EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

FERMILAB-PUB-15-026-CMS

CERN-PH-EP/2015-001
2015/01/23

CMS-EXO-12-057

Search for heavy Majorana neutrinos in $\mu^{\pm}\mu^{\pm}$ + jets events in proton-proton collisions at $\sqrt{s} = 8\,\text{TeV}$

The CMS Collaboration*

arXiv:1501.05566v1 [hep-ex] 22 Jan 2015

Abstract

A search is performed for heavy Majorana neutrinos (N) using an event signature defined by two muons of the same charge and two jets ($\mu^{\pm}\mu^{\pm}$jj). The data correspond to an integrated luminosity of $19.7\,\text{fb}^{-1}$ of proton-proton collisions at a center-of-mass energy of 8 TeV, collected with the CMS detector at the CERN LHC. No excess of events is observed beyond the expected standard model background and upper limits are set on $|V_{\mu\text{N}}|^2$ as a function of Majorana neutrino mass m_{N} for masses in the range of 40–500 GeV, where $V_{\mu\text{N}}$ is the mixing element of the heavy neutrino with the standard model muon neutrino. The limits obtained are $|V_{\mu\text{N}}|^2 < 0.00470$ for $m_{\text{N}} = 90\,\text{GeV}$, $|V_{\mu\text{N}}|^2 < 0.0123$ for $m_{\text{N}} = 200\,\text{GeV}$, and $|V_{\mu\text{N}}|^2 < 0.583$ for $m_{\text{N}} = 500\,\text{GeV}$. These results extend considerably the regions excluded by previous direct searches.

Submitted to Physics Letters B

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*See Appendix A for the list of collaboration members

1 Introduction

The non-zero masses of neutrinos and mixing between flavors have been well established by neutrino oscillation experiments and provide evidence for physics beyond the standard model (SM) [1]. The most compelling way of explaining the smallness of the neutrino masses is the "seesaw" mechanism, which can be realized in several different schemes [2–11]. In the simplest model, the SM neutrino mass is given by $m_\nu \approx y_\nu^2 v^2 / m_\mathrm{N}$, where y_ν is a Yukawa coupling of ν to the Higgs field, v is the Higgs vacuum expectation value in the SM, and m_N is the mass of a new heavy neutrino state (N). In this scheme, N is a Majorana particle (which is its own antiparticle), so processes that violate lepton number conservation by two units are possible.

In this paper we describe a search for heavy Majorana neutrinos using a phenomenological approach [12–19]. We follow the studies in Refs. [17–19] and consider a heavy neutrino that mixes only with the SM muon neutrino, with m_N and $V_{\mu\mathrm{N}}$ as free parameters of the model. Here $V_{\mu\mathrm{N}}$ is a mixing element describing the mixing between the heavy Majorana neutrino and the SM muon neutrino.

Early direct searches for heavy Majorana neutrinos based on this model were reported by the L3 [20] and DELPHI [21] experiments at LEP. They searched for $\mathrm{Z} \to \nu_\mu \mathrm{N}$ decays and set limits on $|V_{\mu\mathrm{N}}|^2$ as a function of m_N for Majorana neutrino masses up to approximately 90 GeV. More recently, the CMS experiment at the CERN LHC extended the search region up to about 200 GeV [22]. Several experiments have obtained limits in the low mass region ($m_\mathrm{N} < 5$ GeV), including LHCb [23] at the LHC. Precision electroweak measurements can be used to constrain the mixing elements, resulting in indirect 90% confidence level limits of $|V_{\mu\mathrm{N}}|^2 < 0.0032$ independent of heavy neutrino mass [24]. Other models with heavy neutrinos have also been examined. ATLAS and CMS at the LHC have reported limits on heavy Majorana neutrino production [25, 26] in the context of the Left-Right Symmetric Model. ATLAS have also set limits based on an effective Lagrangian approach [26].

We report on an updated search for the production of a heavy Majorana neutrino in proton-proton (pp) collisions at a center-of-mass energy of $\sqrt{s} = 8$ TeV at the LHC with a data set corresponding to an integrated luminosity of 19.7 fb^{-1} collected with the CMS detector. We assume that the heavy Majorana neutrino is produced by s-channel production of a W boson, which decays via $\mathrm{W}^+ \to \mathrm{N}\mu^+$. The N is assumed to be a Majorana particle, so it can decay via $\mathrm{N} \to \mathrm{W}^-\mu^+$ with $\mathrm{W}^- \to \mathrm{q}\overline{\mathrm{q}}'$, resulting in a $\mu^+\mu^+\mathrm{q}\overline{\mathrm{q}}'$ final state. The charge-conjugate decay chain also contributes and results in a $\mu^-\mu^-\overline{\mathrm{q}}\mathrm{q}'$ final state.

We search for events with two isolated muons of the same sign of electric charge and at least two accompanying jets. The backgrounds to such dimuon final states originate from SM processes that contain isolated prompt same-sign (SS) dimuons in the final state (e.g. WZ production), and from processes such as multijet production in which muons from b-quark decays, or from jets, are misidentified as isolated prompt muons. The misidentified muon background is more significant for low masses ($m_\mathrm{N} < 90$ GeV), while at higher masses the SM prompt dimuon background becomes more important.

2 Detector, signal simulation, and data selection

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, taken as the z axis of the detector coordinate system, with the center of the detector defined to be at $z = 0$. The azimuthal angle ϕ is measured in the plane perpendic-

ular to the z axis, while the polar angle θ is measured with respect to this axis. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. A two-level trigger system selects the most interesting events for analysis.

