Search for excited muons at the future SPPC-based muon-proton colliders

A. Caliskan

Gümüşhane University, Faculty of Engineering and Natural Sciences,
Department of Physics Engineering, 29100, Gümüşhane, Turkey

Abstract

We have investigated the production potential of the spin-1/2 excited muons, predicted by the preonic models, at the four SPPC (Super Proton-Proton Collider)-based muon-proton colliders in different center-of-mass energies. For the signal process \( \mu p \rightarrow \mu^* X \rightarrow \mu \gamma X \), the production cross-section and the decay width values of the excited muons have been calculated. The pseudorapidity and transverse momentum distributions of the final state particles of muons and photons have been obtained to be determine the kinematical cuts best suited for discovery of the excited muons. By applying these cuts we have gotten the discovery, observation and exclusion mass limits of the excited muons for two compositeness scale values. It is shown that the discovery limits on the excited muons in case the compositeness scale equals to 100 TeV are 2.7, 3.9, 3.1 and 6.7 TeV for center-of-mass enerjies of 10.3, 14.2, 14.6 and 20.2 TeV, respectively.

*Electronic address: acaliskan@gumushane.edu.tr
I. INTRODUCTION

In the particle physics all matter and antimatter consist of two kinds of elementary particles: leptons and quarks. The electromagnetic, weak and strong forces among these particles are described very well by the Standard Model (SM). Despite all this success, there are some issues which have not entirely solved by the SM, such as large number of free parameters, fermion mass generation and fermion mixing, CP violation and the electroweak symmetry breaking mechanism. A lot of alternative theories beyond the SM (BSM), like Technicolour [1, 2], Grand Unified Models [3, 4], Supersymmetry [5], Compositeness [6], have been proposed to solve these issues.

One of the most important BSM models is the compositeness that explains the inflation of elementary particles and quark-lepton symmetry in the best manner, introducing the more fundamental constituents in which the leptons, quarks and their antiparticles have a substructure called preons. Countless preonic models have been suggested so far, by the particle physicists, and some new types of particles are introduced in the framework of these models, such as excited fermions, leptoquarks, leptogluons and color sextet quarks. The simplest preon model, for example, is Harari-Shupe model [7, 8] in which leptons and quarks are bound states of two elementary, massles spin-1/2 preons, called T- and V-rishons, which carry both color and hypercolor charges. New hypercolor interactions among the fermions should exist at the scale of energies that bind the preons together. This energy scale is an important parameter that is commonly used in the all composite models, and called the compositeness scale, \( \Lambda \). The quarks and leptons are composed of three preons for this model, and they are hypercolor singlets below the \( \Lambda \) while the all preons become confined.

If the SM fermions are composite, they must have the excited states as a result of the compositeness. Therefore the excited fermions could be considered as the excited state of the SM fermions that are in ground state and should be observed experimentally. The excited fermions are predicted by the preonic models. They were firstly proposed in 1977, and studied in detail in the following years [9–12]. The excited leptons and quarks can have spin-1/2 and spin-3/2 states, and it is expected that their masses are heavier than ones of the SM fermions. In the present study we have interested in the excited muons with spin-1/2 as a continuation of our recent works about the excited leptons [13, 14]. There are also considerable phenomenological studies on the excited quarks [15] and leptons [16–18] in the
Even though no signals for the excited leptons can be found in the experimental studies at the LEP [19], HERA [20], TEVATRON [21], ATLAS [22] and CMS [23] experiments, the more powerful accelerators that will be established in the future will continue to be hopeful for their discovery. A possible discovery of the excited leptons will provide a direct evidence of the excited lepton compositeness. The recent experimental mass limits on the excited muons for pair and single production are provided by the OPAL and ATLAS collaborations, respectively [24]. Exclusion limits of the excited muons are \( m_{\mu^*} > 103.2 \text{ GeV} \) for \( e^+e^- \rightarrow \mu^*\mu^* \) and \( m_{\mu^*} > 3000 \text{ GeV} \) for \( pp \rightarrow \mu\mu^*X \), assuming the coupling parameter of \( f = f' = 1 \) and the energy scale of \( \Lambda = m_{\mu^*} \). The excited muons can be also obtained via contact interactions, but in this paper we only concentrated the gauge interactions. The four fermion contact interactions have a different Lagrangian in itself, and it may be studied in the framework of the another study.

