Research Article
Search for Excited Spin-3/2 Neutrinos at LHeC

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We study the potential of the next ep collider, namely, LHeC, with two options $\sqrt{s} = 1.3$ TeV and $\sqrt{s} = 1.98$ TeV, to search for excited spin-1/2 and spin-3/2 neutrinos. We calculate the single production cross-section of excited spin-1/2 and spin-3/2 neutrinos according to their effective currents describing their interactions between gauge bosons and SM leptons. We choose the $\nu^{\star} \rightarrow eW$ decay mode of excited neutrinos and $W \rightarrow jj$ decay mode of W-boson for the analysis. We put some kinematical cuts for the final state detectable particles and plot the invariant mass distributions for signal and the corresponding backgrounds. In order to obtain accessible limits for excited neutrino couplings, we show the $f - f'$ and $c_{iV} - c_{iA}$ contour plots for excited spin-1/2 and excited spin-3/2 neutrinos, respectively.

1. Introduction

The Standard Model (SM) of the particle physics agrees with experimental results from the operating colliders. The first run of the Large Hadron Collider (LHC) brought the expected Higgs boson discovery, so a crucial part of the SM has been completed. But there is still no satisfying explanation of the three-family structure of leptons and quarks and their mass hierarchy. An attractive explanation is lepton and quark compositeness [1–3]. In composite models, known leptons and quarks have a substructure characterized by an energy scale called the compositeness scale, Λ. A natural consequence of compositeness is the occurrence of excited states [4–7]. Phenomenologically, an excited lepton can be regarded as a heavy lepton sharing the same leptonic quantum number with the corresponding SM lepton. If leptons present composite structures, they can be considered as spin-1/2 bound states containing three spin-1/2 or spin-1/2 and spin-0 subparticles. Bound states of spin-3/2 leptons are also possible with three spin-1/2 [1–3] or spin-1/2 and spin-1 subparticles in the framework of composite models [8]. The motivations for spin-3/2 particles come from two different scenarios; spin-3/2 leptons appear in composite models [9–13] and a spin-3/2 gravitino is the superpartner of graviton in

supergravity [14]. Theories beyond the Standard Model that contain exotic particles are discussed in [15–19].

Both excited spin-1/2 and spin-3/2 neutrinos can be produced at future high energy lepton, hadron, and lepton-hadron colliders. Elaborate studies on excited spin-1/2 neutrinos can be found in [20–30]. Also, one can find excited spin-1/2 neutrino production by ultra-high energy neutrinos in [31] and the impact of excited spin-1/2 neutrinos on $\nu\bar{\nu} \rightarrow \gamma\gamma$ process in [32].

The mass limit for excited spin-1/2 neutrinos obtained from their pair production ($e^{+}e^{-} \rightarrow \nu^{\star}\nu^{\star}$ process) by L3 Collaboration at $\sqrt{s} = 189 - 209$ GeV, assuming $f = -f'$, where f and f' are the new couplings determined by the composite dynamics, is $m^{\star} > 102.6$ GeV [33]. Assuming $f = f'$ and $f/\Lambda = 1/m^{\star}$, for single production of excited spin-1/2 neutrino in ep collisions taking into account all the decay channels, the H1 Collaboration sets the exclusion limit for the mass range of excited neutrino $m^{\star} > 213$ GeV at 95% C.L. [34]. Recently, a search was performed by the ATLAS Collaboration taking into account pair production of excited spin-1/2 neutrinos either through contact or gauge-mediated interactions and their decay proceeds via the same mechanism. Considering events with at least three charged leptons with $\Lambda = m^{\star}$, with $f = f' = 1$ and with an integrated luminosity of

TABLE 1: Branching ratios and total decay width of excited spin-1/2 neutrinos for $f = -f' = 1$ ($f = f' = 1$). Here it is taken as $\Lambda = m^\star$.

$m^\star$ (GeV)	Γ (GeV)	% BR ($\nu^\star \to \nu\gamma$)	% BR ($\nu^\star \to \nu Z$)	% BR ($\nu^\star \to eW$)
300	1.91	30.5 (0)	10.7 (38.3)	58.9 (61.7)
500	3.36	28.9 (0)	11.1 (38.9)	60.0 (61.1)
750	5.12	28.4 (0)	11.3 (39.0)	60.3 (61.0)
1000	6.87	28.2 (0)	11.3 (39.1)	60.4 (60.9)
1500	10.35	28.1 (0)	11.4 (39.1)	60.5 (60.9)
2000	13.82	28.1 (0)	11.4 (39.1)	60.5 (60.9)
2500	17.28	28.1 (0)	11.4 (39.1)	60.5 (60.9)
3000	20.75	28.1 (0)	11.4 (39.1)	60.5 (60.9)

$20.3 fb^{-1}$ of pp collisions at $\sqrt{s} = 8$ TeV, a lower mass limit of 1.6 TeV is obtained for every excited spin-1/2 neutrino flavour [35].

Excited spin-3/2 neutrinos are not as well studied in the litterateur as the spin-1/2. An investigation of the production and decay processes of the single heavy spin-3/2 neutrino was performed in [36, 37]. A study of the potential of future high energy e^+e^- linear colliders to probe excited spin-3/2 neutrino signals in different decay modes by considering three phenomenological currents taking into account the corresponding background was done in [8].

