Resonant Production of Color Octet Muons at the Future Circular Collider Based Muon-Proton Colliders*

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Abstract: We investigate the resonant production of color octet muons in order to explore the discovery potential of the FCC-based $\mu p$ colliders. It is shown that search potential of $\mu p$ colliders essentially surpass the potential of the LHC and would exceed that of the FCC $pp$ collider.

Key words: leptogluons, lepton-hadron interactions, composite models, muon-proton colliders, color octet muon, beyond the standard model

1 Introduction

High energy physics experiments performed in recent decades show that Standard Model (SM) is consistent in a low energy regime. However, there are still phenomenological and theoretical problems and questions to be answered. Experimental research for the new physics, searching for these answers for higher energies, relies on recently developed accelerator technologies. Energy frontier lepton colliders seem to be prominent candidates to investigate the validity of the SM at high energies, and they have the potential to reveal novelties that lie beyond the Standard Model (BSM). Producing and colliding muon beams with intense bunches to achieve sufficiently high luminosities is still a promising topic. In this regard, a recent paper by the Muon Accelerator Program (MAP) addressed designs of various center of mass (CM) energy muon colliders ($\mu C$) from 126 GeV (Higgs-factory) to multi-TeV (energy frontier) options [1]. Also ultimate case muon colliders with CM energy up to 100 TeV were considered in another study, and parameters of these colliders were given [2].

Developing the technology of lepton colliders makes high luminosity and high CM energy lepton-hadron colliders possible. In this manner, one can utilize the advantages of their vital role in understanding the fundamental structure of matter using the highest energy hadron beams, which will be provided by the Future Circular Collider (FCC) [3]. In the near future, it is expected that the construction of $\mu p$ machines can also be considered, depending on the solutions to the principal issues of the $\mu^+\mu^-$ colliders. Some advantages of the highest energy $\mu p$ machines can be listed briefly as follows. Firstly, multi-TeV scale muon-proton collisions are testing mechanisms of composite models and may give us clear hints about the fermion mixing and generation replication puzzle of the SM fermions. In addition, they would present experimental results that enable us to understand QCD better. Exotic particle productions are more probable compared to the ep colliders since the large mass ratio between muon and electron [4].

Muon-proton colliders were proposed two decades ago. Construction of additional proton ring in $\sqrt{s} = 4$ TeV muon collider tunnel was suggested in [4] to handle $\mu p$ collider with the same CM energy. However, luminosity value, namely $L_{\mu p} = 3 \times 10^{33} cm^{-2}s^{-1}$, was extremely overestimated, a realistic value for this should be three orders smaller [5]. Then, construction of additional 200 GeV energy muon ring in the Tevatron tunnel in order to handle $\sqrt{s} = 0.9$ TeV $\mu p$ collider with $L_{\mu p} = 10^{32} cm^{-2}s^{-1}$ was considered in [6]. Also in Ref. [5] the ultimate case of muon beams with 50 TeV energy [2] had been taken into account as an option for 100 TeV CM energy $\mu p$ colliders assuming that a 50 TeV proton ring would be added into the $\mu C$ tunnel and a luminosity value $\sim 10^{33} cm^{-2}s^{-1}$ is estimated. The FCC based muon-proton and muon-lead ion colliders’ main parameter calculations were performed in a recent paper which considers beam-beam effects and a basic collider parameter optimization [7].

In Ref. [8], the physics potentials of $\mu p$ colliders with several energy and luminosity options (from $\sqrt{s} = 314$ GeV, $L_{\mu p} = 0.1 fb^{-1}$ per year to $\sqrt{s} = 4899$ GeV,

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$L_{\mu p} = 280 \, fb^{-1} \text{ per year}$) were studied. The sensitivity reach of each collider was calculated for some BSM phenomena such as R-parity violating squarks, leptoquarks, leptogluons and extra-dimensions. Similarly, R-parity violating resonances were examined for Tevatron based $\mu p$ collider with $\sqrt{s} = 0.9 \, TeV$ and $L_{\mu p} = 10^{32} \, cm^{-2} \, s^{-1}$ in [9]. In a recent study excited muon production was analyzed at muon-hadron colliders based on the FCC [10].

