Commun.Fac.Sci.Univ.Ank.Series A2-A3
Volume 61, Number 1, Pages 111-128 (2019)
DOI: 10.33769/aupse.560812
ISSN 1303-6009 E-ISSN 2618-6462
http://communications.science.ankara.edu.tr/index.php?series=A2A3

# INVESTIGATING DOUBLY CHARGED LEPTONS AT FUTURE ENERGY FRONTIER MUON-PROTON COLLIDERS

Aysuhan OZANSOY

ABSTRACT. We study the doubly charged leptons considered in extended isospin models at muon-proton colliders. We respect the lepton flavor conservation and take into consideration the single production of the doubly charged leptons related to second generation. We give the effective Lagrangian describing the doubly charged lepton gauge interactions. We calculate the signal and corresponding background cross sections and analyze the kinematical distributions to obtain the suitable cuts for the discovery. We choose the $W$-boson hadronic decay channel to get the accessible mass limits and couplings of doubly charged leptons for various muon-proton colliders.

## 1. INTRODUCTION

The fundamental particle spectrum of the Standard Model (SM) has a pattern with three generations of quarks and leptons. These generations are replication of each other except from their mass. A natural explanation for the SM fermionic family replication would be that there could be one more layer of matter constituents. In composite models, known fermions are bound states of more fundamental constituents called preons [1-3]. Compositeness is one of the beyond the SM (BSM) theories that give satisfying explanations for the fermionic family replication, quark-lepton symmetry and fundamental particle inflation in the SM. Observation of excited fermionic states would be a direct evidence of compositeness [4-8]. Spin and isospin-1/2 excited fermions are considered as lowest radial and orbital excited

Received by the editors: May 06, 2019; Accepted: May 31, 2019.
*Key word and phrases:* Doubly charged leptons, muon-proton colliders, weak isospin.

states. Excited leptons with weak isospin states $I_W$=0 (singlet) and $I_W$=1/2 (doublet) are studied widely in the literature [9- 25].

Here, we take into consideration a different point of view of the compositeness: the weak isospin ($I_W$) invariance. In extended isospin models the weak isospin values are extended to $I_W$=1 (triplet) and $I_W$=3/2 (quadruplet) multiplets. Excited leptonic states with exotic charges with $Q$ = -2$e$ (doubly charged leptons) take part in these exotic multiplets [26]. Any signal for the doubly charged leptons at future colliders would give considerable explanation for the SM flavor structure and hints for the new physics.

There are great effort to build more powerful particle colliders for the Large Hadron Collider (LHC) era and post LHC era. These projects can be classified in three groups concerning the colliding particle types:

*1) Lepton colliders:* International Linear Collider (ILC) with $\sqrt{s} = 0.5-1$ TeV [27] and Compact Linear Collider (CLIC) with up to $\sqrt{s} = 3$ TeV [28] as $e^+e^-$ colliders, and muon colliders with center-of-mass energies from Higgs resonance up to $\sqrt{s} = 6$ TeV [29, 30]. Recently, a 100 TeV muon collider was proposed in [31].

*2) Hadron colliders:* Future Circular Collider (FCC) is proposed as *pp* collider with $\sqrt{s} = 100$ TeV [32] at CERN. (Besides the *pp* option, FCC has also an $e^+e^-$ option known as TLEP or FCC-*ee* [33] and several *ep* collider options [34]). Super proton-proton Collider (SppC) is Chinese analog of the FCC with center-of-mass energy about 70 TeV [35].

*3) Lepton-hadron colliders:* Large Hadron-electron Collider (LHeC) with $\sqrt{s} = 1.3$ TeV and possibly upgraded to $\sqrt{s} = 1.96$ TeV [36, 37] is proposed as *ep* collider at CERN. Other designments are FCC-based lepton-hadron (*ep* and $\mu p$ colliders) [34], SppC-based lepton-hadron colliders [38], and LHC-based muon-proton colliders [39].

Aside from compositeness, one may encounter doubly charged leptonic states in Type II seesaw mechanisms [40-42], in some extensions of supersymmetric models [43-47], in flavor models in warped extra dimensions and in more general models [48-49], and also in string inspired models [50]. In the literature, phenomenological searches for doubly charged leptons are investigated so far at the LHC [51-60], at the future linear colliders [61-64], at the LHeC [65], and at the FCC-based *ep* colliders [66].

In this work, we give the effective Lagrangians responsible for the gauge interactions of doubly charged leptons and calculate the decay widths in Section 2. In Section 3, we introduce the various muon-proton colliders. We give our analysis in Section 4 and then we conclude.