Studies are ongoing for the development of a new ep collider, the Large Hadron Electron Collider (LHeC), with an electron beam of 60 GeV, to possibly 140 GeV, and a proton beam of the LHC [38–41] or in the future the Future Circular Collider lepton-hadron collider (FCC-eh) [42, 43]. The LHeC is the highest energy lepton-hadron collider under design and is considered as a linac-ring collider. Linac-ring type colliders were proposed in [44] and the physics potentials and advantages of these type lepton-hadron colliders are discussed in [45, 46]. Latest results for excited neutrino searches coming from the first ep collider HERA have showed that ep colliders are so competitive to pp and e^+e^- colliders and very important for the investigation of beyond SM physics [34, 38–41]. With the design luminosity of 10^{33} cm^{-2} s^{-1} the LHeC is intended to exceed the HERA luminosity by a factor of ~100. So it would be a major opportunity to push forward the investigations done in the LHC.

This work is a continuation of the previous works on excited neutrinos [8, 25]. In this work, in Section 2 we introduce the phenomenological currents for excited neutrinos and give their decay widths. In Section 3, we consider single production of excited spin-1/2 and spin-3/2 neutrinos at ep colliders. We take into account the signal in $\nu^\star \to eW$ decay mode of excited neutrinos as well as corresponding backgrounds at LHeC with $\sqrt{s} = 1.3$ TeV and $\sqrt{s} = 1.98$ TeV. We plot the invariant mass distributions for single production of excited neutrinos with spin-1/2 and spin-3/2. Last, we plot the contour plots for the excited neutrino couplings to obtain the exclusion limits. Investigation on excited fermions with spin-1/2 takes an important part in the physics program of LHeC [38, 39]. Although the latest limit for excited spin-1/2 neutrinos set by the ATLAS experiment is high, it is important to examine the excited neutrinos with different spins at high energy lepton-hadron colliders. This work is the only dedicated work which gives the comparative results for both excited spin-1/2 and spin-3/2 neutrinos to comprehend the potential of next ep collider.

2. Physical Preliminaries

An excited spin-1/2 neutrino is the lowest radial and orbital excitation according to the classification by $SU(2) \times U(1)$ quantum numbers. Interactions between excited spin-1/2 neutrino and ordinary leptons are of the magnetic transition type [47–49]. The effective current for the interaction between an excited spin-1/2 neutrino, a gauge boson ($V = \gamma, Z, W^\pm$), and the SM lepton is given by

$$J^\mu\left(\frac{1}{2}\right) = \frac{g_e}{2\Lambda}\overline{u}\left(p, \frac{1}{2}\right)i\sigma^{\mu\nu}q_\nu\left(1 - \gamma_5\right)f_V u\left(k, \frac{1}{2}\right), \quad (1)$$

where Λ is the new physics scale; g_e is electromagnetic coupling constant with $g_e = \sqrt{4\pi\alpha}$; k, p, and q are the four momentum of the SM lepton, excited spin-1/2 neutrino, and the gauge boson, respectively. f_V is the new electroweak coupling parameter corresponding to the gauge boson V and $\sigma^{\mu\nu} = i(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)/2$ with γ^μ being the Dirac matrices. An excited neutrino has three possible decay modes, each one of which is related to a vector boson γ, W, and Z. These decay modes are radiative decay $\nu^\star \to \nu\gamma$, neutral weak decay $\nu^\star \to \nu Z$, and charged weak decay $\nu^\star \to eW$. Neglecting SM lepton mass we find the decay width of the excited spin-1/2 neutrino as

$$\Gamma\left(l^{\star(1/2)} \longrightarrow lV\right)$$
$$= \frac{\alpha m^{\star 3}}{4\Lambda^2}f_V^2\left(1 - \frac{m_V^2}{m^{\star 2}}\right)^2\left(1 + \frac{m_V^2}{2m^{\star 2}}\right), \quad (2)$$

where $f_\gamma = (f - f')/2$, $f_Z = (f\cot\theta_W + f'\tan\theta_W)/2$, and $f_W = f/\sqrt{2}\sin\theta_W$; θ_W is the weak mixing angle and m_V is the mass of the gauge boson. The couplings f and f' are the scaling factors for the gauge couplings of $SU(2)$ and $U(1)$. Unless $f = f'$, the electromagnetic interaction of excited neutrino and SM neutrino exists. Branching ratios of excited spin-1/2 neutrino for two choices $f = -f' = 1$ and $f = f' = 1$ are presented in Table 1. One may note that for the choice $f = -f' = 1$ the branching ratio for the eW channel is ≈60%. Hence, to choose the $\nu^\star \to eW$ mode for the analysis is more feasible.

The two phenomenological currents for the interactions between an excited spin-3/2 neutrino, a gauge boson ($V = \gamma, Z, W^{\pm}$), and the SM lepton are given by

$$J_1^{\mu}\left(\frac{3}{2}\right) = g_e \bar{u}^{\mu}\left(p, \frac{3}{2}\right)(c_{1V} - c_{1A}\gamma_5) u\left(k, \frac{1}{2}\right),$$

$$J_2^{\mu}\left(\frac{3}{2}\right) = \frac{g_e}{\Lambda} \bar{u}^{\lambda}\left(p, \frac{3}{2}\right) q_{\lambda}\gamma^{\mu} (c_{2V} - c_{2A}\gamma_5) u\left(k, \frac{1}{2}\right), \quad (3)$$

where $u^{\mu}(p, 3/2)$ represents the Rarita-Schwinger vector-spinor [50].

