Resonant production of leptogluons at the FCC based lepton-hadron colliders

Y. C. Acar∗ and B. B. Oner†

TOBB University of Economics and Technology, Ankara, Turkey

U. Kaya‡

TOBB University of Economics and Technology, Ankara, Turkey and Department of Physics, Faculty of Sciences, Ankara University, Ankara, Turkey

S. Sultansoy§

TOBB University of Economics and Technology, Ankara, Turkey and ANAS Institute of Physics, Baku, Azerbaijan

Abstract

Resonant production of leptogluons at the FCC based ep and µp colliders have been analyzed. It is shown that e-FCC and µ-FCC will cover much wider region of $e_8$ and $\mu_8$ masses than the LHC. While leptogluons with appropriate masses (if exist) will be discovered earlier by the FCC pp collider, lepton-proton colliders will give opportunity to handle very important additional information. For example, compositeness scale can be probed up to multi-hundred TeV region.

∗Electronic address: ycacar@etu.edu.tr
†Electronic address: boner@etu.edu.tr
‡Electronic address: ukaya@etu.edu.tr
§Electronic address: ssultansoy@etu.edu.tr
I. INTRODUCTION

Color octet leptons are predicted by preonic models (see [1] and references therein) with colored preons (see, for example, fermion-scalar models [2, 3]). From phenomenological viewpoint their status is similar to that of excited leptons and leptoquarks. Concerning experimental searches situation is quite different: excited leptons and leptoquarks occupy an important place in the research program of almost all collider experiments, however, this is not the case for leptogluons (see Chapter titled “Quark and Lepton Compositeness, Search for” in [4] and references therein).

As for the phenomenological studies at TeV colliders: pair production of leptogluons at the LHC have been considered in [3, 5–7]. Resonant production of color octet electrons at the LHC based ep colliders is analyzed in [8–10]. In [11] indirect manifestations of color octet electrons at ILC and CLIC have been considered. Resonant production of color octet muons at muon collider based µp colliders was considered in [12]. It is interesting that color octet neutrinos may be the source of the IceCube PeV events [13].

Experimental bound on $l_8$ mass presented in [4], namely, $m_{l_8} > 86$ GeV is based on 25 years old CDF search for pair production of unit-charged particles which leave the detector before decaying [14]. As mentioned in [15] DO clearly exclude 200 GeV leptogluons decaying within the detector and could naively place the constraint $m_{l_8} > 325$ GeV. The twenty years old H1 search for color octet electron has excluded the compositeness scale $\Lambda < 3$ TeV for $m_{e_8} \approx 100$ GeV and $\Lambda < 240$ GeV for $m_{e_8} \approx 250$ GeV [16, 17]. While the LEP experiments did not perform dedicated search for leptogluons, low limits for excited lepton masses, namely 103.2 GeV [4], certainly is valid for color octet leptons, too. Finally, reconsideration of CMS results on leptoquark searches performed in [6] leads to the strongest limit $m_{e_8} > 1.2$-1.3 TeV.

In this paper we analyze the potential of the FCC [18] based ep and $\mu$p colliders for charged leptogluon search. In Section II we present main parameters of the FCC based lepton-hadron colliders. Phenomenology of leptogluons is given in Section III. Resonant production of color octet electrons at e-FCC and color octet muons at $\mu$-FCC is analysed in Sections IV and V, respectively. In section VI achievable values of compositeness scale are presented. Finally, section VII contains summary of obtained results.
II. FCC BASED  $e^p$ AND $\mu p$ COLLIDERS

FCC is future 100 TeV center-of-mass (CM) energy pp collider proposed at CERN and supported by European Union within the Horizon 2020 Framework Programme for Research and Innovation. It includes also an electron-positron collider options at the same tunnel (TLEP), as well as ep collider options. Construction of future $e^+e^−$ colliders (or special e-linac) and $\mu^+\mu^−$ colliders tangential to FCC will give opportunity to achieve highest CM energies in ep and $\mu p$ collisions. CM energy and luminosity values for different options are given in Table 1.