## 2. Effective lagrangians and decay widths

In the beginning of hadron physics, strong isospin invariance enlightened so much to find out some patterns of baryon and meson resonances despite the existence of quarks and gluons were not understood yet. Identically, similar situations may be occured in the electroweak sector. By using the weak isospin symmetry arguments, the possible fermionic resonances can be placed into electroweak isospin multiplets. Accordingly, the quantum numbers of excited fermionic states could be obtained without needing the dynamics of the preons explicitly. Since light fermions have $I_W = 0$ or $1/2$ (singlets or doublets), and gauge bosons have $I_W = 0$ or $1$; excited fermionic states with $I_W \leq 3/2$ can be allowed. Basics of extended isospin model is discussed in [26]. In the extended isospin models exotic doubly charged leptons appear in triplets with $I_W=1$ and in quadruplets with $I_W=3/2$. The form of these multiplets are listed as

$$L_1 = \begin{pmatrix} L^0 \\ L^- \\ L^{--} \end{pmatrix}, \qquad L_{3/2} = \begin{pmatrix} L^+ \\ L^0 \\ L^- \\ L^{--} \end{pmatrix} \tag{1}$$

and similar for the antiparticles. To calculate the decay widths and cross sections, it is necessary to specify the doubly charged lepton couplings to SM leptons and gauge fields. For the reason that all the gauge fields have *Y*=0 hypercharge, a given exotic multiplet couples through the gauge fields to a SM multiplet only with the same *Y*. To satisfy the gauge invariance, the couplings have to be of anomalous magnetic moment type. Therefore, doubly charged leptons can couple to SM fermions only via *W*-boson. The interaction Lagrangians describing the gauge interaction of doubly charged leptons with ordinary leptons are

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

$$\mathcal{L}_{GM}^{(3/2)} = i\frac{gf_3}{\Lambda}\left(\bar{L}\sigma_{\mu\nu}\partial^{\nu}W^{\mu}\frac{1-\gamma_5}{2}l\right) + h.c. \quad (3)$$

where where $g$ is the $SU(2)$ coupling constant which is equals to $g = g_e/\sin\theta_W$ where $g_e = \sqrt{4\pi\alpha}$ . $f_1$ and $f_3$ are dimensionless new coupling constants related to effective interactions of exotic multiplets $I_W$=1 and $I_W$=3/2. Their exact values can only be obtained from the underlying model for compositeness. $L$ and $l$ stand for doubly charged lepton and SM lepton, respectively. Λ is the compositeness scale and $\sigma_{\mu\nu} = i\left(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu\right)/2$ where $\gamma_\mu$ being the Dirac matrices.

Since doubly charged leptons can interact with the SM leptons only via the *W*-boson, doubly charged leptons decay to SM leptons only with $L^{--} \to l^- W^-$ process ($L^{--}$ is the lightest one among the new exotic leptons). The same values of decay width for the doubly charged leptons are obtained whether one can use the interaction Lagrangian given in Eq. (3) or Eq. (4). The decay width of the doubly charged lepton with respect to its mass ($M_L$) for $f_1$=1 (or $f_3$=1 ) is given in Figure 1 for two different values of compositeness scale.

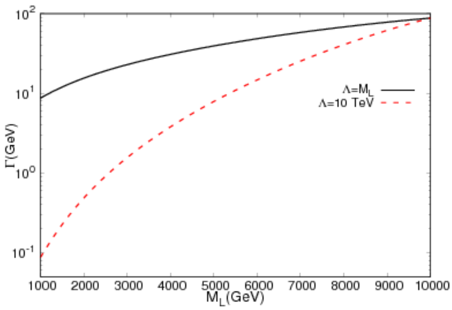


FIGURE 1. Total decay width of doubly charged lepton as a function of its mass for Λ=$M_L$ and Λ=10 TeV.

## 3. Muon-proton colliders

Muon-proton colliders were proposed in the original work [67] by making the suggestion of construction of an additional proton ring in √s=4 TeV muon collider tunnel. Afterwards, construction of additional muon ring with 200 GeV energy in the Tevatron tunnel in order to handle √s=0.9 TeV *μp* collider was considered in [68], and ultimate *μp* collider with 50 TeV proton ring was suggested in [69]. Recently, future *pp* colliders FCC and SppC based energy frontier muon-proton colliders were proposed in [34] and [38], respectively. Also LHC-based *μp* colliders were considered in [39]. We list briefly the main parameters of proposed *μp* colliders in Tables 1 – 3.

A lot of BSM topics such as excited muon, excited muon neutrino, second family leptoquarks, supersymmetry (SUSY), doubly charged leptons related to second family, color octet muon, contact interactions etc. can be investigated at *μp* colliders.

**Table 1.** Main parameters of LHC-based *μp* colliders. (*These values are obtained from* [39]).

| $E_\mu$ (TeV) | $E_p$ (TeV) | √s (TeV) | $L_{\mu p}$ ($cm^{-2}s^{-1}$) |
|---|---|---|---|
| 0.75 | 7 | 4.58 | $1.4\times10^{33}$ |
| 1.5 | 7 | 6.48 | $2.3\times10^{33}$ |
| 3 | 7 | 9.16 | $0.9\times10^{33}$ |

**Table 2.** Main parameters of SppC-based *μp* colliders. (*These values are obtained from* [38]).

| $E_\mu$ (TeV) | $E_p$ (TeV) | √s (TeV) | $L_{\mu p}$ ($cm^{-2}s^{-1}$) |
|---|---|---|---|
| 0.75 | 35.6 | 10.33 | $5.5\times10^{32}$ |
| 0.75 | 68 | 14.28 | $12.5\times10^{32}$ |
| 1.5 | 35.6 | 14.61 | $4.9\times10^{32}$ |
| 1.5 | 68 | 20.2 | $42.8\times10^{32}$ |

