

## Research Article

# Doubly Charged Lepton Search Potential of the FCC-Based Energy-Frontier Electron-Proton Colliders

A. Ozansoy 

Department of Physics, Faculty of Sciences, Ankara University, 06100 Tandogan, Ankara, Turkey

Correspondence should be addressed to A. Ozansoy; aozansoy@science.ankara.edu.tr

Received 15 December 2019; Revised 23 March 2020; Accepted 25 March 2020; Published 5 June 2020

Academic Editor: Enrico Lunghi

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We search for the doubly charged leptons ( $L^{--}$ ) predicted in composite models including extended weak isospin multiplets, namely,  $I_W = 1$  and  $I_W = 3/2$ , at the Future Circular Collider- (FCC-) based energy-frontier electron-proton colliders with the center-of-mass energies of  $\sqrt{s} = 3.46$  TeV,  $\sqrt{s} = 10$  TeV, and  $\sqrt{s} = 31.6$  TeV, respectively. We deal with the  $e^-p \rightarrow L^{--}X \rightarrow e^-W^-X$  process, calculate the production cross sections, and give the normalized transverse momentum and pseudorapidity distributions of final-state electron to obtain the kinematical cuts for the discovery. We show the statistical significance (SS) of the expected signal yield as a function of doubly charged lepton mass (SS- $M_L$  plots) to attain the doubly charged lepton discovery mass limits for both the  $I_W = 1$  and  $I_W = 3/2$ . It is obtained that discovery mass limits on the mass of doubly charged lepton for  $I_W = 1$  ( $I_W = 3/2$ ) are 2.21 (2.73) TeV, 5.46 (8.47) TeV, and 12.9 (20.0) TeV for  $\sqrt{s} = 3.46$  TeV,  $\sqrt{s} = 10$  TeV, and  $\sqrt{s} = 31.6$  TeV, respectively.

## 1. Introduction

The spectacular operation of the Large Hadron Collider (LHC) has so far confirmed the validity of the Standard Model (SM) of particle physics with great precision. Especially, Higgs boson discovery by ATLAS and CMS Collaborations at the LHC in 2012 was a great triumph of the SM [1, 2]. Nevertheless, there are some issues that the SM gives no explanation such as particle dark matter, neutrino masses, large number of fundamental particles, lepton-quark symmetry, and fermionic family replication, and it is expected that these issues will be answered at the forthcoming decades by the future high-energy colliders. Currently, the spectrum of the SM matter particles has a pattern with three generations listed in a growing mass both for lepton and quark sectors. The second and third fermionic families are replicas of the first family in the context of charge, spin, weak isospin, and color charge but only differ in mass. The fundamental particle inflation in the SM and family replication are natural indicators for a further level of substructure. Compositeness is one of the beyond the SM (BSM) theories that predict a fur-

ther level of matter constituents called preons as the ultimate building blocks and known fermions are composites of them [3–5]. A conspicuous consequence of lepton and quark substructure would be the existence of excited states [6–10]. Considering the known fermions as ground state, spin-1/2 and weak isospin-1/2 excited fermions are accepted as the lowest radial and orbital excitations by the composite models. Excited fermions with higher spins take part in composite models and are considered as higher excitations [11–15].

Mostly, excited fermions belonging to weak isospin singlets or doublets, i.e.,  $I_W = 0$  and  $I_W = 1/2$ , are studied in detail at various colliders, so far. Phenomenological studies on spin-1/2 excited leptons ( $l^*$ ) can be found for the lepton and lepton-hadron colliders in [16–24],  $e\gamma$  and  $\gamma\gamma$  colliders in [25–29], and hadron colliders in [30–36]. The LHC sets the most stringent bounds on excited leptons and quarks with spin-1/2. The mass limits were obtained from single production ( $pp \rightarrow ll^*X$ ,  $l = e, \mu, \tau$ ) at  $\sqrt{s} = 8$  TeV including contact interactions in the  $l^*$  production and decay mechanism taking into account that the compositeness scale is equal to excited lepton mass ( $\Lambda = m^*$ ) and  $f = f' = 1$ , where

TABLE 1: Main parameters of the FCC-based  $ep$  colliders with the proton beam energy of  $E_p = 50$  TeV.

Collider name	$E_e$ (TeV)	$\sqrt{s}$ (TeV)	$L_{\text{int}}$ ( $\text{fb}^{-1}$ per year)
ERL60 $\otimes$ FCC	0.06	3.46	100
ILC $\otimes$ FCC	0.5	10	10-100
PWFA-LC $\otimes$ FCC	5	31.6	1-10

$f$  and  $f'$  are the dimensionless couplings determined by the composite dynamics; the ATLAS Collaboration sets the mass limits as  $m_{e^*} > 3000$  GeV,  $m_{\mu^*} > 3000$  GeV, and  $m_{\tau^*} > 2500$  GeV at the 95% confidence level (C.L.) [37]. Also, the obtained mass limits for the excited neutrinos from pair production processes ( $pp \rightarrow \nu^* \nu^* X$ ) were set as  $m_{\nu^*} > 1600$  GeV for all types of excited neutrinos [37] and for the excited quarks from single production processes ( $pp \rightarrow q^* X$ ), the mass limit was set as  $m_{q^*} > 6000$  GeV [38]. For the other mass limits and scale limits within the scope of lepton and quark compositeness searches, see [39]. Very recently, the first search for excited leptons at  $\sqrt{s} = 13$  TeV is published by the CMS Collaboration [40]. Under the assumption  $\Lambda = m^*$ , excited electrons and muons are excluded for masses below 3.9 and 3.8 TeV, respectively, at 95% C.L. Also, the best observed limit on the compositeness scale is obtained as  $\Lambda > 25$  TeV for both excited electrons and muons for  $m^* \sim 1.0$  TeV. Furthermore, it is shown in [41] that the effective models for excited fermions violate unitarity in a certain parameter region of the excited fermion mass and compositeness scale.

In this work, we consider another aspect of compositeness: weak isospin invariance. From this point of view, usual weak isospin singlets and doublets are extended to include triplets and quartets ( $I_W = 1$  and  $I_W = 3/2$ ) [42]. Excited states with exotic charges with  $Q = -2e$  for the lepton sector and  $Q = 5/3e$  and  $Q = -4/3e$  for the quark sector are included in these exotic multiplets. Here, we only concentrate on doubly charged leptons appearing in  $I_W = 1$  and  $I_W = 3/2$  multiplets. If there is any signal for doubly charged leptons at future colliders, SM fermionic family structure and replication could be explained satisfactorily.

In the literature, doubly charged leptonic states appear in type II seesaw mechanisms [43–45], in models of strong electroweak symmetry breaking [46], in some extensions of supersymmetric models [47–51], in flavor models in warped extra dimensions and in more general models [52, 53], in string inspired models [54], and in  $3-3-1$  models [55, 56]. Also, stable doubly charged leptons have been considered an acceptable candidate for cold dark matter [57].

