± 1.4 | 4 |
| \(e^-e^+e^-\) | 3.9 2.8 2.0 1.0 1.0 0.63 | - | - | - | - | - | - |

7. Results

Table 3 presents the results of our search for the fermionic \(\Sigma\) 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, \(\mu S\), eS) described in Section 1 is considered separately 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 \(\sigma \times B\), on the product of the production cross section of \(\Sigma^- \Sigma^0\) and its branching fraction \(B\) to the three-lepton final states, where the lepton can be an electron, muon or \(\tau\) (contributing through \(\tau \rightarrow l\nu_l\nu_l\)). The branching fraction to three-lepton final states depends on \(M_\Sigma\) [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 \(\sigma \times B\) as a function of fermion mass \(M_\Sigma\), combining for all channels by multiplying the corresponding likelihood functions, are shown in Fig. 3, 4, and 5, for FDS, \(\mu S\), 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 the 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 \(M_\Sigma\) using the theoretical dependence of the cross section on \(M_\Sigma\), 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.

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
the CLs criterion and a Bayesian approach. respectively, the observed limits computed following a frequentist method based on the SM contributions. The asterisks and the black points show, 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 expected (dashed line) and observed (asterisks and black points) exclusion limits at 95% confidence level on $\sigma B$ as a function of the fermion mass $M_{\Sigma}$, assuming $b_0 = 0$, $b_1 = 1$, $b_1 = 0$ ($\mu S$) for the signal. The solid (blue) curve represents the predictions of the 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.

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staffs at CERN and other CMS institutes, and acknowledge support from BMWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MEYS (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MSI (New Zealand); NSC and NIS (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MON, RosAtom, and RFBR (Russia); MSTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); ThEPC, IPST and NECTEC (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA). Individuals have received support from the Marie-Curie programme and the European Research Council (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l’Industrie et dans l’Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (Czech Republic); the Council of Science and Industrial Research, India; the Compagnia di San Paolo (Torino); and the HOMING PLUS programme of Foundation for Polish Science, cofinanced from European Union, Regional Development Fund.

Open access

This article is published Open Access at sciencedirect.com. It is distributed under the terms of the Creative Commons Attribution License 3.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original authors and source are credited.

References

[1] M.C. Gonzalez-Garcia, M. Maltoni, J. Salvado, JHEP 1004 (2010) 056, arXiv: 1001.4524, http://dx.doi.org/10.1007/JHEP04(2010)056.

[2] T. Schwetz, M. Tortola, J.W.F. Valle, New J. Phys. 13 (2011) 109401, arXiv: 1108.1376, http://dx.doi.org/10.1088/1367-2630/13/10/109401.
CMS Collaboration, Particle-flow reconstruction in CMS and performance
E. Ma, Phys. Rev. Lett. 81 (1998) 1171, arXiv:hep-ph/9805219v4, http://
Universiteit Antwerpen, Antwerpen, Belgium
A. Van Spilbeeck
R. Rougny, M. Selvaggi, Z. Staykova, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel,
M. Bansal, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, 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, Brussels, 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, Brussels, 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. Cead, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco, J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrzowski, N. Schul, J.M. Vizan Garcia

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

N. Beliy, T. Caeberts, 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, C.A. Bernardes, F.A. Dias, T.R. Fernandez Perez Tomei, E.M. Gregores, C. Lagana, F. Marinho, P.G. Mercadante, S.F. Novaes, Sandra S. Padula

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

V. Genchev, P. Iaydjiev, 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, D. Polic, I. Puljak

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. Assran1, S. Elgammal2, A. Ellithi Kamel3, S. Khalil4, M.A. Mahmoud5, A. Radi6,7
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. Besançon, 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. Bluj7, 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, CNRS/IN2P3, Palaiseau, France

J.-L. Agram14, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte14, F. Drouhin14, C. Ferro, J.-C. Fontaine14, 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 Nucléaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France, Villeurbanne, France

S. Beauceron, N. Beaufere, O. Bondu, G. Boudoul, J. Chasserat, R. Chierici5, 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
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. Shrivpuri

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, L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Ganguly, M. Guchait, M. Maity, 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. Arfai, H. Bakhshiansohi, S.M. Etasmi, A. Fahim, M. Hashemi, H. Hesari, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdibadi, B. Safarzadeh, M. Zeinali

