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Anomalous single production of the fourth generation neutrino at future *ep* colliders

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Abstract

Possible single productions of the fourth standard model generation neutrino via anomalous interactions at the future *ep* colliders are studied. Signatures of such anomalous processes and backgrounds are discussed in detail. Discovery limits for neutrino mass and achievable values of anomalous coupling strength are determined.

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Keywords: Anomalous interactions; Colliders; Fourth generation neutrino

1. Introduction

It is known that the Standard Model (SM) does not predict number of fundamental fermion generations. This number is restricted from below with LEP I data on invisible decays of Z boson as $n_g \geqslant 3$ [1]. On the other hand, $n_g < 9$ from asymptotic freedom of QCD. According to recent precision electroweak data, existence of three or four SM generations is at the same status [2–4].

The flavor democracy is a natural hypothesis in the framework of SM as well as a number of models dealing with new physics (see review [5] and references therein). Concerning Standard Model, flavor democracy predicts the existence of a heavy fourth SM generation [6–8]. The Dirac masses of the new fermions are predicted to be almost degenerate and lie between 300 and 700 GeV, whereas, the masses of known fermions belonging to lighter three generations appear due to small deviations of the democracy [9–11]. The quark masses and CKM matrix are given in [9,10]. Ref. [11] gives both masses and CKM matrix (MNS matrix for leptons) for both quarks and leptons.

Obviously, TeV energy colliders are needed for discovery of the fourth SM generation fermions. The fourth generation quarks will be produced in pairs copiously at the Large Hadron Collider (LHC) [12,13]. Recently, this process is proposed as the best scenario (after Higgs) for discovery at the LHC [14–16]. Linear lepton colliders are the best place for pair production of the fourth generation charged lepton and neutrino [11,17,18]. However, discovery limits for pair production at lepton colliders are $2m < \sqrt{s}$. For example, International Linear Collider (ILC) with 500 GeV center of mass energy will cover $m < 250$ GeV. The discovery capacity of lepton collider could be enlarged if the anomalous interactions of the fourth generation fermions with the first three ones exist. Such anomalous interactions seems to be quite natural due to large masses of the fourth generation fermions (see argumentation for anomalous interaction for t quark presented in Ref. [19]). These anomalous interactions could provide also single production of

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the fourth generation fermions at future lepton–hadron colliders (see review [20] and references therein). Depending on the center of mass energy lepton–hadron colliders are named QCD Explorer with $\sqrt{s} = 1.4$ TeV and Energy Frontier *ep* collider with $\sqrt{s} = 3.74$ TeV [20–27].

Recently, anomalous production of the fourth generation charged lepton and neutrino at future *ep* colliders is considered in [28] and [29], respectively. Unfortunately results of the latter one are erroneous due to the wrong Lagrangian for $\nu_4 eW$ interactions. Therefore, anomalous production of the fourth generation neutrino at future *ep* colliders should be reconsidered.

In Section 2 the correct Lagrangian for SM and the anomalous interactions of the fourth generation neutrino is presented; the experimental limits and the theoretical predictions on corresponding MNS matrix elements are discussed; the decay width and branching ratios of the fourth generation neutrino are evaluated. Production of the fourth generation neutrino at future *ep* colliders is studied in Section 3: $ep \to \nu_4 X \to \mu W X$ and $ep \to \nu_4 X \to e W X$ processes as well as their SM backgrounds are considered; the statistical significance of the signal and achievable values of anomalous coupling strength are evaluated.

2. Anomalous interactions of the fourth SM generation neutrino

The charged current Lagrangian for SM and the anomalous interactions of the fourth generation neutrino can be rewritten from [30,31] with minor modifications as:

$$L_{cc} = \left(\frac{g_W}{\sqrt{2}}\right)\bar{l_i}\left[|V_{\nu_4 l_i}|\gamma_\mu + \frac{i}{2\Lambda}\kappa_W^{\nu_4 l_i}\sigma_{\mu\nu}q^\nu\right]P_L \nu_4 W^\mu + \text{h.c.}$$
$$(i = 1, 2, 3). \quad (1)$$

The main error of corresponding Lagrangian in [29] is absence of the MNS matrix element $|V_{\nu_4 l_i}|$. Furthermore, the neutral current Lagrangian for the anomalous interactions of the fourth generation neutrino is

