Signatures for Majorana Neutrinos at Hadron Colliders

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The Majorana nature of neutrinos may only be experimentally verified via lepton-number violating processes involving charged leptons. We explore the $\Delta L = 2$ like-sign dilepton production at hadron colliders to search for signals of Majorana neutrinos. We find significant sensitivity for resonant production of a Majorana neutrino in the mass range of 10–80 GeV at the current run of the Tevatron with 2 fb^{-1} integrated luminosity and in the range of 10–400 GeV at the CERN LHC with 100 fb^{-1}.

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Neutrinos are arguably the most elusive particles in the standard model (SM) spectrum. The evidence is strong that neutrinos are massive and their flavors defined with respect to the charged leptons oscillate [1], indicating the need of extension beyond the SM. We do not know the nature of the mass generation and flavor mixing. In particular, we are clueless if neutrinos are of Dirac or Majorana type—the former preserves the lepton number (L), and the latter violates it by two units. Thus, the unambiguous proof of the existence of a Majorana neutrino is the observation of a lepton-number violation process, which would have profound implications in particle physics, nuclear physics, and cosmology. Since neutrinos are so weakly interacting and leave no trace in ordinary detectors, the only appropriate signatures must involve charged leptons via the charge-current interactions for a $\Delta L = 2$ process.

The simplest extension of the standard model to include Majorana neutrinos is to introduce n right-handed SM singlet neutrinos N_{aR} ($a = 1, 2, \ldots, n$) and $n \geq 2$ in order to generate at least two massive neutrinos. Besides the Dirac masses m_D from the Yukawa interactions, there is also a possible heavy Majorana mass term $\sum_{b,b'=1}^{n} \bar{N^c}_{bL} B_{bb'} N_{b'R}$ + H.c. The diagonalized mass terms thus read

$$\frac{1}{2}\left(\sum_{m=1}^{3} m_m^\nu \bar{\nu}_{mL} \nu_{mR}^c + \sum_{m'=4}^{3+n} m_{m'}^N \bar{N}_{m'L}^c N_{m'R}\right)$$

plus the Hermitian conjugate, with the mixing relations between the flavors defined with respect to the charged leptons ℓ and mass eigenstates

$$\nu_{\ell L} = \sum_{m=1}^{3} U_{\ell m} \nu_{mL} + \sum_{m'=4}^{3+n} V_{\ell m'} N_{m'L}^c, \qquad UU^\dagger + VV^\dagger = I.$$

In the simplest incarnation without further flavor structure or new states, the light neutrino masses m_m^ν are of the order of magnitude m_D^2/B, while the heavy neutrino masses are $m_{m'}^N \simeq B$. The corresponding mixing angles are of $VV^* \sim m_m^\nu/m_{m'}^N$, and thus $UU^\dagger \approx I$. However, we will take a phenomenological approach toward the mass and mixing parameters without assuming any relationship *a priori*.

In terms of the mass eigenstates, the gauge interaction Lagrangian can be written as

$$\begin{aligned}\mathcal{L} = &-\frac{g}{\sqrt{2}} W_\mu^+ \left(\sum_{\ell=e}^{\tau} \sum_{m=1}^{3} U_{\ell m}^* \bar{\nu}_m \gamma^\mu P_L \ell\right) + \text{H.c.} \\ &-\frac{g}{\sqrt{2}} W_\mu^+ \left(\sum_{\ell=e}^{\tau} \sum_{m'=4}^{3+n} V_{\ell m'}^* \bar{N}_{m'}^c \gamma^\mu P_L \ell\right) + \text{H.c.} \\ &-\frac{g}{2\cos_W} Z_\mu \left(\sum_{\ell=e}^{\tau} \sum_{m'=4}^{3+n} V_{\ell m'}^* \bar{N}_{m'}^c \gamma^\mu P_L \nu_\ell\right) + \text{H.c.},\end{aligned}$$

where P_L is the left-handed chirality projection operator. There exist constraints on the heavy neutrino mass and the mixing elements $V_{\ell m'}$. Since we are interested in the collider searches, we consider $m_N \gg 1$ GeV. By far, the strongest bound is from the nonobservation of the neutrinoless double-β decay ($0\nu\beta\beta$) [2]. It translates to a bound on the mass and mixing element

$$\sum_N \frac{|V_{eN}|^2}{m_N} < 5 \times 10^{-8}\ \text{GeV}^{-1}. \tag{1}$$

The other relevant constraints come from the CERN LEP experiments [3,4], typically leading to $|V_{\mu N}|^2, |V_{\tau N}|^2 \lesssim 10^{-4}$–$10^{-5}$ for $m_N \sim 5$ GeV–80 GeV.