**Table 3.** Main parameters of FCC-based *μp* colliders. (*These values are obtained from* [34]).

| $E_\mu$ (TeV) | $E_p$ (TeV) | √s (TeV) | $L_{\mu p}$ ($cm^{-2}s^{-1}$) |
|---|---|---|---|
| 0.063 | 50 | 3.50 | $0.2\times10^{31}$ |

| | | | |
|---|---|---|---|
| 0.75 | 50 | 12.2 | $4.9\times10^{32}$ |
| 1.5 | 50 | 17.3 | $4.3\times10^{32}$ |

## 4. Cross sections

Respecting the lepton family number conservation, we searched for the doubly charged leptons which carry muonic lepton number. They can be produced singly through the process $\mu^- p \to L^{--} X$ at $\mu p$ colliders. The Feynman diagrams representing the subprocess $\mu^- q(\bar{q}^{'}) \to L^{--} q^{'}(\bar{q})$ are given in Figure 2.


FIGURE 2. Feynman diagrams for the subprocess $\mu^- q(\bar{q}^{'}) \to L^{--} q^{'}(\bar{q})$ .

In our analysis, we considered only $I_W$=1 multiplet. We embedded the doubly charged lepton interaction vertices in high-energy simulation programme CALCHEP [70-72] and used it for our calculations. To make a comparison between the $\mu p$ colliders listed in Table 1-3; we chose the muon beam energy as 0.75 TeV and proton beam energies 7, 35.6, and 50 TeV for the LHC, SppC, and FCC, respectively. We summarized our selection in Table 4.

**Table 4.** Selected $\mu p$ colliders to make a comparision in our calculations.

| **$\mu p$ Collider Name** | **$E_p$ (TeV)** | **$E_\mu$ (TeV)** | **√s (TeV)** |
|---|---|---|---|
| LHC-$\mu p$ | 7 | 0.75 | 4.58 |
| SppC-$\mu p$ | 35.6 | 0.75 | 10.33 |
| FCC-$\mu p$ | 50 | 0.75 | 12.2 |

Total production cross section for the single production of doubly charged leptons ($\mu^- p \to L^{--} X$) at various $\mu p$ colliders for $\Lambda$=$M_L$ and $f$ =1 is shown in Figure 3. (Since we take into consideration only $I_W$=1 multiplet, $f$ is refer to $f_1$ henceforth). In numerical calculations we used the CTEQ6L [73] parton distribution function.

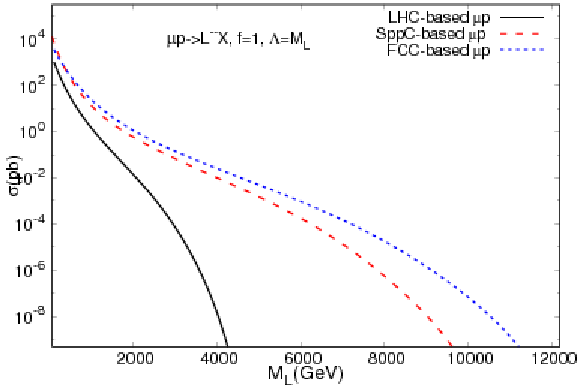


FIGURE 3. Total cross section for the single production of doubly charged leptons at various $\mu p$ colliders.

After the decay of $L^{--}$, we deal with the $\mu^- q(\bar{q}^{'}) \rightarrow W^- \mu^- q^{'}(\bar{q})$ process. We impose the generic cuts for the final state muon and jets as

$$\begin{aligned} p_T^{\mu} &> 20\ GeV \\ p_T^{j} &> 30\ GeV. \end{aligned} \tag{4}$$

By applying the generic cuts we get the transverse momentum ($p_T$) and normalized pseudorapidity ($\eta$) distributions of final state muon. We show these kinematical distributions in Figures 4-9.

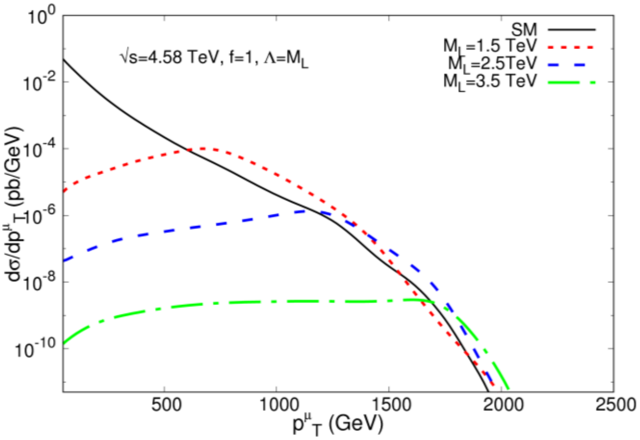


FIGURE 4. Muon $p_T$ distribution for the LHC-$\mu p$.