Decay widths of excited spin-3/2 neutrinos for the $\nu^{\star} \rightarrow \nu\gamma$ decay mode for the two currents are given by

$$\Gamma_1\left(\nu^{\star(3/2)} \longrightarrow \nu\gamma\right) = \frac{\alpha}{4}\left(c_{1V}^{\gamma^2} + c_{1A}^{\gamma^2}\right) m^{\star},$$

$$\Gamma_2\left(\nu^{\star(3/2)} \longrightarrow \nu\gamma\right) = \frac{\alpha}{24}\left(c_{2V}^{\gamma^2} + c_{2A}^{\gamma^2}\right) m^{\star}\left(\frac{m^{\star}}{\Lambda}\right)^2, \quad (4)$$

and for the neutral and charged weak decay modes ($\nu^{\star} \rightarrow \nu Z$ and $\nu^{\star} \rightarrow eW$), they are given as

$$\Gamma_1\left(\nu^{\star(3/2)} \longrightarrow lV\right)$$
$$= \frac{\alpha}{48}\left(c_{1V}^2 + c_{1A}^2\right) m^{\star} \frac{(1-\kappa)^2}{\kappa}\left(1 + 10\kappa + \kappa^2\right),$$

$$\Gamma_2\left(\nu^{\star(3/2)} \longrightarrow lV\right)$$
$$= \frac{\alpha}{48}\left(c_{2V}^2 + c_{2A}^2\right) m^{\star}\left(\frac{m^{\star}}{\Lambda}\right)^2 \frac{(1-\kappa)^4}{\kappa}(1 + 2\kappa), \quad (5)$$

where $\kappa = (m_V/m^{\star})^2$, $V = Z, W$, and $l = e, \nu$. Branching ratios and total decay width of excited spin-3/2 neutrinos with J_1 and J_2 are given in Tables 2 and 3, respectively. Also, total decay width of excited neutrinos as a function of their mass ($m^{\star}$) is shown in Figure 1.

3. Single Production at ep Collider

The excited spin-1/2 and spin-3/2 neutrinos can be produced singly at future ep colliders via t-channel W exchange. In our calculations we use the program CALCHEP [51–53]. The Feynman diagrams for the subprocesses $e^- q \rightarrow \nu^{\star} q'$ and $e^- \bar{q}' \rightarrow \nu^{\star} \bar{q}$ are shown in Figure 2.

Neglecting SM quark masses, the explicit formulas for the differential cross-section of the subprocesses $e^- q \rightarrow \nu^{\star} q'$ and $e^- \bar{q}' \rightarrow \nu^{\star} \bar{q}$ for the two phenomenological spin-3/2 currents J_1 and J_2 are

$$\frac{d\sigma_1}{dt} = \frac{-2g_e^2 g_W^2 \left|V_{qq'}\right|^2 \left(-m^{\star 2} + t\right)\left[\left(c_{1A}^2 + c_{1V}^2\right) A_1\right]}{96m^{\star 2}\pi s^2 \left[M_W^4 + t^2 + M_W^2\left(-2t + \Gamma_W^2\right)\right]},$$
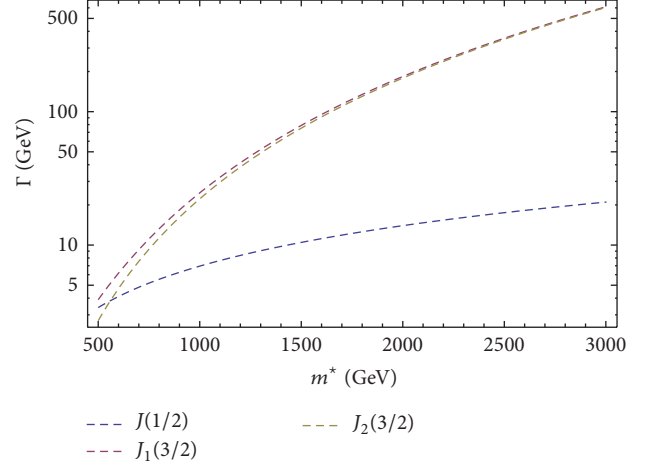
$$A_1 = s(s+t) - m^{\star 2}(s+2t),$$

FIGURE 1: Total decay width of excited neutrinos according to their mass. Here, it is taken as $\Lambda = m^{\star}$ and $f = -f' = 1$ for excited spin-1/2 neutrinos and $c_{iV} = c_{iA} = 0.5$ ($i = 1, 2$) for excited spin-3/2 neutrinos for the two phenomenological currents.
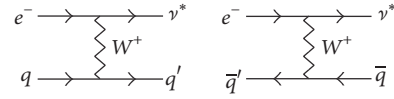

FIGURE 2: Feynman diagrams.

$$\frac{d\sigma_2}{dt} = \frac{-2g_e^2 g_W^2 \left|V_{qq'}\right|^2 \left(m^{\star 2} - t\right)^2 \left(c_{2A}^2 + c_{2V}^2\right) A_2}{192\Lambda^2 m^{\star 2}\pi s^2 \left[M_W^4 + t^2 + M_W^2\left(-2t + \Gamma_W^2\right)\right]},$$

$$A_2 = -2s^2 - 2st - t^2 + m^{\star 2}(2s + t), \quad (6)$$

where $V_{qq'}$ is the CKM matrix element, t is the Mandelstam variable, and s is the square of center-of-mass energy of the collider. Also, differential cross-section expression for the excited spin-1/2 neutrino is

$$\frac{d\sigma}{dt}$$
$$= \frac{g_e^2 g_W^2 f_W^2 \left|V_{qq'}\right|^2 t\left(-m^{\star 4} - 2s(s+t) + m^{\star 2}(2s + t)\right)}{32\Lambda^2 \pi s^2 \left[M_W^4 + t^2 + M_W^2\left(-2t + \Gamma_W^2\right)\right]}. \quad (7)$$

Total cross-section as a function of excited neutrino mass is shown in Figure 3 for the center-of-mass energies $\sqrt{s} = 1.3$ TeV and $\sqrt{s} = 1.98$ TeV.