We first consider the heavy Majorana neutrino decay width. The decay modes of a heavy Majorana neutrino are to a W or a Z or a Higgs boson plus a corresponding SM lepton. The total width of a heavy Majorana neutrino goes like

$$\Gamma_N \approx \begin{cases} \sum_\ell |V_{\ell N}|^2 \frac{G_F m_N^3}{8} & \text{for } m_N > m_Z, m_H \\ \sum_\ell |V_{\ell N}|^2 \frac{G_F^2 m_N^5}{10^3} & \text{for } m_N \ll m_W. \end{cases}$$

It remains rather narrow even for $m_N \sim 1$ TeV for small mixing angles. The branching ratios of heavy Majorana neutrino decay are $\mathrm{Br}(N \to \ell^- W^+) \simeq \mathrm{Br}(N \to Z\nu) \simeq \mathrm{Br}(N \to H\nu) \simeq 25\%$.

Representative Feynman diagrams for $\Delta L = 2$ processes induced by Majorana neutrinos in $q\bar{q}'$ collisions are depicted in Fig. 1. The contribution via WW fusion shown by the first diagram is the direct collider-analogue to the $0\nu\beta\beta$ and has been discussed in Ref. [5]. We reiterate that the rate is very small due to the suppression of $|V_{\ell' N}|^4$. We emphasize that a Majorana neutrino can be produced in resonance as seen in the second diagram if kinematically accessible $m_N < \sqrt{s}$, thus substantially enhancing the production rate, which is proportional to $|V_{\ell N}|^2$. This was noted earlier in Ref. [6], where only $m_N > 100$ GeV was considered for the $e^\pm e^\pm$ mode. We extend the calculation to include an arbitrary mass m_N and general mixing for final state lepton flavors. The constraint of Eq. (1) from $0\nu\beta\beta$ is very strong [2] and discourages the hope for signals involving an electron, which has been the focus so far in the literature [5,6]. We thus propose the like-sign dimuons $\mu^\pm\mu^\pm$, easier for detection than electrons in hadronic collisions, as the best signature for a heavy Majorana neutrino at both the Tevatron and LHC energies. The final state W boson is reconstructed in hadronic decay channels because of the need of no neutrinos involved in the final state to assure the unambiguous identification of $\Delta L = 2$.

For the mass range of our current interest, the width of the heavy neutrino is small, so that the signal cross section can be approximated as

$$\sigma(p\bar{p} \to \mu^\pm\mu^\pm W^\mp) \approx \sigma(p\bar{p} \to \mu^\pm N)\mathrm{Br}(N \to \mu^\pm W^\mp) \equiv S_{\mu\mu}\sigma_0, \quad (2)$$

where $S_{\mu\mu}$ is the "effective mixing parameter" of N with a muon, defined by

$$S_{\mu\mu} = \frac{|V_{\mu N}|^4}{\sum_\ell |V_{\ell N}|^2}, \quad (3)$$

and σ_0 is "bare cross section," essentially independent of the mixing parameters when the heavy neutrino decay width is narrow. We calculated the exact matrix elements including all contributing diagrams and found that the factorization of Eq. (2) is a good approximation. Our results are shown in Fig. 2.

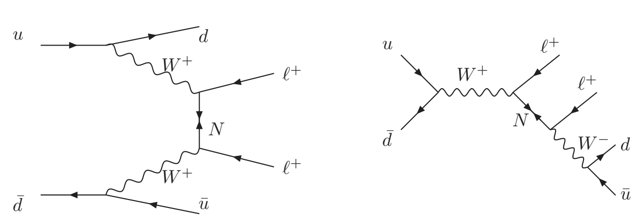

FIG. 1. Feynman diagrams for $\Delta L = 2$ processes induced by a Majorana neutrino N in $q\bar{q}'$ collisions.

The Tevatron.—To be more realistic in estimating the signal observability, we introduce the basic acceptance on leptons and jets to simulate the CDF/D0 detector coverage in the transverse momentum (p_T) and pseudorapidity (η)

$$p_T(\mu) > 5 \text{ GeV}, \qquad |\eta(\mu)| < 2.0, \quad (4)$$

$$p_T(j) > 10 \text{ GeV}, \qquad |\eta(j)| < 3.0. \quad (5)$$

The important characteristics for the signal are the two well-isolated like-sign leptons, with no missing energy. We thus require the events to have μ-jet separation and small missing energy

$$\Delta R_{\mu j}^{\min} > 0.5, \qquad \not{p}_T < 20 \text{ GeV}. \quad (6)$$

The fully reconstructed events should reflect the nature of an on-shell W of the final states in either $m_W \approx m(jj)$ or $m(jj\mu\mu)$. We thus select events

$$60 \text{ GeV} < m_{\text{cluster}} < 100 \text{ GeV}, \quad (7)$$

where m_{cluster} is the invariant mass of W either in the jj or in the $jj\mu\mu$ final state. Furthermore, the signal distribution should naturally present a peak at $m(jj\mu) \approx m_N$.