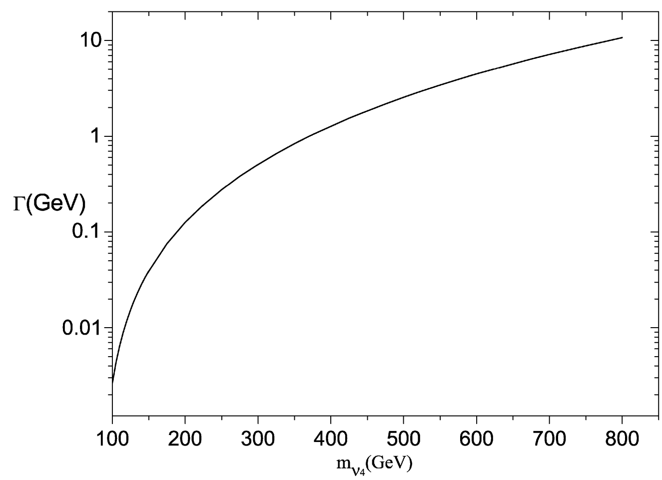
$$L_{nc} = \left(\frac{g_Z}{2}\right)\bar{\nu_i}\frac{i}{2\Lambda}\kappa_Z^{\nu_4\nu_i}\sigma_{\mu\nu}q^\nu P_L \nu_4 Z^\mu + \text{h.c.}$$
$$(i = 1, 2, 3). \quad (2)$$

In Eqs. (1) and (2), $\kappa_W^{\nu_4 l_i}$ and $\kappa_Z^{\nu_4\nu_i}$ are the anomalous couplings for the charged and neutral currents with a W boson and a Z boson, respectively (in numerical calculations, we suppose $\kappa_W^{\nu_4 l_i} = \kappa_Z^{\nu_4\nu_i} = \kappa$). Λ is the cutoff scale for the new physics and P_L is the left handed projection operator; g_W and g_Z are the electroweak coupling constants. In the above equations $\sigma_{\mu\nu} = i(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)/2$.

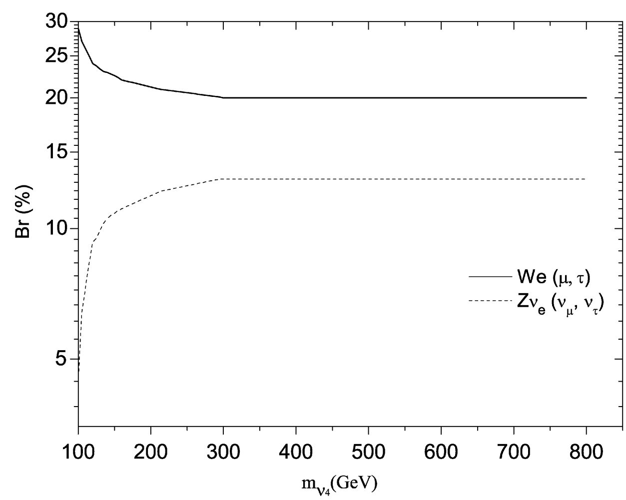
Obviously new interactions will lead to additional decay channels of the fourth family neutrino in addition to enhancement of some SM decay channels. In order to compute decay widths, we have implemented the new interaction vertices into the CompHEP [32]. Results of the calculations for different decay channels of ν_4 assuming $(\kappa/\Lambda) = 1$ TeV^{-1} are given in Table 1. Experimental upper limit for $|V_{\nu_4 l_i}|$ is 0.02 [4]. Therefore, while calculating values in Table 1, we have used $|V_{\nu_4 l_i}| = 0.02$. The total decay width Γ of the fourth generation neutrino and the relative branching ratios are plotted in Fig. 1. More realistic values for MNS matrix elements can be taken from Ref. [17], namely: $V_{\nu_4\tau} = 2.34 \times 10^{-5}$, $V_{\nu_4\mu} = 6.81 \times 10^{-4}$, $V_{\nu_4 e} = 4.64 \times 10^{-4}$. Consequently, we have used these values at rest of our calculations (note that the values in Table 1 as well as Fig. 1 practically do not change). Concerning the anomalous coupling strength, the value $(\kappa/\Lambda) = 1$ TeV^{-1} is rather conservative (we consider Dirac neutrinos, therefore the mass scale is order of electroweak scale).

Table 1
Branching ratios and total decay widths for m_{ν_4} (GeV)

m_{ν_4}	$We^-(\mu^-, \tau^-)$	$Z\nu_e(\nu_\mu, \nu_\tau)$	Γ_{Tot} (GeV)
100	29	4	0.0026
150	22	11	0.039
200	21	12	0.126
300	20	13	0.508
700	20	13	7.160



(a)



(b)

Fig. 1. (a) The total decay width Γ in GeV of the fourth family neutrino and (b) the branching ratios (%) depending on the mass of the fourth generation neutrino.

