Majorana Neutrino and $W_R$ at TeV scale $e p$ Colliders

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Abstract

Production of heavy Majorana neutrino $N_e$ predicted by left-right symmetric extension of the Standard Model at future TeV scale $e p$ colliders have been considered. In order to estimate potential of $e p$ colliders for $N_e$ search we consider backgroundless process $e^- p \rightarrow e^+ X$ which is consequence of Majorana nature of $N_e$. It is shown that linac-LHC and linac-FCC based $e p$ colliders will cover much wider regions of $N_e$ and $W_R$ masses than corresponding linear electron-positron colliders.
1. INTRODUCTION

The discovery of the Higgs boson \[1, 2\] has completed basics of the Standard Model (SM). However, this is not the end of the story. First of all, SM could not answer many fundamental questions; for instance, left-handed structure of charged weak currents is put by hand, mass and mixing pattern of the SM fermions are not clarified etc. For these reasons a number of Beyond the SM (BSM) models are developed. Fortunately, future running of the LHC with upgraded parameters will shed light on answers for some of these questions. Secondly, Higgs field provides only 2% of the mass of the visible universe. In order to understand the origin of remaining 98% we should clarify basics of the QCD, especially small-\(x\) (Bjorken) region. This is why the QCD Explorer option of the LHC-based \(ep\) colliders is mandatory \[3\].

TeV scale colliders can be classified using colliding particles or collider types. While the first classification includes hadron-hadron, lepton-hadron and lepton-lepton collisions the other includes collider types with ring-ring, linac-ring and linac-linac options. Concerning the energy frontiers linac-ring type colliders provide the sole realistic way to handle (multi) TeV scale in lepton-hadron collisions at constituent level \[4\] (see, also, review \[5\]). Certainly, hadron colliders (LHC and FCC) should be considered as the main discovery tools for new particles. In this respect, priority of lepton-lepton or lepton-hadron colliders will be determined by the LHC or FCC results. If the observed BSM physics will be connected to the first family fermions, \(ep\) colliders will have priority due to larger center-of-mass energy comparing to electron-positron colliders.

Left-handed structure of charged weak currents has most elegant explanation in \(SU_L(2) \times SU_R(2) \times U(1)_{B-L}\) models \[6\], where the mass of \(W_R\) boson is much higher than the mass of \(W_L\) boson. In addition, these models predict existence of the second heavy Z boson, as well as, three heavy Majorana neutrinos \((N_e, N_\mu, N_\tau)\) and a number of additional Higgs bosons, including double-charged ones. Therefore, there are a lot of interesting phenomena, that can be investigated at TeV energy colliders. For example, production of \(W_R\) at hadron colliders, followed by \(W_R \rightarrow N_l l\) decays, leads to a very clear signature, namely two same-sign leptons in association with two jets \[7\]. Recently, the process \(pp \rightarrow W_R + X\) followed by \(W_R \rightarrow lljj\) decay has been investigated by CMS collaboration \[8\], where 2.8\(\sigma\) excess at \(m(ee jj) = 2.1\) TeV is observed. However, only one of the 14 reconstructed events contains same-sign electrons, while it is expected half of the events to be same-sign in the case of
Majorana $N_e$.

In this paper, we analyze production of $N_e$ at future $ep$ colliders via the back-groundless process $e^- p \rightarrow e^+ X$. In Section 2 tentative parameters of possible LHC and FCC based $ep$ colliders are presented. A brief description of the $SU_L(2) \times SU_R(2) \times U(1)_{B-L}$ model is given in Section 3. In Section 4, we show production cross-sections depending on $N_e$ mass for several values of $W_R$ mass and different center-of-mass energies, as well as $3\sigma$ and $5\sigma$ plots in $N_e-W_R$ mass plane. Rough comparison of $pp$, $ep$ and $e^+e^-$ colliders potentials for $N_e$ investigation is performed in Section 5. Finally, in Section 6 we give some conclusions and recommendations.

2. FUTURE TEV SCALE $EP$ COLLIDERS

Electron-proton scattering experiments have played a very important role in the development of our knowledge of the structure of matter. For example, quark-parton structure was discovered in deep-inelastic scattering. As mentioned above, QCD Explorer option ($E_e = 60$ GeV) of the LHC-based $ep$ colliders (LHeC) is mandatory for clarifying dynamics of strong interactions at extremely small-$x$ and, at the same time, sufficiently high $Q^2$ region. In addition, EIC (e-RHIC) will give opportunity to investigate another critical region, namely, $x \approx 1$.