This paper shows a follow up work of our previous study which was based on the search potential of the FCC-based ep colliders on color octet electrons [11] (besides, there are number of papers devoted to the study of color octet electron production at the LHC [12–15] and LHeC [16–18]).

We now consider another design, namely, the construction of a muon ring tangential to the FCC, which is schematically shown in Fig. 1. The aim is to achieve the highest possible CM energies in lepton-hadron colliders in order to make some of the BSM physics research possible. Here, the physics potential of these future colliders is revealed by quantitatively exploring resonant production of color octet muons. Parameters of the FCC-based muon proton colliders are given in Table I. The first four colliders [7] use the most recent design parameters of MAP [1]. The last row corresponds to the ultimate case with 20 TeV muon beams in the FCC tunnel. 20 TeV choice is due to synchrotron radiation loss of muons which is desired to be limited at 1 GeV/turn for a muon accelerator with 100 km circumference [19].

### Table 1. Main parameters of the FCC based $\mu p$ colliders.

| Collider     | $E_\mu$ (TeV) | CM Energy (TeV) | $L_{int}$, fb$^{-1}$ (per year) |
|--------------|---------------|-----------------|---------------------------------|
| $\mu 630@$FCC| 0.063         | 3.55            | 0.02                            |
| $\mu 750@$FCC| 0.75          | 12.2            | 5                               |
| $\mu 1500@$FCC| 1.5           | 17.3            | 5                               |
| $\mu 3000@$FCC| 3.0           | 24.5            | 5                               |
| $\mu 20000@$FCC| 20           | 63.2            | 10                              |

The rest of the paper is organized as follows. In Section II, we present phenomenology of color octet muon. Section III covers signal-background analyses and is closed by giving the results of discovery limit searches of muon-proton colliders. Section IV addresses the determination of compositeness scales via muon-proton collider options under two possible cases regarding the results of the FCC. Finally, Section V contains summary of the obtained results.

### 2 Color octet muon

One of the possible answer to the problems mentioned in the Introduction may hide behind the concept of compositeness. Fermion-scalar and three-fermion models are the most proper options which enable known SM leptons to be constructed from more fundamental particles, namely preons. If the SM leptons are composed of color triplet fermions and color triplet scalars, then the mass of leptons to be constructed from more fundamental particles to be the most proper options which enable known SM leptons to be constructed from more fundamental particles, namely preons. If the SM leptons are composed of color triplet fermions and color triplet scalars, then the mass of leptons to be constructed from more fundamental particles to be the most proper options which enable known SM leptons to be constructed from more fundamental particles, namely preons. If the SM leptons are composed of color triplet fermions and color triplet scalars, then

$$\ell = (F S) = 3 \otimes 3 = 1 \oplus 8$$

(1)

$$\ell = (FFF) = 3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10.$$  (2)

Interaction lagrangian of $\ell_8$ with leptons and gluons can be written as

$$L = \frac{1}{2\Lambda} \sum_i \{ \bar{\ell}_8^i g_8 G_{\mu \nu}^{\alpha} \sigma^{\mu \nu} (\eta_L \ell_L + \eta_R \ell_R) + h.c. \}. \tag{3}$$

where $g_8$ is strong coupling constant, $\Lambda$ denotes compositeness scale, $G_{\mu \nu}$ is gluon field strength tensor, $\ell_{L(R)}$ stands for left (right) spinor components of lepton, $\ell = e, \mu, \tau$; $\sigma^{\mu \nu}$ is the antisymmetric tensor ($\sigma^{\mu \nu} = \frac{i}{2} [\gamma^\mu, \gamma^\nu]$), $\eta_L, (\eta_R)$ symbolizes chirality factor. Keeping in mind leptonic chiral invariance ($\eta_L, \eta_R = 0$), we take $\eta_L = 1$ and $\eta_R = 0$. Decay width of $\ell_8$ is given by

$$\Gamma(\ell_8 \to \ell + g) = \frac{\alpha_s M_{\ell_8}^3}{4\Lambda^2} \tag{4}$$

where $\alpha_s = g_8/4\pi$. Dependence of the decay width on the mass of $\mu_8$ is presented in Fig. 2 for $\Lambda = M_{\mu_8}$ and $\Lambda = 100 \, TeV$ cases.

