Single production of the excited electrons at the future FCC-based lepton-hadron colliders

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Abstract

We study composite electron production at the FCC-based three electron-proton colliders with the center-of-mass energies of 3.46, 10 and 31.6 TeV. For the signal process of \( ep \rightarrow e^*X \rightarrow e\gamma X \), the production cross-sections and decay widths of the excited electrons have been calculated. The differences of some kinematical quantities of the final state particles between the signal and background have been analyzed. For this purpose, transverse momentum and pseudorapidity distributions of electron and photon have been obtained and the kinematical cuts for discovery of the excited electrons have been assigned. We have finally determined the mass limits of excited electrons for observation and discovery by applying these cuts. It is shown that the mass limit for discovery obtained from the collider with \( \sqrt{s} = 31.6 \) TeV (called PWFA-LC⊗FCC) is 22.3 TeV for the integrated luminosity \( L_{\text{int}} = 10 \, fb^{-1} \).
I. INTRODUCTION

The Standard Model (SM) of particle physics provides a successful description of the properties of electromagnetic, weak and strong interactions of the elementary particles. It also shows a great concordance with the all experiments carried out up to date, and has been finally reached its last estimation on Higgs particle by the ATLAS and the CMS collaborations, which both announced the discovery of this particle in 2012 [1, 2]. Since there are some phenomena that the SM does not explain, such as large number of elementary particles, quark-lepton symmetry and family replication, it is not a fundamental theory in particle physics, but is supposed to be effective model of a more comprehensive theory. To find a solution to these deficiencies in the SM, a lot of theory beyond the SM (BSM) have been therefore proposed until now, such as supersymmetry (SUSY), grand unified theories (GUTs), extra dimensions and compositeness. The compositeness is one of the most important BSM theories, because it explains the subjects of the family replication, the inflation of elementary particles and the quark-lepton symmetry in the best manner, introducing the more fundamental matter and antimatter constituents in which the leptons and quarks have a substructure called preons [3].

The lepton and quark compositeness were first proposed at the end of 1970s [4–7], and many preonic models have been discussed until today, such as haplon model [8, 9], rishon model [10, 11], and so on. Many new types of particles have been suggested in the framework of the preonic models, for example, diquarks, excited fermions, leptoquarks, color sextet quarks, color sextet leptons, dileptons and leptogluons. As a results of the compositeness, new interactions among the fermions should occur at the scale of the constituent binding energies. This energy scale is a characteristical parameter of the composite models, and called the compositeness scale, $\Lambda$.

If the known fermions have a substructure they should be regarded as the ground state to a rich and heavier spectrum of the excited states. Excited leptons and quarks are predicted by the composite models. We have interested in the excited electrons with spin-1/2 in this paper, as a continuation of our previous works performed for the excited muons [12] and neutrinos [13] at the FCC-based lepton-hadron colliders. In addition to these studies there are also many important phenomenological studies carried out recently in the literature for the excited leptons [14–20] and quarks [21, 22].
Even though there is no evidence for the excited leptons in the experimental studies performed in HERA \[23\], Tevatron \[24\], ATLAS \[25\] and CMS \[26\], the colliders with higher center-of-mass energy and luminosity, planned to be installed in the future, will continue to be hope for their discovery. A possible discovery of the any excited fermion will be a direct proof of the lepton and quark compositeness. The most recent experimental results on the excited electron mass are provided by the OPAL and the ATLAS collaborations \[27\]. The mass exclusion limits of the excited electrons are $m_{e^*} > 103.2$ GeV for pair production ($e^+e^-\rightarrow e^*e^*$) and $m_{e^*} > 3000$ GeV for single production, assuming $f = f' = 1$ and $\Lambda = m_{e^*}$.

We have analyzed the production potential of the excited electrons at the future electron-proton colliders. We present the main parameters of the FCC-based ep colliders in the section 2, the interaction Lagrangian responsible for the gauge interactions of the excited electrons, their decay widths and the cross-sections in the section 3, and the signal and background analysis in the section 4. Finally we summarized the all results in the last section.

