Excited muon searches at the FCC based muon-hadron colliders

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Abstract

We study the excited muon production at the FCC-based muon-hadron colliders. We give the excited muon decay widths and production cross-sections. We deal with the $\mu p \rightarrow \mu^* q \rightarrow \mu \gamma q$ process and we plot the transverse momentum and normalized pseudorapidity distributions of final state particles to define the kinematical cuts best suited for discovery. By using these cuts, we get the mass limits for excited muons. It is shown that the discovery limits obtained on the mass of $\mu^*$ are 2.2, 5.8, and 7.5 TeV for muon energies of 63, 750, and 1500 GeV, respectively.
I. INTRODUCTION

Discovery of the Higgs boson by ATLAS and CMS collaborations in 2012 [1, 2] has proved the accuracy and reliability of the Standard Model (SM) of the particle physics. But, many questions about dark matter, supersymmetric particles, extra dimensions, neutrino masses, asymmetry between matter and anti-matter, existence of new fundamental interactions, and fermion substructure are keeping their mystery and waiting to be solved. Many theories beyond the SM (BSM) have been proposed for these puzzling phenomena. Evidently, it is necessary to perform the particle physics experiments in more powerful colliders with higher energies and luminosities.

Compositeness is one of the BSM models that intend to solve the problem of fermionic families replication, by introducing more fundamental matter constituents called preons. Excited fermions are predicted by preonic models and their existence would be a strong evidence for fermion substructure [3–5]. If known quarks and leptons present composite structures, reasonable explanations could be given for the still unanswered questions about the number and replication of SM families and their mass hierarchy. The appearance of excited states is an indisputable consequence of composite structure of known fermions [6–9]. In composite models, SM fermions are considered as ground states of a rich and heavier spectrum of excited states. Charged \((e^*, \mu^*, \tau^*)\) and neutral \((\nu^*_e, \nu^*_\mu, \nu^*_\tau)\) excited leptons come on the scene in the framework of composite models. Excited leptons with spin-1/2 and weak-isospin-1/2 are considered as the lowest radial and orbital excitations. Excited states with higher spins also appear in composite models [10–14].

Considerable searches for the spin-1/2 charged and neutral excited lepton signatures have been performed for the \(e^+e^-\) and \(ep\) colliders [15–18]; \(\gamma\gamma\) [19–22] and \(e\gamma\) [14, 23] colliders; \(pp\) [24–27] and \(p\bar{p}\) [28–30] colliders. Production and decay properties of spin-1/2 excited leptons in a left-right symmetric scenario are studied in [31]. Also, spin-3/2 excited leptons are studied at various colliders in [32–38].

Excited electrons \((e^*)\) are extensively investigated in the field of excited leptonic state studies. To perform a main comparison it is necessary to study the other charged excited leptons \((\mu^* \text{ and } \tau^*)\). In principle, \(\mu^* \text{ and } \tau^*\) contributions would be differ from \(e^*\) contribution in the mass and decay products of the SM leptons.

The mass limit for excited spin-1/2 muons obtained from their pair production \((e^+e^- \rightarrow\)
(µ⁺µ⁻) by OPAL collaboration at √s = 189–209 GeV is m_{µ^*} > 103.2 GeV \[39\]. From single production (pp → µµ*X), in events with three or more charged leptons at √s = 8 TeV including contact interactions in the µ* production and decay mechanism, the ATLAS collaboration sets the mass limits as m_{µ^*} > 3000 GeV \[40\]. Other studies on excited muon searches can be found in \[41–51\].

Enormous efforts are being made for the research and development of new particle colliders for the Large Hadron Collider (LHC) era and post-LHC era. A staged approach will be taken into consideration for the planning of these energy frontiers. The first stage is low-energy lepton colliders to make the precision measurements of the LHC discoveries. These projects are the International Linear Collider (ILC) \[52\] with a center-of-mass energy of √s = 0.5 TeV and low-energy muon collider (a µ⁺µ⁻ collider, shortly µC) \[53\]. Lepton-hadron collider projects would be considered as a second stage, including an ep collider under design, namely, Large Hadron Electron Collider (LHeC) with √s = 1.3 TeV (possibly upgraded to √s = 1.96 TeV) \[54, 55\], and a hypothetical µp collider µ-LHC at this stage. The ILC with an increased center-of-mass energy (√s = 1 TeV), the Compact Linear Collider (CLIC) \[56\] with an optimal center-of-mass energy of 3 TeV, and the Plasma Wake-Field Accelerator-Linear Collider project (PWFA-LC) \[57\] are high-energy linear e⁺e⁻ colliders under consideration to be built after the LHC. On the side of muon colliders, µC with √s up to 3 TeV is planned as a high-energy muon collider \[53\].

The Future Circular Collider (FCC) \[58\] project investigates the various concepts of the circular colliders at CERN for the post-LHC era. The FCC is proposed as the future pp collider with √s = 100 TeV and supported by European Union within the Horizon 2020 Framework Programme for research and innovation. Besides the pp option, it is also being planned to include the e⁺e⁻ collider option (TLEP or FCC-ee) \[59\] and several ep collider options \[60, 61\].