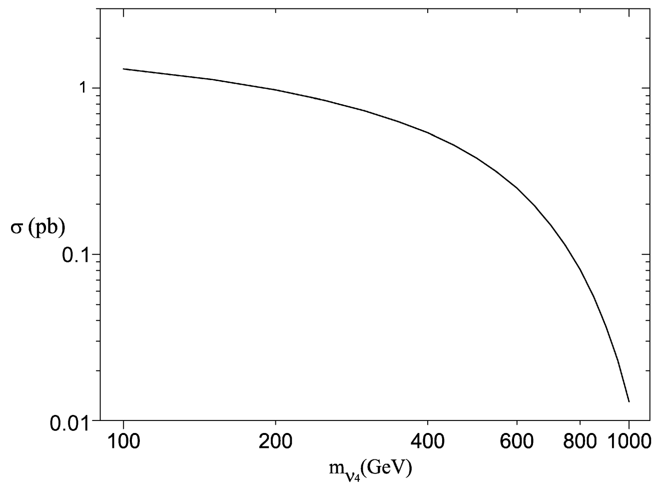


Fig. 2. The total production cross section of the process $ep \to \nu_4 X$ as a function of m_{ν_4} with the center of mass energy $\sqrt{s} = 1.4$ TeV.

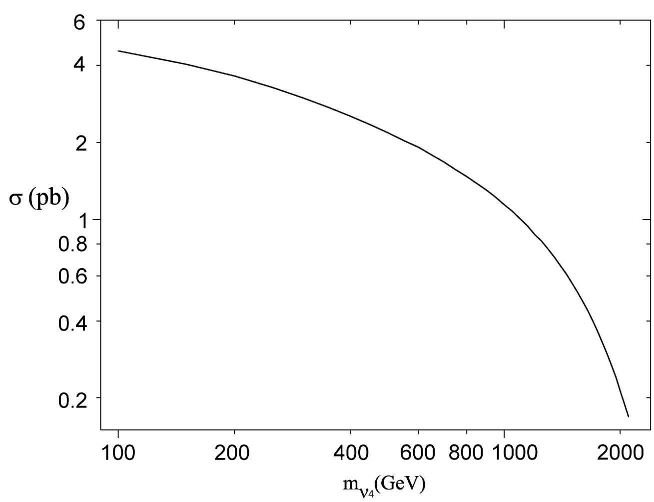


Fig. 3. The total production cross section of the process $ep \to \nu_4 X$ as a function of m_{ν_4} with the center of mass energy $\sqrt{s} = 3.74$ TeV.

3. Anomalous single production of the fourth SM generation neutrino at *ep* colliders

Single anomalous production of the fourth SM generation neutrino is considered at *ep* colliders with $\sqrt{s} = 1.4$ TeV (QCD Explorer) and $\sqrt{s} = 3.74$ TeV (Energy Frontier). The calculated cross sections for ν_4 are given for QCD Explorer and Energy Frontier *ep* collider in Figs. 2 and 3, respectively. We consider $ep \to \nu_4 X \to \mu W X$ and $ep \to \nu_4 X \to e W X$ processes as signatures of anomalous interactions of the fourth generation neutrino. In order to extract the fourth generation neutrino signal and to suppress the background, we impose cuts on the eW invariant mass. Following [29], cuts of $|m_{eW} - m_{\nu_4}| < 25$ GeV for the mass range $m_{\nu_4} = 100$–1000 GeV and $|m_{eW} - m_{\nu_4}| < 50$ GeV for the mass range of 1–2.6 TeV together with $p_T^{q,l} > 10$ GeV are applied. In numerical calculations CTEQ6L parton distribution functions are used [33]. The first process can be detected easily at *ep* colliders due to no background. Number of events for this process at $\sqrt{s} = 1.4$ TeV and $\sqrt{s} = 3.74$ TeV are presented in Tables 2 and 3, respectively. The computed signal and background cross sections for the second process are given in Tables 4 and 5 for $\sqrt{s} = 1.4$ TeV and $\sqrt{s} = 3.74$ TeV options, respectively. In the last two columns of these tables we present statistical significance (SS) values of the signal (evaluated from $SS = (\sigma_S/\sqrt{\sigma_B})\sqrt{L_{\text{int}}}$, where L_{int} is the integrated luminosity of the collider).