In our analysis we chose the $\nu^{\star} \rightarrow eW$ mode because of the high branching ratio of the charged current decay channel. $\nu^{\star} \rightarrow \nu\gamma$ and $\nu^{\star} \rightarrow \nu Z$ decay modes will have larger uncertainty because of the missing transverse momentum ($\not{p}_T$) due to the neutrino in the final state. We consider the $ep \rightarrow \nu^{\star} X \rightarrow e^- W^+ X$ process and put some kinematical cuts for the final state detectable particles. We deal with the
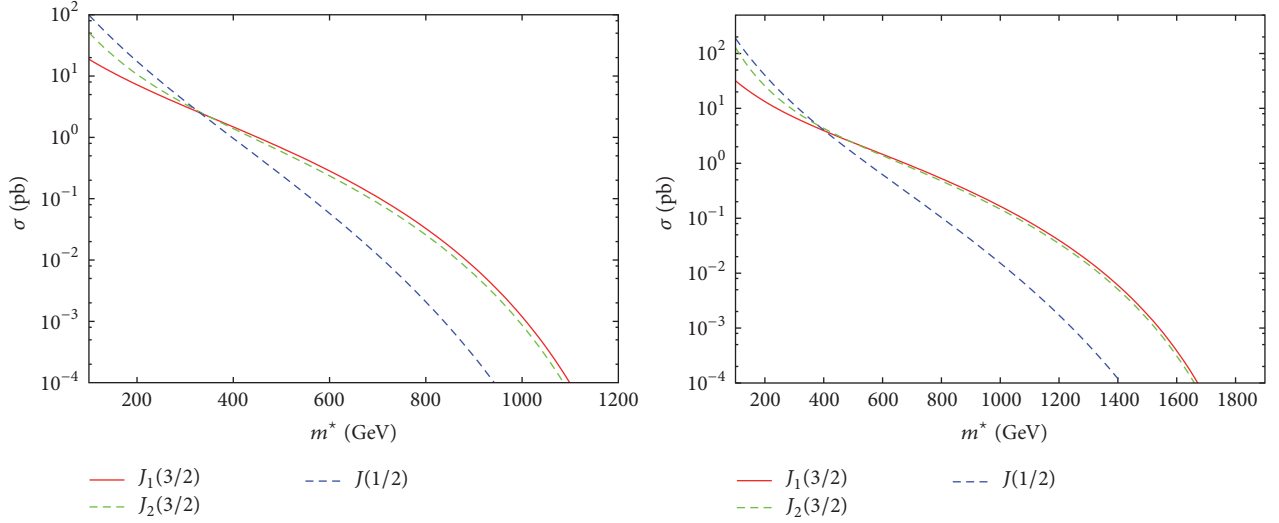
FIGURE 3: Cross-sections for the excited neutrino production with $\Lambda = m^\star$ and $f = -f'$ for spin-1/2 ones and $c_{iV} = c_{iA} = 0.5$ ($i = 1, 2$) for spin-3/2 ones at ep collider at $\sqrt{s} = 1.3$ TeV and $\sqrt{s} = 1.98$ TeV.

TABLE 2: Branching ratios and total decay width of excited spin-3/2 neutrinos with J_1. Here it is taken as $c_{1V} = c_{1A} = 0.5$ and $\Lambda = m^\star$.

$m^\star$ (GeV)	Γ (GeV)	% BR ($\nu^\star \to \nu\gamma$)	% BR ($\nu^\star \to \nu Z$)	% BR ($\nu^\star \to eW$)
300	1.21	24.0	34.4	41.6
500	3.89	12.5	39.0	48.5
750	11.11	6.5	41.2	52.3
1000	24.61	3.9	42.1	54.0
1500	78.89	1.8	42.8	55.3
2000	183.50	1.1	43.1	55.9
2500	355.20	0.7	43.2	56.1
3000	611.00	0.5	43.3	56.2

subprocess $e^- q(\overline{q'}) \to W^+ e^- q'(\overline{q})$ and impose the acceptance cuts

$$p_T^{e,q} > 20 \text{ GeV},$$
$$|\eta^{e,q}| < 2.5. \tag{8}$$

Feynman diagrams for the $e^- q \to e^- W^+ q'$ SM process are presented in Figure 4. The main background process that gives the same final state as excited neutrino signal is multijet neutral current deep inelastic scattering (NC DIS) events. After applying these cuts we obtained the SM background cross-section for the process $ep \to \nu^\star X \to e^- W^+ X$ as $\sigma_B = 0.334$ pb for $\sqrt{s} = 1.3$ TeV and $\sigma_B = 0.928$ pb for $\sqrt{s} = 1.98$ TeV. In order to discriminate the excited neutrino signal we plot the invariant mass distributions for the eW system for the masses $m^\star = 400, 500, 600$ GeV at $\sqrt{s} = 1.3$ TeV and for the masses $m^\star = 700, 800, 900$ GeV at $\sqrt{s} = 1.98$ TeV in Figures 5 and 6, respectively.

We plot the rate of σ_{B+S}/σ_B as a function of excited neutrino mass in Figure 7 to examine the contribution of excited neutrinos to the process $e^- q(\overline{q'}) \to W^+ e^- q'(\overline{q})$ and also to investigate the separation of different excited neutrino models. Here σ_{B+S} corresponds the cross-section calculated

for the presence of excited neutrino (signal) and Standard Model (background) both, and σ_B is the SM (background) cross-section. In these figures, the separation of spin-1/2, spin-3/2 with J_1 and spin-3/2 with J_2 excited neutrinos can be easily seen.