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

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

\(^{a}\) INFN Sezione di Bari, Bari, Italy
\(^{b}\) Università di Bari, Bari, Italy
\(^{c}\) Politecnico di Bari, Bari, Italy

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

\(^{a}\) INFN Sezione di Bologna, Bologna, Italy
\(^{b}\) Università di Bologna, Bologna, Italy

S. Albergo, G. Cappello, M. Chiorboli, S. Costa, R. Potenza, A. Tricomi, C. Tuve

\(^{a}\) INFN Sezione di Catania, Catania, Italy
\(^{b}\) Università di Catania, Catania, Italy
G. Barbaglia\textsuperscript{a}, V. Ciulli\textsuperscript{a,b}, C. Civinini\textsuperscript{a}, R. D'Alessandro\textsuperscript{a,b}, E. Focardi\textsuperscript{a,b}, S. Frosali\textsuperscript{a,b}, E. Gallo\textsuperscript{a}, S. Gonzi\textsuperscript{a,b}, M. Meschini\textsuperscript{a}, S. Paoletti\textsuperscript{a}, G. Sguazzoni\textsuperscript{a}, A. Tropiano\textsuperscript{a,b}

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

L. Benussi, S. Bianco, S. Colafranceschi\textsuperscript{25}, F. Fabbri, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

P. Fabbricatore\textsuperscript{a}, R. Musenich\textsuperscript{a}, S. Tosi\textsuperscript{a,b}

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

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

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

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

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

P. Azzia\textsuperscript{a,b}, N. Bacchetta\textsuperscript{a,5}, P. Bellana\textsuperscript{a,b}, C. Biggio\textsuperscript{a,b,28}, D. Bisello\textsuperscript{a,b}, F. Bonnet\textsuperscript{a}, A. Branca\textsuperscript{a,b,5}, R. Carlin\textsuperscript{a,b}, P. Checchia\textsuperscript{a}, T. Dorigo\textsuperscript{a}, F. Gasparini\textsuperscript{a,b}, A. Gozzelli\textsuperscript{a}, K. Kanishchev\textsuperscript{a,c}, S. Lacaprara\textsuperscript{a}, I. Lazzizzera\textsuperscript{a,c}, M. Margoni\textsuperscript{a,b}, A.T. Meneguzzo\textsuperscript{a,b}, M. Nespolo\textsuperscript{a,5}, J. Pazzini\textsuperscript{a,b}, N. Pozzobon\textsuperscript{a,b}, P. Ronchese\textsuperscript{a,b}, F. Simonetto\textsuperscript{a,b}, E. Torassa\textsuperscript{a}, M. Tosi\textsuperscript{a,b}, S. Vanini\textsuperscript{a,b}, P. Zotto\textsuperscript{a,b}, G. Zumerle\textsuperscript{a,b}

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

M. Gabusia\textsuperscript{a,b}, S.P. Ratti\textsuperscript{a,b}, C. Riccardi\textsuperscript{a,b}, P. Torre\textsuperscript{a,b}, P. Vitullo\textsuperscript{a,b}

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

M. Biasinia\textsuperscript{a,b}, G.M. Bile\textsuperscript{a}, L. Fanò\textsuperscript{a,b}, P. Lariccia\textsuperscript{a,b}, G. Mantovani\textsuperscript{a,b}, M. Menichelli\textsuperscript{a}, A. Nappi\textsuperscript{a,b,†}, F. Romeo\textsuperscript{a,b}, A. Saha\textsuperscript{a}, A. Santocchia\textsuperscript{a,b}, A. Spiezia\textsuperscript{a,b}, S. Taroni\textsuperscript{a,b}

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

P. Azzurri\textsuperscript{a,c}, G. Bagliesi\textsuperscript{a,j}, J. Bernardini\textsuperscript{a}, T. Boccali\textsuperscript{a}, G. Broccolo\textsuperscript{a,c}, R. Castaldi\textsuperscript{a}, R.T. D’Agnolo\textsuperscript{a,c,5}, R. Dell’Orso\textsuperscript{a}, F. Fiori\textsuperscript{a,b,5}, L. Foa\textsuperscript{a,c}, A. Giassi\textsuperscript{a}, A. Kraan\textsuperscript{a}, F. Ligabue\textsuperscript{a,c}, T. Lomtadze\textsuperscript{a}, L. Martin\textsuperscript{a,29}, A. Messineo\textsuperscript{a,b}, F. Palla\textsuperscript{a}, A. Rizzi\textsuperscript{a,b}, A.T. Serban\textsuperscript{a,30}, P. Spagnolo\textsuperscript{a}, P. Squillacioti\textsuperscript{a,5}, R. Tenchini\textsuperscript{a}, G. Tonelli\textsuperscript{a,b}, A. Venturi\textsuperscript{a}, P. Zotto\textsuperscript{a,b}, G. Zumerle\textsuperscript{a,b}