Concerning BSM, new physics higher electron and/or proton beam energies are needed. In Table 1 we present tentative parameters for possible LHC and FCC based $ep$ collider options. OPL, ERL and OPERL denotes one pulse linac, energy recovery linac and one pulse energy recovery linac, respectively. ERL60 is continuous wave superconducting recirculating energy-recovery linac, which has been chosen as the main line for LHeC (see section 7.1.2 in LHeC CDR [9]). OPL60 and OPL140 options for LHeC are considered in Section 7.1.4 of the LHeC CDR, and OPERL150 option is considered in Section 7.1.5, where this option is named as higher-energy LHeC ERL option. Luminosity for OPL500 and OPERL500 options for LHeC are estimated by assuming that electron beam powers are the same as in the OPL140 and OPERL150 cases, respectively (in this case $L$ is inverse proportional to $E_e$). Parameters for the first three options of FCC-based $ep$ colliders are taken from [10]. Luminosity values for the last two options are taken same as OPL140 and OPERL150 LHeC options for following reason: the loss due to higher electron energy $E_e$ is compensated by
smaller proton beam size due to higher $E_p$.

Table I. Parameters of possible LHC and FCC based $ep$ colliders.

|                | $E_e$, GeV | $E_p$, TeV | $\sqrt{s}$, TeV | $L$, $10^{33}$ cm$^{-2}$ s$^{-1}$ | $L_{int}$, fb$^{-1}(10^7$ s) |
|----------------|------------|------------|-----------------|---------------------------------|-----------------------------|
| ERL60-LHC      | 60         | 7          | 1.3             | 1([9])                          | 10                          |
| OPL60-LHC      | 60         | 7          | 1.3             | 0.09([9])                       | 0.9                         |
| OPL140-LHC     | 140        | 7          | 2.0             | 0.04([9])                       | 0.4                         |
| OPL500-LHC     | 500        | 7          | 3.7             | 0.01                            | 0.1                         |
| OPERL150-LHC   | 150        | 7          | 2.0             | 100([9])                        | 1000                        |
| OPERL500-LHC   | 500        | 7          | 3.7             | 30                              | 300                         |
| ERL60-FCC      | 60         | 50         | 3.5             | 10([10])                        | 100                         |
| FCC-e80        | 80         | 50         | 4.0             | 23([10])                        | 230                         |
| FCC-e120       | 120        | 50         | 4.9             | 12([10])                        | 120                         |
| OPL1000-FCC    | 1000       | 50         | 14.1            | 0.04                            | 0.4                         |
| OPERL1000-FCC  | 1000       | 50         | 14.1            | 100                             | 1000                        |

3. MODEL DESCRIPTION

The minimal left-right symmetric model is based on $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ gauge symmetry. Fermions are grouped in $L - R$ symmetric form:

$$q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L : (3, 2, 1, 1/3); \quad q_R = \begin{pmatrix} u \\ d \end{pmatrix}_R : (3, 1, 2, 1/3); \quad (1)$$

$$l_L = \begin{pmatrix} \nu \\ l \end{pmatrix}_L : (1, 2, 1, -1); \quad l_R = \begin{pmatrix} N \\ l \end{pmatrix}_R : (1, 1, 2, -1). \quad (2)$$

In this model electric charge is given by

$$Q_{em} = I_{3L} + I_{3R} + \frac{B - L}{2} \quad (3)$$
The Higgs sector contains one bidoublet and two triplets:

\[ \Phi = \begin{pmatrix} \phi_0^0 & \phi_1^+ \\ \phi_2^- & \phi_0^0 \end{pmatrix} : (1, 2, 2, 0); \quad \Delta_L = \begin{pmatrix} \delta_L^+ / \sqrt{2} & \delta_L^{++} \\ \delta_L^0 & -\delta_L^+ / \sqrt{2} \end{pmatrix} : (1, 3, 1, 2); \quad (4) \]

\[ \Delta_R = \begin{pmatrix} \delta_R^+ / \sqrt{2} & \delta_R^{++} \\ \delta_R^0 & -\delta_R^+ / \sqrt{2} \end{pmatrix} : (1, 1, 3, 2). \quad (5) \]

Therefore, there are two additional intermediate vector bosons \( (W_R \text{ and } Z_R) \) as well as a number of additional scalar bosons (2 neutral, 2 charged and 2 double charged). The most stringent limit on \( W_R \) mass from low energy data, namely, \( m_{W_R} > 2.5 \text{ TeV} \), comes from \( K_L - K_S \) mixing [11]. Search for \( W_R \rightarrow lN_l \) performed by ATLAS and CMS using 7 TeV data lead to the same limit for \( m_{N_l} \) around 1 TeV [12, 13]. Recent CMS analysis of this channel increases the limit up to 3 TeV [8].

### 4. PRODUCTION OF MAJORANA NEUTRINO AT TEV ENERGY EP COL-LIDERS

For numerical calculations we include interactions of \( W_R \) boson with fermions, namely,

\[ \mathcal{L} = -\frac{g_R}{2\sqrt{2}} \left[ \bar{e}_\gamma^\mu \left(1 + \gamma^5\right) \nu + \bar{d}_\gamma^\mu \left(1 + \gamma^5\right) u \right] W_R^{-\mu} + h.c. \quad (6) \]

into the CalcHEP software [14]. At this stage we ignore possible mixing in fermions and vector boson sectors. In Fig. 1 we present production cross-sections as a function of \( m_N \) for \( \sqrt{s} = 1.3 \text{ TeV} \) and different values of \( m_{W_R} \). Similar distributions for \( \sqrt{s} = 2.0, 4.0 \) and 14.1 TeV are presented in Figs.2, 3 and 4, respectively. Keeping in mind, integral luminosity values given in the last column of the Table 1, one can see that ERL60, OPL60 and OPL140 options of the LHC based \( ep \) colliders could not provide essential contributions to the \( N_e \) investigation.