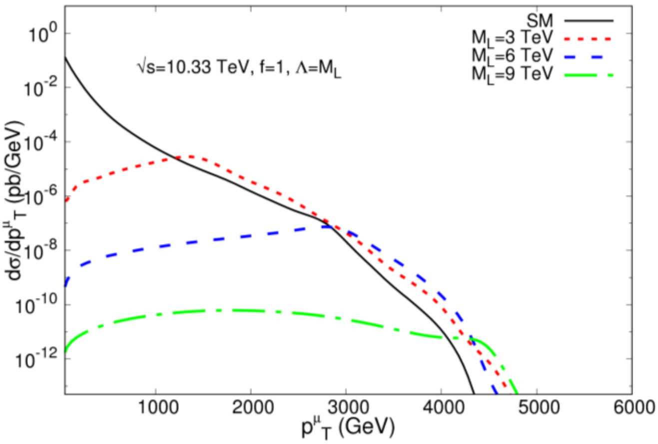


FIGURE 5. Muon $p_T$ distribution for the SppC-$\mu p$.

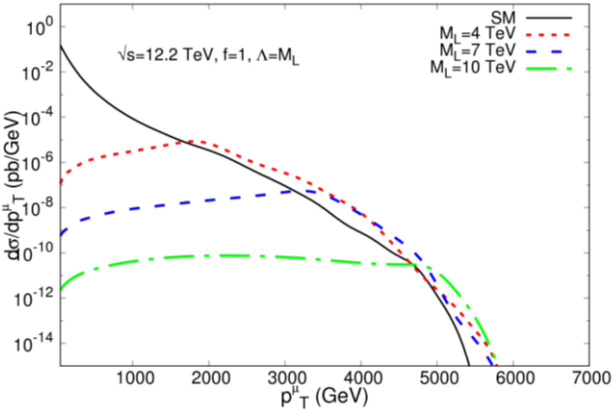


FIGURE 6. Muon $p_T$ distribution for the FCC-$\mu p$.

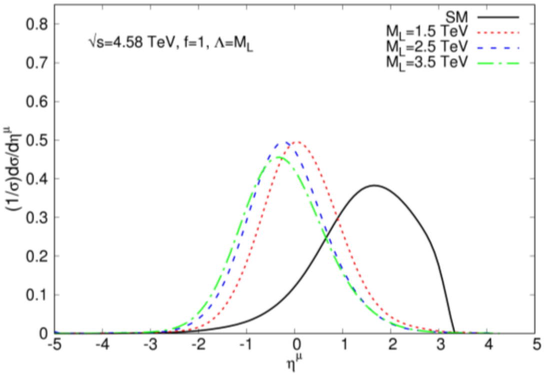


FIGURE 7. Muon normalized $\eta$ distribution for the LHC-$\mu p$.

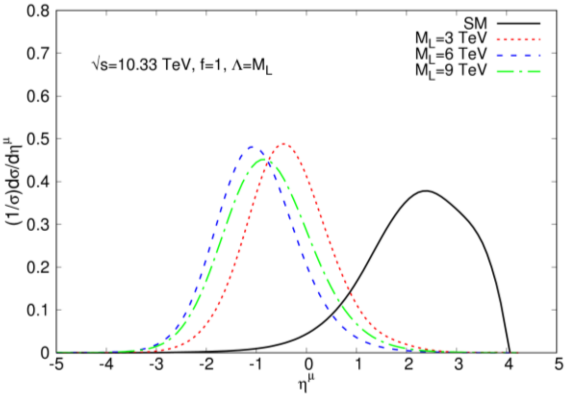


FIGURE 8. Muon normalized $\eta$ distribution for the SppC-$\mu p$.

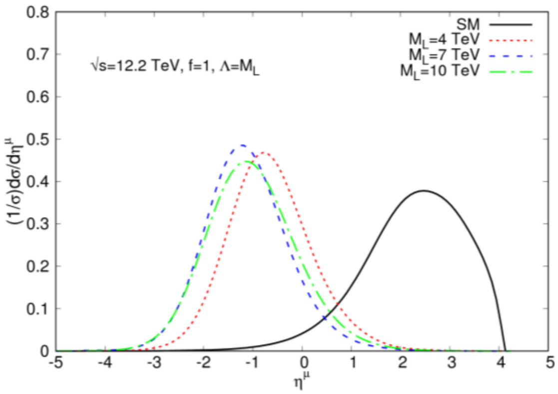


FIGURE 9. Muon normalized $\eta$ distribution for the FCC-$\mu p$.

As it can be seen from Figures 4-6, doubly charged leptons carry high transverse momentum having a peak around $M_L$ / 2, and from Figures 7-9, they are produced mainly in the backward direction. We define the cuts best suited for the discovery by investigating these kinematical distributions. To find out the discovery cuts we seek for the appropriate regions where we remove the most of the background but at the same time do not influence the signal so much. These cuts are presented in Table 5.

**Table 5.** Discovery cuts for the doubly charged lepton production at $\mu p$ colliders.

| $\mu p$ **Collider Name** | $p_T^\mu$ ***cut*** | $\eta^\mu$ **cut** |
|---|---|---|
| LHC-$\mu p$ | $p_T^\mu > 600$ GeV | $-2 < \eta^\mu < 1$ |
| SppC-$\mu p$ | $p_T^\mu > 1200$ GeV | $-2.5 < \eta^\mu < 0.9$ |
| FCC-$\mu p$ | $p_T^\mu > 1700$ GeV | $-2.5 < \eta^\mu < 0.6$ |

We choose hadronic decay mode of $W$-boson as $W \to 2j$ and no further cut is made on these jets. We define the statistical significance as

$$SS = \frac{\sigma_S}{\sqrt{\sigma_B}}\sqrt{L_{\text{int}}} \tag{5}$$

where $\sigma_S$ and $\sigma_B$ are the signal and background cross sections, respectively; $L_{int}$ is the integrated luminosity of the collider.