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

L. Barone\textsuperscript{a,b}, F. Cavallari\textsuperscript{a}, D. Del Re\textsuperscript{a,b}, M. Diemoz\textsuperscript{a}, C. Fanelli\textsuperscript{a,b}, M. Grassi\textsuperscript{a,b,5}, E. Longo\textsuperscript{a,b}, P. Meridians\textsuperscript{a,5}, F. Micheli\textsuperscript{a,b}, S. Nourbakhsh\textsuperscript{a,b}, G. Organtini\textsuperscript{a,b}, R. Paramatti\textsuperscript{a}, S. Rahatlou\textsuperscript{a,b}, M. Sigamani\textsuperscript{a}, L. Sofi\textsuperscript{a,b}

\textsuperscript{a} INFN Sezione di Roma, Roma, Italy
\textsuperscript{b} Università di Roma, Roma, Italy
N. Amapane\textsuperscript{a,b}, R. Arcidiacono\textsuperscript{a,c}, S. Argiro\textsuperscript{a,b}, M. Arneodo\textsuperscript{a,c}, C. Biino\textsuperscript{a}, N. Cartiglia\textsuperscript{a}, M. Costa\textsuperscript{a,b}, N. Demaria\textsuperscript{a}, C. Mariotti\textsuperscript{a,5}, S. Maselli\textsuperscript{a}, E. Migliore\textsuperscript{a,b}, V. Monaco\textsuperscript{a,b}, M. Musich\textsuperscript{a,5}, M.M. Obertino\textsuperscript{a,c}, N. Pastrone\textsuperscript{a}, M. Pelliccioni\textsuperscript{a}, A. Potenza\textsuperscript{a,b}, A. Romero\textsuperscript{a,b}, M. Ruspa\textsuperscript{a,c}, R. Sacchi\textsuperscript{a,b}, A. Solano\textsuperscript{a,b}, A. Staiano\textsuperscript{a}, A. Vilela Pereira\textsuperscript{a}.

\textsuperscript{a} INFN Sezione di Torino, Torino, Italy
\textsuperscript{b} Università di Torino, Torino, Italy
\textsuperscript{c} Università del Piemonte Orientale (Novara), Torino, Italy

S. Belforte\textsuperscript{a}, V. Candelise\textsuperscript{a,b}, M. Casarsa\textsuperscript{a}, F. Cossutti\textsuperscript{a}, G. Della Ricca\textsuperscript{a,b}, B. Gobbo\textsuperscript{a}, M. Marone\textsuperscript{a,b,5}, D. Montanino\textsuperscript{a,b,5}, A. Penzo\textsuperscript{a}, A. Schizzi\textsuperscript{a,b}.

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

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

Kangwon National University, Chuncheon, 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 Potosi, 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
B. Asavapibhop, N. Srinanobhas
Chulalongkorn University, Bangkok, Thailand

A. Adiguzel, M.N. Bakirci, S. Cerci, D. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, G. Karapinar, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk, A. Polatoz, K. Sogut, D. Sunar Cerci, B. Tali, H. Topakli, 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, M. Kaya, O. Kaya, S. Ozkorucuklu, N. Sonmez
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. Facher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams
University of Bristol, Bristol, United Kingdom

L. Basso, K.W. Bell, A. Belyaev, 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, A. Papageorgiou, J. Pela, M. Pesaresi, K. Petridis, M. Pioppi, 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
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, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephens, F. Stöckli, K. Sumorok, K. Sung, 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. Vuosalvo, 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
11 Also at British University, Cairo, Egypt.
12 Now at Am 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, Genoa, Italy.
29 Also at Università degli Studi di Siena, Siena, Italy.
30 Also at University of Bucharest, Faculty of Physics, București-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 Izmır Institute of Technology, Izmır, 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 Erciyes University, Kayseri, 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.