| Collider name     | $E_l$, TeV | $\sqrt{s}$, TeV | $L_{int} = fb^{-1}(\text{per year})$ |
|-------------------|------------|-----------------|-------------------------------------|
| ERL60-FCC         | 0.06       | 3.46            | 100                                 |
| FCC-e80           | 0.08       | 4.00            | 230                                 |
| FCC-e120          | 0.12       | 4.90            | 120                                 |
| FCC-e175          | 0.175      | 5.92            | 40                                  |
| OPL500-FCC        | 0.5        | 10.0            | 10 - 100                            |
| OPERL500-FCC      | 0.5        | 10.0            | 100 - 300                           |
| OPL1000-FCC       | 1.0        | 14.1            | 5 - 50                              |
| OPERL1000-FCC     | 1.0        | 14.1            | 50 - 150                            |
| OPL5000-FCC       | 5.0        | 31.6            | 1 - 10                              |
| OPERL5000-FCC     | 5.0        | 31.6            | 10 - 30                             |
| $\mu_{63}$-FCC    | 0.063      | 3.50            | 0.1 - 1                             |
| $\mu_{175}$-FCC   | 0.175      | 5.92            | 2 - 20                              |
| $\mu_{750}$-FCC   | 0.75       | 12.2            | 5 - 50                              |
| $\mu_{1500}$-FCC  | 1.5        | 17.3            | 5 - 50                              |
| $\mu_{3000}$-FCC  | 3.0        | 24.5            | 10 - 100                            |

In Table 1 ERL60 denotes conventional energy recovery; e80, e120 and e175 denote e-ring in the FCC tunnel; OPL denotes one pass linac tangential to the FCC; OPERL denotes adding second (decelerating) linac shoulder for energy recovery. Last 5 rows denote construction of $\mu$-rings tangential to the FCC (for details see [19]).
III. COLOR OCTET LEPTONS

Following reference [3] we assume that preons are color triplets and follow usual statistics (Fermi-Dirac for fermions and Bose-Einstein for bosons), which means that SM fermions should contain odd number of fermionic preons. In fermion-scalar models leptons are bound states of one fermionic preon and one scalar anti-preon

\[ l = (FS) = 1 + 8 \] (1)

therefore, each SM lepton has one color octet partner. In three-fermion models the color decomposition is

\[ l = (FFF) = 1 + 8 + 8 + 10 \] (2)

therefore, each SM lepton has two color octet and one color decuplet partners. As for quark sector, each SM quark has anti-sextet partner in fermion-scalar models (anti-triplet, anti-sextet and 15-plet partners in three-fermion models).

Concerning the relation between compositeness scale and masses of leptogluons, two scenarios can be considered: \( m_{l_{8}} \approx \Lambda \) (QCD-like scenario) and \( m_{l_{8}} << \Lambda \) (Higgs-like scenario). In the second scenario SM-like hierarchy may be realized, namely, \( m_{e_{8}} << m_{\mu_{8}} << m_{\tau_{8}} << \Lambda \). Hereafter, numerical calculations will be performed for \( \Lambda = m_{l_{8}} \) and \( \Lambda = 100 \text{ TeV} \) cases.

For the interaction of leptogluons with the corresponding lepton and gluon we use the following Lagrangian [4, 9]:

\[ L = \frac{1}{2\Lambda} \sum_{l} \left\{ \ell_{g_{8}} G_{\mu\nu}^{a} \sigma^{\mu\nu} (\eta_{L} l_{L} + \eta_{R} l_{R}) + h.c. \right\} \] (3)

where \( G_{\mu\nu}^{a} \) is the field strength tensor for gluon, index \( a = 1, 2, ..., 8 \) denotes the color, \( g_{s} \) is Gauge coupling, \( \eta_{L} \) and \( \eta_{R} \) are the chirality factors, \( l_{L} \) and \( l_{R} \) denote left and right spinor components of lepton, \( \sigma^{\mu\nu} \) is the antisymmetric tensor and \( \Lambda \) is the compositeness scale. The leptonic chiral invariance implies \( \eta_{L} \eta_{R} = 0 \). For numerical calculations we add leptogluons into the CalcHEP program [20].