Doubly charged lepton phenomenology is investigated so far at the LHC [58–68], at future linear colliders [69–72], and at the Large Hadron-electron Collider (LHeC) [73]. Doubly charged leptons related to the second lepton family are investigated at various possible future muon-proton colliders in [74]. Also, the ATLAS and CMS Collaborations have performed the searches for long-lived doubly charged states by Drell-Yan-like pair production processes. The ATLAS Col-

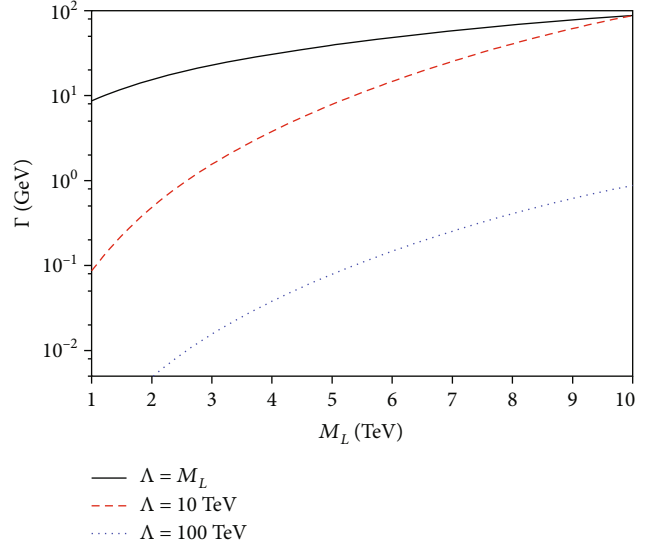


FIGURE 1: Decay width of doubly charged leptons for  $\Lambda = M_L$ ,  $\Lambda = 10$  TeV, and  $\Lambda = 100$  TeV.

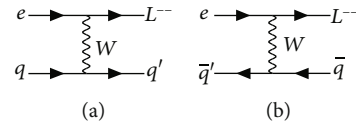


FIGURE 2: Feynman diagrams responsible for the subprocess  $e^-q \rightarrow L^{--}q'$  (a) and  $e^-q' \rightarrow L^{--}\bar{q}$  (b).

laboration has excluded long-lived doubly charged lepton state masses up to 660 GeV based on the run at  $\sqrt{s} = 8$  TeV with  $L = 20.3 \text{ fb}^{-1}$  [75], and the CMS Collaboration sets the lower mass limit up to 685 GeV based on the run at  $\sqrt{s} = 8$  TeV with  $L = 18.8 \text{ fb}^{-1}$  [76].

LHC is the world's largest particle physics laboratory, and it is necessary to extend its discovery potential and to plan for the colliders after it. Firstly, a major upgrade of the LHC is High-Luminosity phase (HL-LHC) [77, 78] with an integrated luminosity of  $3 \text{ ab}^{-1}$  at  $\sqrt{s} = 14$  TeV and, secondly, a possible further upgrade of the LHC is High-Energy phase (HE-LHC) [79] with the 27 TeV center-of-mass energy in 2020s.

The Future Circular Collider (FCC) project is an exciting and consistent post-LHC high-energy  $pp$  collider project at CERN with a center-of-mass energy of 100 TeV, and it is supported by the European Union within the Horizon 2020 Framework Programme for Research and Innovation [80, 81]. Besides the  $pp$  option (FCC-hh), FCC includes an electron-positron collider option (FCC-ee) known as TLEP [82, 83] in the same tunnel and also an  $ep$  collider option (FCC-eh) providing the electron beam with an energy of 60 GeV by an energy recovery linac (ERL) [80]. The FCC-eh would operate concurrently with the FCC-hh. The same ERL design has been studied in detail as the main option for the LHeC project [84, 85]. Concerning ERL that would be positioned inside the FCC tunnel, energy of the electron

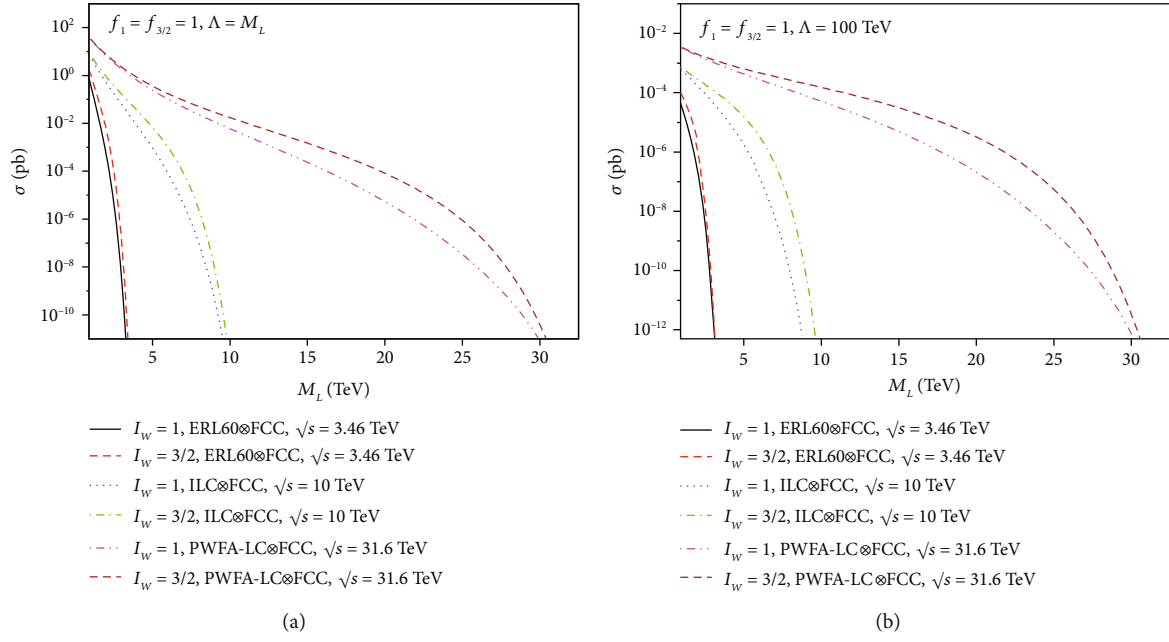


FIGURE 3: Production cross sections for the single production of doubly charged leptons at future  $ep$  colliders for  $\Lambda = M_L$  (a) and  $\Lambda = 100 \text{ TeV}$  (b).

