EFFECTS OF HEAVY MAJORANA NEUTRINOS AT
LEPTON-PROTON COLLIDERS

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Abstract. We discuss the prospects of detecting the processes
$e^+p \rightarrow \tilde{\nu}_e \ell^+ \ell'^+ X$
and $\nu_e p \rightarrow e \ell^+ \ell'^+ X$ ($\ell, \ell' = e, \mu, \tau$) under the conditions of the present $ep$ collider
HERA and of future colliders. These high-energy processes are assumed to be
mediated by the exchange of heavy Majorana neutrinos (HMN). We consider two
simple scenarios for the HMN mass spectrum: the effective singlet ($m_1 \ll m_2 < m_3 \cdots$)
and the effective doublet ($m_1 < m_2 \ll m_3 \cdots$). For the latter case, the
cross section includes information about $CP$-violating phases.

Introduction

At the moment there are experimental evidences for nonzero neutrino masses
[1, 2]. The nature of neutrino mass, whether it is Dirac or Majorana, is one
of the fundamental and still unsolved problems in particles physics. A Dirac
neutrino carries a lepton number distinguishing a particle from an antiparticle.
In contrast to that, a Majorana neutrino is identical to its own antiparticle.
The Majorana mass term in the total Lagrangian does not conserve lepton
number, but changes its value by two units. Therefore Majorana neutrinos can
lead to various lepton number violating processes. For example, they induce
same-sign dilepton production in collisions at high energies: $pp \rightarrow \ell^+ \ell'^+ X$ [3],
$e^+p \rightarrow \tilde{\nu}_e \ell^+ \ell'^+ X$ [4] etc.

In theories extending the Standard Model the seesaw mechanism is often
used to provide a natural generation of small neutrino masses (for a review, see,
e.g., [5,6]). Unlike the usual way of Dirac mass generation through weak SU(2)-
breaking, this mechanism doesn’t need extremely small Yukawa couplings ($\lesssim 10^{-12}$). For three families of leptons and $s$ right-handed SU(2) singlets the
seesaw mechanism leads to $3$ light and $s$ heavy massive Majorana neutrino
states

$$\nu_\ell = \sum_{i=1}^{3} \tilde{U}_{\ell i} \nu_i + \sum_{j=1}^{s} U_{\ell j} N_j,$$

where $\nu_\ell$ is a neutrino of definite flavor ($\ell = e, \mu, \tau$), the coefficients $\tilde{U}_{\ell i}$ and
$U_{\ell j}$ form the leptonic mixing matrices.

Heavy mass states give a relatively small contribution to neutrino flavor
states. Nevertheless effects of light and heavy Majorana neutrinos (HMN)
compete in lepton number violating processes, because small values of the mixing parameters $U_{ij}$ for heavy neutrinos $N_j$ may be compensated by smallness of the masses of light neutrinos $\nu_i$.

**The process $e^+ p \rightarrow \bar{\nu}_e \ell^+ \ell'^+ X$**

In this report, we investigate the possibilities of observation of the process

$$e^+ p \rightarrow \bar{\nu}_e \ell^+ \ell'^+ X \tag{1}$$

and its cross symmetric process $\nu_e p \rightarrow e\ell^+ \ell'^+ X$ ($X$ denotes hadron jets) under the conditions of the present $ep$ collider HERA (DESY) [1] and of future $ep$ colliders. We assume that these processes at high energies

$$\sqrt{s} \gg m_W$$

are mediated by HMN. The leading-order Feynman diagram for the process (1) is shown in Fig. 1. (There is also a crossed diagram with interchanged lepton lines.) For calculating the cross sections, we use the leading effective vector-boson (EVB) approximation [7] neglecting transverse polarizations of $W$ bosons and quark mixing. For this case, cross sections for the process and the crossed channel turn to be equal. As an observation criteria for the process we have chosen the condition

$$\sigma L \geq 1,$$

where $\sigma$ denotes the cross section and $L$ is the integrated luminosity per year for a collider.

![Figure 1: Feynman diagram for the process $e^+ p \rightarrow \bar{\nu}_e \ell^+ \ell'^+ X$ mediated by the HMN, $N$.](image)

We should note that lepton-proton collisions are free of the Standard Model background [4] in contrast to the proton-proton collisions [8].

**Effective Singlet Case**

At first we take the simplest pattern of the HMN mass spectrum

$$m_1 \ll m_2 < m_3 \cdots$$
(m_{N_i} \equiv m_i) assuming the condition to be held
\sqrt{s} \ll m_2.