Decay width of the color octet lepton is given by

\[ \Gamma(l_{8} \rightarrow l + g) = \frac{\alpha_{s} M_{l_{8}}^{3}}{4\Lambda^{2}} \] (4)
In Fig. 1 the decay width of leptogluons are presented for two scenarios, namely, $\Lambda = m_{l_8}$ and $\Lambda = 100$ TeV. The resonant $l_8$ production cross sections for different options of the FCC based lp colliders (Table I), evaluated using CalcHEP with CTEQ6L parametrization for parton distribution functions, are presented in Figs. 2 and 3 (for $\Lambda = m_{l_8}$ and $\Lambda = 100$ TeV, respectively). At this stage we ignore beamstrahlung effects, which leads to reduction of cross sections at ep colliders (see next section).

Figure 1: Leptogluon decay width vs its mass for $\Lambda = m_{l_8}$ and $\Lambda = 100$ TeV.

Figure 2: Resonant $l_8$ production at the FCC based lp colliders for $\Lambda = m_{l_8}$. 
IV. COLOR OCTET ELECTRONS AT THE FCC BASED EP COLLIDERS: SIGNAL VS BACKGROUND

In this case beamstrahlung reduces production cross-section of color octet electrons, especially at large $m_{e_8}$ values. This reduction is illustrated in Table 2 for ERL60-FCC. Analysis in this section is performed taking into account beamstrahlung effects using "beamstrahlung on" option for initial electron state in CalcHEP.

| $m_{e_8}$, GeV | Cross-section, fb | Reduction |
|----------------|-------------------|-----------|
|                | Beamstrahlung on  | Beamstrahlung off |       |
| 1000           | $3.59 \times 10^5$ | $3.87 \times 10^5$ | 0.93 |
| 2000           | $2.32 \times 10^3$ | $2.67 \times 10^3$ | 0.87 |
| 3000           | 6.49              | 7.66       | 0.85 |

In order to determine appropriate cuts we start with consideration of $p_t$ and $\eta$ distributions for signal and background processes. Numerical calculations are performed at the partonic level using CalcHEP simulation program [20] with CTEQ6L parton distribution functions [21] and generic cuts $p_t(e) > 30$ GeV, $p_t(j) > 50$ GeV, where j means gluon for signal and quarks for background processes. Main contributions to the background came from
lepton-quark scatterings via photon and Z-boson exchange.

Transverse momentum distributions of final state jets for signal (with $\Lambda = m_{e8}$) and background are shown in Fig. 4. Let us mention that same distributions are valid for final electrons, too. It is seen that $p_t > 400$ GeV cut essentially reduces background, whereas signal is almost unaffected (especially for large $m_{e8}$ values). Below we use $p_t(e) > 400$ GeV, $p_t(j) > 400$ GeV as a discovery cut for all ep colliders, keeping in mind $m_{e8} > 1.2$ TeV from the LHC $\sqrt{s} = 8$ TeV data \[6\]. Pseudo-rapidity distributions for final electrons and jets are presented in Figs. 5 and 6, respectively. Corresponding discovery cuts for different ep collider options are given in Table 3.

![Figure 4: Transverse momentum distributions of final state jets (and electrons) for signal and background at ERL60-FCC (left) and OPL1000-FCC (right).](image)

![Figure 5: Normalized pseudo-rapidity distributions of final electrons for signal and background at ERL60-FCC (left) and OPL1000-FCC (right).](image)
Figure 6: Normalized pseudo-rapidity distributions of final jets for signal and background at ERL60-FCC (left) and OPL1000-FCC (right).

Table III: Pseudorapidity cuts for different ep collider options

| Electron Energy, GeV | 60  | 175 | 500 | 1000 |
|---------------------|-----|-----|-----|------|
| η_e                 | 1<η_e<4 | 0<η_e<4 | -1<η_e<4 | -1.5<η_e<4 |
| η_j                 | 2<η_j<4 | 1<η_j<4 | 0<η_j<4 | -0.5<η_j<4 |

In Table 4 we present observation (3σ) and discovery (5σ) limits on masses of color octet electrons for different FCC based ep collider options. For statistical significance we use

\[ S = \frac{\sigma_s}{\sqrt{\sigma_s + \sigma_b}} \sqrt{L_{\text{int}}} \]  

(5)

where \( \sigma_s \) (\( \sigma_b \)) means signal (background) cross section and \( L_{\text{int}} \) is integrated luminosity.