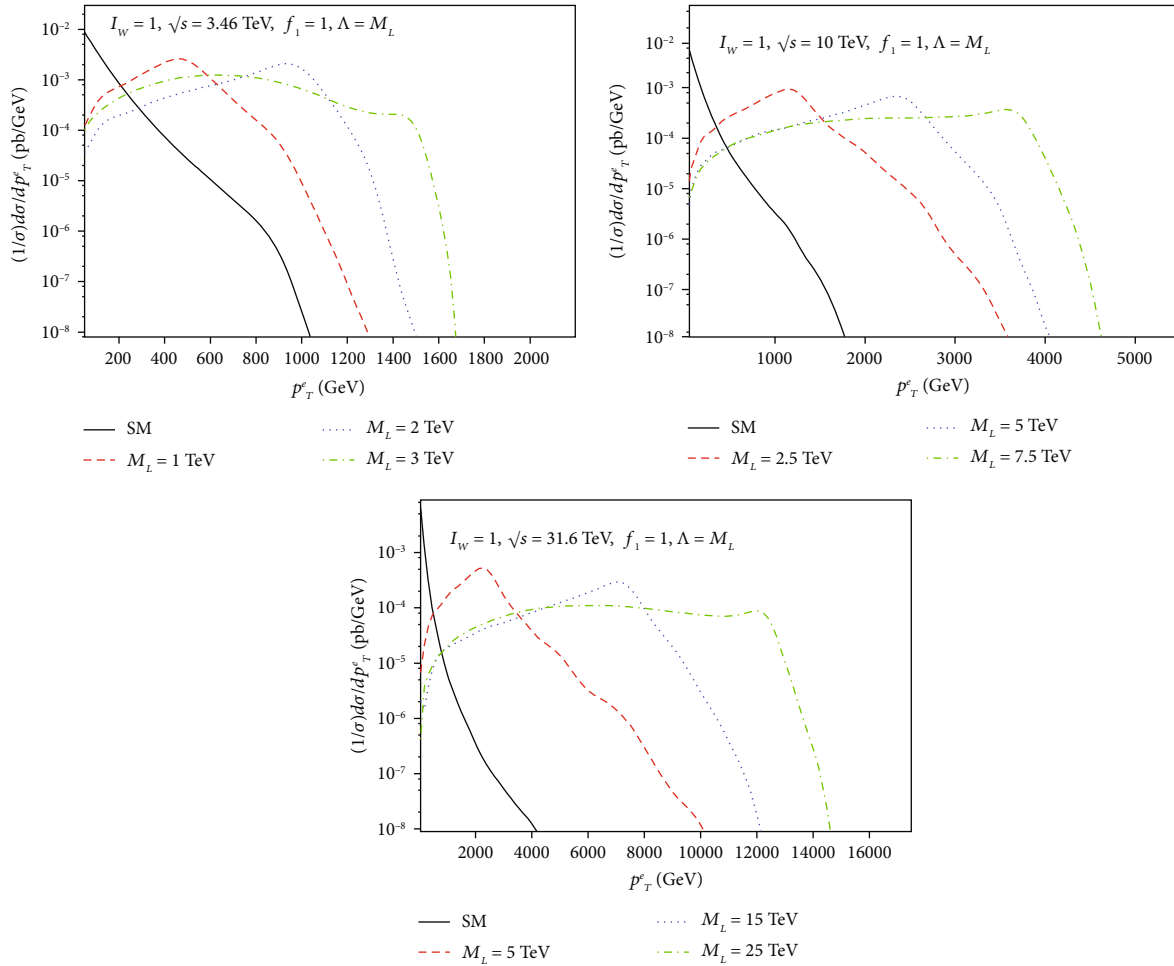


FIGURE 4: Normalized  $p_T$  distributions of the final-state electron for the  $I_W = 1$  multiplet for  $f_1 = 1$  and  $\Lambda = M_L$  for various  $ep$  colliders.

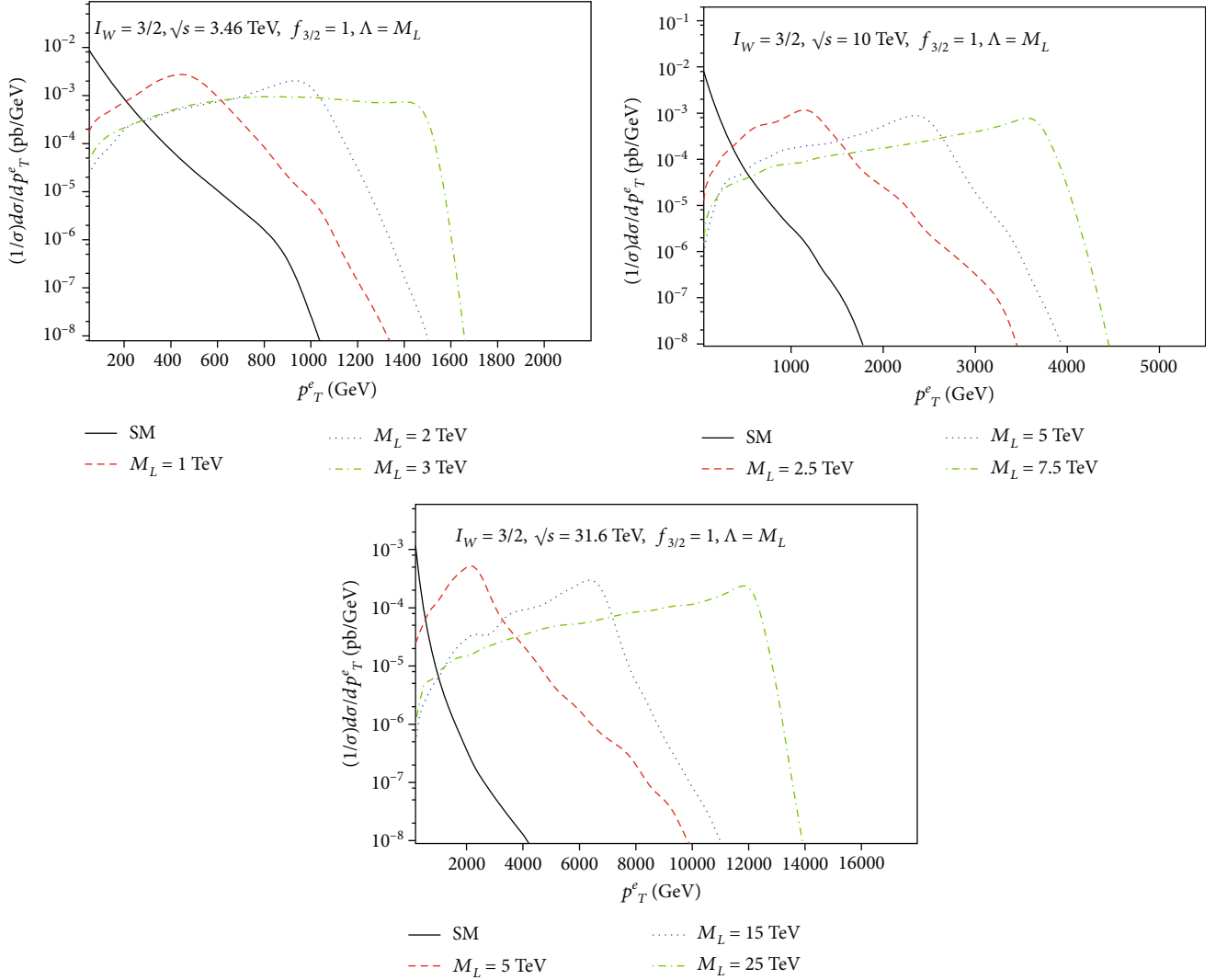


FIGURE 5: Normalized  $p_T$  distributions of the final-state electron for the  $I_W = 3/2$  multiplet for  $f_{3/2} = 1$  and  $\Lambda = M_L$  for various  $ep$  colliders.

beam is limited ( $E_e < 200$  GeV) due to the large synchrotron radiation. To achieve higher electron beam energies for the  $ep$  option of the FCC, linear colliders should be constructed tangential to the FCC [86]. Besides the main choice of FCC-eh, namely, ERL60, other designs of FCC-based  $ep$  collider could be configured using the main parameters of International Linear Collider (ILC) [87] and Plasma Wake Field Accelerator-Linear Collider (PWFA-LC) [88]. A very detailed consideration on the multi-TeV  $ep$  colliders based on FCC and linear colliders (LC) can be found in [86]. Another remarkable and important post-LHC project is the Super proton-proton Collider (SppC) project which is planned to be built in China with the center-of-mass energy about 70 TeV [89]. Different options of FCC-based  $ep$  colliders are listed in Table 1.

In this work, in Section 2, we give the basics of extended weak isospin models and introduce the effective Lagrangians for the gauge interactions of doubly charged leptons. We consider the production of doubly charged leptons at future various high-energy  $ep$  colliders, show our analysis to obtain

the best cuts for the discovery, and give the obtained mass limits in Section 3, and then, we conclude.