We have investigated the excited muon production at the four different center-of-mass energies of the SPPC-based muon-proton colliders. We present the SPPC-based muon-proton colliders and their main parameters in the Section 2, the excited muon interaction Lagrangian, its decay widths and the cross-sections in the Section 3, and the signal-background analysis in the Section 4. Finally, we have reported the all results in the last section.

II. THE SPPC-BASED MUON-PROTON COLLIDERS

The discovery of the Higgs particle with a mass of 125 GeV at the Large Hadron Colider (LHC) in 2012 [25, 26] confirmed the electroweak symmetry breaking mechanism of the SM. With this discovery the particle physics has reached the Higgs era, but it is not known whether the observed Higgs particle is the fundamental scalar. To study the properties of the Higgs boson in detail and understand its true nature, the world high-energy physics community has started to investigate the feasibility of a Higgs factory. It is known that the hadron colliders like the LHC have the highest center-of-mass energy values, so they are called the discovery machines, while the lepton and lepton-hadron colliders provide the smaller ones, and called the precision machines. Recently, various future collider projects have begun to be designed by the accelerator physicists such as the ILC (International Linear Collider) [27], LHeC (Large Hadron Electron Collider) [28] and CLIC (Compact
Linear Collider) [29] to search primarily the Higgs physics.

In the post-LHC era the most important collider project in Europe is no doubt the international Future Circular Collider (FCC) [30] with a center-of-mass energy of 100 TeV, has been launched in 2010-2013 at the CERN, and supported by the European Union within the Horizon 2020 Framework for Research and Innovation. The main purpose of this project is to establish a 100 TeV energy-frontier hadron collider (FCC-hh) to be allocated in a new 80-100 km tunnel at the CERN. As an intermediate step of the FCC project, it also involves a high-luminosity lepton collider (FCC-ee or TLEP [31]) with a center-of-mass energy of 90-400 GeV, to be installed in the same tunnel, as well as a lepton-hadron collider option (FCC-he). The FCC will give us the opportunity to explore the properties of Higgs boson, new interactions beyond the SM, top quark et cetera, at the highest energies. The CDR (Conceptual Design Report) of the FCC is expected to be completed in 2018.

In parallel with the developments related to the FCC project in Europe, the chinese physicist have initiated the design study of a two-stage circular collider project in 2012, called the CEPC-SPPC. The first stage of the project is a circular electron-positron collider (CEPC) with a center-of-mass energy of 240 GeV, to search the properties of Higgs particle. After completing its missions, the CEPC will be upgraded to the second stage that is a Super Proton-Proton Collider (SPPC) with a center-of-mass energy of more than 70 TeV, aiming at researching the BSM physics. The Preliminary Conceptual Design Report (Pre-CDR) of the CEPC-SPPC project has been completed by the CEPC-SPPC study group in 2015 [32]. By using the same tunnel as the CEPC that is 54.7 km in circumference, center-of-mass energy of about 70 TeV will be tried to be reached. But, larger circumference options for the SPPC collider are also being considered. Table 1 presents the main parameters for the all design options of the SPPC collider [33].

If a TeV energy muon collider is installed tangentially to the SPPC, a muon-proton collider, at the high center-of-mass energy, can be obtained. Taking into account the energy values of 0.75 and 1.5 TeV for muon beam, and design options of 35.6 and 68 TeV of the SPPC, four muon-proton collider options have been recently proposed [34]. The excited muon production potential at the these four muon-proton colliders have been analyzed in this paper, and its basic parameters are shown in the Table 2.
Table I: The main parameters of proton beams in the SPPC collider for the various design options.