![Fig. 1. Possible configuration of the FCC, linear collider (LC) and muon collider ($\mu$C).](image)
The resonant $\mu_8$ production (see Figure 3) cross sections for different stages of the FCC based $\mu p$ colliders from Table I were calculated using MadGraph5 event generator [20]. CTEQ6L1 parametrization [21] was used as parton distribution function and results were presented in Figure 4. MadGraph5-Pythia6 interface was used for parton showering and hadronization [22]. The same tools were used for the rest of the study and further calculations did not take detector effects into account.

Fig. 3. Feynman diagram for the resonant $\mu_8$ production.
Fig. 4. Resonant color octet muon production at the FCC based $\mu p$ colliders given in Table I for (a) $\Lambda = M_{\mu 8}$ and for (b) $\Lambda = 100$ TeV ($\mu p \rightarrow \mu 8 X \rightarrow \mu j X$).

3 Signal - Background Analysis

In this section, results of the numerical calculations are shown for the process $p\mu \rightarrow j\mu$ to leading order in order to analyze the search potential of the FCC based muon-proton colliders on the $\mu 8$ discovery via resonant production within $\Lambda = M_{\mu 8}$ scenario. Let us mention that jet corresponds to gluon for signal ($\mu g \rightarrow \mu 8 \rightarrow \mu g$ at partonic level) and quarks for main background ($\mu q \rightarrow \mu q$ through $\gamma$ and $Z$ exchanges) processes.

A staged approach was applied to determine mass limits as follows. $\mu 63$@FCC, the $\mu p$ collider with minimum CM energy, was chosen as the initial collider where discovery limit of $\mu 8$ mass was to be sought. After the discovery limit was determined, a worse scenario was considered where $\mu 8$ was assumed to have a larger mass. It was supposed that the previous collider had excluded $\mu 8$ mass up to the corresponding discovery limit and necessary cuts regarding this assumption were applied for the next higher CM energy $\mu p$ collider. Latter colliders follow the rows of Table I respectively. This procedure ends up with the ultimate $\mu p$ collider with CM energy 63.2 TeV which was given in the last row of the Table I. One should note that a sequential building of these colliders seems not to be the realistic case. Therefore, if a muon-proton collider is built, color-octet muon search discovery cuts would depend on up-to-date experimental exclusion limits.
Kinematical distributions of $\mu 63\otimes$FCC with generic cuts ($p_{T\mu} > 20$ GeV, $p_{Tj} > 30$ GeV) are given in Fig. 5. Reconsideration of the ATLAS/CMS results in the search for the second generation leptoquarks [23, 24] (which have the same decay channel as $\mu_6$) leads us to the strongest current limit on the color octet muon mass, $M_{\mu_6} \gtrsim 1$ TeV. Therefore, we chose the discovery cut for transverse momentum to be $p_{T\mu} > 350$ GeV on our initial $\mu p$ collider. This transverse momentum cut was applied on final state muon as well as leading-jet. In order to suppress the background while keeping the signal cross section as much as possible, the following pseudorapidity cuts were also applied: $2.00 < \eta_j < 4.00$, $0.5 < \eta_\mu < 4.74$. Maximum possible value of $\eta_\mu$ and $\eta_j$ was taken 4.74 which corresponds to 1° in proton direction. This value can be covered by very forward detector as in the LHeC case [25]. Effects of these discovery cuts can be seen by comparing Fig. 5(d) with Fig. 6 where invariant mass of $\mu_6$ was reconstructed from final state particles $\mu$ and leading-jet. After these cuts, cross sections of signals remained almost the same while background cross-section decreased remarkably.