Muons are measured in the pseudorapidity range $|\eta| < 2.4$, defined as $\eta = -\ln[\tan(\theta/2)]$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Charged-particle trajectories are measured in a silicon pixel and strip tracker covering $0 \leq \phi \leq 2\pi$ in azimuth and $|\eta| < 2.5$. Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum resolution for muons with $20 < p_{\mathrm{T}} < 100\,\mathrm{GeV}$ of 1.3–2.0% in the barrel and better than 6% in the endcaps. The p_{T} resolution in the barrel is better than 10% for muons with p_{T} up to 1 TeV [28].

The heavy Majorana neutrino production and decay process are simulated using the leading-order (LO) event generator described in Ref. [18] and implemented in ALPGEN v2.14 [29]. The LO cross section at $\sqrt{s} = 8\,\mathrm{TeV}$ for $\mathrm{pp} \to \mathrm{N}\mu^{\pm} \to \mu^{\pm}\mu^{\pm}\mathrm{q}\overline{\mathrm{q}}'$ with $|V_{\mu\mathrm{N}}|^2 = 1$ has a value of 1515 pb for $m_{\mathrm{N}} = 40\,\mathrm{GeV}$, dropping to 3.56 pb for $m_{\mathrm{N}} = 100\,\mathrm{GeV}$, and to 2.15 pb for $m_{\mathrm{N}} = 500\,\mathrm{GeV}$ [18]. The cross section is proportional to $|V_{\mu\mathrm{N}}|^2$. We scale the leading order cross section by a factor of 1.34 to account for higher-order corrections, based on the next-to-next-to-leading-order calculation in Refs. [30, 31] for s-channel W' production that has the same production kinematics as the signal. We use the CTEQ6M parton distribution functions (PDFs) [32]. Parton showering and hadronization are simulated using PYTHIA v6.4.22 [33]. The Monte Carlo (MC) event generator is interfaced with CMS software, where GEANT4 [34] detector simulation, digitization of simulated electronic signals, and event reconstruction are performed. To ensure correct simulation of the number of additional interactions per bunch crossing (pileup), Monte Carlo simulated events are mixed with multiple minimum bias events with weights chosen using the distribution of the number of reconstructed pp interaction vertices observed in data.

A dimuon trigger is used to select the signal sample. This trigger requires the presence of one muon reconstructed from matching tracks in the muon system and tracker with transverse momentum (p_{T}) above 17 GeV and a second muon with $p_{\mathrm{T}} > 8\,\mathrm{GeV}$ formed from a track in the tracker matched to hits in one of the muon detectors. The trigger efficiency for the signal sample is measured using $\mathrm{Z} \to \mu^{+}\mu^{-}$ events selected in data, and is found to be in the range 85–95%, varying with p_{T} and η.

Additional selections are performed to ensure the presence of well-identified muons and jets. Events are first required to have a well-reconstructed pp interaction vertex (primary vertex) identified as the reconstructed vertex with the largest value of $\sum p_{\mathrm{T}}^2$ for its associated charged tracks reconstructed in the tracking detectors [35].

Leptons, jets, and missing transverse energy ($\not{E}_{\mathrm{T}}$) in the event are reconstructed using the standard CMS particle-flow techniques [36, 37]. The missing transverse momentum vector is defined as the projection on the plane perpendicular to the beams of the negative vector sum of the momenta of all reconstructed particles in an event. Its magnitude is referred to as $\not{E}_{\mathrm{T}}$. Jets are formed from clusters based on the anti-k_{T} algorithm [38], with a distance parameter of 0.5, and are required to be within the pseudorapidity range $|\eta| < 2.5$. Muon candidates are required to have $|\eta| < 2.4$ and to be consistent with originating from the primary 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 [28]. Muon candidates must be isolated from other activity in the event, which is insured by requiring their relative isolation parameter (I_{rel}) to be less than 0.05. Here I_{rel} is defined as the scalar sum of transverse energy present within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ of the candidate's direction, excluding the candidate itself, divided by the muon candidate's transverse momentum. The muon selection criteria are the same as those used in Ref. [39] except for the more stringent requirement on I_{rel} used here.

Events are required to contain two same-sign muons, one with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and the other with $p_{\mathrm{T}} > 15\,\mathrm{GeV}$, and at least two jets with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$. Events with a third muon are rejected to suppress diboson events such as WZ. To reduce backgrounds from top-quark decays, events in which at least one jet is identified as originating from a b quark are rejected, where the medium working point of the combined secondary vertex tagger [40] has been used.

Further selection requirements are made based on two Majorana neutrino mass search regions. In the low-mass search region ($m_{\mathrm{N}} \lesssim 80\,\mathrm{GeV}$) the W-boson propagator is on-shell and the final state system of $\mu^{\pm}\mu^{\pm}\mathrm{q}\bar{\mathrm{q}}'$ should have an invariant mass close to m_{W}. In this region the following selections are imposed: missing transverse energy <30 GeV; $\mu^{\pm}\mu^{\pm}\mathrm{jj}$ invariant mass <200 GeV, where the two jets chosen are those which result in $m(\mu^{\pm}\mu^{\pm}\mathrm{jj})$ closest to m_{W}; and dijet invariant mass of these two jets $m(\mathrm{jj}) < 120\,\mathrm{GeV}$. In the low-mass region the transverse momenta of the muons and jets are relatively low and the overall efficiency is considerably smaller than at higher masses. Therefore, the invariant mass requirements in this region are chosen to be relatively loose.