II. THE FCC-BASED ELECTRON-PROTON COLLIDERS

The Large Hadron Collider (LHC) is the most powerful energy-frontier hadron collider ever constructed. The LHC is presently in operation at the CERN, and will continue to work until the middle of 2030s in the framework of its high-luminosity upgrade programme. The international Future Circular Collider (FCC) study \[28\] has been launched in 2010-2013 at the CERN, and supported by European Union within the Horizon 2020 Framework for Research and Innovation, as a next-generation collider for the post-LHC era. Its main goal is to construct an energy-frontier hadron collider with a center-of-mass energy of the order of 100 TeV in a new $\sim 100$ km tunnel near the Geneva. The FCC will have almost 4 times bigger in circumferences, and nearly 7 times higher center-of-mass energy than ones of the LHC. The FCC hadron collider (FCC-hh) could enable us to search for the physics of the BSM theories at the highest energies. The Conceptual Design Report (CDR) of the FCC is expected to be issued in 2018.

The FCC project also includes the design of a 90-400 GeV high luminosity electron-positron collider (FCC-ee or TLEP) \[29\], which could be installed in the same tunnel, to search the top quark, W, Z and Higgs bosons, as an intermediate step of the project. Construction of a such collider in the same tunnel will give us the opportunity to collide the
Table I: Main parameter of the FCC-based ep colliders.

| Colliders       | $E_e$(TeV) | CM Energy (TeV) | $L_{int}$(fb$^{-1}$per year) |
|-----------------|-----------|-----------------|-------------------------------|
| ERL60⊗FCC      | 0.06      | 3.46            | 100                           |
| ILC⊗FCC        | 0.5       | 10              | 10 – 100                      |
| PWFA-LC⊗FCC    | 5         | 31.6            | 1 – 10                        |

proton beam with the electron beam, which is known as FCC-he option. The energy of the electrons in the electron ring of the TLEP is limited because of the large synchrotron radiation. Therefore, to reach higher energy electron beam the establishment of a linear electron accelerator tangential to the FCC ring has been recently proposed in [30], using the parameters of the known linear electron collider projects, namely ILC (International Linear Collider) [31] and PWFA-LC (Plasma Wake Field Accelerator - Linear Collider) [32]. Thus, the FCC-based many electron-proton collider options have been obtained when we also consider the nominal energy values, that can be upgraded, of the ILC and the PWFA-LC.

In the numerical calculations, we have used the parameters of the FCC-based electron-proton colliders shown in the Table 1, in which there are three collider options that have the different center-of-mass energies. In here, the ERL60 denotes the Energy Recovery Linac with the electron energy of 60 GeV, which had been chosen as the main option for the LHeC [33]. The same ERL can be used for the FCC-based ep collider [34].

III. INTERACTION LAGRANGIAN, DECAY WIDTHS AND CROSS-SECTIONS

For the interaction of a spin-1/2 excited lepton with the SM leptons and a gauge boson we have used the following SU(2)xU(1) invariant Lagrangian [35–38],

$$L = \frac{1}{2\Lambda} \bar{l}_R^* \sigma^{\mu\nu} [f g \frac{\not\tau}{2} \vec{W}_{\mu\nu} + f' g' \frac{Y}{2} B_{\mu\nu}] l_L + h.c.,$$  \hspace{1cm} (1)$$

where $l$ and $l^*$ represent the SM lepton and the excited lepton, respectively, $\Lambda$ is the compositeness scale, $g$ and $g'$ are the gauge couplings, $\vec{W}_{\mu\nu}$ and $B_{\mu\nu}$ are the field strength tensors, $f$ and $f'$ are the scaling factors for the gauge couplings, $Y$ is hypercharge, $\sigma^{\mu\nu} = i(\gamma^\mu \gamma^\nu - \gamma^\nu \gamma^\mu)/2$ where $\gamma^\mu$ are the Dirac matrices, and $\not\tau$ denotes the Pauli matrices.
For the excited electrons, three decay channels are possible: $\gamma$-channel ($e^* \rightarrow e\gamma$), $Z$-channel ($e^* \rightarrow eZ$) and $W$-channel ($e^* \rightarrow eW$). We have chosen the electromagnetic decay mode ($\gamma$-channel) for this study, because of the easy detection of this channel compared to the others.