We show the $SS$ - $M_L$ plot for the LHC-based $\mu p$ collider in Figure 10, for the SppC-based $\mu p$ collider in Figure 11, and for the FCC-based $\mu p$ collider in Figure 12, specifying the $2\sigma$ (exclusion), $3\sigma$ (observation), and $5\sigma$ (discovery) regions, respectively. In Table 6, we determine the doubly charged lepton mass limits at different $\mu p$ colliders for $f$=1 and $\Lambda$=$M_L$, taking into account the criteria $SS \geq 2$, $SS \geq 3$ and $SS \geq 5$ which denote the $2\sigma$, $3\sigma$ and $5\sigma$ limits, respectively.

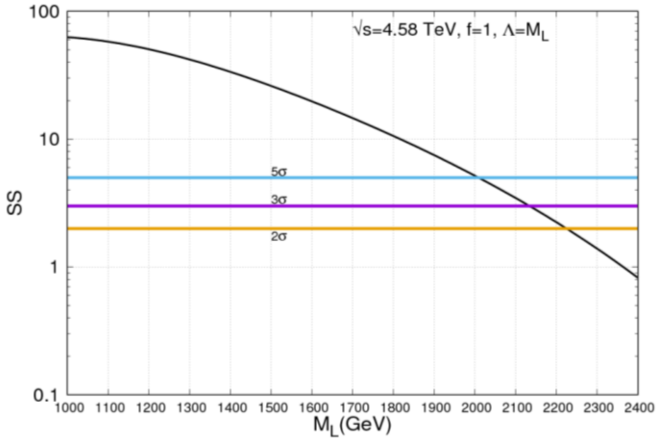


FIGURE 10. *SS* as a function of $M_L$ for the LHC-$\mu p$.

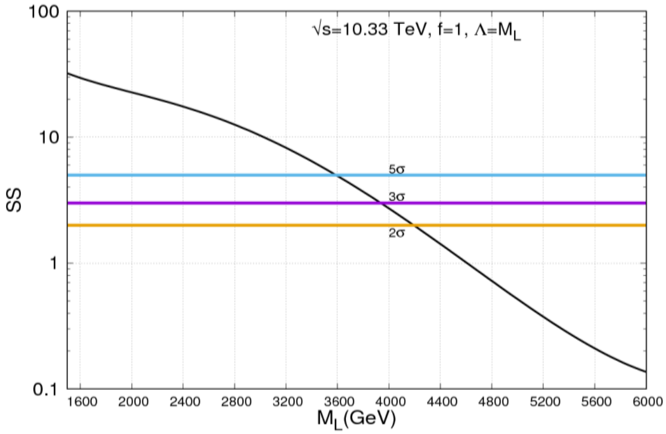


FIGURE 11. *SS* as a function of $M_L$ for the SppC-$\mu p$.

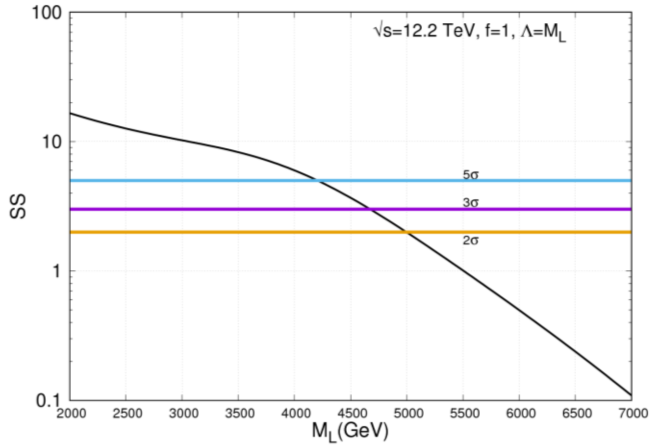


FIGURE 12. *SS* as a function of $M_L$ for the FCC-$\mu p$.

**Table 6.** Mass limits for doubly charged lepton at different $\mu p$ colliders.

| **Collider name** | **$L_{int}$ ($pb^{-1}$)** | **2σ (Exclusion)(GeV)** | **3σ (Observation)(GeV)** | **5σ (Discovery) (GeV)** |
|---|---|---|---|---|
| **LHC-μp (√s = 4.58 TeV)** | $1.4 \times 10^4$ | 2220 | 2140 | 2000 |
| **SppC-μp (√s = 10.33 TeV)** | $5.5 \times 10^3$ | 4200 | 3900 | 3600 |
| **FCC-μp (√s = 12.2 TeV)** | $4.9 \times 10^3$ | 5000 | 4700 | 4200 |

## 5. CONCLUSION

The weak isospin invariance is a particular point of view of the compositeness. We can use the weak isospin invariance to extend the weak isospin values to $I_W$ =1 (triplet) and $I_W$ =3/2 (quadruplet) multiplets. These multiplets contain exotic lepton states of charge *Q* = -2*e*, namely doubly charged leptons. $\mu p$ colliders will give the oppurtunity to search for the doubly charged leptons related to second family. In our study, we make a comparison for the search potential of doubly charged leptons at future energy frontier muon-proton colliders. Taking into account the lepton flavor conservation, we showed doubly charged leptons carrying muonic lepton number can be observed up to 2.1, 3.9, and 4.7 TeV at LHC-$\mu p$, SppC-$\mu p$ and FCC-$\mu p$, respectively.