In the high-mass search region ($m_{\mathrm{N}} \gtrsim 80\,\mathrm{GeV}$) the W-boson propagator is off-shell but the W boson from the N decay is on-shell, so the $\mathrm{W} \to \mathrm{q}\bar{\mathrm{q}}'$ decay should result in a dijet invariant mass close to m_{W}. As the decay particles are more energetic in this region, the following selections are imposed: missing transverse energy less than 35 GeV (relaxed to increase signal efficiency); dijet invariant mass $50 < m(\mathrm{jj}) < 110\,\mathrm{GeV}$, where the two jets with the invariant mass closest to m_{W} are chosen. In both the low-mass and high-mass search regions, the upper cutoff on the missing transverse energy suppresses SM background processes in which a W boson decays leptonically ($\mathrm{W} \to \mu\nu$), including W + jet and $\mathrm{t\bar{t}}$ production.

The low-mass selection gives the best sensitivity for masses below 90 GeV, while for $m_{\mathrm{N}} \geq 90\,\mathrm{GeV}$ the high-mass selection gives the best sensitivity. Therefore, we use the low-mass selection for $40 < m_{\mathrm{N}} < 90\,\mathrm{GeV}$ and the high-mass selection for $m_{\mathrm{N}} \geq 90\,\mathrm{GeV}$. For masses less than 40 GeV the overall acceptance for the Majorana neutrino signal is less than 1% and we do not search in this region.

After applying all the selection criteria above, a final selection is applied based on optimizing the signal significance using a figure of merit [41] defined by $\epsilon_S/(a/2 + \delta B)$ with the number of standard deviations $a = 2$ and where ϵ_S is the signal selection efficiency and δB is the uncertainty in the estimated background.

At each Majorana neutrino mass point, the optimization is performed by varying the lower bound of three selections: the transverse momentum p_{T1} of the highest p_{T} muon (or "leading" muon), the transverse momentum p_{T2} of the second muon (or "trailing" muon), and the invariant mass $m(\mu^{\pm}\mu^{\pm}\mathrm{jj})$. The two jets used in this optimization are those selected as described above for the low- and high-mass regions.

The overall signal acceptance includes trigger efficiency, geometrical acceptance, and efficiencies of all selection criteria. The overall acceptance for heavy Majorana neutrino events ranges between 0.69% for $m_{\mathrm{N}} = 40\,\mathrm{GeV}$ to 12% for $m_{\mathrm{N}} = 500\,\mathrm{GeV}$. The lower acceptance at low m_{N}

is due to the smaller average p_T of the jets and muons in these events. The acceptance dips when m_N approaches m_W because the muon p_T becomes small. Above the W-boson mass the acceptance increases again up to 400–500 GeV at which point the boosted decay products of the Majorana neutrino begin to overlap.

3 Background estimation

There are three potential sources of same-sign dimuon backgrounds: SM sources such as WZ production, events resulting from misidentified muons, and opposite-sign dimuon events (e.g. from $Z \to \mu^+\mu^-$) in which the charge of one of the muons is mismeasured. The latter source is found to be negligible for muons with p_T in the range of interest for this analysis, based on MC studies and studies with cosmic ray muons. Estimation of the remaining two sources of background is discussed below.

An important background source is the irreducible background from SM production of two genuine isolated muons of the same sign, which can originate from sources such as WZ and ZZ diboson production, double W-strahlung $W^\pm W^\pm qq$ processes, WH production, $t\bar{t}W$ production, double parton scattering (two $qq' \to W$), and triboson production. These processes have relatively small cross sections, and are consequently estimated using MC simulations. We use PYTHIA to simulate ZZ and WZ production and MADGRAPH v5.1.3.30 [42] for the remaining processes.

The second significant background source originates from events containing objects misidentified as prompt muons. These "prompt muons" originate from b-quark decays or light-quark or gluon jets. Examples of this background include: multijet production in which two jets are misidentified as muons; $W(\to \mu\nu)$ + jets events in which one of the jets is misidentified as a muon; and $t\bar{t}$ decays in which one of the top-quark decays yields a prompt isolated muon ($t \to Wb \to \mu\nu_\mu b$), and the other muon of same charge arises from a b-quark decay or a jet misidentified as an isolated prompt muon. These backgrounds are estimated using control samples from collision data as described below.

To estimate the misidentified muon background we use the method described in Ref. [22]. An independent data sample enriched in multijet events is used to calculate the probability for a jet that passes minimal muon selection requirements ("loose muons") to also pass the more stringent requirements used to define muons selected in the heavy Majorana neutrino signal selection ("tight muons"). This probability is binned in p_T and η and is used as a weight in the calculation of the background in events that pass all the signal selections except that one or both muons fail the tight criteria, but pass the loose ones.

The sample enriched in multijet production is selected by requiring a loose muon and a jet, resulting in events that are mostly dijet events with one jet containing a muon. Only one muon is allowed and upper cutoffs on missing transverse energy ($\not{E}_T < 20\,\text{GeV}$) and the transverse mass ($m_T < 25\,\text{GeV}$) are applied, where m_T is calculated using the muon p_T and $\not{E}_T$. These requirements suppress contamination from W and Z boson decays. We also require the loose muon and jet to be separated in azimuth by $\Delta\phi > 2.5$. This away-side jet is used as a tag and the loose muon is a probe used to determine the misidentification probability. The transverse energy of the tag jet is an essential ingredient to calibrate the characteristics of the probe (loose muon).

Loose muons are defined by relaxing the identification requirements (used to select signal events) as follows: the isolation requirement is relaxed from $I_{rel} < 0.05$ to $I_{rel} < 0.4$; the trans-

verse impact parameter of the muon track is relaxed from <0.05 mm to <2 mm; the chi squared per degree of freedom of the muon track fit is relaxed from 10 to 50.