The cross section
\[ \sigma_1 = C \left( 1 - \frac{1}{2} \delta_{\ell \ell'} \right) |U_{\ell 1}U_{\ell' 1}|^2 \left( \frac{m_1}{m_W} \right)^2 \int \frac{dy}{y} \int \frac{dx}{x} p(x, x s) h \left( \frac{y}{x} \right) \omega \left( \frac{y s}{m_1^2} \right) \]
for the process is determined by the convolution of three functions given in [3]: \( p(x, x s) \), the quark distribution density having a fraction \( x \) of the proton momentum evaluated at the scale \( Q^2 = x s \), \( h \), the normalized luminosity of \( W^+W^+ \) pairs in the quark-lepton system, and \( \omega \), the normalized cross section for the subprocess \( W^+W^+ \to \ell^+\ell^+ \). Here, \( y_0 = 4m_W^2/s \) and the characteristic constant \( C \) has the value
\[ C = G_F^4 m_W^6 / (8\pi^5) = 0.80 \text{ fb}. \] (3)

In the numerical calculation we have used the set of parton distributions CTEQ6 [9]. Using the bounds on the mixing parameters \( U_{\ell N} \) from precision electroweak data [10]
\[ \sum_N |U_{e N}|^2 < 6.6 \times 10^{-3}, \sum_N |U_{\mu N}|^2 < 6.0 \times 10^{-3}, \sum_N |U_{\tau N}|^2_{eff} < 3.1 \times 10^{-3} \] (4)
and the constraint from the neutrinoless double beta decay [11]
\[ \left| \sum_N U_{e N}^2 m_{N_1}^{-1} \right| < 5 \times 10^{-5} \text{ TeV}^{-1} \]
(the sum is over the heavy neutrinos), we find that the process is practically unobservable at HERA even with a very optimistic luminosity (\( \sqrt{s} = 318 \text{ GeV}, L = 1 \text{ fb}^{-1} \)) and also at the projected supercollider VLHC (see, e.g., [12]) (\( \sqrt{s} = 6320 \text{ GeV}, L = 1.4 \text{ fb}^{-1} \)). For example, for \( m_1 \sim 1 \text{ TeV} \), we get \( \sigma L \sim 10^{-10} \) (10^{-5}) for HERA (VLHC). For a possible detection of the process, the luminosity and/or the energy of the \( ep \)-collider should be substantially increased. Taking for example the luminosity \( L = 100 \text{ fb}^{-1} \), the observation of the most probable events (\( m_\tau \) and \( m_\mu \)) is possible if \( \sqrt{s} > 23 \text{ TeV} \). For \( \sqrt{s} = 25 \text{ TeV} \) such a collider will be sensitive to a range of neutrino masses about 1–3 TeV.

**Effective Doublet Case**

We consider also the neutrino mass spectrum of the effective doublet type
\[ m_1 < m_2 \ll m_3 \cdots \]
with the bound on energy $\sqrt{s} \ll m_3$. In this scenario, the cross section for the process (1)

$$\sigma_2 = \frac{C}{2} \int_{y_0}^{y} \frac{dy}{y} \int_{x}^{1} \frac{dx}{x} p(x, x s) h \left(\frac{y}{y_s} \frac{y_s}{m_1^2} \frac{y_s}{m_2^2}\right)$$

(5)

includes the normalized cross section for the subprocess

$$W(t_1, t_2) = m_W^{-2} \left[\rho_1^2 m_1^2 \omega(t_1) + 2c\rho_2 m_1 m_2 \Omega(t_1, t_2) + \rho_2^2 m_2^2 \omega(t_2)\right],$$

(6)

which contains the individual contributions of the neutrinos $N_1$ and $N_2$, $\omega(t)$, and the interference of the two, $\Omega(t_1, t_2)$, where

$$\Omega(t_1, t_2) = 2 - \frac{1}{t_1 + t_2 - t_1 t_2} \left[\frac{t_2(t_2 - 2t_1 t_2 - 2t_2)}{t_1(t_1 - t_2)} \ln(1 + t_1) + (t_1 \leftrightarrow t_2)\right];$$

$$\omega(t) = \lim_{t' \to t} \Omega(t, t') = 2 + \frac{1}{1 + t} - \frac{2(3 + 2t)}{t(2 + t)} \ln(1 + t).$$