| Parameters                        | Option-1 (Pre-CDR) | Option-2 | Option-3 | Option-4 | Option-5 |
|-----------------------------------|--------------------|----------|----------|----------|----------|
| Beam energy (TeV)                 | 35                 | 35       | 50       | 68       | 50       |
| Circumference (km)                | 54.7               | 54.7     | 100      | 100      | 78       |
| Dipole field (T)                  | 20                 | 19.69    | 14.73    | 20.03    | 19.49    |
| Peak luminosity \(x10^{35}\text{cm}^{-2}\text{s}^{-1}\) | 1.1                | 1.2      | 1.52     | 10.2     | 1.52     |
| Particle per bunch \(10^{11}\)    | 2                  | 2        | 2        | 2        | 2        |
| Norm. transverse emittance (\(\mu\text{m}\)) | 4.1                | 3.72     | 3.65     | 3.05     | 3.36     |
| Bunch number per beam             | 5835               | 5835     | 10667    | 10667    | 8320     |
| Bunch length (mm)                 | 75.5               | 56.5     | 65       | 15.8     | 70.6     |
| Bunch spacing (ns)                | 25                 | 25       | 25       | 25       | 25       |

Table II: The main parameters of the SPPC-based muon-proton colliders.

| Colliders         | \(E_\mu\) (TeV) | \(E_p\) (TeV) | \(\sqrt{s}\) (TeV) | \(L_{int}\) (\(fb^{-1}\)) | \(\xi_\mu\) | \(\xi_p\) |
|-------------------|-----------------|---------------|---------------------|-----------------------------|-------------|-----------|
| \(\mu750\)-SPPC1 | 0.75            | 35.6          | 10.33               | 5.5                         | 8.7x10^{-3} | 6x10^{-2} |
| \(\mu750\)-SPPC2 | 0.75            | 68            | 14.28               | 12.5                        | 8.7x10^{-3} | 8x10^{-2} |
| \(\mu1500\)-SPPC1| 1.5             | 35.6          | 14.61               | 4.9                         | 8.7x10^{-3} | 6x10^{-2} |
| \(\mu1500\)-SPPC2| 1.5             | 68            | 20.2                | 42.8                        | 8.7x10^{-3} | 8x10^{-2} |

III. THE EXCITED MUONS

The interactions of an excited lepton with ordinary leptons are of magnetic transition type, and the effective Lagrangian that describes the interaction between a spin-1/2 excited lepton, the SM lepton and a gauge boson is given as \[35\] \[36\] \[37\] \[38\],

\[
L = \frac{1}{2\Lambda} l^\dagger \sigma^{\mu\nu} \left[ fg \vec{\tau} \cdot \vec{W}_{\mu\nu} + f' g' \frac{Y}{2} B_{\mu\nu} \right] l + h.c.,
\]

where \(l\) and \(l^*\) represent the SM lepton and the excited lepton, respectively, \(\Lambda\) is the new physics scale, \(\vec{W}_{\mu\nu}\) and \(B_{\mu\nu}\) are the field strength tensors, \(g\) and \(g'\) are the SM gauge couplings of SU(2) and U(1), \(f\) and \(f'\) are the new 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 \(\vec{\tau}\) denotes the Pauli matrices.
Figure 1: The total decay widths of the excited muons for \( \Lambda = m_{\mu^*} \) and \( \Lambda = 100 \) TeV, assuming \( f = f' = 1 \).

The excited muons can decay into three channels that are \( \gamma \)-channel \((\mu^* \rightarrow \mu\gamma)\), \( Z \)-channel \((\mu^* \rightarrow \mu Z)\) and W-channel \((\mu^* \rightarrow \mu W)\). The decay widths of the excited muons are given the following formula,

\[
\Gamma(l^* \rightarrow lV) = \frac{\alpha m^* v}{4\Lambda^2} f_V^2 (1 - \frac{m_V^2}{m^*^2})^2 (1 + \frac{m_V^2}{2m^*^2}),
\]

(2)

where \( m^* \) is the mass of the excited electron, \( m_V \) is the mass of the gauge boson, \( f_V \) 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 \( \alpha \) is the electromagnetic coupling constant.

For the numerical calculations we implemented the excited muon interaction vertices into the high-energy simulation programme of CALCHEP [39]. Figure 1 shows the total decay widths of the excited muons for energy scales \( \Lambda = m_{\mu^*} \) and \( \Lambda = 100 \) TeV. The total cross-sections of the excited muons produced at the four different muon-proton colliders, which are \( \mu750\text{-SPPC1}, \mu750\text{-SPPC2}, \mu750 - SPPC2, \mu1500\text{-SPPC1}, \mu1500\text{-SPPC2} \), are shown in the Figure 2, using the program CALCHEP with the CTEQ6L parton distribution functions [40]. It is unambiguously seen from the figure that the excited muons have sufficiently high cross-sections for both energy scales.
Figure 2: The total cross-section values of the excited muons with respect to its mass at the various muon-proton colliders for $\Lambda = m_{\mu^*}$ (left) and $\Lambda = 100$ TeV (right), assuming $f = f' = 1$.