## 2. Extended Weak Isospin Multiplets

Long before the experimental verification of the existence of quarks and gluons, strong isospin symmetry allowed to designate the possible patterns of baryonic and mesonic states and to learn about the properties of these hadronic states. With the same point of view, using the weak isospin symmetry arguments, possible fermionic resonances could be revealed. Thus, without knowing about the dynamics of the fermionic integral parts (preons) exactly, we could obtain the quantum numbers of the excited fermionic spectrum. The weak isospin invariance is used to determine the allowed exotic states. SM fermions exist in singlets or doublets ( $I_W = 0$  or  $I_W = 1/2$ ), and gauge bosons have  $I_W = 0$  (for photons) or  $I_W = 1$  (for weak bosons), so only  $I_W \leq 3/2$  states can be allowed. Therefore, usual weak isospin states can be extended to  $I_W = 1$  and  $I_W = 3/2$  states. The details of

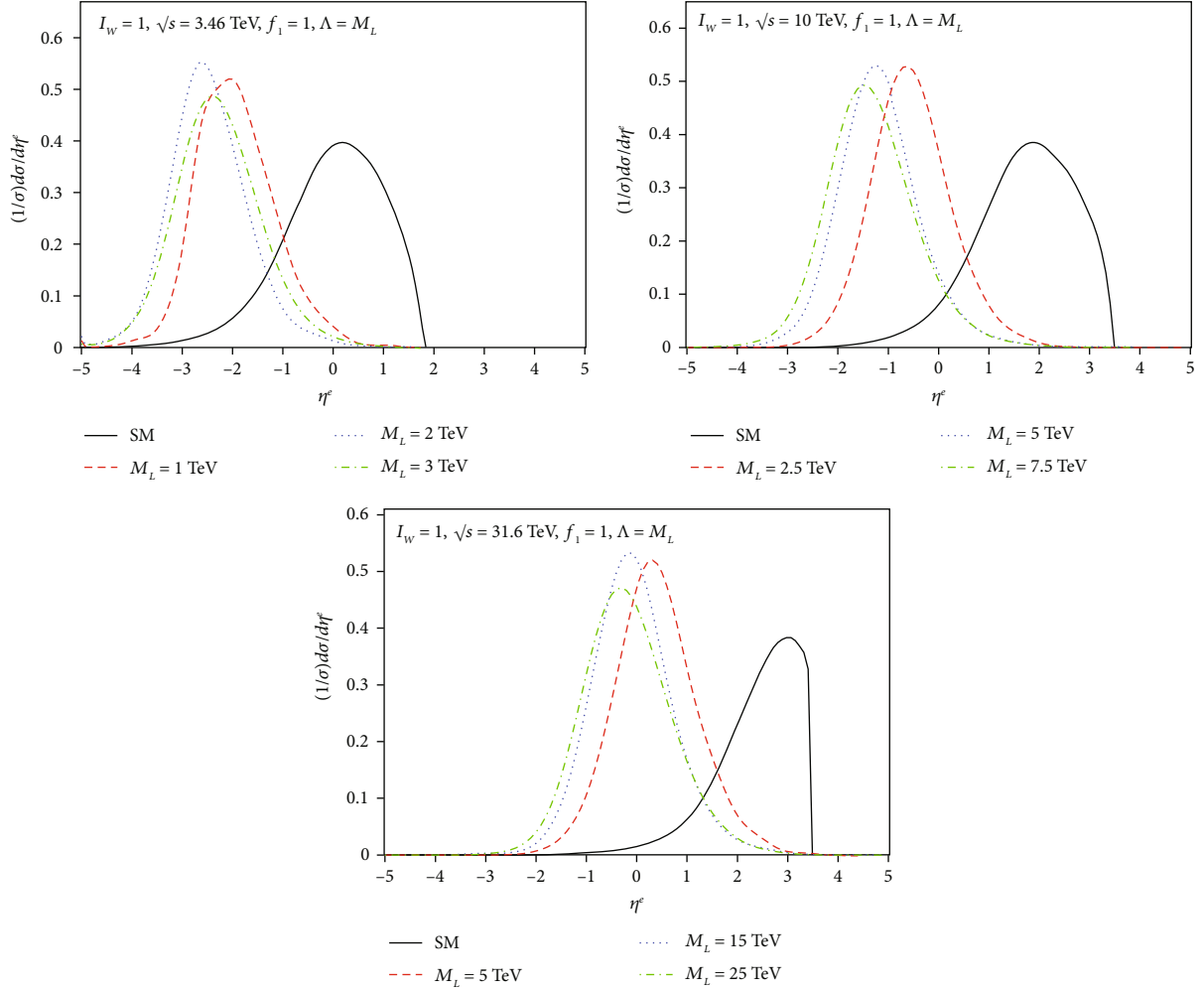


FIGURE 6: Normalized  $\eta$  distribution of the final-state electron for the  $I_W = 1$  multiplet for  $f_1 = 1$  and  $\Lambda = M_L$  for various  $ep$  colliders.

extended isospin models can be found in [42]. The form of these exotic  $I_W = 1$  and  $I_W = 3/2$  multiplets is

$$L_1 = \begin{pmatrix} L^0 \\ L^- \\ L^{--} \end{pmatrix}, \quad (1)$$

$$L_{3/2} = \begin{pmatrix} L^+ \\ L^0 \\ L^- \\ L^{--} \end{pmatrix}$$

and similar for the antiparticles. These multiplets can be arranged for all flavors of leptons. Also, exotic multiplets with  $I_W = 1$  and  $I_W = 3/2$  exist in the quark sector.

To attain the decay widths and production cross sections, we have to specify the doubly charged lepton couplings to SM leptons and gauge bosons. Due to the lack of knowledge

about the explicit dynamics of preons, we use the effective Lagrangian method. Since all the gauge fields have  $Y = 0$  weak hypercharge, a certain exotic multiplet couples through the gauge fields to a SM multiplet with the same  $Y$ . According to the well-known Gell-Mann-Nishijima formula ( $Q = I_3 + Y/2$ ), exotic multiplet  $I_W = 1$  has  $Y = -2$  and  $I_W = 3/2$  has  $Y = -1$ , so  $L^{--}$  from  $I_W = 1$  couples to SM right-handed leptons (singlets) and  $L^{--}$  from  $I_W = 3/2$  couples to SM left-handed leptons (doublets). To assure the current conservation, the couplings have to be of anomalous magnetic moment type. The only contribution that involves both  $I_W = 1$  and  $I_W = 3/2$  comes from the isovector current. Thus, doubly charged leptons can couple to SM leptons only via  $W^\pm$  gauge bosons. Relevant gauge-mediated interaction Lagrangians which are made of dimension five operators to describe the interactions between a doubly charged lepton, a SM lepton, and  $W$  boson for the exotic multiples are given by

$$\mathcal{L}_{\text{GM}}^{(1)} = i \frac{gf_1}{\Lambda} \left( \bar{L} \sigma_{\mu\nu} \partial^\nu W^\mu \frac{1 + \gamma_5}{2} \ell \right) + h.c., \quad (2)$$

