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

CMS Collaboration

1. Introduction

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

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

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

The production and decay process is simulated using the event generator described in Ref. [12] and implemented in ALPGEN [23]. We use the CTEQ5M parton distribution functions [24]. Parton showering and hadronization are simulated using PYTHIA [25]. The Monte Carlo generated events are interfaced with CMS software, where GEANT4 [26] detector simulation, digitization of simulated electronic signals, and event reconstruction are performed. Monte Carlo simulated events are mixed with multiple minimum bias events with weights chosen using the distribution of the number of reconstructed primary vertices observed in data to ensure correct simulation of the number of interactions per bunch crossing (∆φ). The average number of interactions per crossing in the data used in this analysis is approximately 9. The cross section for the process shown in Fig. 1 for $|V_{\text{FN}}|^2 = 1$ has a value of 866 pb for $m_N = 50$ GeV, which drops to 2.8 pb for $m_N = 100$ GeV, and to 83 fb for $m_N = 210$ GeV [12].

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

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

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

Muon and electron candidates are required to have $|\eta| < 2.4$ and to be consistent with originating from the primary interaction vertex. Muon candidates are reconstructed by matching tracks in the silicon tracker to hits in the outer muon system, and are also required to satisfy specific track-quality and calorimeter-deposition requirements. Electron candidates are reconstructed from energy depositions in the ECAL. These are matched to tracks in the silicon tracker and are required to satisfy shower distribution and cluster-track matching criteria. Electron candidates within $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.4$ of a muon candidate are rejected to remove spurious electron candidates formed from the track of a muon that has an associated photon from bremsstrahlung. Electron candidates from photon conversions are suppressed by looking for a partner track and requiring that this track has no missing hits in the inner layers of the silicon tracker.

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

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

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

3. Background estimation

There are three potential sources of same-sign dilepton backgrounds. The first and most important originates from events containing leptons from b-quark decays or generic jets that are misidentified as leptons. Examples of this background include: (i) multijet production in which two jets are misidentified as leptons; (ii) $W(\ell\nu)+$ jets events in which one of the jets is misidentified as a lepton; and (iii) tt decays in which one of the top quarks decays giving a prompt isolated lepton ($t \to Wb \ell_v$, $b \to \ell_qq'$), and the other lepton of same charge arises from a b-quark decay. From Monte Carlo studies we find that the dominant contribution to this background is from multijet production, with the sum of $W(\ell\nu)+$ jets and tt events comprising approximately 15–35% of the total misidentified lepton background. These backgrounds are estimated using control samples in collision data as described below.

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

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

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

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

The overall systematic uncertainty on the misidentified lepton
background is determined from the variation of the background es-
timate with the loose lepton definition and the variation with the
offline muon selection efficiency is taken from Monte Carlo sim-
ulations. We use \textsc{pythia} to simulate ZZ and WZ produc-
tion and \textsc{madgraph} [31] for the remaining processes.

4. Systematic uncertainties

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

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

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

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

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

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

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

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

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

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

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

5. Results and discussion

After applying all the final selections we observe 65 events
in data in the muon channel and expect a total SM background
of \(70 \pm 4\) (stat.) \(\pm 22\) (syst.) events, with the dominant con-
tribution of \(63 \pm 4\) (stat.) \(\pm 22\) (syst.) events arising from the
misidentified muon background. The data are in agreement with
the estimated background. In the electron channel we observe
201 events in data, and estimate the total SM background as
\(219 \pm 6\) (stat.) \(\pm 62\) (syst.) events, with the dominant contribution
of \(177 \pm 5\) (stat.) \(\pm 62\) (syst.) events arising from the misidentified
electron background. The data are again in agreement with the es-
timated background. The final estimates for the two channels are
given in Table 1.
Majorana neutrino mass compared with taking either the leading ton is found to give better performance for reconstruction of the jets for events passing the signal selection. The plots show the data, standard model backgrounds, and three choices for the irreducible SM backgrounds and the expected signals, the first uncertainty is due to the statistical error associated with the finite size of the Monte Carlo event samples used.