Ignoring the SM electron mass, the decay widths of the excited electrons are obtained as,

$$\Gamma(l^* \rightarrow lV) = \frac{\alpha m_l^3}{4\Lambda^2} f_V^2 (1 - \frac{m_V^2}{m_l^2})^2 (1 + \frac{m_V^2}{2m_l^2}),$$

(2)

where $m^*$ is the mass of the excited electron, $f_V$ is the new electroweak coupling parameter corresponding to the gauge boson $V$, where $V=W, Z, \gamma$, and $f_{\gamma} = -(f + f')/2$, $f_Z = (-f \cot \theta_W + f \tan \theta_W)/2$, $f_W = (f/\sqrt{2} \sin \theta_W)$, where $\theta_W$ is the weak mixing angle, and $m_V$ is the mass of the gauge boson.

For the numerical calculations we have implemented the excited electron interaction vertices into the CALCHEP [39], which is a high-energy simulation programme. We show the total decay widths of the excited electron in Fig.1, for $\Lambda = m_{e^*}$ and $\Lambda = 100$ TeV, which are commonly used for the new physics scale. Figure 2 presents the total cross-sections for the excited electron production at the three electron-proton colliders, which are ERL60⊗FCC, ILC⊗FCC and PWFA-LC⊗FCC, using the CALCHEP program with the CTEQ6L parton distribution functions [40]. It is clearly seen from this figure that the excited electrons have
Figure 2: The total cross-section values of the excited electrons with respect to its mass at the ep colliders with various center-of-mass energies for $\Lambda = m_{e^*}$ (left) and $\Lambda = 100$ TeV (right), assuming the coupling $f = f' = 1$.

adequately high cross-sections for $\Lambda = m_{e^*}$ and $\Lambda = 100$ TeV, at the high mass values of the excited electron.

The four fermion contact interactions can also contribute to the production of the excited electrons, besides the gauge interactions. It is particularly well known that the contact interactions are more dominant at proton-antiproton colliders. In a recent analysis (see ref. [19]), it is shown that at the LHC energies the production cross-sections of the excited leptons for the contact interaction are higher than ones of the gauge interactions. In this study, for the electron-proton type colliders only gauge interaction mechanism has been taken into account, but the contribution of contact interaction can not be ignored. Therefore, the contact interaction version of this work will be addressed in a future study.

IV. SIGNAL AND BACKGROUND ANALYSIS

The FCC-based electron-proton colliders will allow us to explore the excited electrons via $ep \rightarrow e^*X$ process with subsequent decays of the excited electrons into an electron and photon. Thus, our signal process is $ep \rightarrow e\gamma X$, and subprocesses are $eq(\overline{q}) \rightarrow e\gamma q(\overline{q})$, while the background process is $ep \rightarrow e, \gamma, j$ through $\gamma$ and $Z$ exchange, where $j$ represents jets which are composed of quarks ($u, \overline{u}, d, \overline{d}, c, \overline{c}, s, \overline{s}, b, \overline{b}$). In this section we discuss the differences of some kinematical quantities between the signal and the background to determine appropriate kinematical cuts for discovery of the excited electrons. This analysis is at the
parton level since for a such collider an appropriate detector has not been designed yet. Figure 3 shows angular distributions and transverse momentum distributions of the final state particles, electron and photon, from the ERL60-FCC collider. The pseudorapidity distributions (top-left and bottom-left) of the signal are peaked almost at \( \eta = [-2, -3] \) interval for a given parameter values \( (m_{e^*} = 1000, 2000, 3000 \text{ GeV} \) and \( \Lambda = m_{e^*} \) of both particles. Since pseudorapidity is defined as \( \eta = -\ln \tan(\theta/2) \), where \( \theta \) is polar angle, it is understand that electrons and photons are of backward, consequently the excited electrons are produced in the backward direction. Also, the signal and background are very well separated for the all mass values. To drastically reduce the background we have applied a cut on the pseudorapidity as \(-5 < \eta^e < -1 \) and \(-5 < \eta^\gamma < -1.5 \).

As for the transverse momentum distributions (top-right and bottom-right), it is clearly seen that the signal and background distributions are very well separated from each other for both particles. So, we easly cut off the most of the background by applying a cut at 250 GeV (for electron) and at 200 GeV (for photon).

