Same-Sign Dilepton Production via Heavy Majorana Neutrinos in Proton-Proton Collisions

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SAME-SIGN DILEPTON PRODUCTION VIA HEAVY MAJORANA NEUTRINOS IN PROTON–PROTON COLLISIONS

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Abstract. We discuss same-sign dilepton production mediated by Majorana neutrinos in high-energy proton-proton collisions $pp \rightarrow \ell^+\ell'^+X$ for $\ell, \ell' = e, \mu, \tau$ at the LHC energy $\sqrt{s} = 14$ TeV. Assuming one heavy Majorana neutrino of mass $m_N$, we present discovery limits in the $(m_N, |U_{\ell N}U_{\ell' N}|)$ plane where $U_{\ell N}$ are the mixing parameters. Taking into account the present limits from low energy experiments, we show that at LHC one has sensitivity to heavy Majorana neutrinos up to a mass $m_N \leq 2 – 5$ TeV in the dilepton channels $\mu\mu$, $\tau\tau$, and $\mu\tau$, but the dilepton states $e\ell$ will not be detectable due to the already existing constraints from neutrinoless double beta decay.

1 Introduction

While impressive, and providing so far the only evidence of new physics, the solar and atmospheric neutrino experiments do not probe the nature of the neutrino masses, i.e., they can not distinguish between the Dirac and Majorana character of the neutrinos. The nature of neutrino mass is one of the main unsolved problems in particle physics and there are practically no experimental clues on this issue \cite{1}.

If neutrinos are Majorana particles then their mass term violates lepton number by two units $\Delta L = \pm 2$ \cite{2}. Being a transition between a neutrino and an antineutrino, it can be viewed equivalently as the annihilation or creation of two neutrinos. In terms of Feynman diagrams, this involves the emission (and absorption) of two like-sign $W$-boson pairs ($W^-W^-$ or $W^+W^+$). If present, it can lead to a large number of processes violating lepton number by two units, of which neutrinoless double beta decay ($\beta\beta^0\nu$) is a particular example. The seesaw models \cite{3} provide a natural framework for generating a small Majorana neutrino mass which is induced by mixing between an active (light) neutrino and a very heavy Majorana sterile neutrino of mass $M_N$. The light state has a naturally small mass $m_\nu \sim m_D^2/M_N \ll m_D$, where $m_D$ is a quark or charged lepton mass. There is a heavy Majorana state corresponding to each light (active) neutrino state. Typical scale for $M_N$ in Grand unified theories (GUT) is of order the GUT-scale, though in general, there exists a large number of seesaw models in which both $m_D$ and $M_N$ vary over many orders of magnitude,

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with the latter ranging somewhere between the TeV scale and the GUT-scale.

If \( M_N \) is of order GUT-scale, then it is obvious that there are essentially no low energy effects induced by such a heavy Majorana neutrino state. However, if \( M_N \) is allowed to be much lower, or if the light (active) neutrinos are Majorana particles, then the induced effects of such Majorana neutrinos can be searched for in a number of rare processes. Among them neutrinoless double beta decay, like-sign dilepton states produced in rare meson decays and in hadron-hadron, lepton-hadron, and lepton-lepton collisions have been extensively studied. (See, e.g., the papers: \( \beta\beta^0 \nu \) \cite{5–8}, \( K^+ \to \pi^- \mu^+ \mu^+ \) \cite{9–11}, \( pp \to \ell^+ \ell^+ X \) \cite{12}, \( pp \to \ell^+ \ell^+ W^\pm X \) \cite{13}, \( e^\pm p \to \nu' \ell^+ \ell'^\pm X \) \cite{14, 15}.)

Of the current experiments which are sensitive to the Majorana nature of neutrino, the neutrinoless double beta decay, which yields an upper limit on the \( ee \) element of the Majorana mass matrix, is already quite stringent \cite{5}. Likewise, precision electroweak physics experiments severely constrain the mixing elements \cite{16–18}.

Taking into account these constraints, we obtain discovery limits for heavy Majorana neutrinos involved in the process of same-sign dilepton production in the proton-proton collision:

\[ pp \to \ell^+ \ell'^+ X \]  

with \( \ell, \ell' = e, \mu, \tau \) at the LHC energy \( \sqrt{s} = 14 \text{ TeV} \).

2 **Dilepton production in high-energy \( pp \) collisions**

We have calculated the cross section for the process \( \begin{array}{c} \text{pp} \\ \to \ell^+ \ell'^+ X \end{array} \) at high energies,

\[ \sqrt{s} \gg m_W, \]  

via an intermediate heavy Majorana neutrino \( N \) in the leading effective vector-boson approximation \cite{19} neglecting transverse polarizations of \( W \) bosons and quark mixing. We use the simple scenario for neutrino mass spectrum

\[ m_{N_1} \equiv m_N \ll m_{N_2} < m_{N_3}, \ldots, \]

and single out the contribution of the lightest Majorana neutrino assuming

\[ \sqrt{s} \ll m_{N_2}. \]

The cross section for the process in question is then parameterized by the mass \( m_N \) and the corresponding neutrino mixing parameters \( U_{\ell N} \) and \( U_{\nu N} \):

\[ \sigma \left( pp \to \ell^+ \ell'^+ X \right) = \frac{(G_F m_W)^2}{8\pi^5} \left( 1 - \frac{1}{2} \delta_{\ell'\ell} \right) |U_{\ell N} U_{\nu' N}|^2 F(E, m_N), \]