The overall systematic uncertainty in the misidentified muon background is determined from the variation of the background estimate with respect to the isolation requirement for the loose muons and the p_T requirement for the tagging jet. Increasing and decreasing the p_T requirement for the tag jet changes the p_T spectrum of the recoiling muon in the event and is found to have the largest impact on the background level. The misidentified muon rate is comparatively stable with respect to variations in loose muon isolation requirements. As a result, the 28% overall systematic uncertainty in the misidentified muon background estimate is dominated by the p_T requirement on the tag jet.

We evaluate the method used to estimate the background from misidentified muons by checking the procedure using MC simulated event samples in which the true origin of the muons, either from W or Z boson decays or from a quark decay, is known. The misidentification probabilities are obtained from multijet events and are used to estimate the misidentified muon backgrounds in $t\bar{t}$, W + jets, and independent multijet events by applying the background estimation method described above. The predicted backgrounds agree with the expectations within the systematic uncertainties.

In addition, to test the validity of the background estimation method, we define two signal-free control regions in data. We apply the background estimation method in these regions and compare the result with the observed yields. The control regions in the two mass ranges are defined as follows. In both the low-mass range ($40 < m_N < 90$ GeV) and the high-mass range ($m_N > 90$ GeV) the control region is the same as the signal selection, without the final optimized selections but with either missing transverse energy greater than 50 GeV or one or more jets that are tagged as originating from a b quark. In the low-mass control region we predict a total background of 51.4 ± 1.9 (stat) ± 8.3 (syst) events compared to an observed yield of 45 events, while in the high mass control region we predict a total background of 87.6 ± 2.5 (stat) ± 12.3 (syst) compared to the observed yield of 81 events. The misidentified muon background accounts for about 2/3 of the total background in both regions. In both regions the predictions are in agreement with the observations and well within the systematic uncertainty, which is dominated by the 28% uncertainty in the misidentified muon background. The observed distributions of all relevant observables also agree with the predictions, within uncertainties.

4 Systematic uncertainties

The main sources of systematic uncertainties are associated with the background estimates. As described above, the overall systematic uncertainty in the misidentified muon background is 28%. The systematic uncertainties in the normalizations of irreducible SM backgrounds are 12% for WZ, 9% for ZZ [43], and 22% for W^+W^- [43]. For the other processes the uncertainty is 25%, determined by varying the renormalization and factorization scales from the nominal value of Q^2 to $4Q^2$ and $Q^2/4$, and following the PDF4LHC recommendations [44, 45] to estimate the uncertainty due to the choice of PDFs. The overall systematic uncertainty in the SM irreducible background estimate, including those discussed below, is 19%.

Sources of systematic uncertainty associated with the estimates of the heavy Majorana neutrino signal and of the SM irreducible background are summarized in Table 1. To evaluate the uncertainty due to imperfect knowledge of the integrated luminosity [46], jet energy scale [47], jet energy resolution [47], b-tagging [40], muon trigger and selection efficiency, and the cross section for minimum bias production used in the pileup reweighting procedure in simulation,

Table 1: Summary of systematic uncertainties in the estimation of the heavy Majorana signal, SM background (SM Bkgd.), and misidentified muon background (Misid. Bkgd.) for low-mass selection (first number) and high mass selection (second number in square brackets).

Source	Signal (%)	SM Bkgd. (%)	Misid. Bkgd. (%)
Background estimate from data	—	—	28 [28]
SM cross section	—	9–25 [9–25]	—
Jet energy scale	5–12 [1–3]	3 [5]	—
Jet energy resolution	6–12 [2–3]	7 [10]	—
Event pileup	6–7 [3–6]	7 [4]	—
Unclustered energy	2 [1]	3 [1]	—
Integrated luminosity	2.6 [2.6]	2.6 [2.6]	—
Muon trigger and selection	2 [2]	2 [2]	—
b-tagging	1 [1]	1.5 [1]	—
PDF	3.5 [3.5]	—	—
Renormalization/Factorization scales	8–10 [1–6]	—	—
Signal MC statistics	3–9 [1–4]	—	—

the input value of each parameter is changed by ± 1 standard deviation from its central value. Energy not clustered in the detector affects the overall missing transverse energy scale resulting in an uncertainty in the event yield due to the upper cutoff on $\not{E}_{\mathrm{T}}$. Additional uncertainties in the heavy Majorana neutrino signal estimate arise from the choice of PDFs and renormalization and factorization scales used in the ALPGEN MC event generator.

5 Results and discussion

The selections determined by the optimization for each Majorana neutrino mass point are shown in Table 2 together with the overall signal acceptance. Figure 1 shows the transverse momentum distributions of the two muons, p_{T1} and p_{T2}, and the invariant mass $m(\mu^{\pm}\mu^{\pm}\mathrm{jj})$ for the low-mass region after all selections are applied except for the final optimization requirements. The corresponding distributions for the high-mass region are shown in Fig. 2.

After applying all the final optimized selections we obtain the results shown in Table 3. The expected signal depends on m_{N} and $|V_{\mu\mathrm{N}}|^2$. For $m_{\mathrm{N}} = 50\,\mathrm{GeV}$ and $|V_{\mu\mathrm{N}}|^2 = 1 \times 10^{-3}$ the expected number of events is 226. For $m_{\mathrm{N}} = 100\,\mathrm{GeV}$ and $|V_{\mu\mathrm{N}}|^2 = 1 \times 10^{-3}$ the expected number of events is 4.4, while for $m_{\mathrm{N}} = 500\,\mathrm{GeV}$ and $|V_{\mu\mathrm{N}}|^2 = 1$ it is 6.9.