The kinematical distributions of the final state particles for the ILC-FCC collider are shown in the Figure 4. As seen from pseudorapidity distributions (top-left and bottom-left), the signals are peaked at the negative region, as for the ERL-FCC. So, the excited electrons are produced in the backward direction compared to beam axis. We have easly assigned the kinematical cuts, as \(-4 < \eta^e < 0.5, -3.5 < \eta^\gamma < -0.5, p_T^{e,\gamma} > 600 \text{ GeV} \), on the pseudorapidity and transverse momentum distributions for both particles, because the signal and background are separated very well from each other for the all distributions in Figure 4. With these cuts the background is substantially suppressed whereas the signal remains almost unchanged.

The pseudorapidity distributions of the electron and photon for PWFALC-FCC collider, as seen from Figure 5 (top-left and bottom-left), are slightly different from those of the previous colliders. The angular distribution for \( m_{e^*} = 3000 \text{ GeV} \) are peaked in the positive region for both final state particles. Thus, the excited electrons with the small masses like 300 GeV are produced in the forward direction. The kinematical discovery cuts of this collider are determined as \(-3 < \eta^e < 2.5, -2.5 < \eta^\gamma < 2, p_T^{e,\gamma} > 800 \text{ GeV} \).

In order to see effect on the background, we plotted the invariant mass distributions of both the signal and background after the application of these discovery cuts. Figure 6 shows these distributions with statistical errors for three collider options. It is seen that
Figure 3: The normalized pseudorapidity distributions of electron (top-left) and photon (bottom-left), and normalized transverse momentum distributions of electron (top-right) and photon (bottom-right) for $f = f' = 1$ and $\Lambda = m_{e^*}$ at the ERL60$\otimes$FCC collider.

The background values are below the signal peaks when the distributions are examined. We have applied an additional cut, to extract the signal, on the $e\gamma$ invariant mass system as $m_{e^*} - 2\Gamma_{e^*} < m_{e\gamma} < m_{e^*} + 2\Gamma_{e^*}$, using the decay width ($\Gamma$) of the excited electron. For the calculation of statistical significance (SS) of the expected signal yield, we have used the formula of

$$ SS = \frac{\sigma_S}{\sigma_B} \sqrt{L_{int}}, $$

where $\sigma_S$ and $\sigma_B$ denote signal and background cross sections, respectively, and $L_{int}$ is the integrated luminosity of the collider. We have calculated the discovery ($SS \geq 5$) and observation ($SS \geq 3$) mass limits of the excited electrons, assuming the $f = f' = 1$ and $\Lambda = m_{e^*}$. The all results are reported in Table 2.
Figure 4: The normalized pseudorapidity distributions of electron (top-left) and photon (bottom-left), and normalized transverse momentum distributions of electron (top-right) and photon (bottom-right) for \( f = f' = 1 \) and \( \Lambda = m_{e^*} \) at the ILC⊗FCC collider.

V. CONCLUSION

In this paper, the production potential of the excited electrons predicted by composite models at the three FCC-based electron-proton colliders, namely ERL60⊗FCC (\( \sqrt{s} = 3.46 \) TeV), the ILC⊗FCC (\( \sqrt{s} = 10 \) TeV) and the PWFALC⊗FCC (\( \sqrt{s} = 31.6 \) TeV), has been investigated. In the analysis made, transverse momentum and pseudorapidity distributions of the final state particles (electrons and photons) have been compared for signal and background, and the appropriate cuts for discovery of the excited electrons have been determined. And finally, the statistical significance of the expected signal yield has been calculated and the mass limits of the excited electrons have been assigned.

It is shown that FCC-based electron-proton colliders will be able to search a very large mass range to detect the excited electrons. Among them, the collider of PWFALC⊗FCC has the highest center-of-mass energy. If the excited electrons had not been observed at the
Figure 5: The normalized pseudorapidity distributions of electron (top-left) and photon (bottom-left), and normalized tranverse momentum distributions of electron (top-right) and photon (bottom-right) for $f = f' = 1$ and $\lambda = m_e^*$ at the PWFALC⊗FCC collider.

ERL60⊗FCC and the ILC⊗FCC, they would have explored up to the mass of 22.3 TeV at the PWFALC⊗FCC collider.