## References


[1] Terazawa H., Chikashige Y., and Akama K., Unified Model of the Nambu-Jona-Lasino Type for all Elementary Particle Forces, Phys. Rev. D 15-2 (1977) 480-487.

[2] Ne'eman Y., Primitive Particle Model, Phys. Lett. 82B-1 (1979) 69-70.

[3] Terazawa H., Yasue M., Akama K., and Hayashi M., Observable Effects of the Possible Sub-structure of Leptons and Quarks, Phys. Lett. 112B 4-5 (1982) 387-392.

[4] Renard F. M., Excited Quarks and New Hadronic States, Il Nuovo Cimento A 77-1 (1983) 1-20.

[5] Eichten E. J., Lane K. D., and Peskin M. E., New Tests for Quark and Lepton Substructure, Phys. Rev. Lett. 50-11 (1983) 811-814.

[6] de Rujula A., Maiani L., and Petronzio R., Search for Excited Quarks, Phys. Lett. 140B 3-4 (1984) 253-258.

[7] Cabibbo N., Maiani L., and Srivastava Y. N., Anomalous Z Decays: Excited Leptons?, Phys. Lett. 139B 5-6 (1984) 459-463.

[8] Kühn J. and Zerwas P. M., Excited Quarks and Leptons, Phys. Lett. 147B 1-3 (1984) 189-196.

[9] Hagiwara K., Komamiya S., and Zeppenfeld D., Excited Lepton Production at LEP and HERA, Z. für Physik C 29-1 (1985) 115-122.

[10] Boudjema F., Djouadi A., and Kneur J. L., Excited Fermions at $e^+e^-$ and eP Colliders, Z. für Physik C 57-3 (1993) 425-449.

[11] Cakir O., Yilmaz A., and Sultansoy S., Single Production of Excited Electrons at Future $e^+e^-$, ep and pp Colliders, Phys. Rev. D 70-7 (2004) 075011.

[12] Cakir O., Turk Cakir I., and Kirca Z., Single Production of Excited Neutrinos at Future $e^+e^-$, ep and pp Colliders Phys. Rev. D 70-7 (2004) 075017.

[13] Caliskan A., Kara S. O., and Ozansoy A., Excited Muon Searches at the FCC-Based Muon-Hadron Colliders, Adv. High Energy Phys. 2017 (2017) 1540243.

[14] Caliskan A., Excited Neutrino Search Potential of the FCC-Based Electron-Hadron Colliders, Adv. High Energy Phys. 2017 (2017) 4726050.

[15] Caliskan A. and Kara S. O., Single Production of the Excited Electrons at the Future FCC-Based Lepton-Hadron Colliders, Int. J. Mod. Phys. A 33-24 (2018) 1850141.

[16] Ginzburg I. F. and Ivanov D. Yu., Excited Leptons and Quarks at $\gamma\gamma$ / $\gamma e$ Colliders, Phys. Lett. B276 1-2 (1992) 214-218.

[17] Koksal M., Analysis of Excited Neutrinos at the CLIC, Int. J. Mod. Phys. A 29-24 (2014) 1450138.