Although there is no SM process as a background with $\Delta L = 2$, there are processes that lead to like-sign leptons. Those include $W^\pm W^\pm jj$ production via gluon exchange or electroweak gauge boson exchange, with $W^\pm$ decaying leptonically, or $W^\pm W^\pm W^\mp$ with the unlike-sign $W^\mp$ decaying hadronically. It turns out that the leading background is from a cascade decay of $t\bar{t}$ production: $t \to \ell^+\nu b$, $\bar{t} \to W\bar{b} \to$ jets $\bar{c}\ell^+$. With the cuts imposed above, the background can be essentially eliminated.

We smear the jet energy and the muon momentum according to the Gaussian response of the detector. We consider Poisson statistics for the low event rate when calculating the signal significance. For instance, a 95% (2σ) bound on the signal for no background would need

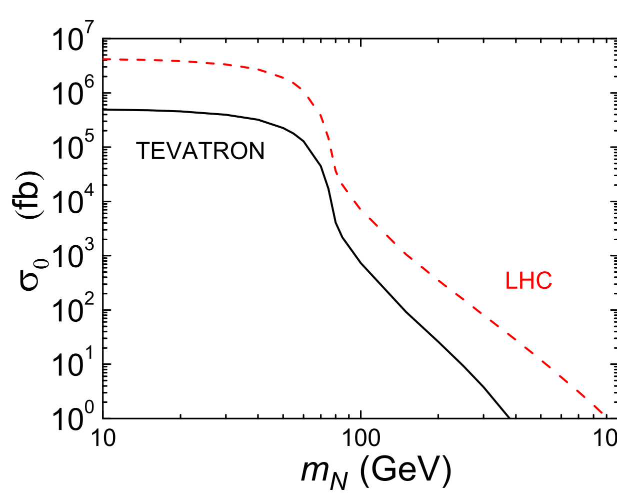

FIG. 2 (color online). The bare cross section σ_0 versus the heavy neutrino mass at the Tevatron and the LHC.

a signal event rate $N_S = \mathcal{L}\sigma_0(m_N)S_{\mu\mu} \geq 3$. We show our final results at the Tevatron in Fig. 3, the bare cross section σ_0 after all of the cuts and the sensitivity on the mixing parameter $S_{\mu\mu}$. We see that there is significant sensitivity at the Tevatron in the mass range of $m_N = 10$–80 GeV. The mixing parameters can be probed to a few times 10^{-5} at a 2σ level with 2 fb^{-1} integrated luminosity, surpassing the L3 95% C.L. bound [3], and reaching about 10^{-4} at a 5σ level. While the Tevatron run II will be soon accumulating substantially more data, the search for a heavy Majorana neutrino will be particularly interesting due to the fact that this would be a low-background clean channel.

The LHC.—At the LHC, we adopt the judicious cuts

$$p_T(\mu) > 10\ \text{GeV}, \qquad |\eta(\mu)| < 2.5, \tag{8}$$

$$p_T(j) > 15\ \text{GeV}, \qquad |\eta(j)| < 3.0, \tag{9}$$

$$\Delta R_{lj}^{\min} > 0.5, \qquad \not{p}_T < 25\ \text{GeV}. \tag{10}$$

A similar W mass reconstruction is required as in Eq. (7).