Since the process $ep \to \nu_4 X \to \mu W X$ has no SM background one can use 10 events as a discovery limit. As seen from

Table 2
Event numbers of $ep \to \nu_4 X \to \mu W X$ for $\sqrt{s} = 1.4$ TeV, $(\kappa/\Lambda) = 1$ TeV^{-1}

m_{ν_4} (GeV)	N_S	
	$L_{\text{int}} = 1$ fb^{-1}	$L_{\text{int}} = 10$ fb^{-1}
200	201	2010
300	148	1480
400	106	1060
500	74	740
600	47	470
700	27	270
800	14	140
900	6	60
1000	2	22

Table 3
Event numbers of $ep \to \nu_4 X \to \mu W X$ for $\sqrt{s} = 3.74$ TeV, $(\kappa/\Lambda) = 1$ TeV^{-1}

m_{ν_4} (GeV)	N_S	
	$L_{\text{int}} = 100$ pb^{-1}	$L_{\text{int}} = 1$ fb^{-1}
200	74.3	743
300	60.3	603
400	50.4	504
500	42.7	427
600	36.4	364
700	30.7	307
800	25.9	259
900	21.4	214
1000	20.1	201
1200	13.8	138
1400	8.8	88
1600	5.3	53
1800	2.9	29
2000	1.5	15
2200	0.7	7
2400	0.3	3
2600	0.1	1

Table 4
The cross section of signal and background of $ep \to \nu_4 X \to e W X$ for $\sqrt{s} = 1.4$ TeV, $(\kappa/\Lambda) = 1$ TeV^{-1}

m_{ν_4} (GeV)	σ_S (pb)	σ_B (pb)	SS	
			$L_{\text{int}} = 1$ fb^{-1}	$L_{\text{int}} = 10$ fb^{-1}
200	0.201	0.560	8.49	26.86
300	0.148	0.293	8.64	27.34
400	0.106	0.172	8.08	25.56
500	0.074	0.086	7.98	25.23
600	0.047	0.049	6.71	21.23
700	0.027	0.025	5.40	17.07
800	0.014	0.012	4.04	12.78
900	0.006	0.005	2.64	8.34
1000	0.002	0.004	1.10	3.48

Table 5
The cross section of signal and background of $ep \to \nu_4 X \to eWX$ for $\sqrt{s} =$ 3.74 TeV, $(\kappa/\Lambda) = 1$ TeV^{-1}

m_{ν_4} (GeV)	σ_S (pb)	σ_B (pb)	SS	
			$L_{\text{int}} = 100$ pb^{-1}	$L_{\text{int}} = 1$ fb^{-1}
200	0.743	1.605	5.86	18.54
300	0.603	0.954	6.17	19.52
400	0.504	0.560	6.73	21.30
500	0.427	0.380	6.93	21.90
600	0.364	0.280	6.88	21.75
700	0.307	0.209	6.71	21.23
800	0.259	0.157	6.53	20.67
900	0.214	0.125	6.05	19.14
1000	0.201	0.188	4.63	14.66
1200	0.138	0.116	4.05	12.81
1400	0.088	0.075	3.21	10.16
1600	0.053	0.044	2.52	8.00
1800	0.029	0.026	1.80	5.69
2000	0.015	0.014	1.27	4.01
2200	0.007	0.008	0.80	2.47
2400	0.003	0.004	0.50	1.50
2600	0.001	0.002	0.20	0.71

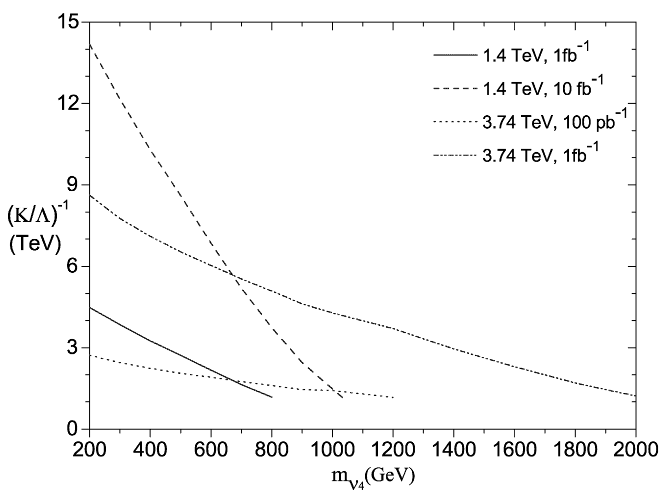


Fig. 4. Achievable values of anomalous coupling strength as a function of the fourth generation neutrino mass for $ep \to \nu_4 X \to \mu WX$ process.