With the pair production channel, the 14 TeV LHC can probe color octet electrons with masses up to 2.5 TeV with 100 fb\(^{-1}\) of integrated luminosity. It is seen that FCC based ep colliders cover essentially wider region of \( e_8 \)'s mass.
Table IV: Observation (3σ) and discovery (5σ) limits for color octet electrons

| Collider Name          | $\Lambda$ | $L_{int}$, fb$^{-1}$ | $m_{e8}$, GeV |
|------------------------|-----------|----------------------|---------------|
|                        |           |                     | 3σ | 5σ |
| ERL60-FCC $\sqrt{s} = 3.46$ TeV |           |                     |    |    |
| $m_{e8}$               | 10        | 2990                 | 2900|    |
|                       | 100       | 3150                 | 3085|    |
| 100 TeV               |           |                     |    |    |
|                       | 10        | 1150                 | -   |    |
|                       | 100       | 1690                 | 1485|    |
| FCC-e175 $\sqrt{s} = 5.92$ TeV |           |                     |    |    |
| $m_{e8}$               | 40        | 5110                 | 4970|    |
|                       | 100       | 2675                 | 2350|    |
| 100 TeV               |           |                     |    |    |
| OPL500-FCC $\sqrt{s} = 10.0$ TeV |           |                     |    |    |
| $m_{e8}$               | 10        | 7825                 | 7500|    |
|                       | 100       | 8450                 | 6600|    |
| 100 TeV               |           |                     |    |    |
|                       | 10        | 3800                 | 3200|    |
|                       | 100       | 5070                 | 4520|    |
| OPL1000-FCC $\sqrt{s} = 14.1$ TeV |           |                     |    |    |
| $m_{e8}$               | 5         | 10200                | 9640|    |
|                       | 50        | 11220                | 10800|   |
| 100 TeV               |           |                     |    |    |
|                       | 5         | 5000                 | 4100|    |
|                       | 50        | 6750                 | 6000|    |

V. COLOR OCTET MUONS AT THE FCC BASED $\mu$P COLLIDERS: SIGNAL VS BACKGROUND

For illustration we consider $\mu750$-FCC. Transverse momentum distributions of final state muons for signal (with $\Lambda = m_{e8}$) and background are shown in Fig. 7. Let us remind that same distributions are valid for final state jets, too. Similar to ep case, we use $p_t(\mu) > 400$ GeV, $p_t(j) > 400$ GeV as a discovery cut for all $\mu$p colliders (rough estimations show that color octet muons with masses below 1 TeV are excluded by the LHC $\sqrt{s} = 8$ TeV data). Pseudo-rapidity distributions for final muons and jets are presented in Figs. 8 and 9, respectively. Corresponding discovery cuts for different $\mu$p collider options are given in Table 5.
Figure 7: Transverse momentum distributions of final state muons (and jets) for signal and background at $\mu_{750}$-FCC.

Figure 8: Normalized pseudo-rapidity distributions of final muons for signal and background at $\mu_{750}$-FCC.
Figure 9: Normalized pseudo-rapidity distributions of final jets for signal and background at $\mu$750-FCC.

Table V: Pseudorapidity cuts for different $\mu p$ collider options

| Muon Energy, GeV | 63 | 175 | 750 |
|------------------|----|-----|-----|
| $\eta_\mu$       | $1<\eta_\mu<4$ | $0<\eta_\mu<4$ | $-1<\eta_\mu<4$ |
| $\eta_j$         | $2<\eta_j<4$ | $1<\eta_j<4$ | $0<\eta_j<4$ |

In Table 6 we present observation ($3\sigma$) and discovery ($5\sigma$) limits on masses of color octet muons for different FCC based $\mu p$ collider options. Again FCC based $\mu p$ colliders cover essentially wider region of $\mu_8$’s mass comparing to the LHC.
Table VI: Observation (3σ) and discovery (5σ) limits for color octet muons

| Collider Name | Λ | $L_{int}$, fb$^{-1}$ | $m_{\mu_8}$, GeV | 3σ | 5σ |
|---------------|---|------------------|------------------|-----|----|
| µ63-FCC $\sqrt{s} = 3.50$ TeV | $m_{\mu_8}$ | 0.1 | 2580 | 2430 |
| | | 1 | 2880 | 2760 |
| | 100 TeV | 0.1 | - | - |
| | | 1 | - | - |
| µ175-FCC $\sqrt{s} = 5.92$ TeV | $m_{\mu_8}$ | 2 | 4700 | 4500 |
| | | 20 | 5080 | 4930 |
| | 100 TeV | 2 | 1450 | - |
| | | 20 | 2230 | 1900 |
| µ750-FCC $\sqrt{s} = 12.2$ TeV | $m_{\mu_8}$ | 5 | 9225 | 8780 |
| | | 50 | 10060 | 9730 |
| | 100 TeV | 5 | 3900 | 3200 |
| | | 50 | 5350 | 4700 |