**IV. SIGNAL AND BACKGROUND ANALYSIS**

The SPPC-based muon-proton colliders will allow us to explore the excited muons via $\mu p \rightarrow \mu^* X$ process with subsequent decays of the excited muons into a muon and photon. Therefore, our signal process is $\mu p \rightarrow \mu \gamma X$, and subprocesses are $\mu q(\overline{q}) \rightarrow \mu \gamma q(\overline{q})$. In order to separate the excited muon signals from the background we have applied prime transverse momentum cuts to the final state particles of muon, photon and jets, as $p_T^{\mu,\gamma,j} > 20$ GeV. The SM cross-section values after the application of these prime cuts have been obtained as $\sigma_B = 73.15$ pb for $\mu 750$-SPPC1, $\sigma_B = 82.11$ pb for $\mu 750$-SPPC2, $\sigma_B = 84.65$ pb for $\mu 1500$-SPPC1, $\sigma_B = 126.84$ pb for $\mu 1500$-SPPC2 collider. To be assign the kinematical cuts best suited for the discovery of the excited muons, we have to look at the transverse momentum ($p_T$) and pseudorapidity ($\eta$) distributions of the final state particles for both the signal and background.

The normalized $\eta$ and $p_T$ distributions of the final state muons and normalized $\eta$ distributions of the final state photons are shown in the Fig.3 for $\mu 750$-SPPC1, Fig.4 for $\mu 750$-SPPC2, Fig.5 for $\mu 1500$-SPPC1 and Fig.6 for $\mu 1500$-SPPC2, for both the signal and background. Since the $p_T$ distributions of the muons are the same as those of the photons for the all colliders, we have only shown the ones of the muons in these figures. In these distributions we have chosen optimal regions where we cut off the most of the background but at the same time keep the signal almost unchanged. The determined discovery cuts are reported in Table 3.
Figure 3: The normalized pseudorapidity (left) and transverse momentum (middle) distributions of the final state muons and the normalized pseudorapidity distributions of the final state photons (right) at the $\mu 750$-SPPC1 collider, for $f = f' = 1$ and $\Lambda = m_{\mu^*}$.

Figure 4: The normalized pseudorapidity (left) and transverse momentum (middle) distributions of the final state muons and the normalized pseudorapidity distributions of the final state photons (right) at the $\mu 750$-SPPC2 collider, for $f = f' = 1$ and $\Lambda = m_{\mu^*}$.

Figure 5: The normalized pseudorapidity (left) and transverse momentum (middle) distributions of the final state muons and the normalized pseudorapidity distributions of the final state photons (right) at the $\mu 1500$-SPPC1 collider, for $f = f' = 1$ and $\Lambda = m_{\mu^*}$.
Table III: The discovery cuts for the excited muons.

| Colliders      | $p_T^{\mu}$ | $p_T^{\gamma}$ | $\eta^{\mu}$ | $\eta^{\gamma}$ |
|----------------|-------------|----------------|--------------|-----------------|
| $\mu^{750}$-SPPC1 | $p_T^{\mu} > 500$ GeV | $p_T^{\gamma} > 500$ GeV | $-5 < \eta^{\mu} < 1$ | $-4.8 < \eta^{\gamma} < 0$ |
| $\mu^{750}$-SPPC2 | $p_T^{\mu} > 600$ GeV | $p_T^{\gamma} > 500$ GeV | $-5 < \eta^{\mu} < 1.5$ | $-5 < \eta^{\gamma} < 0.5$ |
| $\mu^{1500}$-SPPC1 | $p_T^{\mu} > 600$ GeV | $p_T^{\gamma} > 500$ GeV | $-5 < \eta^{\mu} < 2$ | $-5 < \eta^{\gamma} < 1.5$ |
| $\mu^{1500}$-SPPC2 | $p_T^{\mu} > 750$ GeV | $p_T^{\gamma} > 750$ GeV | $-5 < \eta^{\mu} < 2.2$ | $-5 < \eta^{\gamma} < 1.4$ |

The invariant mass distributions of the $\mu\gamma$ system after the application of all discovery cuts are presented in the Fig.7. As seen clearly from this figure that the separation of the signal from the background got better.