Statistical significance ($SS$) is calculated using the formula below:

$$SS = \sqrt{2L_{int}\sqrt{(\sigma_S+\sigma_B)\ln(1+(\sigma_S/\sigma_B))}} - \sigma_S \quad (5)$$

where $\sigma_S$ and $\sigma_B$ denote cross-section values of signal and background, respectively. Integrated luminosity values, $L_{int}$, of each collider per year was estimated in [7]. Discovery ($SS = 5$) and observation ($SS = 3$) limits for $0.02 fb^{-1} \mu 63\otimes$FCC integrated luminosity were found to be 2380 and 2460 GeV, respectively. Regarding these results of the minimum energy $\mu p$ collider, $p_{T\mu} > 800$ GeV was considered appropriate for the next stage $\mu 750\otimes$FCC.
Table 2. Kinematical discovery cuts and observation (3σ) and discovery (5σ) limits for $\mu_8$ at different $\mu p$ colliders. Transverse momentum cuts are given in TeV. Significance values are calculated locally.

| Collider Name | $L_{int}, fb^{-1}$ | Kinematical Cuts | $M_{\mu_8} \pm PDF\% \pm scale\%$, TeV |
|---------------|------------------|-----------------|----------------------------------|
|               |                  | $p_{T_{min}}$ | $\eta_{\mu_{min}}$ | $\eta_{\mu_{max}}$ | $\eta_{j_{min}}$ | $\eta_{j_{max}}$ | $3\sigma$ | $5\sigma$ |
| $\mu 63\otimes$FCC | 0.02 | 0.350 | 0.5 | 4.74 | 2.0 | 4.0 | 2.46 | 2.38 |
|                 |                | $+2.60% +1.63%$ | $-1.83% -1.75%$ | $+1.34% +0.63%$ | $-1.15% -1.27%$ | $+1.46% +0.74%$ | $-1.20% -1.37%$ |
| $\mu 750\otimes$FCC | 5 | 0.800 | -1.3 | 4.74 | 1.0 | 4.1 | 9.60 | 9.21 |
|                 |                | $+1.30% +0.51%$ | $-1.01% -0.87%$ | $+1.36% +0.53%$ | $-1.14% -1.06%$ | |
| $\mu 1500\otimes$FCC | 5 | 3.00 | -1.7 | 4.74 | 0.7 | 3.9 | 13.8 | 13.2 |
|                 |                | $+1.22% +0.53%$ | $+1.27% +0.44%$ | $+1.36% +0.53%$ | $-1.01% -0.63%$ | $-1.22% -0.77%$ | |
| $\mu 3000\otimes$FCC | 5 | 4.40 | -2.1 | 4.74 | 0.3 | 3.5 | 18.9 | 18.1 |
|                 |                | $+1.27% +0.44%$ | $+1.22% +0.34%$ | $+1.61% +0.63%$ | $-1.29% -0.58%$ | $-1.37% -0.77%$ | |
| $\mu 20000\otimes$FCC | 10 | 6.00 | -2.7 | 4.74 | -0.7 | 2.7 | 42.7 | 41.5 |
|                 |                | $+1.57% +0.59%$ | $-1.01% -0.63%$ | $+1.61% +0.63%$ | $-1.40% -0.60%$ | $-1.37% -0.77%$ | |

and similar analyses were performed. These consecutive calculations gave us mass reach of each collider as given in Table II. Applied discovery cuts were also given in the same table and mass window formulation was kept same for all calculations: $M_{\mu_8} - 2\Gamma_{\mu_8} < M_{\mu_8} < M_{\mu_8} + 2\Gamma_{\mu_8}$.

Signal and background event numbers were calculated directly in this mass window without using any binning algorithm. Invariant mass distributions after discovery cuts related to higher energy colliders are presented in Figure 7.

![Invariant mass distributions](image)

Fig. 7. Invariant mass distributions for signal and background at a) $\mu 750\otimes$FCC, b) $\mu 1500\otimes$FCC, c) $\mu 3000\otimes$FCC and for d) the ultimate case $\mu 20000\otimes$FCC colliders after discovery cuts.
4 Limits on compositeness scale

If the $\mu_8$ is discovered by the FCC-pp option, $\mu p$ colliders will give opportunity to estimate compositeness scale. In this regard, two distinct possibilities should be considered:

a) $\mu_8$ is discovered by the FCC but not observed at $\mu$-FCC. In this case one can put lower limit on compositeness scale,

b) $\mu_8$ is discovered by the FCC and also observed at $\mu$-FCC. In this case one can determine compositeness scale.