In order to get accessible limits for the excited neutrinos at high energy ep collider, we plot the contours for excited neutrinos with spin-1/2 and spin-3/2. We choose the W boson decay as $W \to 2j$. Here we consider the statistical significance:

$$\text{SS} = \frac{\sigma_S}{\sqrt{\sigma_B}}\sqrt{L_{\text{int}}}. \tag{9}$$

Here L_{int} is the integrated luminosity of the ep collider and we choose $L_{\text{int}} = 100 \ fb^{-1}$ as the LHeC design luminosity. Our results for the SS are shown in Tables 4 and 5.

For the criteria SS $\geqslant 3$ (95% C.L.) we plot the $c_{iV} - c_{iA}$ ($i = 1, 2$) contour plot for excited spin-3/2 neutrinos for both phenomenological currents and the $f - f'$ contour plot for the excited spin-1/2 neutrinos. In Figures 8 and 9, we choose the excited neutrino mass $m^\star = 400$ GeV for the analysis at $\sqrt{s} = 1.3$ TeV and $m^\star = 800$ GeV for the analysis at $\sqrt{s} = 1.98$ TeV. We see from these figures the allowed regions
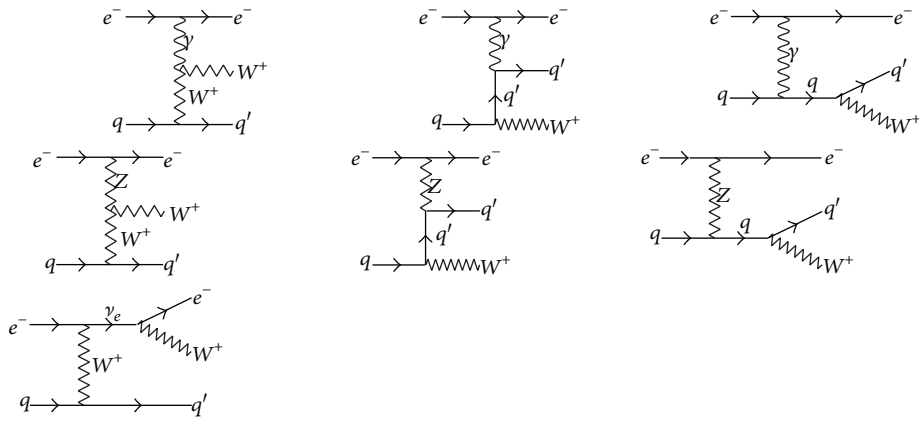
FIGURE 4: Feynman diagrams for the SM background process $e^- q \rightarrow e^- W^+ q'$.
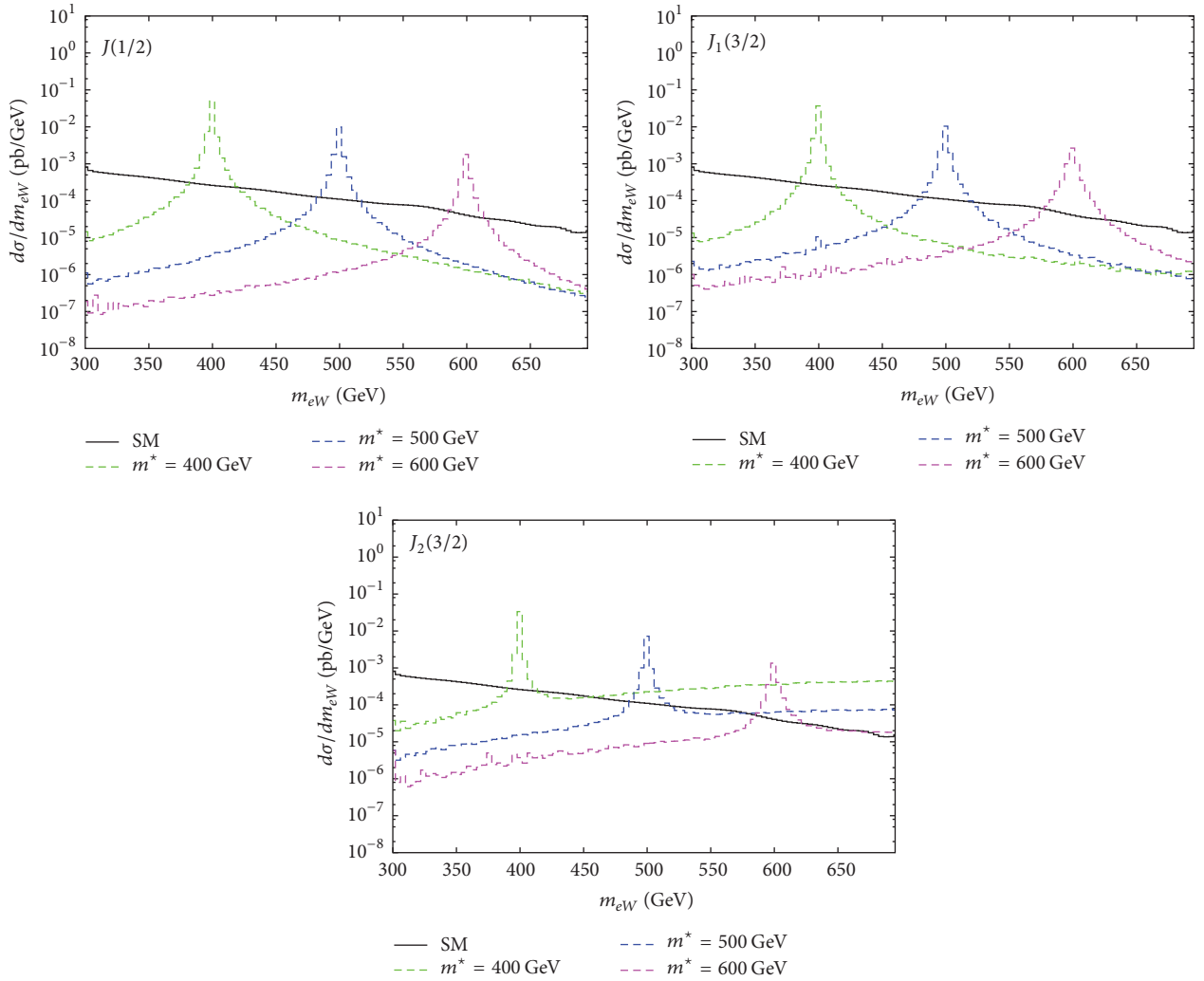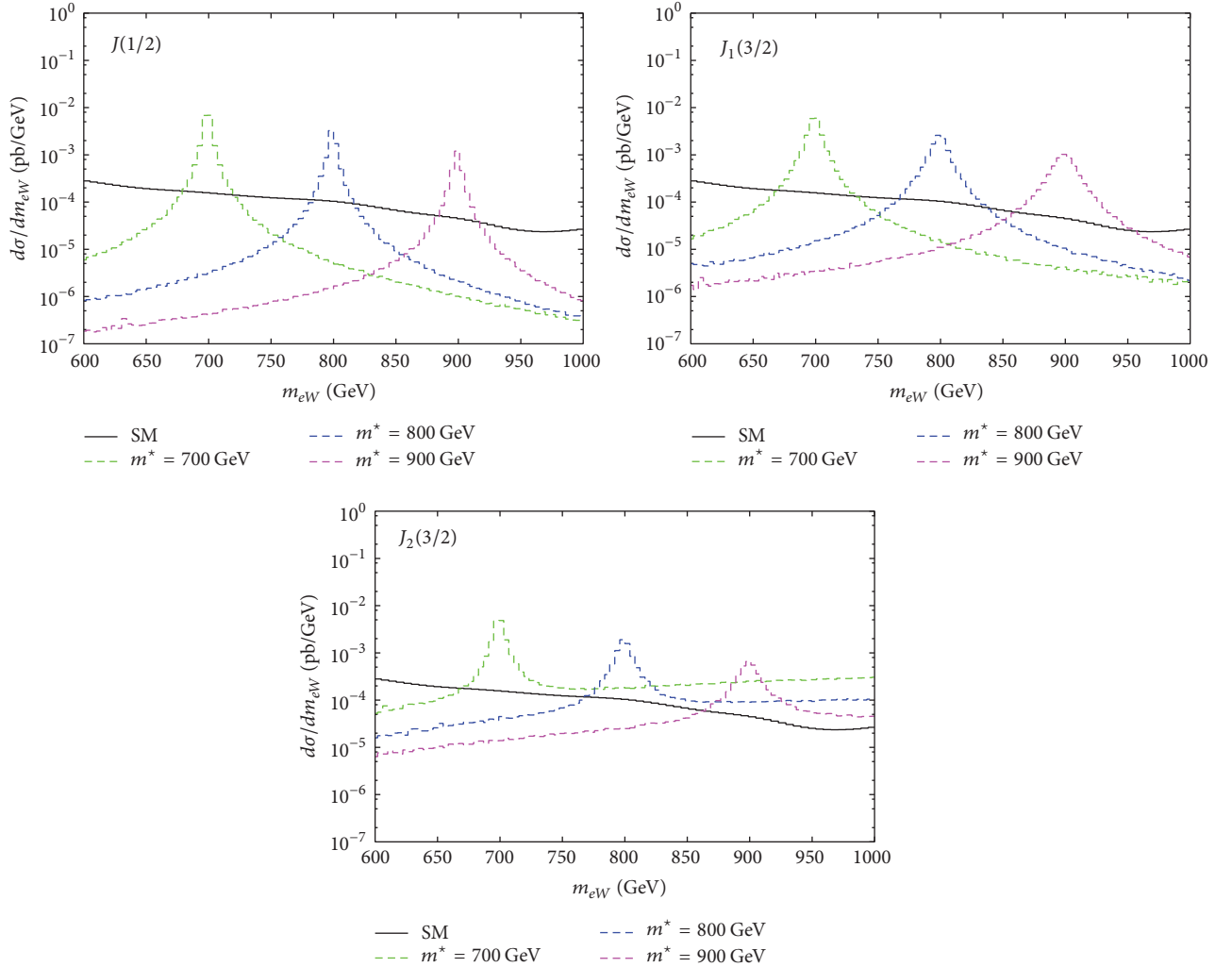