Building a muon collider as dedicated µ-ring tangential to the FCC will give opportunity to handle multi-TeV scale µp and µA colliders \[62, 63\]. Assumed values for muon energy, center-of-mass energy, and average instantaneous luminosity for different FCC-based µp collider options are given in Table I.
Excited muon searches would provide complementary information for the compositeness studies. This work is dedicated to search for excited muons at future FCC-based muon-proton colliders. We introduce the effective Lagrangian responsible for the gauge interactions of excited muons and give their decay widths in Section II. Production cross-sections and the analysis for the $\mu^* \to \mu \gamma$ decay mode are presented in Section III. We summarized our results in Section IV.

II. EFFECTIVE LAGRANGIAN

A spin-1/2 excited lepton is the lowest radial and orbital excitation according to the classification by $SU(2) \times U(1)$ quantum numbers. Interactions between excited spin-1/2 leptons and ordinary leptons are of magnetic transition type \cite{15, 16, 64}. The effective Lagrangian for the interaction between a spin-1/2 excited lepton, a gauge boson ($V = \gamma, Z, W^\pm$), and the SM lepton is given by

$$L = \frac{1}{2\Lambda} \bar{l}_R \sigma^{\mu\nu} \left[ f g \frac{\bar{\tau}}{2} W^\nu_{\mu\nu} + f' g' \frac{Y}{2} B^\nu_{\mu\nu} \right] l_L + h.c.,$$ \hspace{1cm} (1)

where $\Lambda$ is the new physics scale, $W^\nu_{\mu\nu}$ and $B^\nu_{\mu\nu}$ are the field strength tensors, $\bar{\tau}$ denotes the Pauli matrices, $Y$ is the hypercharge, $g$ and $g'$ are the gauge couplings, and $f$ and $f'$ are the scaling factors for the gauge couplings of $SU(2)$ and $U(1)$; $\sigma^{\mu\nu} = i(\gamma^\mu \gamma^\nu - \gamma^\nu \gamma^\mu)/2$ with $\gamma^\mu$ being the Dirac matrices. An excited lepton has three possible decay modes: radiative decay $l^* \to l \gamma$, neutral weak decay $l^* \to lZ$, and charged weak decay $l^* \to \nu W$. Neglecting the SM lepton mass, we find the decay width of excited leptons as

$$\Gamma(l^* \to lV) = \frac{\alpha m^* \times 3}{4\Lambda^2} f^2_{V}(1 - \frac{m^2_{V}}{m^*})^2(1 + \frac{m^2_{V}}{2m^*}),$$ \hspace{1cm} (2)
where \( f_V \) is the new electroweak coupling parameter corresponding to the gauge boson \( V \), and \( f_\gamma = -(f + f')/2, f_Z = -(f\cot\theta_W + f't\tan\theta_W)/2 \), and \( f_W = f/\sqrt{2}\sin\theta_W \); \( \theta_W \) is the weak mixing angle, and \( m_V \) is the mass of the gauge boson, and \( m^* \) is the mass of the excited lepton. Total decay widths of excited leptons for \( \Lambda = m^* \) and \( \Lambda = 100 \text{ TeV} \) are given in Figure 1.

![Figure 1: Decay width of excited leptons for \( \Lambda = m^* \) and \( \Lambda = 100 \text{ TeV} \).](image)

III. EXCITED MUON PRODUCTION AT \( \mu p \) COLLIDERS

The FCC-based \( \mu p \) colliders will provide the potential reach for excited muon searches through the \( \mu p \rightarrow \mu^*X \) process. Feynman diagrams for the subprocesses \( \mu q(\bar{q}) \rightarrow \mu^* q(\bar{q}) \) are shown in Figure 2. We implemented excited muon interaction vertices in high-energy physics simulation programme CALCHEP \[65, 67\] and used it in our calculations.

![Figure 2: Leading-order Feynman diagrams for the \( \mu^* \) production at \( \mu p \) collider.](image)
Total cross-section for the process $\mu p \rightarrow \mu^* X$ as a function of the excited muon mass is shown in Figure 3. We used the CTEQ6L parton distribution function in our calculations.

![Figure 3](image)

Figure 3: Total cross-section as a function of the excited muon mass for the $\mu p$ colliders with various center-of-mass energies for $\Lambda=m^*$ (left) and $\Lambda=100$ TeV, respectively.

For the analysis we take into account the $\mu\gamma$ decay mode of the $\mu^*$. We deal with the process $\mu p \rightarrow \mu^* X \rightarrow \mu\gamma X$ (subprocess $\mu q(\bar{q}) \rightarrow \mu\gamma q(\bar{q})$) and impose generic cuts, $p_T > 20$ GeV, for the final state muon, photon and jets.