Table 2, QCD Explorer will reach $m_{\nu_4} = 850$ GeV (1100 GeV) with integrated luminosity of 1 fb^{-1} (10 fb^{-1}) for $(\kappa/\Lambda) =$ 1 TeV^{-1}. Corresponding limit for Energy Frontier is 1300 GeV (2100 GeV) with $L_{\text{int}} = 100$ pb^{-1} (1 fb^{-1}). Achievable values of anomalous coupling strength as a function of the fourth generation neutrino mass for process under consideration are shown in Fig. 4 for different ep collider options. One can see that values as low as 0.077 TeV^{-1} are reachable for (κ/Λ).

For the process $ep \to \nu_4 X \to eWX$ we require $SS > 5$ as a discovery criterion. It is seen from Tables 4 and 5, that QCD Explorer will cover masses of the fourth generation neutrino up to 750 GeV (950 GeV) with $L_{\text{int}} = 1$ fb^{-1} (10 fb^{-1}), whereas Energy Frontier ep collider will extend the mass region up to $m_{\nu_4} = 950$ GeV (1900 GeV) with $L_{\text{int}} = 100$ pb^{-1} (1 fb^{-1}). Fig. 5 show that this channel is less promising than above one concerning achievable values of anomalous coupling strength.

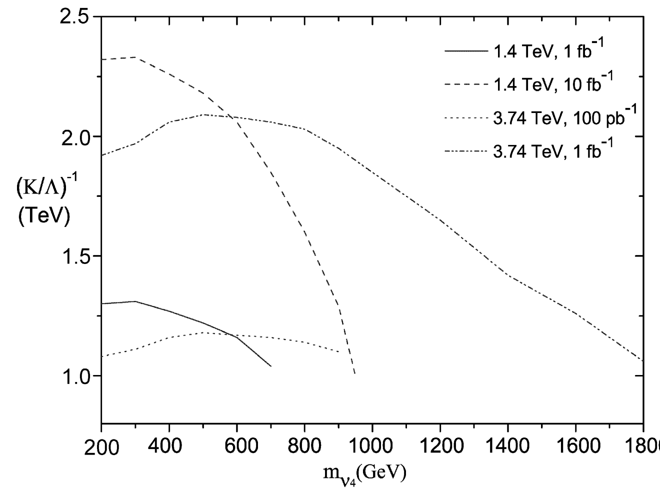


Fig. 5. Achievable values of anomalous coupling strength as a function of the fourth generation neutrino mass for $ep \to \nu_4 X \to eWX$ process.

4. Conclusion

The correct Lagrangian for SM and the anomalous interactions of the fourth generation neutrino change the results drastically. For example, at ep collider with $\sqrt{s} = 3.74$ TeV the production cross section for 200 GeV mass neutrino is 98.23 pb^{-1} in Ref. [29] comparing to 0.743 pb^{-1} in our Letter. The main reason for this difference is that authors of Ref. [29] are used $|V_{\nu_4 l_i}| = 1$, whereas the experimental upper limit is 0.02. More than 2 order difference in production cross section is drastically significant for experimental search.

Combining results of studies on anomalous single production of the fourth SM generation charged lepton [28] and neutrino (this study) at future ep colliders we conclude that they have promising potential on the subject. For example, if $m_{\nu_4} = m_{l_4} = 500$ GeV and $(\kappa/\Lambda) = 1$ TeV^{-1}, the numbers of produced events are 740 for $ep \to \nu_4 X \to eWX$ and 1100 for $ep \to l_4 X \to eZX$ at $\sqrt{s} = 1.4$ TeV with $L_{\text{int}} = 10$ fb^{-1}. Finally, QCD Explorer cover $m_{\nu_4, l_4} < 1$ TeV, whereas Energy Frontier enlarge the region up to 2 TeV.

In this Letter we have assumed that the flavor democracy takes place in SM sector only. However, following Ref. [19] one can expect that the kappa matrices will also originate in a flavor democratic way. Then, in the mass basis this will lead to suppression of the off-diagonal elements in the kappa matrices (in principle, depending on the nature of anomalous interactions, democracy violation in anomalous sector could be stronger than in SM sector). In this case, our results on (κ/Λ) values should be interpreted as those rescaled with corresponding suppression. The scale of $(\kappa/\Lambda)^{-1}$ should be compared with electroweak scale (≈ 250 GeV). Therefore, $(\kappa/\Lambda) \approx$ TeV^{-1} corresponds to the suppression factor about 4. As it is seen from Fig. 4, QCD Explorer will be sensitive to the suppression factor up to 50.

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