FIGURE 5: Invariant mass distributions of eW system for the single production of excited spin-1/2 for $f = -f' = 1$ and excited spin-3/2 neutrinos with J_1 and J_2 for $c_{iV} = c_{iA} = 0.5$ ($i = 1, 2$) at $\sqrt{s} = 1.3$ TeV.

TABLE 3: Branching ratios and total decay width of excited spin-3/2 neutrinos with J_2. Here it is taken as $c_{2V} = c_{2A} = 0.5$ and $\Lambda = m^\star$.

$m^\star$ (GeV)	Γ (GeV)	% BR ($\nu^\star \to \nu\gamma$)	% BR ($\nu^\star \to \nu Z$)	% BR ($\nu^\star \to eW$)
300	0.55	8.8	38.4	52.8
500	2.71	3.0	41.8	55.3
750	9.31	1.3	42.7	56.0
1000	22.21	0.7	43.0	56.2
1500	75.26	0.3	43.3	56.4
2000	178.7	0.2	43.4	56.5
2500	349.2	0.1	43.4	56.5
3000	603.6	0.1	43.4	56.5

FIGURE 6: Invariant mass distributions of eW system for the single production of excited spin-1/2 for $f = -f' = 1$ and excited spin-3/2 neutrinos with J_1 and J_2 for $c_{iV} = c_{iA} = 0.5$ ($i = 1, 2$) at $\sqrt{s} = 1.98$ TeV.

for the $c_{iV} - c_{iA}$ ($i = 1, 2$) and $f - f'$ couplings for the masses $m^\star = 400$ GeV at $\sqrt{s} = 1.3$ TeV and $m^\star = 800$ GeV at $\sqrt{s} = 1.98$ TeV. The values which we chose in our calculations for the coupling parameters ($c_{iV} = c_{iA} = 0.5$ for the excited spin-3/2 neutrinos and $f = -f' = 1$ for the excited spin-1/2 neutrinos) are compatible with the contour plots.