In order to estimate the potential of \( ep \) colliders for \( N_e \) search, we consider back-groundless process \( e^- p \rightarrow e^+ X \) which is consequence of Majorana nature of \( N_e \). Corresponding Feynman diagram is shown in Fig. 5. In this case cross-sections given in Figs. 1 – 4 should be multiplied by factor 1/2. In Figs. 6 – 9, we present 3\( \sigma \) (observation) and 5\( \sigma \) (discovery)
Figure 1. $N_e$ production cross-sections for different $m_{W_R}$ at $\sqrt{s} = 1.3\, TeV$

Figure 2. $N_e$ production cross-sections for different $m_{W_R}$ at $\sqrt{s} = 2.0\, TeV$
Figure 3. $N_e$ production cross-sections for different $m_{WR}$ at $\sqrt{s} = 4.0\, TeV$

Figure 4. $N_e$ production cross-sections for different $m_{WR}$ at $\sqrt{s} = 14.1\, TeV$
Figure 5. Feynmann diagram for $e^{-}p \rightarrow e^{+} + X$

Figure 6. Observation (3$\sigma$) and discovery (5$\sigma$) limits in the $m_{N_{e}} - m_{W_{R}}$ plane for OPERL150 and OPERL500 options of LHeC.

plots in $m_{N_{e}} - m_{W_{R}}$ plane. For 3$\sigma$ and 5$\sigma$ limits we use 9 and 25 events, respectively. As one can see from Fig. 6, LHC based $ep$ colliders could probe larger $m_{W_{R}}$ mass values than LHC if $N_{e}$ has relatively light mass.
Figure 7. Observation (3σ) limit in the $m_{N_e} - m_{W_R}$ plane for FCC-e80, FCC-e120, ERL60-FCC and OPL1000-FCC.
Figure 8. Discovery (5σ) limit in the $m_{N_e} - m_{W_R}$ plane for FCC-e80, FCC-e120, ERL60-FCC and OPL1000-FCC.
5. ROUGH COMPARISON OF \( pp, ep \) AND \( e^+e^- \) COLLIDERS

As it is mentioned in the introduction, TeV scale \( ep \) colliders are crucial for understanding of the origin of 98% of the mass of the visible universe. Concerning BSM physics, detailed comparison of physics search potential of (multi)TeV scale hadron, lepton and lepton-hadron colliders should be performed for each phenomena (such as new particles and new interactions). Rough estimations \[15\] show that \( ep \) colliders are advantageous comparing to lepton colliders for a lot phenomena. Moreover, analysis of excited electron production performed in the article by O.Cakir et al.\[16\] "show that LC\(\oplus\)LHC is more promising than the LHC and much more promising than the LC for the processes considered". In this analysis following collider parameters were used: \( \sqrt{s} = 14 \) TeV and \( L = 10^{34} cm^{-2}s^{-1} \) for LHC, \( \sqrt{s} = 0.5 \) TeV and \( L = 10^{34} cm^{-2}s^{-1} \) for LC, \( \sqrt{s} = 3.74 \) TeV and \( L = 10^{31} cm^{-2}s^{-1} \) for LC\(\oplus\)LHC.

In principle, for effective planning of the post-LHC energy frontier colliders comparison of LHC, LHeC and ILC (for 2020s), as well as FCC (\( pp \) and \( ep \) options), linac-FCC (\( ep \)
and γp options), CLIC and muon collider (for 2030s), search potentials for different BSM phenomena should be performed.

Considering $N_e$ production, lepton collider capacity is kinematically limited by $m_{N_e} < 0.5$ TeV at ILC [17] and $m_{N_e} < 1.5$ TeV at CLIC [18]. As one can see from Figs. 6–9, linac-LHC and especially linac-FCC based ep colliders will cover much higher $m_{N_e}$ values. Below we consider specific examples for LHC and FCC.

1) LHC example: Let us assume that $N_e$ and $W_R$ masses are 0.5 TeV and 8 TeV, respectively. In this case ERL500-LHC will give opportunity to discover $N_e$ at $5\sigma$ level, whereas LHC will not reach even $2\sigma$ level.

2) FCC example: Let us assume that $N_e$ and $W_R$ masses are 2 TeV and 27 TeV, respectively. In this case, OPERL1000-FCC will give opportunity to discover Ne at $3\sigma$ level, whereas FCC will not reach even $2\sigma$ level.

6. CONCLUSION

In this paper we analyzed production of heavy Majorana neutrino via $W_R$ exchange at future ep colliders. The analysis results show that:

1) linac-LHC and linac-FCC based ep colliders will cover much wider regions of $N_e$ and $W_R$ masses than ILC and CLIC,

2) ep colliders seems to be advantageous comparing to corresponding pp colliders for some regions of $N_e$ and $W_R$ masses.

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