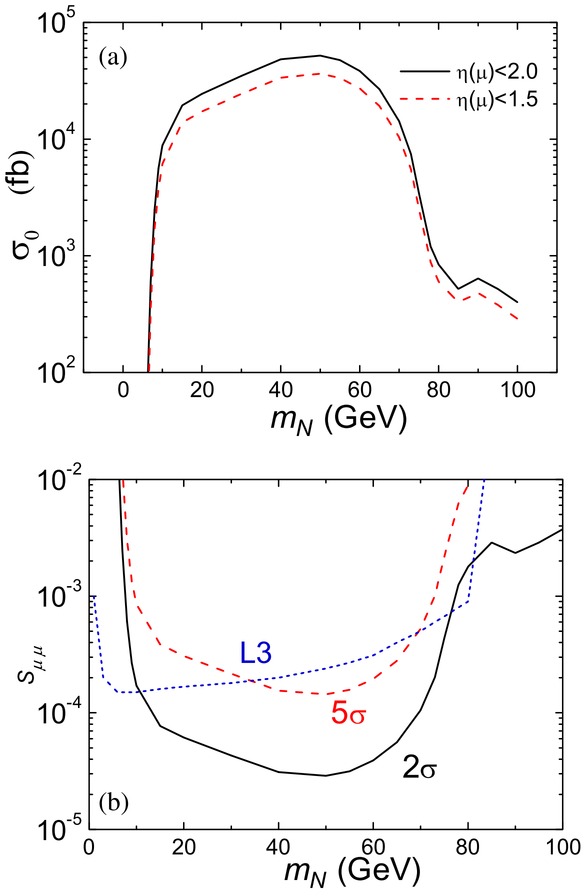

FIG. 3 (color online). Tevatron results: (a) σ_0 versus m_N after all of the cuts with the two cases of muon rapidity acceptance from D0 and CDF; (b) sensitivity on $S_{\mu\mu}$ for 2 fb^{-1}. For comparison, the 95% bound from the L3 search is included.

Along with the background processes studied for the Tevatron, more channels are considered such as $pp \to jjZZ$ and $pp \to jjZW$ that may fake the like-sign dilepton signal when some particles are missing from detection. Although most of the backgrounds can be made small after the cuts, there are some events left to contaminate the purity of the signal. The leading background is $pp \to W^\pm W^\pm W^\mp$. The total background after the cuts is about $(7$–$8) \times 10^{-2}$ fb. One can further strengthen the signal significance by examining the mass window

$$0.8m_N < m(jj\mu) \approx m_N < 1.2m_N. \tag{11}$$

This would reduce the background below 0.04 fb. Our results after the cuts and the signal reconstruction of Eq. (11) are shown in Fig. 4, for the bare cross section σ_0 and the sensitivity on the effective mixing parameter $S_{\mu\mu}$ with an integrated luminosity 100 fb^{-1}. We see that the mass range with significant sensitivity can be extended to $m_N = 10$–400 GeV. The mixing parameter can be probed to 10^{-3} at a 2σ level way beyond the L3 95%

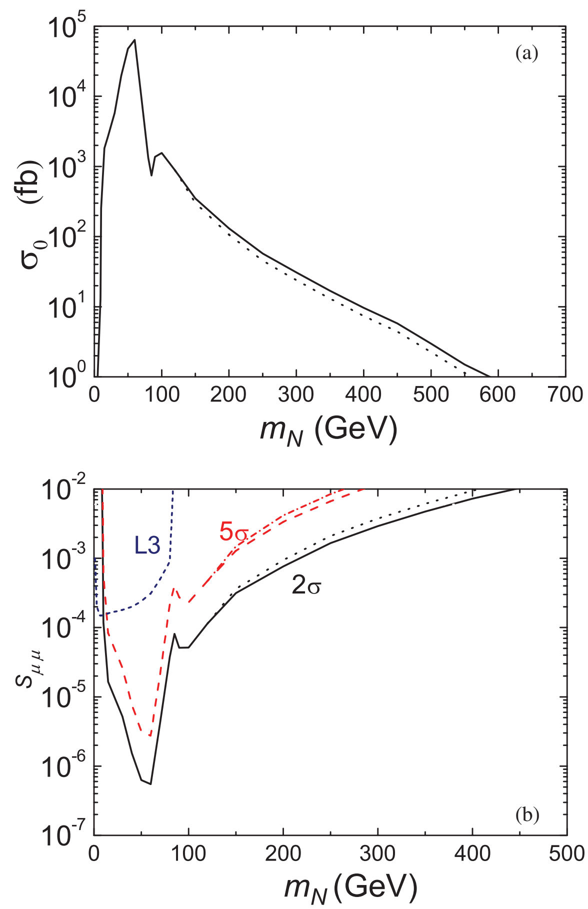

FIG. 4 (color online). LHC results: (a) σ_0 versus m_N after all of the cuts; (b) sensitivity on $S_{\mu\mu}$ for 100 fb^{-1}. For comparison, the 95% bound from the L3 search is included. The dotted lines tracing the curves illustrate the possible Higgs contribution [7] of a mass 120 GeV.

C.L. bound [3] and reaching about 10^{-6} in the low mass region at a 5σ level.

It is only definitive to observe lepton-number violation processes to establish the Majorana nature of the neutrino masses, which would have profound implications in particle and nuclear physics and cosmology. The experiments at the current Tevatron run II and the LHC may have the opportunity to discover it via the distinctive channels of like-sign dilepton production with no missing energy. Hadron colliders may serve as the discovery machine for the mysterious ''sterile Majorana neutrinos.''

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