4. Conclusion

We searched for the excited spin-3/2 neutrino signal at lepton-hadron collider LHeC for two different centers of mass energies. We used two different phenomenological currents for the spin-3/2 excited neutrinos, and we used the same value
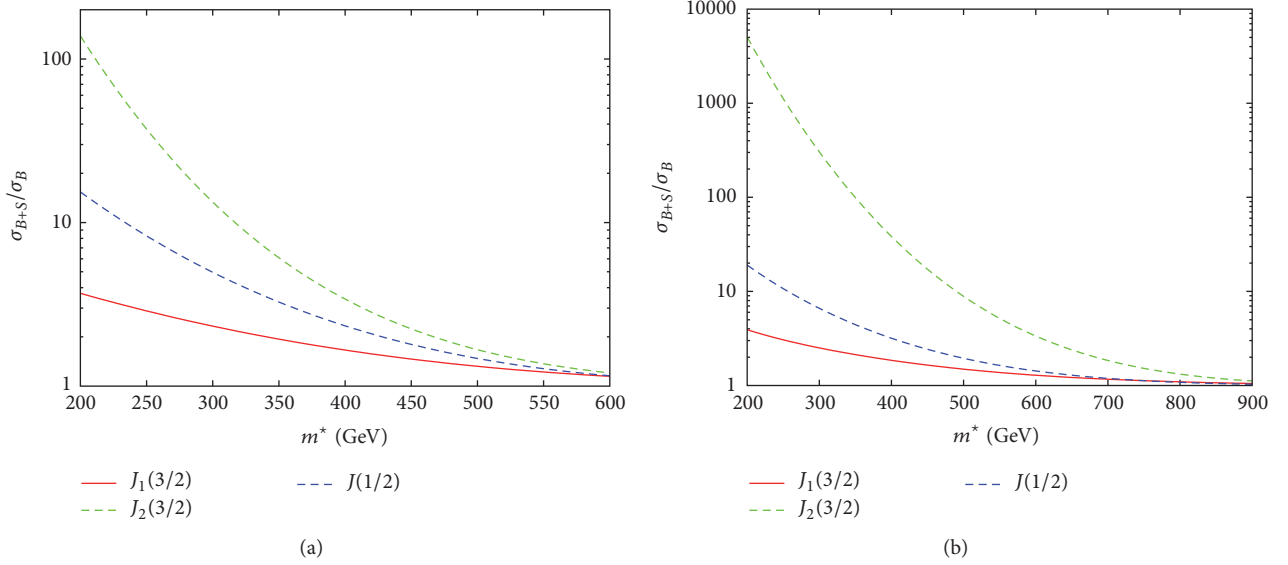
(a)

(b)

FIGURE 7: $\sigma_{B+S}/\sigma_B - m^\star$ plots for $\sqrt{s} = 1.3$ TeV (a) and $\sqrt{s} = 1.98$ TeV (b). ($f = -f' = 1$ for the spin-1/2 and $c_{iV} = c_{iA} = 0.5$ ($i = 1, 2$) for the spin-3/2.)
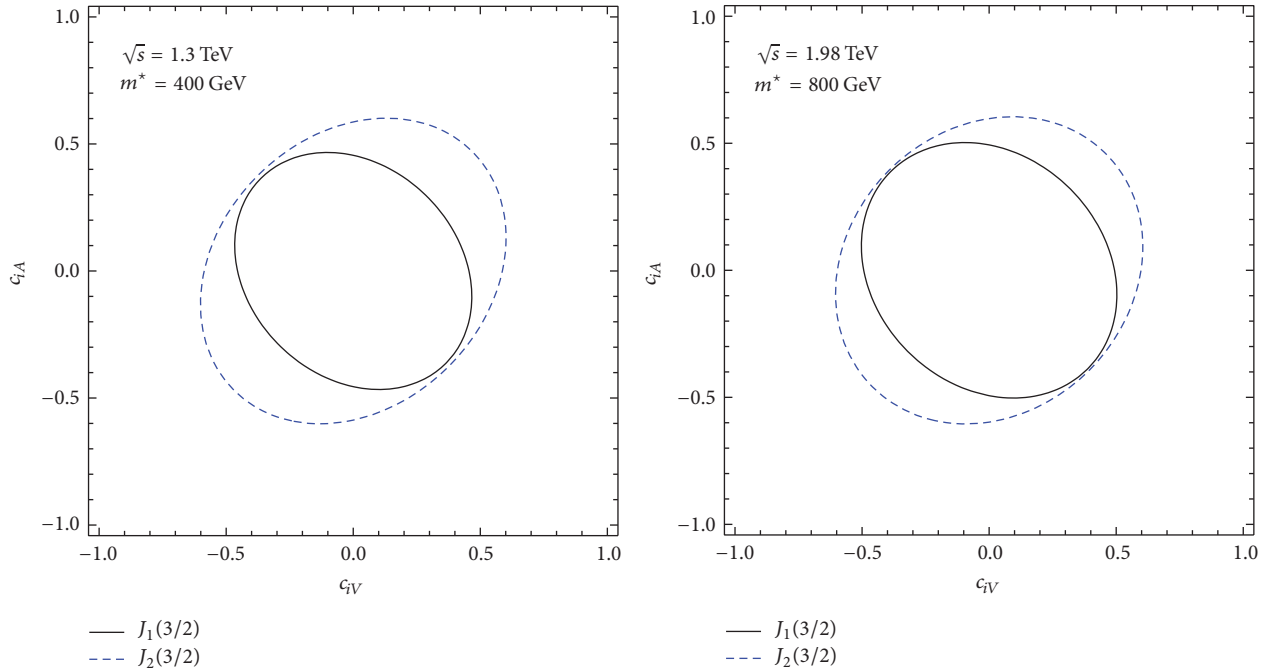