To extract the excited muon signal from the background, in addition to the discovery cuts, we have imposed a cut on the $\mu\gamma$ invariant mass as $m_{\mu\gamma} - 2\Gamma_{\mu^*} < m_{\mu\gamma} < m_{\mu^*} + 2\Gamma_{\mu^*}$, where $\Gamma$ denotes the decay width of the excited muon.

For statistical significance (SS) of the excited muon signal, we have used the following formula,

$$SS = \frac{|\sigma_{S+B} - \sigma_B|}{\sigma_B} \sqrt{L_{int}},$$

where $\sigma_{S+B}$ denotes the cross section from the signal and the background, $\sigma_B$ denotes the background cross section, and $L_{int}$ is the integrated luminosity of the collider. Taking into account the discovery criterion $SS \geq 5$, discovery mass limits on the excited muon have been calculated as 6600, 8700, 7200, 11100 GeV for the colliders of $\mu^{750}$-SPPC1, $\mu^{750}$-SPPC2,
Figure 7: The invariant mass distributions of the excited muon signal and the corresponding background for $\Lambda = m_{\mu^*}$ and $f = f' = 1$ at the colliders of $\mu 750$-SPPC1 (top-left), $\mu 750$-SPPC2 (top-right), $\mu 1500$-SPPC1 (bottom-left) and $\mu 1500$-SPPC2 (bottom-right).

$\mu 1500$-SPPC1, $\mu 1500$-SPPC2, respectively, assuming $f = f' = 1$ and $\Lambda = m_{\mu^*}$. For the $\Lambda = 100$ TeV and the same criteria, excited muon mass limits are 2780, 3900, 3100 and 6700 GeV, respectively also.

V. CONCLUSION

We have performed a search for production of the excited muon at the SPPC-based muon-proton colliders. This work has shown that the these colliders have a great research potential for the excited muon searches. We give a realistic estimate for the excited muon signal and the corresponding background at the SPPC-based muon-proton colliders, namely the $\mu 750$-SPPC1 ($\sqrt{s} = 10.33$ TeV), the $\mu 750$-SPPC2 ($\sqrt{s} = 14.28$ TeV), the $\mu 1500$-SPPC1 ($\sqrt{s} = 14.61$ TeV) and the $\mu 1500$-SPPC2 ($\sqrt{s} = 20.2$ TeV). In the simulations made to obtain the pseudorapidity and transverse momentum distributions, it is assumed that the energy scale is $\Lambda = m_{\mu^*}$ and the coupling parameter is $f = f' = 1$. The mass limits for exclusion, observation, and discovery of the excited muons at the four colliders are reported.
in Table IV, for both $\Lambda = m_{\mu^*}$ and $\Lambda = 100$ TeV. As a result, the future SPPC-based muon-proton colliders offer the possibility to investigate the excited muon in a very wide range of mass.

Table IV: The mass limits for the exclusion ($2\sigma$), observation ($3\sigma$), and discovery ($5\sigma$) of the excited muons at the SPPC-based $\mu p$ colliders assuming the coupling $f = f' = 1$.

| Colliders   | $L_{\text{int}}(fb^{-1})$ | $\Lambda$ | $2\sigma$ (GeV) | $3\sigma$ (GeV) | $5\sigma$ (GeV) |
|-------------|---------------------------|-----------|-----------------|-----------------|-----------------|
| $\mu750$-SPPC1 | 5.5                       | $m_{\mu^*}$ | 7400            | 7000            | 6600            |
|             |                           |           | 100 TeV         | 4010            | 3750            | 2780            |
| $\mu750$-SPPC2 | 12.5                      | $m_{\mu^*}$ | 10600           | 9200            | 8700            |
|             |                           |           | 100 TeV         | 6500            | 5000            | 3900            |
| $\mu1500$-SPPC1 | 4.9                       | $m_{\mu^*}$ | 9000            | 8600            | 7200            |
|             |                           |           | 100 TeV         | 5000            | 4400            | 3100            |
| $\mu1500$-SPPC2 | 42.8                      | $m_{\mu^*}$ | 13200           | 12600           | 11100           |
|             |                           |           | 100 TeV         | 8700            | 8100            | 6700            |

Acknowledgments

I would like to thank A. Ozansoy for model file support. This work has been supported by the Scientific and Technological Research Council of Turkey (TUBITAK) under the grant no 114F337.