We see no evidence for a significant excess in data beyond the backgrounds predicted from the SM and we set 95% confidence level (CL) exclusion limits on the cross section times branching fraction for $\mathrm{pp} \to \mathrm{N}\mu^{\pm} \to \mu^{\pm}\mu^{\pm}\mathrm{q}\bar{\mathrm{q}}'$ as a function of m_{N}, using the CL_s method [48–50] based on the event yields shown in Table 3. We use Poisson distributions for the signal and log-normal distributions for the nuisance parameters. The limits obtained are shown in Fig. 3. We do not consider the mass range below $m_{\mathrm{N}} = 40\,\mathrm{GeV}$ because of the very low selection efficiency for the signal in this mass region.

The behavior of the limit around $m_{\mathrm{N}} = 80\,\mathrm{GeV}$ is caused by the fact that as the heavy Majorana neutrino gets close to the W-boson mass from below or above, the muon produced together with the N or the muon from the N decay have low p_{T}, respectively.

We also set limits on square of the heavy Majorana neutrino mixing parameter $|V_{\mu\mathrm{N}}|^2$ as a function of m_{N}, under the assumption $|V_{\mathrm{eN}}|^2 = |V_{\tau\mathrm{N}}|^2 = 0$. Figure 4 shows the resulting upper limits on $|V_{\mu\mathrm{N}}|^2$ as a function of m_{N}.

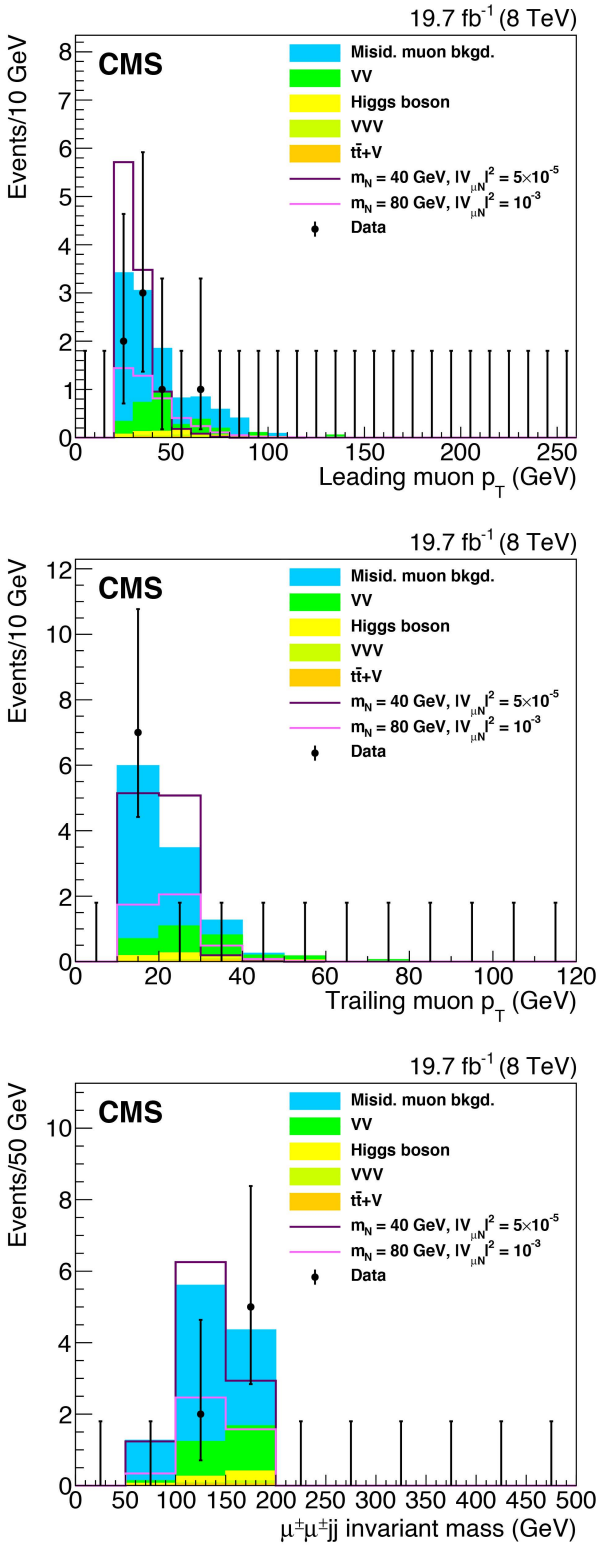

Figure 1: Kinematic distributions for the low-mass region after all selections are applied except for the final optimization requirements: leading muon p_{T} (top), trailing muon p_{T} (middle), and $\mu^{\pm}\mu^{\pm}$jj invariant mass (bottom). The plots show the data, backgrounds, and two choices for the heavy Majorana neutrino signal: $m_{\mathrm{N}} = 40\,\mathrm{GeV}$, $|V_{\mu\mathrm{N}}|^2 = 5 \times 10^{-5}$ and $m_{\mathrm{N}} = 80\,\mathrm{GeV}$, $|V_{\mu\mathrm{N}}|^2 = 1 \times 10^{-3}$. The backgrounds shown are from misidentified muons and from diboson (VV), Higgs boson, triboson (VVV), and $\mathrm{t\bar{t}W}$ production.