\( (3) \)
with
\[
F(E, m_N) = \left( \frac{m_N}{m_W} \right)^2 \int_{z_0}^1 \frac{dz}{z} \int_z^1 \frac{dy}{y} \int_y^1 \frac{dx}{x} p(x, x s) p\left( \frac{y}{x}, \frac{y}{x} s \right) \times h\left( \frac{z}{y} \right) w\left( \frac{s}{m_N^2} z \right).
\]  

(4)

Here, \( z_0 = 4 m_W^2 / s, E = \sqrt{s} \), and
\[
w(t) = 2 + \frac{1}{t + 1} - \frac{2 (2t + 3)}{t (t + 2)} \ln (t + 1)
\]
is the normalized cross section for the subprocess \( W^+ W^+ \rightarrow \ell^+ \ell^+ \) (in the limit (2) it is obtained from the well-known cross section for \( e^- e^- \rightarrow W^- W^- \) [20] using crossing symmetry). The function \( h(r) \) defined as
\[
h(r) = -(1 + r) \ln r - 2 (1 - r)
\]
is the normalized luminosity (multiplied by \( r \)) of \( W^+ W^+ \) pairs in the two-quark system [19], and
\[
p(x, Q^2) = x \sum_i q_i (x, Q^2) = x (u_v + u_s + d_s + c + b + t)
\]
is the corresponding quark distribution in the proton.

In the numerical calculation of the cross section (3) the MRST99 Fortran codes for the parton distributions [21] have been used.

We assume a luminosity \( L = 100 \text{ fb}^{-1} \) and the mixing constraints obtained from the precision electroweak data [17]
\[
\sum |U_{eN}|^2 < 6.6 \times 10^{-3}, \quad \sum |U_{\mu N}|^2 < 6.0 \times 10^{-3} \left( 1.8 \times 10^{-3} \right), \quad \sum |U_{\tau N}|^2 < 1.8 \times 10^{-2} \left( 9.6 \times 10^{-3} \right). \quad (5)
\]
The bound on the mixing matrix elements involving fermions depends on the underlying theoretical scenario. There are the single limit and joint limit [17, 18], obtained by allowing just one fermion mixing to be present or allowing simultaneous presence of all types of fermion mixings, respectively. In our analysis, we have used the conservative constraints for the joint limit case.

We must also include the constraint from the double beta decay \( \beta \beta_{0v} \), mentioned above. For heavy neutrinos, \( m_N \gg 1 \text{ GeV} \), the bound is [20]
\[
\left| \sum_{N(\text{heavy})} U_{eN}^2 \frac{1}{m_N} \right| < 5 \times 10^{-5} \text{ TeV}^{-1}. \quad (6)
\]
In calculating the cross sections for the $\ell\tau$ and $\tau\tau$ processes, we have used the effective value

$$|U_{\tau N}|^2_{\text{eff}} = B_{\tau\mu}|U_{\tau N}|^2 < 3.1 \times 10^{-3}$$

(7)

with $B_{\tau\mu} = \text{Br}(\tau^- \to \mu^-\tau\mu) = 0.1737$ [22], as this $\tau$-decay mode is most suitable for the like-sign dilepton detection at LHC (see, e.g., [15]).

Combining the constraints of Eqs. (5), (7), and (6) and demanding $n = 1, 3, 10$ events for discovery (i.e., $\sigma L > n$), we present the two-dimensional plot for the discovery limits in Fig. 1 for the case of identical same-sign leptons ($\ell = \ell'$). Discovery limits for the case of distinct same-sign leptons, $\ell\ell' = e\mu, e\tau, \mu\tau,

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Left: Discovery limits for $pp \to \ell^+\ell^+X$ as functions of $m_N$ and $|U_{\ell N}|^2$ for $E = 14$ TeV, $L = 100$ fb$^{-1}$ and various values of $n$, the number of events. We also superimpose the experimental limit from $\beta\beta_0\nu$ (Eq. (6)), as well as the experimental limits on $|U_{\ell N}|^2$ [horizontal lines for $\ell = e, \mu$ (Eq. (5)), and $\tau$ (Eq. (7))]. Right: The same as the left figure but for lighter Majorana neutrinos.}
\end{figure}

are shown in Fig. 1.

From Figs. 1 and 2 we see that the strong constraint from $\beta\beta_0\nu$ rules out the observation of the same-sign $e\ell$ processes (with $\ell = e, \mu, \tau$) at the LHC. But there are sizable regions of $m_N - |U_{\ell N}U_{\ell' N}|$ parameter space where observable signals for the same-sign $\mu\mu$, $\tau\tau$, and $\mu\tau$ processes mediated by heavy Majorana neutrinos of mass $m_N \leq 2 - 5$ TeV can be expected. Hence, LHC experiments have a sensitivity to the matrix elements of the Majorana mass matrix in the second and third rows of this matrix.

We have also worked out a large number of rare meson decays of the type $M^+ \to M'\ell^+\ell'^+$, both for the light and heavy Majorana neutrino scenarios,
and argued that the present experimental bounds on the branching ratios are too weak to set reasonable limits on the effective Majorana masses (for details, see [23]).

3 Conclusion

In conclusion, same-sign dilepton production at LHC will provide non-trivial constraints on the Majorana mass matrix in the $\mu\mu$, $\mu\tau$ and $\tau\tau$ sector.

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