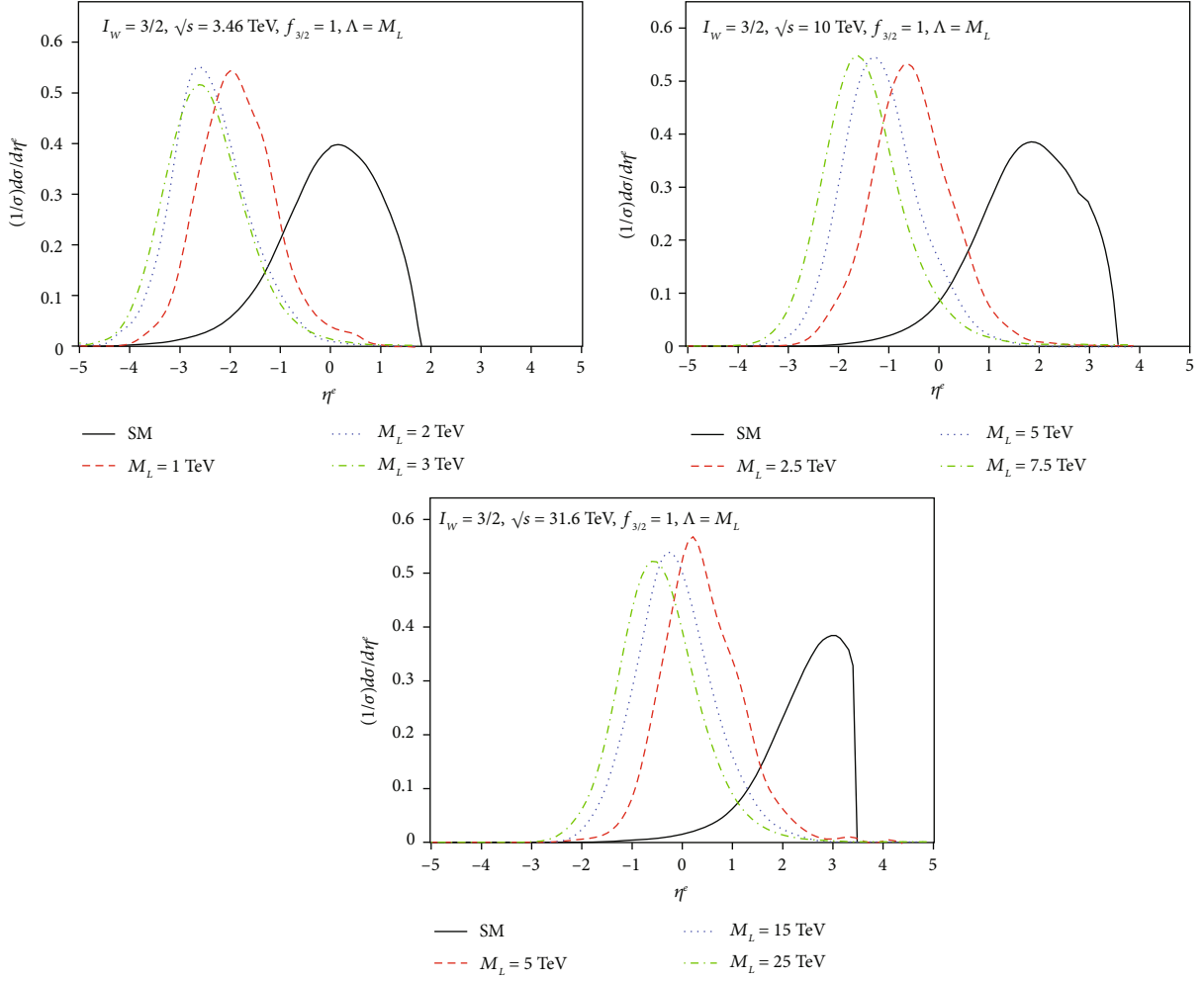


FIGURE 7: Normalized  $\eta$  distribution of the final-state electron for the  $I_W = 3/2$  multiplet for  $f_{3/2} = 1$  and  $\Lambda = M_L$  for various  $ep$  colliders.

TABLE 2: Discovery cuts.

	ERL60 $\otimes$ FCC	ILC $\otimes$ FCC	PWFA-LC $\otimes$ FCC
$I_W = 1$	$p_T^e > 200$ GeV $-4 < \eta^e < -1.1$	$p_T^e > 340$ GeV $-3.3 < \eta^e < 0.5$	$p_T^e > 500$ GeV $-2.1 < \eta^e < 1.5$
$I_W = 3/2$	$p_T^e > 210$ GeV $-4 < \eta^e < -1.1$	$p_T^e > 350$ GeV $-3.3 < \eta^e < 0.5$	$p_T^e > 530$ GeV $-2.1 < \eta^e < 1.5$

$$\mathcal{L}_{GM}^{(3/2)} = i \frac{g f_{3/2}}{\Lambda} \left( \bar{L} \sigma_{\mu\nu} \partial^\nu W^\mu \frac{1 - \gamma_5}{2} \ell \right) + h.c. \quad (3)$$

Here,  $g$  is the SU(2) coupling and equal to  $g_e/\sin\theta_W$ , where  $g_e = \sqrt{4\pi\alpha}$ ,  $\theta_W$  is a weak mixing angle,  $\alpha$  is the fine structure constant,  $\sigma_{\mu\nu}$  is the antisymmetric tensor being  $\sigma_{\mu\nu} = i/2(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)$ ,  $\Lambda$  is the compositeness scale, and  $f_1$  and  $f_{3/2}$  are the couplings which are responsible for the effective interactions of  $I_W = 1$  and  $I_W = 3/2$  multiplets, respectively.  $L$  denotes the doubly charred lepton, and  $l$  denotes the SM lepton. The vertex factors can be inferred

from Equations (2) and (3) as

$$\Theta_\mu^{(i)} = \frac{g_e f_i}{4\Lambda \sin\theta_W} \left( \gamma_\mu \not{q} - \not{q} \gamma_\mu \right) (1 \mp \gamma_5), \quad i = 1, 3/2, \quad (4)$$

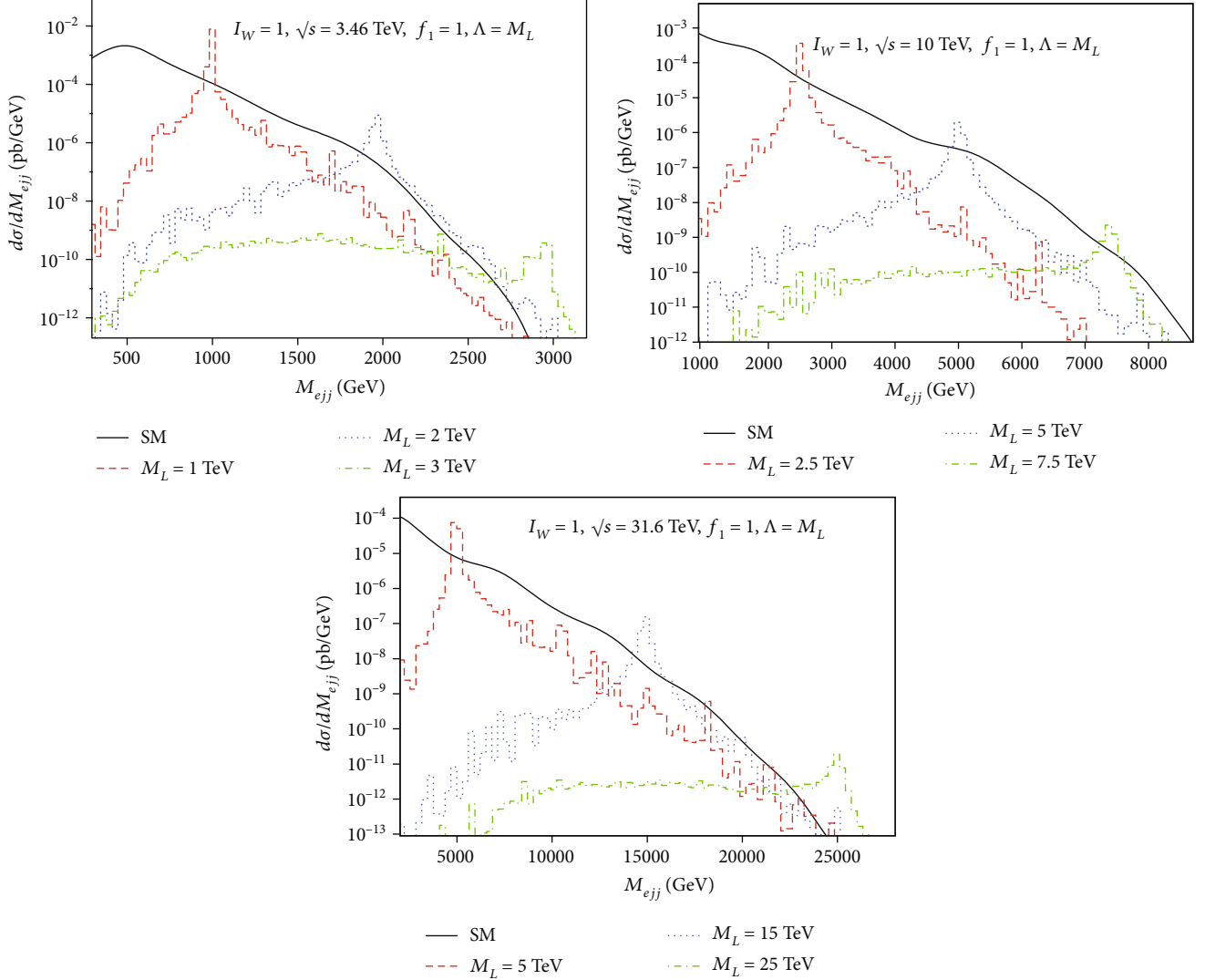
where  $\not{q} = q^\nu \gamma_\nu$  and  $q^\nu$  is the four-momentum of the gauge field. In Equation (4), + is for  $i=1$  and - is for  $i=3/2$ . Due to the fact that the only contribution to the interaction Lagrangian comes from isovector current,  $L^-$  has only one decay mode  $L^- \rightarrow W^- l$ . Neglecting SM lepton mass, the analytical expression for the decay width of doubly charged lepton is