Table 2: Minimum thresholds on discriminating variables determined by the optimization and overall signal acceptance for each Majorana neutrino mass point (m_N). As discussed in the text, the search was divided into low-mass ($m_N \leq 80$ GeV) and high-mass ($m_N > 80$ GeV) regions, and different selection criteria were used in the two regions.

m_N (GeV)	$m(\mu^\pm\mu^\pm jj)$ (GeV)	p_{T1} (GeV)	p_{T2} (GeV)	Acceptance (%)
40	80	20	15	0.69
50	80	20	15	0.80
60	80	20	15	0.64
70	80	20	15	0.26
80	80	20	15	1.2
90	110	20	15	1.2
100	120	20	15	4.7
125	140	25	20	11
150	160	35	25	13
175	200	45	30	15
200	220	50	35	16
250	270	75	35	17
300	290	100	45	15
350	290	100	45	16
400	290	100	45	15
500	290	100	45	12

6 Summary

A search for heavy Majorana neutrinos in $\mu^\pm\mu^\pm jj$ events has been performed in proton-proton collisions at a center-of-mass energy of 8 TeV, using a data set corresponding to an integrated luminosity of 19.7 fb^{-1}. No excess of events beyond the standard model background prediction is found. Upper limits at 95% CL are set on $|V_{\mu N}|^2$, as a function of heavy Majorana neutrino mass m_N, where $V_{\mu N}$ is the mixing element of the heavy neutrino N with the standard model muon neutrino.

These are the first direct upper limits on the heavy Majorana neutrino mixing for $m_N > 200$ GeV. For low mass ($m_N < 90$ GeV) the limits are better or comparable to the L3 [20] and DELPHI [21] limits, which are derived from $Z \to \nu_\ell N$ and are restricted to masses below approximately 90 GeV. The limits reported here extend well beyond this mass and are significantly better than previous LHC limits obtained at a center-of-mass energy of 7 TeV. For $m_N = 90$ GeV we find $|V_{\mu N}|^2 < 0.00470$. Furthermore, the direct limits on $|V_{\mu N}|$ have been extended from $m_N \approx 200$ GeV up to $m_N \approx 500$ GeV. At $m_N = 200$ GeV the limit is $|V_{\mu N}|^2 < 0.0123$, and at $m_N = 500$ GeV the limit is $|V_{\mu N}|^2 < 0.583$.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS

Table 3: Observed event yields and estimated backgrounds for each Majorana neutrino mass point (m_N). The background predictions from the irreducible SM backgrounds (SM Bkgd.), misidentified muon background (Misid. Bkgd.) and total background (Total Bkgd.) are shown in columns 2–4, while column 5 shows the number of events observed in data. The uncertainties shown are respectively the statistical and systematic components. As discussed in the text, the search was divided into low-mass ($m_N \leq 80$ GeV) and high-mass ($m_N > 80$ GeV) regions, and different selection criteria were used in the two regions.

m_N (GeV)	SM Bkgd.	Misid. Bkgd.	Total Bkgd.	N_{obs}
40	$3.0 \pm 0.4 \pm 0.6$	$6.7 \pm 0.9 \pm 1.9$	$9.8 \pm 1.0 \pm 2.0$	7
50	$3.0 \pm 0.4 \pm 0.6$	$6.7 \pm 0.9 \pm 1.9$	$9.8 \pm 1.0 \pm 2.0$	7
60	$3.0 \pm 0.4 \pm 0.6$	$6.7 \pm 0.9 \pm 1.9$	$9.8 \pm 1.0 \pm 2.0$	7
70	$3.0 \pm 0.4 \pm 0.6$	$6.7 \pm 0.9 \pm 1.9$	$9.8 \pm 1.0 \pm 2.0$	7
80	$3.0 \pm 0.4 \pm 0.6$	$6.7 \pm 0.9 \pm 1.9$	$9.8 \pm 1.0 \pm 2.0$	7
90	$8.7 \pm 0.7 \pm 1.7$	$12.6 \pm 1.1 \pm 3.5$	$21.3 \pm 1.3 \pm 3.9$	19
100	$8.7 \pm 0.7 \pm 1.7$	$11.7 \pm 1.0 \pm 3.3$	$20.4 \pm 1.2 \pm 3.7$	19
125	$7.9 \pm 0.6 \pm 1.5$	$5.9 \pm 0.7 \pm 1.6$	$13.8 \pm 0.9 \pm 2.2$	8
150	$6.4 \pm 0.5 \pm 1.2$	$3.6 \pm 0.6 \pm 1.0$	$9.9 \pm 0.8 \pm 1.6$	7
175	$4.4 \pm 0.4 \pm 0.8$	$1.6 \pm 0.4 \pm 0.5$	$6.0 \pm 0.6 \pm 1.0$	7
200	$3.4 \pm 0.4 \pm 0.7$	$0.8 \pm 0.3 \pm 0.2$	$4.2 \pm 0.5 \pm 0.7$	5
250	$1.9 \pm 0.3 \pm 0.3$	$0.6 \pm 0.2 \pm 0.2$	$2.5 \pm 0.3 \pm 0.4$	3
300	$0.9 \pm 0.2 \pm 0.2$	$0.1 \pm 0.2 \pm 0.0$	$1.0 \pm 0.3 \pm 0.2$	1
350	$0.9 \pm 0.2 \pm 0.2$	$0.1 \pm 0.2 \pm 0.0$	$1.0 \pm 0.3 \pm 0.2$	1
400	$0.9 \pm 0.2 \pm 0.2$	$0.1 \pm 0.2 \pm 0.0$	$1.0 \pm 0.3 \pm 0.2$	1
500	$0.9 \pm 0.2 \pm 0.2$	$0.1 \pm 0.2 \pm 0.0$	$1.0 \pm 0.3 \pm 0.2$	1

detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); MoER, ERC IUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and EPLANET (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 (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS program of Foundation for Polish Science, cofinanced from European Union, Regional Development Fund; the Compagnia di San Paolo (Torino); the Consorzio per la Fisica (Trieste); MIUR project 20108T4XTM (Italy); the Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; and the National Priorities Research Program by Qatar National Research Fund.