Standard Model cross-sections after the application of the generic cuts are $\sigma_B = 24.51$ pb, $\sigma_B = 89.69$ pb, and $\sigma_B = 122.43$ pb for $\sqrt{s} = 3.50$, 12.2 and 17.3 TeV, respectively. We show the transverse momentum distributions in Figure 4 (for $\mu 63$-FCC), in Figure 6 (for $\mu 750$-FCC), and in Figure 8 (for $\mu 1500$-FCC); the normalized pseudorapidity distributions are in Figure 5 (for $\mu 63$-FCC), in Figure 7 (for $\mu 750$-FCC), and in Figure 9 (for $\mu 1500$-FCC). We choose $f = f' = 1$ and $\Lambda = m_{\mu^*}$ in our calculations. As it is seen from Figures 4, 6 and 8 excited muons carry high transverse momentum and these distributions show a peak around $m_{\mu^*}/2$. Also, normalized pseudorapidity distributions are so asymmetric. Since pseudorapidity is defined to be $\eta = -\ln(\tan(\theta/2))$, where $\theta$ is the polar angle, it is concluded that excited muons are produced mostly in the backward direction.
Figure 4: Muon (left) and photon (right) $p_T$ distributions for the $\mu63$-FCC.

Figure 5: Muon (left) and photon (right) normalized $\eta$ distributions for the $\mu63$-FCC.

Figure 6: Muon (left) and photon (right) $p_T$ distributions for the $\mu750$-FCC.
Figure 7: Muon (left) and photon (right) normalized $\eta$ distributions for the $\mu 750$-FCC.

Figure 8: Muon (left) and photon (right) $p_T$ distributions for the $\mu 1500$-FCC.

Figure 9: Muon (left) and photon (right) normalized $\eta$ distributions for the $\mu 1500$-FCC.
By examining these distributions we determine the discovery cuts presented in Table 2. To determine these discovery cuts we specify the optimal regions where we cut off the most of the background but at the same time do not affect the signal so much. Since we choose the $\mu^* \rightarrow \mu \gamma$ decay mode of the excited muon (try to identify the excited muons through its decay products), no further cut is made on jets.

### Table II: Discovery cuts.

| Collider | $p_T^{\mu}$ cut | $p_T^{\gamma}$ cut | $\eta^{\mu}$ cut | $\eta^{\gamma}$ cut |
|----------|-----------------|--------------------|------------------|-------------------|
| $\mu_{63}$-FCC | $p_T^{\mu} > 450$ GeV | $p_T^{\gamma} > 300$ GeV | $-4.5 < \eta^{\mu} < -0.8$ | $-4.8 < \eta^{\gamma} < -1.2$ |
| $\mu_{750}$-FCC | $p_T^{\mu} > 1200$ GeV | $p_T^{\gamma} > 900$ GeV | $-3.5 < \eta^{\mu} < 0.5$ | $-4 < \eta^{\gamma} < 0.3$ |
| $\mu_{1500}$-FCC | $p_T^{\mu} > 1500$ GeV | $p_T^{\gamma} > 1500$ GeV | $-3 < \eta^{\mu} < 1$ | $-4 < \eta^{\gamma} < 0.5$ |
The invariant mass distributions following these cuts are shown in Figure 10. We define the statistical significance of the expected signal yield as

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

where $\sigma_S$ denotes cross-section due to the excited muon production and $\sigma_B$ denotes the SM cross-section, $L_{\text{int}}$ is the integrated luminosity of the collider, and $\epsilon$ is the selection efficiency to detect the signal in the chosen channel ($\epsilon$ is assumed to be the same both on signal and on background). Taking into account the criteria $SS > 3$ (95% CL) and $SS > 5$ (99% CL), we derive the mass limits for excited muons. Our results are summarized in Table 3.

| Collider     | $L_{\mu p}$ ($cm^{-2}s^{-1}$) | $\Lambda$  | $m_{\mu^*}$ (GeV) | 3$\sigma$ | 5$\sigma$ |
|--------------|-------------------------------|------------|-------------------|-----------|-----------|
| $\mu63$-FCC  | $0.2 \times 10^{31}$          | $m_{\mu^*}$| 2300              | 2250      | 100 TeV 2300 | 2180      |
| $\mu750$-FCC | $50 \times 10^{31}$           | $m_{\mu^*}$| 6500              | 5950      | 100 TeV 6000 | 5830      |
| $\mu1500$-FCC| $50 \times 10^{31}$           | $m_{\mu^*}$| 8050              | 7540      | 100 TeV 7930 | 7480      |

IV. CONCLUSION

It is shown that the FCC-based muon-proton colliders have a significant potential in excited muon investigations. We have studied the excited muon production and decay in various FCC-based $\mu p$ collider options with muon energies of 63, 750, and 1500 GeV. Our analysis shows that taking into account the $SS > 5$ criteria, for $\Lambda = m^*$, excited muon mass limits are 2250 GeV, 5950 GeV, and 7540 GeV, for $\sqrt{s} = 3.5, 12.2, \text{ and } 17.3$ TeV, respectively. Also, for the same criteria, for $\Lambda = 100$ TeV, excited muon mass limits are 2180, 5830, and 7480 GeV for $\sqrt{s} = 3.5, 12.2, \text{ and } 17.3$ TeV, respectively.
Acknowledgments

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