The mixing parameters for different $\ell\ell'$ channels of the process are

$$\rho_i = \sqrt{2 - \delta_{\ell\ell'} |U_{\ell i} U_{\ell' i}|}, \quad c = \cos \delta_{\ell\ell'},$$

with

$$\delta_{\ell\ell'} = \phi_1 - \phi_2 \in [0, 2\pi), \quad \phi_i = \arg(U_{\ell i} U_{\ell i}).$$

The phases $\delta_{\ell\ell'}$ carry information about CP-violation. We assume the satu-

![Figure 2: The dependence of $\sigma_2$ (in attobarn) on $m_2$ (in TeV) plotted for $r = 0, 1/4, 1/2, 3/4, 1$ with $\sqrt{s} = 25$ TeV, $m_1 = 1.3$ TeV and $c = 1$. The horizontal line DL is the discovery limit.](image)

ration of the upper bound $B = 6.0 \times 10^{-3}$ in the second sum in (4) only by the first two terms, i.e., $|U_{\mu 1}|^2 = r B, \ |U_{\mu 2}|^2 = (1 - r)B$ with $r \in [0, 1]$. Then for the most probable $\mu\mu$ channel we obtain

$$\sigma_2 = A(r^2 f_1 + 2c\bar{r}^2 f_2 + \bar{r}^2 f_3), \quad \bar{r} = 1 - r,$$

(7)
where \( f_i = f(s, m_i) \) and \( F_{ij} = F(s, m_i, m_j) \) are expressed through obvious convolutions of the functions \( \omega \) and \( \Omega \) with \( h \) and \( p \), respectively (see Eq. (5)), the constant \( A \) has the value \( A = 1.4 \times 10^{-5} \) fb. For \( r = 1 \) \((r = 0)\), only a single neutrino \( N_1 \) \((N_2)\) contributes to the cross section which is reduced to the form given in Eq. (2). Generalization to the case of \( n \) neutrinos is straightforward.

In our calculations, we have chosen the following values for the parameters: \( \sqrt{s} = 25 \) TeV, \( m_1 = 1.3 \) TeV, \( c = 1 \). The cross section (7) as a function of \( m_2 \) for various fixed values of \( r \) is shown in Fig. 2. For the almost degenerate doublet \((m_1 \simeq m_2)\) case and/or for the case of small mixing with \( N_2 \) \((r \simeq 1)\), the cross section \( \sigma_2 \) is close to \( \sigma_1 \), the cross-section for the effective singlet case. But we should note that for the case of destructive interference of the two almost degenerate massive states \( \text{e.g.}, m_2 \simeq m_1, r = 1/2, c = -1 \), the cross section is vanishingly small.

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## References

[1] Particle Data Group Collab.: K. Hagiwara et al., *Phys. Rev.* **D66**, 010001 (2002).

[2] C. Giunti, E-print Archive: hep-ph/0310238; A.Yu. Smirnov, E-print Archive: hep-ph/0311259.

[3] A. Ali, A.V. Borisov, N.B. Zamorin, in *“Frontiers of Particle Physics”* (Proceedings of the 10th Lomonosov Conference on Elementary Particle Physics), ed. by A. Studenikin (World Scientific, Singapore, 2003) p. 74; *Eur. Phys. J.* **C21**, 123 (2001) [hep-ph/0104123].

[4] M. Flanz, W. Rodejohann, K. Zuber, *Phys. Lett.* **B473**, 324 (2000); W. Rodejohann, K. Zuber, *Phys. Rev.* **D62**, 094017 (2000).

[5] P. Langacker, *Nucl. Phys. B (Proc. Suppl.)* **100**, 383 (2001).

[6] B. Kayser, E-print Archive: hep-ph/0211134.

[7] S. Dawson, *Nucl. Phys.* **B249**, 42 (1985); I. Kuss, H. Spiesberger, *Phys. Rev.* **D53**, 6078 (1996).

[8] A. Datta, M. Guchait, D.P. Roy, *Phys. Rev.* **D47**, 961 (1993).

[9] J. Pumplin, D.R. Stump, J. Huston, H.L. Lai, P. Nadolsky, W.K. Tung, E-print Archive: hep-ph/0201195.

[10] E. Nardi, E. Roulet, D. Tommasini, *Phys. Lett.* **B344**, 225 (1995).

[11] G. Belanger, F. Boudjema, D. London, H. Nadeau, *Phys. Rev.* **D53**, 6292 (1996).

[12] M. Blaskiewicz et al., Fermilab Report TM-2158, 29 June 2001; F.M.L. de Almeida Jr., Y.A. Coutinho, J.A. Martins Simões, M.A.B. do Vale, *Phys. Rev.* **D65**, 115010 (2002).