$$\Gamma(L^- \rightarrow W^- l) = \left( \frac{f}{\sin\theta_W} \right)^2 \alpha \left( \frac{M_L^3}{8\Lambda^2} \right) \cdot \left( 1 - \frac{m_W^2}{M_L^2} \right)^2 \left( 2 + \frac{m_W^2}{M_L^2} \right), \quad (5)$$

and Equation (5) has the same form both for  $I_W = 1$  and  $I_W = 3/2$  as we set  $f_1 = f_{3/2} = f$ . In Figure 1, we plot the decay width of doubly charged lepton as a function of

TABLE 3: Final states for the doubly charged lepton production at  $ep$  colliders.

$L^{--}$ decay mode	$W^-$ boson decay mode	Final state
$L^{--} \rightarrow l^- W^-$	Leptonic ( $W^- \rightarrow l^- \nu_l$ )	$l^- (l^- \nu_l) j$ (same-sign leptons+jet+MET)
	Hadronic ( $W^- \rightarrow 2j$ )	$l^- (jj) j$ (single lepton+3 jets)

FIGURE 8: Invariant mass distribution of  $eejj$  system for  $I_W = 1$  after the discovery cuts.

its mass for three different values of  $\Lambda$ . Under the considerations  $\Lambda = M_L$  and  $m_W \ll M_L$ , Equation (5) suggests that doubly charged lepton decay width increases linearly with mass for a specific value of  $f$ .

### 3. Doubly Charged Lepton Production at Future $ep$ Colliders

Doubly charged leptons can be produced singly via the process  $e^- p \rightarrow L^{--} X$ . Feynman diagrams for the subprocesses  $e^- q(\bar{q}') \rightarrow L^{--} q'(\bar{q})$  are shown in Figure 2.

Neglecting SM lepton and quark masses, we find that the analytical expression of differential cross section for taking

into account  $I_W = 1$  for the subprocess  $e^- q \rightarrow L^{--} q'$  is

$$\frac{d\hat{\sigma}}{dt} (eq \rightarrow L^{--} q') = \frac{f_1^2 g^4 \left( (s - M_L^2)(M_L^2 - s - t) t |V_{qq'}|^2 \right)}{32\Lambda^2 \pi s^2 (m_W^2 - t)^2} \quad (6)$$

and for the subprocess  $e^- \bar{q}' \rightarrow L^{--} \bar{q}$  is

$$\frac{d\hat{\sigma}}{dt} (e\bar{q}' \rightarrow L^{--} \bar{q}) = \frac{-f_1^2 g^4 \left( (s + t) t |V_{qq'}|^2 \right)}{32\Lambda^2 \pi s (m_W^2 - t)^2}. \quad (7)$$



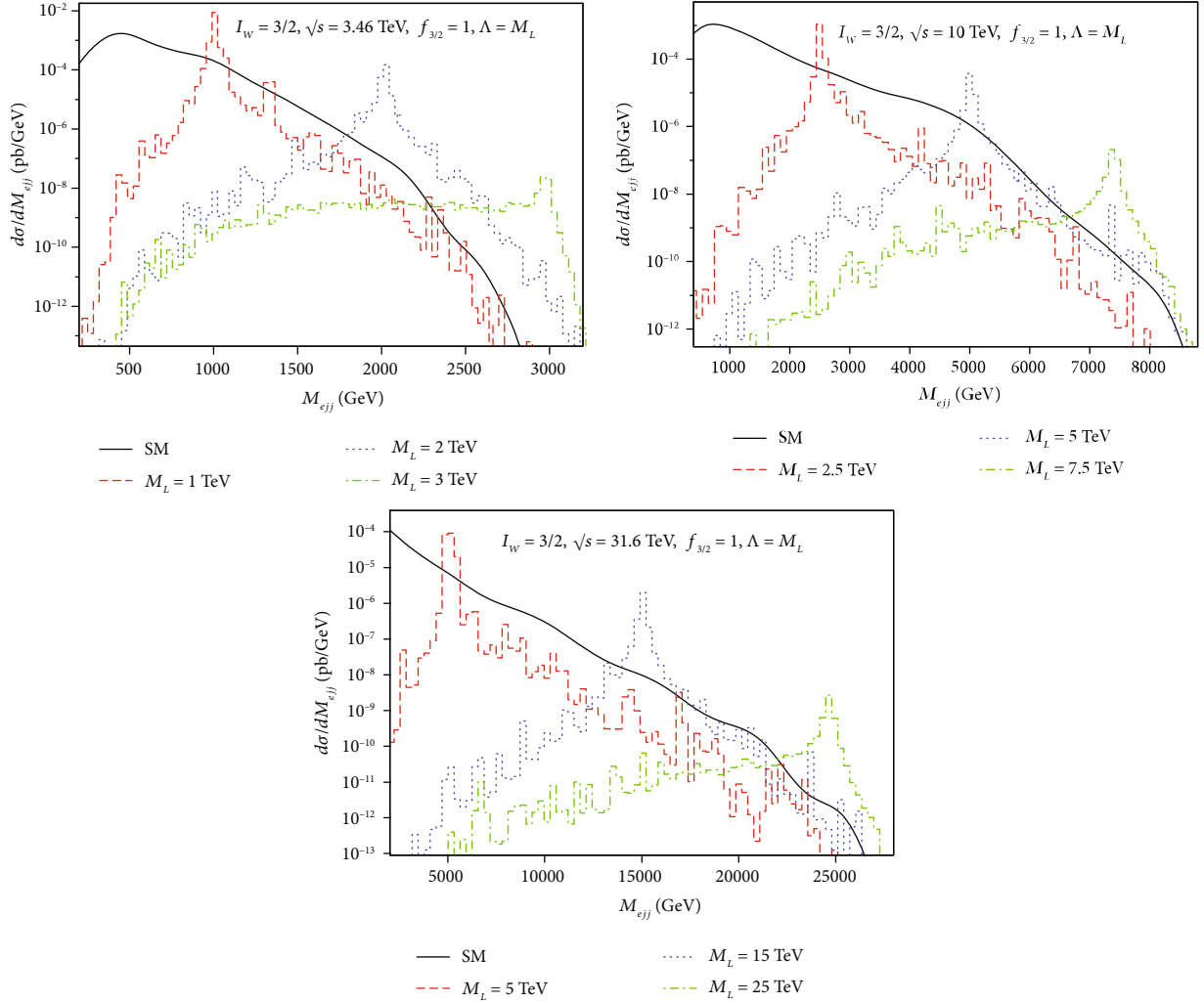


FIGURE 9: Invariant mass distribution of  $ejj$  system for  $I_W = 3/2$  after the discovery cuts.