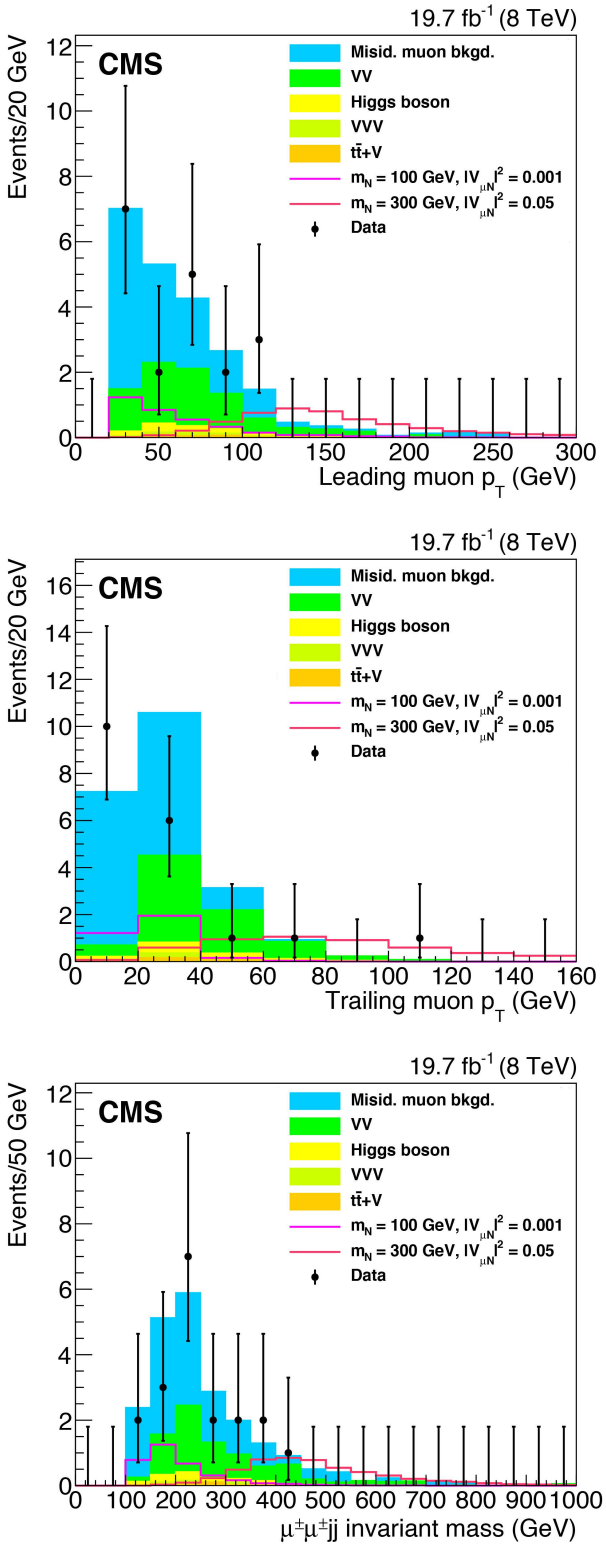

Figure 2: Kinematic distributions for the high-mass region after all selections are applied except for the final optimization requirements: leading muon p_{T} (top), trailing muon p_{T} (middle), and $\mu^{\pm}\mu^{\pm}$jj invariant mass (bottom). The plots show the data, backgrounds, and two choices for the heavy Majorana neutrino signal: $m_{\mathrm{N}} = 100\,\mathrm{GeV}$, $|V_{\mu\mathrm{N}}|^2 = 0.001$ and $m_{\mathrm{N}} = 300\,\mathrm{GeV}$, $|V_{\mu\mathrm{N}}|^2 = 0.05$. The backgrounds shown are from misidentified muons and from diboson (VV), Higgs boson, triboson (VVV), and $\mathrm{t\bar{t}W}$ production.