Table 1

<table>
<thead>
<tr>
<th>Source</th>
<th>$\mu^-\mu^+$</th>
<th>$e^-e^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irreducible SM backgrounds:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WZ</td>
<td>3.2 ± 0.3 ± 0.2</td>
<td>4.9 ± 0.3 ± 0.3</td>
</tr>
<tr>
<td>ZZ</td>
<td>1.0 ± 0.1 ± 0.1</td>
<td>2.1 ± 0.1 ± 0.1</td>
</tr>
<tr>
<td>W$^-$</td>
<td>0.75 ± 0.27 ± 0.07</td>
<td>1.7 ± 0.4 ± 0.2</td>
</tr>
<tr>
<td>tW</td>
<td>1.06 ± 0.05 ± 0.53</td>
<td>0.62 ± 0.04 ± 0.31</td>
</tr>
<tr>
<td>W$^+$W$^-$qq</td>
<td>0.76 ± 0.06 ± 0.38</td>
<td>0.73 ± 0.07 ± 0.37</td>
</tr>
<tr>
<td>W$^-$W$^+$qq</td>
<td>0.45 ± 0.03 ± 0.23</td>
<td>0.27 ± 0.02 ± 0.13</td>
</tr>
<tr>
<td>Double-parton W$^-$W$^+$</td>
<td>0.07 ± 0.02 ± 0.04</td>
<td>0.19 ± 0.03 ± 0.10</td>
</tr>
<tr>
<td>Total irreducible SM background</td>
<td>7.3 ± 0.4 ± 0.7</td>
<td>10.6 ± 0.6 ± 0.6</td>
</tr>
<tr>
<td>Charge misidentification background</td>
<td>0.012</td>
<td>31.9 ± 2.7 ± 8.0</td>
</tr>
<tr>
<td>Misidentified lepton background</td>
<td>63.1 ± 4.2 ± 22.1</td>
<td>176.8 ± 4.7 ± 61.9</td>
</tr>
<tr>
<td>Total background</td>
<td>70 ± 4 ± 22</td>
<td>219 ± 6 ± 62</td>
</tr>
<tr>
<td>Data</td>
<td>65</td>
<td>201</td>
</tr>
<tr>
<td>Expected signal:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_N = 130$ GeV/c$^2$, $</td>
<td>V_{1N}</td>
<td>^2 = 0.1$</td>
</tr>
<tr>
<td>$m_N = 210$ GeV/c$^2$, $</td>
<td>V_{1N}</td>
<td>^2 = 0.1$</td>
</tr>
</tbody>
</table>

![Fig. 2](image2.png)

Fig. 2. Invariant mass of the second leading $p_T$ lepton and the two leading jets for events passing the signal selection. The plots show the data, standard model backgrounds, and three choices for the heavy Majorana-neutrino signal: $m_N = 80$ GeV/c$^2$, $|V_{1N}|^2 = 0.025$, $m_N = 130$ GeV/c$^2$, $|V_{1N}|^2 = 0.025$, and $m_N = 210$ GeV/c$^2$, $|V_{1N}|^2 = 0.025$. (a) Distributions for $\mu^-\mu^+$ events; (b) distributions for $e^-e^+$ events.

![Fig. 3](image3.png)

Fig. 3. Exclusion region at 95% CL in the square of the heavy Majorana-neutrino mixing parameter as a function of the heavy Majorana-neutrino mass: (a) $|V_{1N}|^2$ vs. $m_N$; (b) $|V_{2N}|^2$ vs. $m_N$. The long-dashed black line is the expected upper limit, with one and two standard-deviation bands shown in dark green and light yellow, respectively. The solid red line is the observed upper limit, and is very close to the expected limit such that the two curves almost overlap. Also shown are the upper limits from L3 [14] and DELPHI [15]. The regions above the exclusion lines are ruled out at 95% CL. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this letter.)

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

For low $m_N$ the limits in both channels are less stringent than the existing limits from DELPHI and L3 shown in Figs. 3(a) and 3(b), due to the higher backgrounds at the LHC. However, the DELPHI and L3 limits are derived from $Z \rightarrow \ell^+\ell^-$ and are restricted to masses below approximately 90 GeV. The limits reported here extend well beyond this mass. For $m_N = 90$ GeV we find $|V_{1N}|^2 < 0.07$ and $|V_{2N}|^2 < 0.22$. At $m_N = 210$ GeV we find $|V_{1N}|^2 < 0.43$, while for $|V_{2N}|^2$ the limit reaches 1.0 at a mass of 203 GeV.

6. Summary

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

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