As a result, if the composite electrons exist its probability of being discovered is high at these FCC-based electron-proton colliders.

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Figure 6: The invariant mass distributions, including the statistical errors, of the electron and photon system for \( f = f' = 1 \) and \( \Lambda = m_{e^*} \) at the colliders of ERL60\( \otimes \)FCC (top-left), ILC\( \otimes \)FCC (top-right) and PWFALC\( \otimes \)FCC (bottom), after the application of discovery cuts.

Table II: The calculated mass limits for the excited electrons at the FCC-based electron-proton colliders assuming the coupling \( f = f' = 1 \).

| Colliders        | \( \Lambda \) | \( L_{int} (fb^{-1}) \) | \( m_{e^*} (TeV) \) |
|------------------|----------------|-------------------------|---------------------|
|                  |                |                         | 3\( \sigma \)     | 5\( \sigma \) |
| ERL60\( \otimes \)FCC | \( m_{e^*} \)  | 100                     | 2.4                 | 2.3                 |
|                  | 100\( TeV \)  |                         | 2.9                 | 2.7                 |
| ILC\( \otimes \)FCC | \( m_{e^*} \)  | 10                      | 5.2                 | 4.7                 |
|                  | 100\( TeV \)  |                         | 5.9                 | 5.6                 |
|                  | 10             | 100                     | 7.9                 | 7.1                 |
|                  | 100\( TeV \)  |                         | 8.3                 | 8.1                 |
| PWFALC\( \otimes \)FCC | \( m_{e^*} \)  | 1                       | 12.5                | 11.1                |
|                  | 10             |                         | 15.7                | 14.2                |
|                  | 100\( TeV \)  |                         | 19.7                | 18.8                |
|                  | 10             |                         | 25                  | 22.3                |
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[1] ATLAS Collaboration, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”, Phys. Lett. B, 716 (1), 1-29 (2012).
[2] CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, Phys. Lett. B, 716 (1), 30-61 (2012).
[3] I.A. D’Souza and C.S. Kalman, PREONS: Models of leptons, quarks and gauge bosons as composite objects, World Scientific Publishing, 1992.
[4] H. Terazawa, Y. Chikashige and K. Akama, “Unified model of the Nambu-Jona-Lasinio type for all elementary-particle forces”, Phys. Rev. D, 15 (2), 480 (1977).
[5] H. Terazawa, “Subquark model of leptons and quarks”, Phys. Rev. D, 22 (1), 184 (1980).
[6] H. Terazawa, M. Yasue, K. Akama and M. Hayashi, “Observable effects of the possible substructure of lepton and quarks”, Phys. Lett. B, 112 (4-5), 387-392 (1982).
[7] H. Terazawa, “A fundamental theory of composite particles and fields”, Phys. Lett. B, 133 (1-2), 57-60 (1983).
[8] H. Fritzsch and G. Mandelbaum, “Weak interactions as manifestations of the substructure of leptons and quarks”, Phys. Lett. B, 102 (5), 319-322 (1981).
[9] O.W. Greenberg and J. Sucher, “A quantum structure dynamic model of quarks, leptons, weak vector bosons and Higgs mesons”, Phys. Lett. B, 99 (4), 339-343 (1981).
[10] H. Harari, “A schematic model of quarks and leptons”, Phys. Lett. B, 86 (1), 83-86 (1979).
[11] M.A. Shupe, “A composite model of leptons and quarks”, Phys. Lett. B, 86 (1), 87-92 (1979).
[12] A. Caliskan, S.O. Kara, A. Ozansoy, “Excited muon searches at the FCC-based muon-hadron colliders”, Adv. High Energy Phys., 2017, 1540243 (2017).
[13] A. Caliskan, “Excited neutrino search potential of the FCC-based electron-hadron colliders”, Adv. High Energy Phys., 2017, 4726050 (2017).
[14] A. Ozansoy and A.A. Billur, “Search for excited electrons through γγ scattering”, Phys. Rev. D, 86,055008 (2012).
[15] M. Köksal, “Analysis of excited neutrinos at the CLIC”, Int. J. Mod. Phys., A29, 1450138 (2014).
[16] A. Ozansoy, V. Ari, V. Cetinkaya, “Search for excited spin-3/2 neutrinos at LHeC, Adv. High
Energy Phys., 2016, 1739027 (2016).