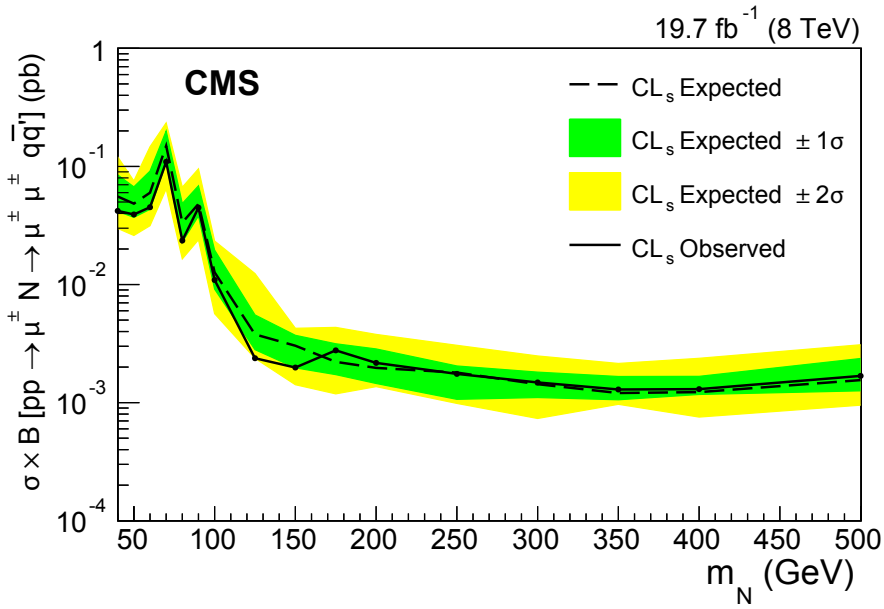

Figure 3: Exclusion region at 95% CL in the cross section times branching fraction, as a function of the heavy Majorana neutrino mass. The long-dashed black curve is the expected upper limit, with one and two standard-deviation bands shown in dark green and light yellow, respectively. The solid black curve is the observed upper limit. The region above the exclusion curves is ruled out at 95% CL.

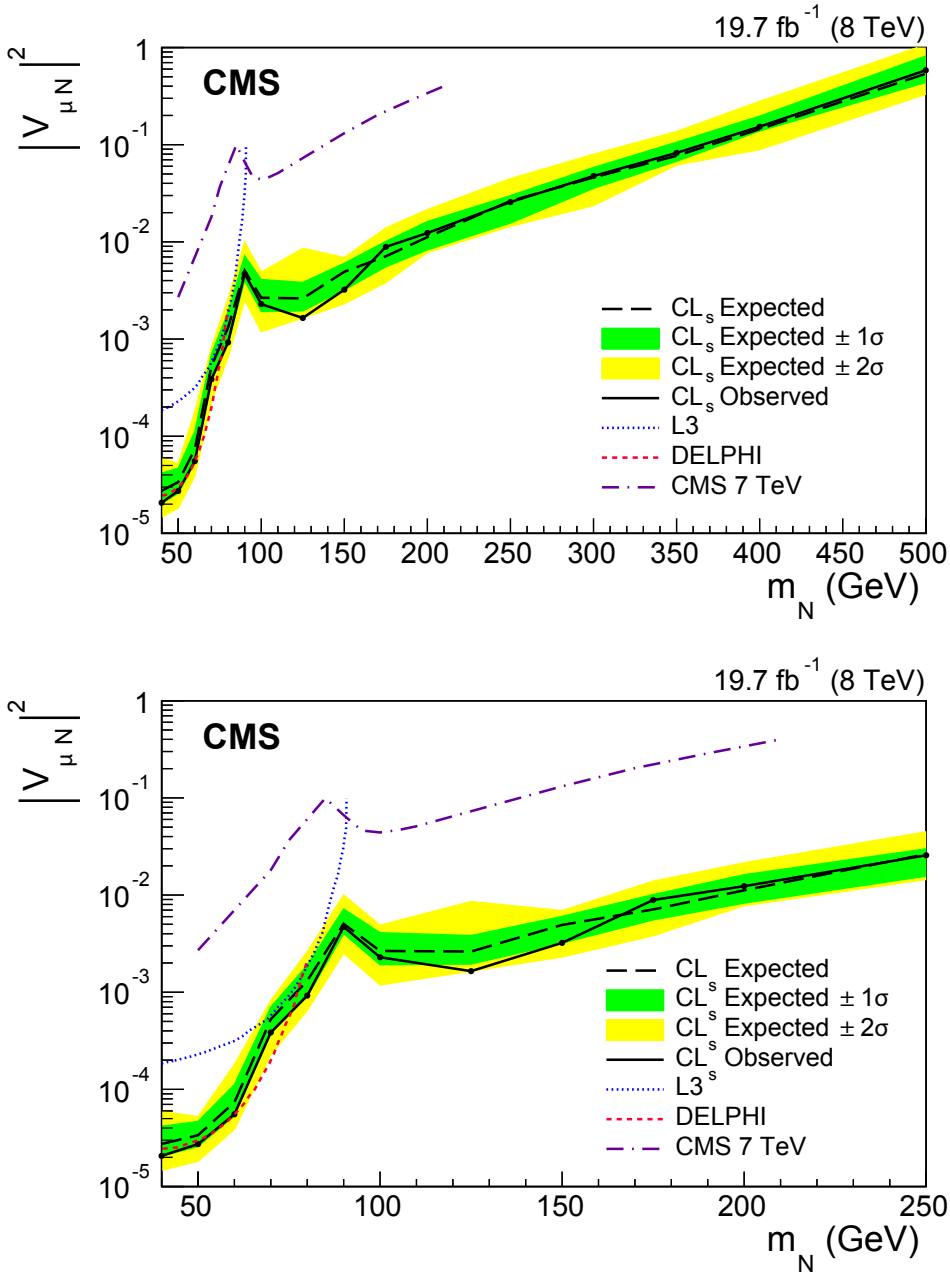

Figure 4: Exclusion region at 95% CL in the square of the heavy Majorana neutrino mixing parameter as a function of the heavy Majorana neutrino mass: ($|V_{\mu N}|^2$ vs. m_N). The long-dashed black curve is the expected upper limit, with one and two standard-deviation bands shown in dark green and light yellow, respectively. The solid black curve is the observed upper limit. Also shown are the upper limits from other direct searches: L3 [20], DELPHI [21], and the upper limits from CMS obtained with the 2011 LHC data at $\sqrt{s} = 7$ TeV [22]. The regions above the exclusion curves are ruled out at 95% CL. The lower panel shows an expanded view of the region 40 GeV $< m_N <$ 250 GeV.

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