[18] Ozansoy A. and Billur A. A., Search for Excited Electrons Through γγ Scattering, Phys. Rev. D 86-5 (2012) 055008.
[19] Kirca Z., Cakir O., and Aydin Z. Z., Production of Excited Electrons at TESLA and CLIC Based e gamma Colliders, Acta Phys. Polon. B 34-8 (2003) 4079.
[20] Eboli O. J., Lietti S. M., and Mathews P., Excited Leptons at the CERN Large Hadron Collider, Phys. Rev. D 65-7 (2002) 075003.
[21] Inan S. C., Exclusive Excited Leptons Search in Two Lepton Final States at the CERN LHC, Phys. Rev. D81-11 (2010) 115002.
[22] Cakir O., Leroy C., Mehdiyev R., and Belyaev A., Production and Decay of Excited Electrons at the LHC, Eur. Phys. J. C 32-2 (2004) s1-s17.
[23] Belyaev A., Leroy C., and Mehdiyev R., Production of Excited Neutrinos at the LHC, Eur. Phys. J. C 41-2 (2005) 1-10.
[24] Boos E., Volodgin A., Toback D., and Gaspard J., Prospects of Searching for Excited Leptons During Run II of the Fermilab Tevatron, Phys. Rev. D 66-1 (2002) 013011.
[25] Baur U., Spira M., and Zerwas P. M., Excited Quark and Lepton Production at Hadron Colliders, Phys. Rev. D 42-3 (1990) 815-824.
[26] Pancheri G. and Srivastava Y. N., Weak Isospin Spectroscopy of Excited Quarks and Leptons, Phys. Lett. 146B (1984) 87-94.
[27] Carwardine J. (Editorial Board Chair), The International Linear Collider Technical Design Report – Volume 3. II: Accelerator Baseline Design, (2013) https://arxiv.org/abs/1306.6328.
[28] Aicheler M., Burrows P., Draper M., Garvey T., Lebrun P., Peach K., Phinney N., Schmickler H., Schulte D., and Toge N. (editors), A Multi-TeV Linear Collider Based on CLIC Technology: CLIC Conceptual Design Report, CERN-2012-007, KEK Report JAI-2012-001, 2012-1, PSI-12-01, SLAC-R-985, CERN, Geneva, Switzerland, (2012) https://edms.cern.ch/ui/file/1234244/7/CERN-2012-007.pdf.
[29] Delahaye J-P., Ankenbrandt C., Bogacz A., Brice S., Bross A., Denisov D., Eichten E., Huber P., Kaplan D. M., Kirk H., Lipton R., Neuffer D., Palmer M. A., Palmer R., Ryne R., and Snopok P. (editors), Enabling Intensity and Energy Frontier Science with a Muon Accelerator Facility in the U.S. : A White Paper Submitted to the 2013 U.S. Community Summer Study of the Division of Particles and Fields of the American Society, FERMILAB-CONF-13-307-APC (2013), https://arxiv/org/abs/1308.0494
[30] Palmer R. B., Muon Colliders, Rev. Accel. Science and Technology 7 (2014) 137-159.
[31] Zimmermann F., LHC/FCC-Based Muon Colliders, 9th Int. Particle Accel. Conference, IPAC2018, doi:10.18429/JACow-IPAC2018-MOPMF065 (2018) 273-276.
[32] Future Circular Collider Study (FCC), https://fcc.web.cern.ch
[33] Bicer M. et al. (The TLEP Design Study Working Group), First Look at the Physics Case of TLEP, Journal of High Energy Physics 2014-1 (2014) 164.
[34] Acar Y. C., Akay A. N., Beser S., Canbay A. C., Karadeniz H., Kaya U., and Oner B.B., Future Circular Collider Based Lepton-Hadron and Photon-Hadron Colliders: Luminosity and Physics, Nuclear Inst. and Methods in Phys. Research A 871 (2017) 47-53.

[35] Su F., Gao J., Xiao M., Wang D., Wang Y-W., Bai S., Bian T-J., Method Study of Parameter Choice for a Circular Proton-Proton Collider Chin. Phys. C 40-1 (2016) 017001.

[36] Abelleira Fernandez J. L. et al. (LHeC Study Group), A Large Hadron Electron Collider at CERN, Journal of Phys. G 39 (2012) 075001.

[37] Bruening O. and Klein M., The Large Hadron Electron Collider, Mod. Phys. Lett. A 28 - 16 (2013) 1330011.

[38] Canbay A. C., Kaya U., Ketenoglu B., Oner B. B., and Sultansoy S., SppC Based Energy Frontier Lepton-Proton Colliders: Luminosity and Physics, Adv. in High Energy Phys. 2017 (2017) 4021493.

[39] Kaya U., Ketenoglu B., and Sultansoy S., The LHC Based μp Colliders, (2018) https://arxiv.org/abs/1807.09867.

[40] Chua C. K. and Law S. S. C., Phenomenological Constraints on Minimally Coupled Exotic Lepton Triplets, Phys. Rev D 83 (2011) 055010.

[41] Foot R., Lew H., He X. G., and Joshi G. C., Seesaw Neutrino Masses Induced by a Triplet of Leptons, Zür. Phys. C 44 (1989) 441-444.

[42] Kumericki K., Picek I., and Radovcic B., Exotic Seesaw-Motivated Heavy Leptons at the LHC, Phys. Rev. D 84 (2011) 093002.

[43] Demir D. A., Frank M., Huitu K., Kumar Rai S., and Turan I., Signals of Doubly-Charged Higgsinos at the CERN Large Hadron Collider, Phys. Rev. D 78 (2008) 035013.

[44] Franceschini M. and Mohapatra R., Radiatively Induced Type II Seesaw Models and Vectorlike 5/3 Charge Quarks, Phys. Rev. D 89-5 (2014) 055013.

[45] Dutta B., Mohapatra R. N., and Muller D. J., The Signature at the Tevatron for the Light Doubly Charged Higgsino of the Supersymmetric Left-Right Model, Phys. Rev. D 60 (1999) 095005.

[46] Chacko Z. and Mohapatra R. N., Supersymmetric Left-Right Model and Light Doubly Charged Higgs Bosons and Higgsinos, Phys. Rev. D 58 (1998) 015003.

[47] Frank M., Doubly Charged Higgsino Mediated Lepton Flavor Violating Decays, Phys. Rev. D 62 (2000) 053004.

[48] Cirelli M., Fornengo N., and Strumia A., Minimal Dark Matter, Nucl. Phys. B 753 (2006) 178-194.

[49] del Aguila F., de Blas J., and Perez-Victoria M., Effects of New Leptons in Electroweak Precision Data, Phys. Rev. D 78 (2008) 013010.

[50] Cvetic M., Halverson J., and Langacker P., Implications of String Constraints for Exotic Matter and Z' s Beyond the Standart Model, Journal of High Energy Phys. 1111 (2011) 058.