[1] S. Weinberg, “Implications of dynamical symmetry breaking”, Phys. Rev. D, 13, 974-996 (1976).
[2] L. Susskind, “Dynamics of spontaneous symmetry breaking in the Weinberg-Salam theory”, Phys. Rev. D, 20, 2619-2625 (1979).
[3] H. Georgi and S. L. Glashow, “Unity of all elementary-particle forces”, Phys. Rev. Lett., 32, 438 (1974).
[4] J. C. Pati and A. Salam, “Lepton number as the fourth 'color'”, Phys. Rev. D, 10, 275 (1974).
[5] Y. A. Golfand and E. P. Likhtman, “Extension of the algebra of poincare group generators and violation of P invariance”, JETP Lett., 13, 323 (1971).
[6] I.A. D’Souza and C.S. Kalman, PREONS: Models of leptons, quarks and gauge bosons as composite objects, World Scientific Publishing, 1992.

[7] H. Harari, “A schematic model of quarks and leptons”, Phys. Lett. B, 86, 83-86 (1979).

[8] M. A. Shupe, “A composite model of leptons and quarks”, Phys. Lett. B, 86, 87-92 (1979).

[9] 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).

[10] H. Terazawa, “Subquark model of leptons and quarks”, Phys. Rev. D, 22 (1), 184 (1980).

[11] 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).

[12] H. Terazawa, “A fundamental theory of composite particles and fields”, Phys. Lett. B, 133 (1-2), 57-60 (1983).

[13] A. Caliskan, S.O. Kara, A. Ozansoy, “Excited muon searches at the FCC-based muon-hadron colliders”, Adv. High Energy Phys., 2017, 1540243 (2017).

[14] A. Caliskan, “Excited neutrino search potential of the FCC-based electron-hadron colliders”, Adv. High Energy Phys., 2017, 4726050 (2017).

[15] 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).

[16] A. Ozansoy and A.A. Billur, “Search for excited electrons through γγ scattering”, Phys. Rev. D, 86, 055008 (2012).

[17] M. Köksal, “Analysis of excited neutrinos at the CLIC”, Int. J. Mod. Phys., A29, 1450138 (2014).

[18] A. Ozansoy, V. Ari, V. Cetinkaya, “Search for excited spin-3/2 neutrinos at LHeC”, Adv. High Energy Phys., 2016, 1739027 (2016).

[19] L3 Collaboration, “Search for excited leptons at LEP”, Phys. Lett. B, 568, 1 (2003).

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

[21] D0 Collaboration, “Search for excited electrons in pp collision at √s=1.96 TeV”, Phys. Rev. D, 77, 091102 (2008).

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

[23] CMS Collaboration, “Search for excited leptons in proton-proton collisions at √s = 8 TeV”,
JHEP, 2016, 125 (2016).

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

[25] 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).

[26] 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).

[27] C. Adolphsen et al., “The International Linear Collider Technical Design Report - Volume 3. IT”, e-print, arXiv:1306.6328 [physics.acc-ph] (2013).

[28] LHeC Project Web Page: http://lhec.web.cern.ch.

[29] CLIC Collaboration, “The CLIC programme: Towards a staged $e^+e^-$linear collider exploring the terascale”, CLIC Conceptual Design Report, CERN-2012-005, CERN, Geneva (2012).

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

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

[32] The CEPC-SPPC Study Group, CEPC-SPPC Preliminary Conceptual Design Report, Volume I - Physics & Detector, IHEP-CEPC-DR-2015-01, March (2015).

[33] F. Su et al., “SPPC Parameter Choice and lattice design”, Proceedings of IPAC2016, Busan, Korea, 1400-1402 (2016).

[34] A. C. Canbayi U. Kaya, B. Ketenoglu, B. B. Oner, S. Sultansoy, “SppC based energy frontier lepton-hadron colliders: Luminosity and physics”, Adv. High Energy Phys., 2017, 4021493 (2017).

[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. Spira 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).