VI. COMPOSITENESS SCALE

Although the FCC based lp colliders will cover much wider $m_{l_8}$ mass regions than LHC, this is not the case for the FCC pp option: rough estimations show that FCC-pp will give opportunity to discover color octet leptons up to 20 TeV mass values. In this section we analyze potential of e-FCC and $\mu$-FCC for determination of compositeness scale. While the knowledge of color octet electron (and/or muon) mass will give opportunity to further optimization of cuts for purpose of $\Lambda$ determination, in our analysis we use $p_t, \eta_e, \eta_j, \eta_\mu, m_{inv}(l_j)$ cut values given in sections VI and V for $e_8$ and $\mu_8$, respectively. Achievable compositeness scales at the FCC based ep and $\mu$p colliders are presented in Tables 7 and 8, respectively.
Table VII: Achievable compositeness scale in TeV units at the FCC based ep colliders.

| ERL60-FCC | 3σ   | 5σ   |
|-----------|------|------|
|           | L=10 fb⁻¹ | L=100 fb⁻¹ | L=10 fb⁻¹ | L=100 fb⁻¹ |
| 1000      | 100000 | 195000 | 85000   | 150000   |
| 1500      | 62000  | 105000 | 49000   | 82000    |
| 2000      | 32000  | 51000  | 26800   | 48000    |
| 2500      | 15000  | 27000  | 10000   | 20000    |

| FCC-e175  | 3σ   | 5σ   |
|-----------|------|------|
|           | L=40 fb⁻¹ |
| 1000      | 28000 | 21000 |
| 2000      | 135000| 122200|
| 3000      | 60000 | 47200 |
| 4000      | 27500 | 21000 |

| OPL500-FCC | 3σ   | 5σ   |
|------------|------|------|
|            | L=10 fb⁻¹ | L=100 fb⁻¹ | L=10 fb⁻¹ | L=100 fb⁻¹ |
| 1000       | 363000 | 653000 | 277000 | 503000 |
| 3000       | 156250 | 283000 | 119000 | 218000 |
| 5000       | 57500  | 105500 | 43250  | 81000  |
| 7000       | 16750  | 32000  | 12000  | 24000  |

| OPL1000-FCC | 3σ   | 5σ   |
|-------------|------|------|
|             | L=5 fb⁻¹ | L=50 fb⁻¹ | L=5 fb⁻¹ | L=50 fb⁻¹ |
| 1000        | 255000 | 368000 | 191000 | 342000 |
| 2500        | 172500 | 295000 | 126000 | 228000 |
| 5000        | 67000  | 120000 | 52000  | 97000  |
| 7500        | 29000  | 54000  | 22000  | 41000  |
| 10000       | 11420  | 23000  | 7750   | 16750  |
Table VIII: Achievable compositeness scale in TeV units at the FCC based $\mu p$ colliders.

|               | $3\sigma$       | $5\sigma$       |               | $3\sigma$       | $5\sigma$       |
|---------------|-----------------|-----------------|---------------|-----------------|-----------------|
|               | $L=2$ fb$^{-1}$ | $L=20$ fb$^{-1}$ | $L=2$ fb$^{-1}$ | $L=20$ fb$^{-1}$ | $L=2$ fb$^{-1}$ | $L=20$ fb$^{-1}$ |
| FCC-$\mu$175 |                 |                 |               |                 |                 |
| 1000          | 129000          | 234000          | 98000         | 180000          |
| 2000          | 66250           | 119250          | 50000         | 92000           |
| 3000          | 29750           | 54500           | 22250         | 41750           |
| 4000          | 13250           | 25750           | 9500          | 19250           |
| $\mu$750-FCC |                 |                 |               |                 |                 |
| 1000          | 264000          | 474000          | 203000        | 367000          |
| 3000          | 141000          | 254000          | 108000        | 196000          |
| 5000          | 63500           | 114500          | 48250         | 88250           |
| 7000          | 27500           | 50750           | 20750         | 39000           |
| 10000         | 4500            | 10750           | 1250          | 8000            |