[51] Delgado A., Garcia Cely C., Han T., and Wang Z., Phenomenology of Lepton Triplet, Phys. Rev. D 84 (2011) 073007.

[52] Biondini S., Panella O., Pancheri G., Srivastava Y. N., and Fano L., Phenomenology of Excited Doubly Charged Heavy Leptons at the LHC, Phys. Rev. D 85 (2012) 095018.

[53] Alloul A., Frank M., Fuks B., and de Traubenberg M. R., Doubly-Charged Particles at the Large Hadron Collider, Phys. Rev. D 88 (2013) 075004.

[54] Leonardi R., Panella O., and Fano L., Doubly Charged Heavy Leptons at LHC via Contact Interactions, Phys. Rev. D 90-3 (2014) 035001.
[55] You Y., Chong-Xing Y., and Yun X., Pair Production of the Doubly Charged Leptons via Electroweak Vector Boson Fusion at the Large Hadron Collider, Chin. Phys. Lett. 31 (2014) 021201.
[56] Ma T., Zhang B., and Cacciapaglia G., Triplet with a Doubly-Charged Lepton at the LHC, Phys. Rev. D 89-1 015020 (2014); Doubly Charged Lepton from an Exotic Doublet at the LHC, Phys. Rev. D 89-9 (2014) 093022.
[57] Yu Y., Yue C-X., and Yang S., Signatures of the Quintuplet Leptons at the LHC, Phys. Rev. D 91-9 (2015) 093003.
[58] Okada H. and Yagyu K., Three-loop Neutrino Mass Model with Doubly Charged Particles from Isodoublets, Phys. Rev. D 93-1 (2016) 013004.
[59] Chen C-H. and Nomura T., Bounds on LFV Higgs Decays in a Vector-like Lepton Model and Searching for Doubly Charged Leptons at the LHC, Eur. Phys. J. C 76 (2016) 353.
[60] Leonardi R., Alunni L., Romeo F., Fano L., and Panella O., Hunting for Heavy Composite Majorana Neutrinos at the LHC, Eur. Phys. J. C 76 -11 (2016) 593.
[61] Zeng Q-G., Ji L., and Yang S., Pair Production of the Doubly Charged Leptons Associated with a Gauge Boson $\gamma$ or Z in $e^+e^-$ and $\gamma\gamma$ Collisions at Future Linear Colliders, Commun. Theor. Phys. 63-3 (2015) 331-339.
[62] Biondini S. and Panella O., Exotic Leptons at Future Linear Colliders, Phys. Rev. D 92-1 (2012) 015023.
[63] Guo Y-C., Yue C-X., Lui Z-C, The Signatures of Doubly Charged Leptons in Future Linear Colliders, J. Phys. G. Nucl. Part. Phys. 44 (2017) 085004.
[64] Zeng Q-G., Production of the Doubly Charged Leptons at the ILC, Eur. Phys. Lett. 111 (2105) 21003.
[65] Yu Y., Guo Y-C., Lui Z-C., Fan W-J., Mei Y., and Zhang J., The Signatures of Doubly Charged Leptons at LHeC, J. Phys. G. Nucl. Part. Phys. 45 (2018) 125003.
[66] Ozansoy A., Doubly Charged Lepton Search Potential of the FCC-Based Energy Frontier Electron-Proton Colliders, (2019) in preparation .
[67] Ginzburg I. F., Physics at Future ep, $\gamma$p (linac-ring) and $\mu$p Colliders, Turk. J. Phys. 22-7, (1998) 607-610.
[68] Shiltsev V. D., An Asymmetric Muon-Proton Collider: Luminosity Consideration, Proceedings of the Part. Accelerator Conf., Vancouver Canada, Conf. Proc. C970512 (1997) 420-421.
[69] Sultansoy S., The Post-HERA Era: Brief Review of Future Lepton-Hadron and Photon-Hadron Colliders, (1999) https://arxiv.org/abs/hep-ph/9911417.
[70] Belyaev A., Christensen N. D., and Pukhov A., CalcHEP 3.4 for Collider Physics Within and Beyond the Standard Model, Computer Phys. Commun. 184-7 (2013) 1729-1769.

[71] Pukhov A., CalcHEP 2.3: MSSM, Structure Functions, Event Generation, Batchs, and Generation of Matrix Elements for other Packages, (2004) https://arxiv.org/abs/hep-ph/0412191.
[72] Pukhov A., Boos E., Dubinin M., Edneral V., Ilyin V., Kovalenko D., Kryukov A., Savrin V., Shichanin S., and Semenov A., CompHEP- a Package for Evaluation of Feynman Diagrams and Integration Over Multi-particle Phase Space. User's Manual for Version 33, (1999) https://arxiv.org/abs/hep-ph/9908288.
[73] Stump D., Huston J., Pumplin J., Tung W-K., Lai H. L., Kuhlmann S., and Owens J.F, Inclusive jet production, parton distributions and the search for new physics, JHEP 0310 (2003) 046.

*Current Address:* Aysuhan OZANSOY: Ankara University, Faculty of Sciences, Department of Physics, Ankara, TURKEY
E-mail: aozansoy@science.ankara.edu.tr
Orcid ID: https://orcid.org/0000-0002-9042-1372