FIGURE 8: Contour plots for excited spin-3/2 neutrinos for the J_1 and J_2.

of c_{iV}, c_{iA} ($i = 1, 2$) couplings. Since there is no theoretical prediction for the single production of excited neutrinos and the effective currents have unknown couplings, we did not consider the interference between the currents. A more detailed calculation shows an important parameter space in which the interference terms could be important.

We also deal with the spin-1/2 excited neutrinos for comparison. Our analysis shows that the spin-1/2 and spin-3/2 excited neutrino signals discrimination is apparent at next ep

colliders. Here we only take into account the effective currents describing the gauge interactions of excited and standard particles. It is possible to include the contact interactions which may enlarge the mass and coupling limits.

It is possible to search for single production of excited spin-3/2 neutrinos at the LHC but it has smaller cross-section than LHeC. Therefore, the potential of LHeC is better than LHC to determine the limits on couplings of excited spin-3/2 neutrinos.
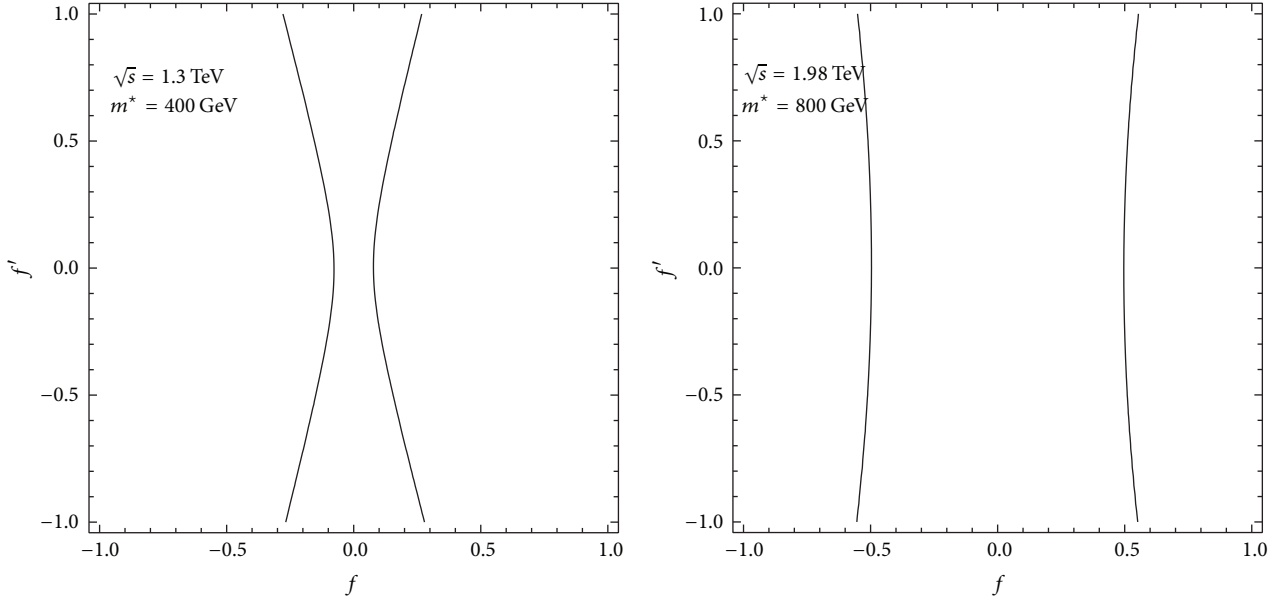
FIGURE 9: Contour plots for excited spin-1/2 neutrinos.

TABLE 4: Statistical significance SS for ep collider with $\sqrt{s}$ = 1.3 TeV for excited spin-1/2 neutrinos and excited spin-3/2 neutrinos with J_1 and J_2.

$m^\star$ (GeV)	SS($J(1/2)$)	SS($J_1(3/2)$)	SS($J_2(3/2)$)
400	110.2	75.4	135.6
500	25.5	30.7	30.0
600	5.5	11.9	7.9
700	1.0	4.2	2.2

TABLE 5: Statistical significance SS for ep collider with $\sqrt{s}$ = 1.98 TeV for excited spin-1/2 neutrinos and excited spin-3/2 neutrinos with J_1 and J_2.

$m^\star$ (GeV)	SS($J(1/2)$)	SS($J_1(3/2)$)	SS($J_2(3/2)$)
600	56.3	51.0	235.9
700	22.4	28.0	76.5
800	8.8	15.1	28.9
900	3.3	8.04	12.0
1000	1.2	4.2	5.3

Excited neutrinos with different spins would manifest themselves in three families. Here, we only investigated the excited electron neutrino. It is also possible to make the same analysis for excited muon neutrinos. Single production of excited muon neutrinos is possible at muon-hadron colliders. Physics of μp colliders was studied in [54]. One can find the main parameters of FCC-based μp collider in [43, 55].

Competing Interests

The authors declare that they have no competing interests.

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