Changing  $f_1 \rightarrow f_{3/2}$ , Equation (6) is valid for  $e^- \bar{q}' \rightarrow L^- \bar{q}$  and Equation (7) is valid for  $e^- q \rightarrow L^- q'$  for  $I_W = 3/2$ . We inserted doubly charged lepton interaction vertices given in Equation (4) into the well-known high-energy physics simulation programme CalcHEP [90–92] and used it for our calculations.

Total production cross section for the process  $e^- p \rightarrow L^- X$  both for  $I_W = 1$  and  $I_W = 3/2$  as a function of doubly charged lepton mass is shown in Figure 3 for taking into account  $\Lambda = M_L$  (a) and  $\Lambda = 100$  TeV (b). We use the CTEQ6L parton distribution function [93]. As seen from Figure 3, total cross sections for the doubly charged leptons for  $I_W = 3/2$  are slightly larger than the ones for  $I_W = 1$ . This result is due to the contribution of valence quarks in the initial state when  $L^-$  is being produced.

Taking into account the decay of  $L^-$ , we consider the kinematical distributions for the process  $e^- q(\bar{q}') \rightarrow e^- W^- q'(\bar{q})$ . Respecting lepton number conservation, we only deal with the doubly charged leptons related to the first generation.

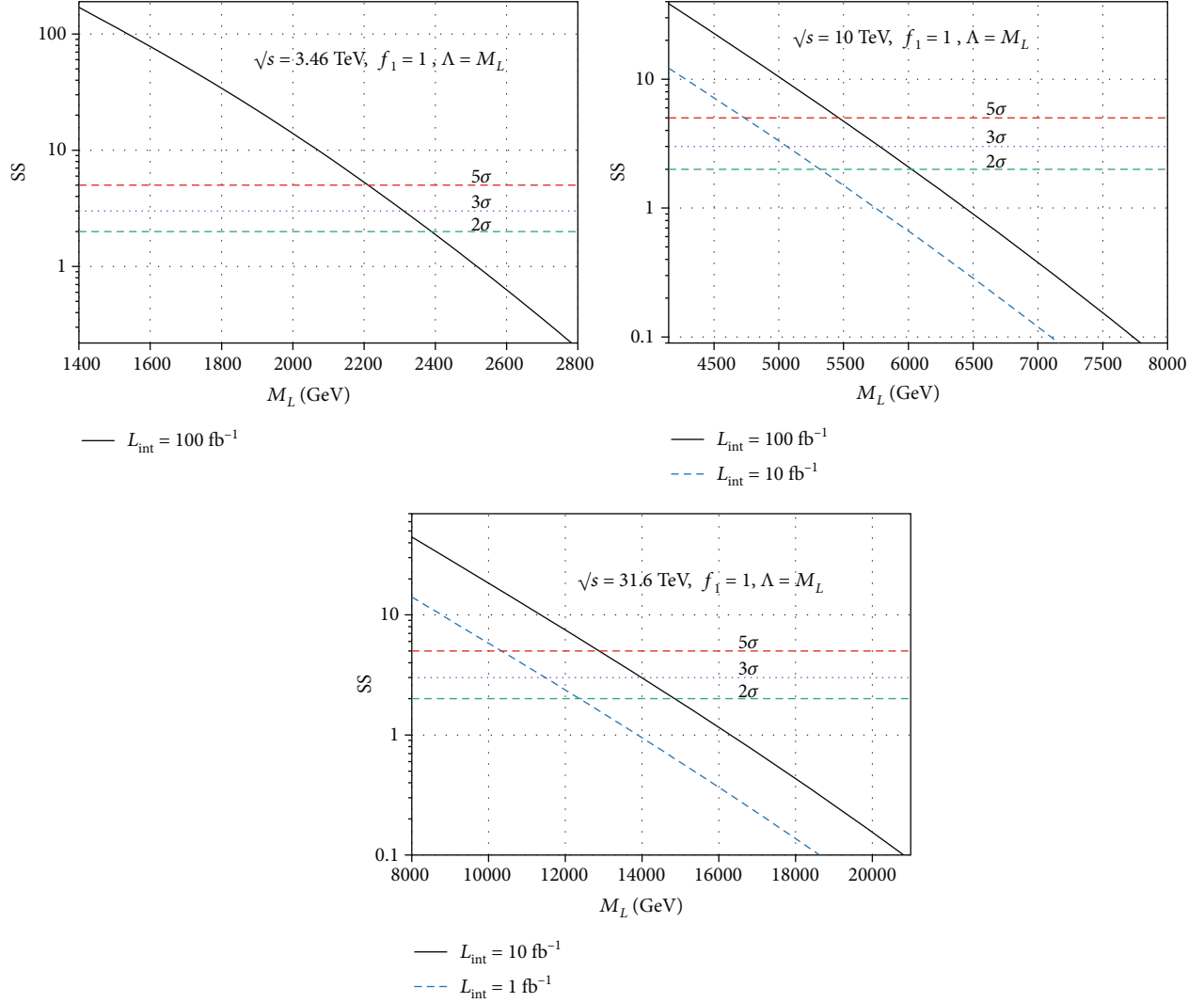
Since design studies are ongoing for an appropriate detector for the  $ep$  colliders considered in this work, our analysis is at the parton level.

We impose the basic cuts for the final-state electron and quarks as

$$\begin{aligned} p_T^e &> 20 \text{ GeV}, \\ p_T^j &> 30 \text{ GeV}. \end{aligned} \quad (8)$$

After applying basic cuts, SM cross sections are  $\sigma_B = 4.04$  pb,  $\sigma_B = 17.52$  pb, and  $\sigma_B = 67.99$  pb for  $\sqrt{s} = 3.46, 10$ , and  $31.6$  TeV, respectively. To reveal a clear signal, it is very important to determine the most appropriate cuts. After applying the basic cuts, we plot the normalized transverse momentum (in Figures 4 and 5) and normalized pseudorapidity (in Figures 6 and 7) distributions of final-state electron originated by the  $L^-$ . These distributions exhibit the same characteristic for  $I_W = 1$  and  $I_W = 3/2$ .



FIGURE 10:  $SS - M_L$  graphics for  $I_W = 1$  multiplet.

From the normalized  $p_T$  distributions, it is inferred that doubly charged leptons have high transverse momentum which shows a peak around  $M_L/2$  in their distributions. From the normalized  $\eta$  distributions of electron, it is seen that the electrons are in a backward direction; consequently,  $L^-$  is produced in the backward direction. As the center-of-mass energy of the collider increases, normalized  $\eta$  distributions become more symmetric.

Examining normalized  $p_T$  and  $\eta$  distributions, we extract the discovery cuts for the final-state electron. We choose the suitable regions where we eliminate most of the background while not losing most of the signal. Our results are summarized in Table 2.