[17] S. Biondini, O. Panella, G. Pancheri, Y. N. Srivastava, L. Fano, “Phenomenology of excited doubly charged heavy leptons at LHC”, Phys. Rev. D, 85, 095018 (2012).

[18] R. Leonardi, O. Panella, L. Fano, “Doubly charged heavy leptons at LHC via contact interactions”, Phys. Rev. D, 90, 035001 (2014).

[19] R. Leonardi, L. Alunni, F. Romeo, L. Fano, O. Panella, “Hunting for heavy composite Majorana neutrinos at the LHC”, Eur. Phys. J. C., 76, 593 (2016).

[20] S. Biondini and O. Panella, “Leptogenesis and composite heavy neutrinos with gauge-mediated interactions”, Eur. Phys. J. C., 77, 644 (2017).

[21] O. Panella, R. Leonardi, G. Pancheri, Y. N. Srivastava, M. Narain, U. Heintz, “Production of exotic composite quarks at the LHC”, Phys. Rev. D, 96, 075034 (2017).

[22] Y.O. Günaydın, M. Sahin and S. Sultansoy, “Resonance production of excited u-quark at the FCC based γp colliders”, e-print, arXiv: 1707.00056 [hep-ph] (2017).

[23] H1 Collaboration, “Search for excited electrons in ep collisions at HERA”, Phys. Lett. B, 666, 2 (2008).

[24] D0 Collaboration, “Search for excited electrons in p̄p collision at \(\sqrt{s} = 1.96 \text{ TeV}\)”, Phys. Rev. D, 77, 091102, (2008).

[25] ATLAS Collaboration, “Search for excited electrons and muons \(\sqrt{s} = 8 \text{ TeV}\) proton-proton collisions with the ATLAS detector”, New J. Phys., 15, 093011 (2013).

[26] CMS Collaboration, “Search for excited leptons in proton-proton collisions at \(\sqrt{s} = 8 \text{ TeV}\)”, JHEP, 2016, 125 (2016).

[27] C. Patrignani et al., (Particle Data Group), “Review of particle physics”, Chin. Phys. C, 40, 100001 (2016).

[28] FCC Project Web Page: https://fcc.web.cern.ch.

[29] TLEP Project Web Page: https://tlep.web.cern.ch.

[30] Y. C. Acar et al., “Future Circular Collider based lepton-hadron and photon-hadron colliders: luminosity and physics”, Nucl. Instrum. Meth., A871, 47-53 (2017).

[31] C. Adolphsen et al., “The International Linear Collider Technical Design Report - Volume 3.2”, e-print, arXiv:1306.6328 [physics.acc-ph] (2013).

[32] J. P. Delahaye et al., “A beam driven plasma-wakefield linear collider from Higgs factory to multi-TeV”, Proceedings of IPAC2014, Dresden, Germany, 3791 (2014).
[33] LHeC Project Web Page: http://lhec.web.cern.ch

[34] F. Zimmermann et al., “Challenges for highest energy circular colliders”, Proceedings of IPAC2014, Dresden, Germany, 1-6 (2014).

[35] K. Hagiwara, D. Zeppenfeld and S. Komamiya, “Excited lepton production at LEP and HERA”, Z. Phys. C, 29, 115 (1985).

[36] U. Baur, M. Spiro and P. M. Zerwas, “Excited-quark and -lepton production at hadron colliders”, Phys. Rev. D, 42, 815 (1990).

[37] F. Boudjema and A. Djouadi, “Looking for the LEP at LEP. The excited neutrino scenario”, Phys. Lett. B, 240, 485-491 (1990).

[38] F. Boudjema, A. Djouadi and J. L. Kneur, “Excited fermions at $e^+e^-$ and $ep$ colliders”, Z. Phys. C, 57, 425 (1993).

[39] A. Belyayev, N. D. Christensen and A. Pukhov, “CalcHEP 3.4 for collider physics within and beyond the Standard Model”, Comput. Phys. Commun., 184, 1729 (2013).

[40] D. Stump et al., “Inclusive jet production, parton distributions and the search for new physics”, JHEP, 0310, 046 (2003).