VII. CONCLUSIONS

Certainly, if color octet leptons have mass values covered by the FCC based lp colliders, they will be observed earlier at the FCC pp option. Nevertheless, e-FCC and $\mu$-FCC will give opportunity to obtain very important information which cannot be handled by the FCC-pp. As shown in section VI, compositeness scale well above 100 TeV can be probed. Very important feature of OPL-FCC ep colliders, namely, longitudinal polarization of electrons will give opportunity to determine the Lorentz structure of $l_8$-l-g vertex (the work on the subject is under progress). In general, lepton-hadron colliders has cleaner environment than hadron colliders. Finally, possible discovery of color octet leptons at the FCC-pp will determine the type of future lp collider to be installed.
Acknowledgments

This study is supported by TUBITAK under the grant no 114F337.

[1] I.A. D’Souza and C.S. Kalman, “PREONS: Models of Leptons, Quarks and Gauge Bosons as Composite Objects”, World Scientific (1992).
[2] H. Fritzsch and G. Mandelbaum, “Weak interactions as manifestations of the substructure of leptons and quarks”, Phys. Lett. B 102 (1981) 319.
[3] A. Celikel, M. Kantar and S. Sultansoy, “A search for sextet quarks and leptogluons at the LHC”, Phys. Lett. B 443 (1998) 359.
[4] K.A. Olive et al. (Particle Data Group), Chin. Phys. C 38 (2014) 090001.
[5] T. Mandal and S. Mitra, “Probing color octet electrons at the LHC”, Phys. Rev. D 87 (2013) 095008.
[6] D. Gonçalves-Netto et al., “Looking for leptogluons”, Phys. Rev. D 87 (2013) 094023.
[7] T. Jelinski and D. Zhuridov, “Leptogluons in dilepton production at LHC”, e-Print: arXiv:1510.04872 [hep-ph].
[8] A. Celikel and M. Kantar, “Resonance Production of New Resonances at ep and γp Colliders”, Tr. J. of Physics 22 (1998) 401.
[9] M. Sahin, S. Sultansoy and S. Turkoz, “Resonant production of color octet electron at the LHeC”, Phys. Lett. B 689 (2010) 172.
[10] M. Sahin, “Resonant production of spin-3/2 color octet electron at the LHeC”, Acta Physica Polonica B 45 (2014) 1811.
[11] A.N. Akay, H. Karadeniz, M. Sahin and S. Sultansoy, “Indirect search for color octet electron at next-generation linear colliders”, EPL 95 (2011) 31001.
[12] K. Cheung, “Muon-proton colliders: Leptoquarks, contact interactions and extra dimensions”, AIP Conference Proceedings 542 (2000) 160.
[13] A.N. Akay et al., “New IceCube data and color octet neutrino interpretation of the PeV energy events”, Int. J. Mod. Phys. A 30 (2015) 1550163.
[14] F. Abe et al. (CDF Collaboration), “Search for Heavy Stable Charged Particles in 1.8-TeV pp(bar) collisions at the Fermilab Collider”, Phys. Rev. Lett. 63 (1989) 1447.
[15] J.L. Hewett and T.G. Rizzo, “Much ado about leptoquarks: A comprehensive analysis”, Phy. Rev. D 56 (1997) 5709.

[16] I. Abt et al. (H1 Collaboration), “A search for leptoquarks, leptogluons and excited leptons in H1 at HERA”, Nucl. Phys. B 396 (1993) 3.

[17] T. Ahmed et al. (H1 Collaboration), “A search for leptoquarks and squarks at HERA”, Z. Phys. C 64 (1994) 545.

[18] FCC web page: https://fcc.web.cern.ch

[19] Y.C. Acar, U. Kaya, B.B. Oner and S. Sultansoy, “FCC based ep and $\mu p$ colliders”, arXiv:1510.08284 [hep-ex]

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

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