To distinguish the signal and the background, we also imply an invariant mass cut on  $e^- W^-$  system for the mass intervals (we have selected the events within the mass intervals).

$$M_L - 2\Gamma_L < M_{eW} < M_L + 2\Gamma_L, \quad (9)$$

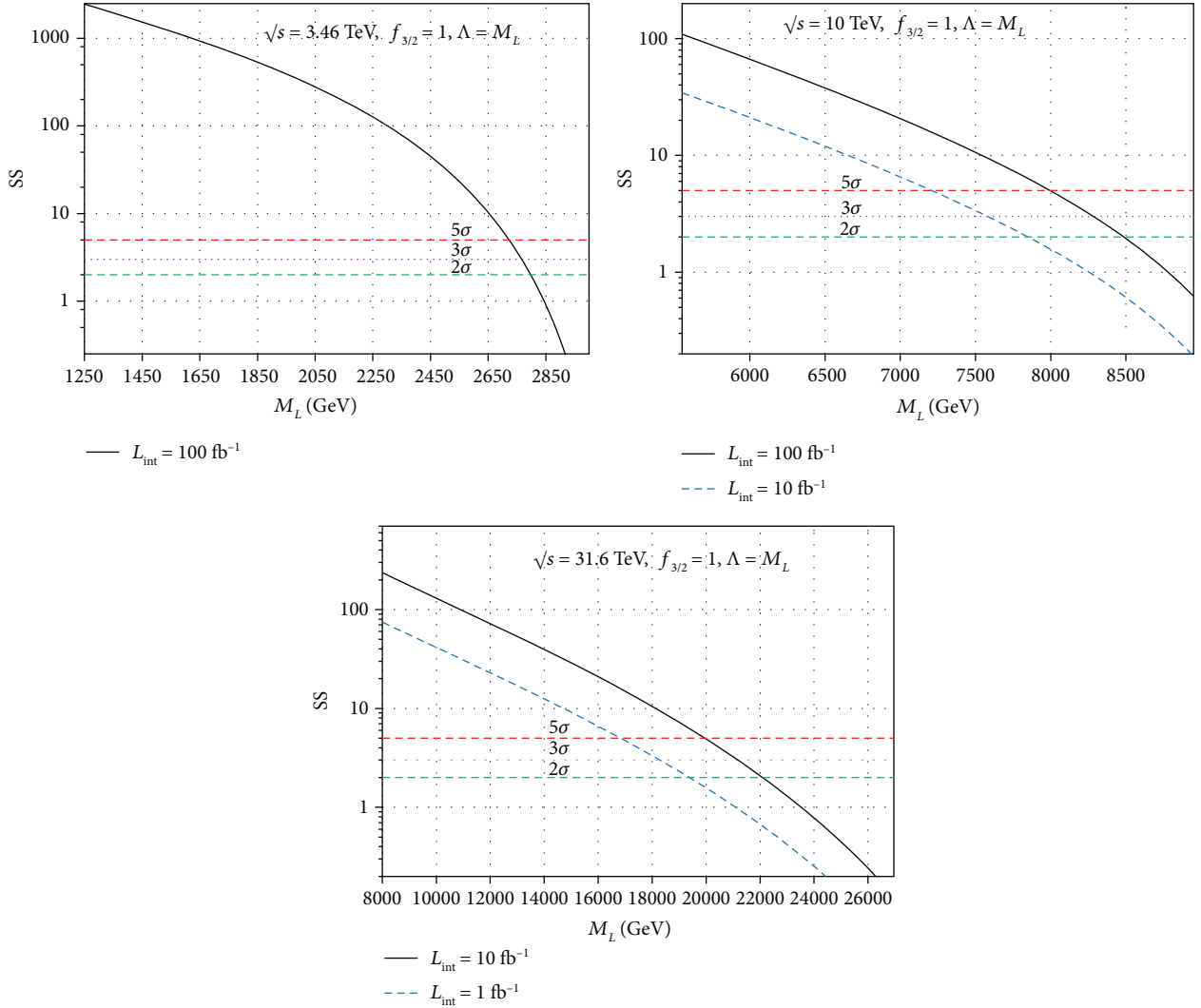
where  $\Gamma_L$  is the decay width of the doubly charged lepton for a given value of  $M_L$ . By carrying out the invariant mass cut, the background cross sections are rather suppressed.

The final-state signatures obtained from the decays of doubly charged lepton and  $W$  boson are given in Table 3. We choose hadronic decay mode of  $W$  boson,  $W \rightarrow jj$ .

After implying discovery cuts presented for the final-state electron in Table 2, we plot the invariant mass distribution of  $e^- jj$  system in Figures 8 and 9 for  $I_W = 1$  and  $I_W = 3/2$ , respectively.

As expected, these distributions show a peak around the chosen mass value of  $L^-$ . Since we try to specify doubly charged lepton signal from its decay products, we do not impose any further cuts on jets. We define the discovery sensitivity as

$$SS = \frac{|\sigma_{S+B} - \sigma_B|}{\sqrt{\sigma_B}} \sqrt{L_{\text{int}}}. \quad (10)$$

FIGURE 11:  $SS - M_L$  graphics for  $I_W = 3/2$  multiplet.TABLE 4: Mass limits for the doubly charged leptons for the FCC-based  $ep$  colliders taking into account  $I_W = 1$  ( $I_W = 3/2$ ).

Collider	$\sqrt{s}$ (TeV)	$L_{\text{int}}$ ( $\text{fb}^{-1}$ per year)	$2\sigma$ (TeV)	$3\sigma$ (TeV)	$5\sigma$ (TeV)
ERL60 $\otimes$ FCC	3.46	100	2.38 (2.80)	2.30 (2.77)	2.21 (2.73)
		10	5.33 (7.20)	5.08 (7.56)	4.74 (7.85)
ILC $\otimes$ FCC	10	100	6.02 (7.99)	5.77 (8.28)	5.46 (8.47)
		1	12.4 (19.4)	11.5 (18.3)	10.3 (16.8)
PWFA-LC $\otimes$ FCC	31.6	1	14.9 (22.1)	13.9 (21.2)	12.9 (20.0)

Here,  $\sigma_{S+B}$  is the cross section due to the presence of doubly charged lepton,  $\sigma_B$  is the SM background cross section, and  $L_{\text{int}}$  is the integrated luminosity of the collider. In Figures 10 and 11, we plot the  $SS - M_L$  to determine the  $2\sigma$  (exclusion),  $3\sigma$  (observation), and  $5\sigma$  (discovery) limits.

In Table 4, we give the doubly charged lepton mass limits at different FCC-based  $ep$  colliders for taking into account  $f_1 = f_{3/2} = 1$  and  $\Lambda = M_L$  concerning the criteria  $SS > 2$ ,  $SS >$

$3$ , and  $SS > 5$  which denote the exclusion, observation, and discovery mass limits, respectively.

#### 4. Conclusion

A distinct and exclusive point of view of the compositeness is weak isospin invariance. It enables us to extend the weak isospin values to  $I_W = 1$  (triplet) and  $I_W = 3/2$  (quadruplet) multiplets. Doubly charged leptons that have an electrical

charge of  $Q = -2e$  appear in these exotic multiplets. To find a clue about such new particles at future high-energy and high-luminosity colliders that would indicate the internal structure of the known fermions, we have presented a phenomenological cut-based study for probing the doubly charged leptons coming from extended weak isospin multiplets at various FCC-based  $ep$  colliders. Taking into consideration the lepton flavor conservation, we have dealt with the decay of  $L^{--}$  as  $L^{--} \rightarrow e^- W^-$  and  $W$  boson as  $W \rightarrow j$  after the single production of doubly charged lepton at  $ep$  colliders. We have provided the  $2\sigma$ ,  $3\sigma$ , and  $5\sigma$  statistical significance (SS) exclusion curves in the  $SS - M_L$  parameter space. Taking into account the criteria  $SS > 5$  that corresponds to discovery, we have obtained the mass limits for doubly charged lepton for the exotic multiplet  $I_W = 1$  ( $I_W = 3/2$ ), 2.21 (2.73) TeV, 5.46 (8.47) TeV, and 12.9 (20.0) TeV at  $\sqrt{s} = 3.46$  TeV,  $\sqrt{s} = 10$  TeV, and  $\sqrt{s} = 31.6$  TeV, respectively. Our study has showed that FCC-based  $ep$  colliders have quite well potential to attain the signals of doubly charged leptons considered in extended weak isospin models.

## Data Availability

No data were used to support this study.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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