In this section we present the analysis of these two possibilities for four different benchmark points, namely, $M_{\mu_8} = 2.5, 5, 7.5$ and $10$ TeV.

4.1 $\mu_8$ is discovered by the FCC but not observed at $\mu$-FCC

If we assume that $\mu_8$ mass is found out by FCC results then it is possible to determine optimal cuts for given $M_{\mu_8}$ at the $\mu$-FCC colliders. Let us start by consideration of $M_{\mu_8} = 5.0$ TeV at $\mu750$$\otimes$FCC.

It is seen from Fig. 8 that $-1.3 < \eta_\mu < 4.74$ and $0.7 < \eta_j < 3.3$ cuts drastically decrease the background whereas the signal is slightly affected. Similar cuts were determined for other $\mu$-FCC collider options and $M_{\mu_8}$ values and these optimal cuts were presented in Table III. Invariant mass window $0.99M_{\mu_8} < M_{\mu j} < 1.01M_{\mu_8}$ has been used in this particular analysis. $\mu63$$\otimes$FCC collider was not included in this section due to its remarkably low potential compared to the other options.

Applying cuts presented in Table III and $p_T > 350$ GeV for all cases one can estimate achievable lower limits on compositeness scale. Using Eq. 5 we obtain $\Lambda$ values given in Table IV. As expected, lower bounds on compositeness scale is decreased with increasing value of the $\mu_8$ mass. It is seen that multi-hundred TeV lower bounds can be put on the compositeness scale if $\mu_8$ is discovered at the FCC and not observed at any $\mu \otimes$ FCC.
Table 3. Optimal cuts for determination of compositeness scale lower bounds.

| Collider       | Cut Type | $\mu_8 = 2.5$ TeV | $\mu_8 = 5.0$ TeV | $\mu_8 = 7.5$ TeV | $\mu_8 = 10$ TeV |
|----------------|----------|-------------------|-------------------|------------------|------------------|
| $\mu750\otimes$FCC | $\eta_\mu$  | -1.7 4.74 -1.3 4.74 -1.2 4.74 - - |
|                | $\eta_j$   | 0.2 2.6 0.7 3.3 1.0 3.9 - - |
| Mass Window (GeV) |          | 2475 2525 4950 5050 7425 7575 - - |
| $\mu1500\otimes$FCC | $\eta_\mu$  | -2.3 4.74 -2.0 4.74 -1.8 4.74 -1.7 4.74 |
|                | $\eta_j$   | -0.6 1.9 -0.1 2.7 0.4 3.1 0.5 3.5 |
| Mass Window (GeV) |          | 2475 2525 4950 5050 7425 7575 9900 10100 |
| $\mu3000\otimes$FCC | $\eta_\mu$  | -2.9 4.74 -2.7 4.74 -2.5 4.74 -2.3 4.74 |
|                | $\eta_j$   | -1.4 1.4 -0.8 2.1 -0.4 2.6 -0.2 3.1 |
| Mass Window (GeV) |          | 2475 2525 4950 5050 7425 7575 9900 10100 |
| $\mu20000\otimes$FCC | $\eta_\mu$  | -3.9 4.74 -3.5 4.74 -3.3 4.74 -3.2 4.74 |
|                | $\eta_j$   | -3.0 -0.9 -2.5 0.1 -2.1 0.5 -1.9 1.0 |
| Mass Window (GeV) |          | 2475 2525 4950 5050 7425 7575 9900 10100 |

Table 4. Lower limits on compositeness scale in TeV units at the FCC based $\mu p$ colliders.

| Collider     | $L_{int}$, fb$^{-1}$ | $M_{\mu_8} = 2.5$ TeV | $M_{\mu_8} = 5.0$ TeV | $M_{\mu_8} = 7.5$ TeV | $M_{\mu_8} = 10$ TeV |
|--------------|----------------------|------------------------|------------------------|------------------------|------------------------|
| $\mu750\otimes$FCC | 5                    | 270 210 170 130 50 35 - - |
| $\mu1500\otimes$FCC | 5                    | 360 280 220 170 130 100 55 40 |
| $\mu3000\otimes$FCC | 5                    | 475 370 320 245 230 170 140 105 |
| $\mu20000\otimes$FCC | 10                   | 1390 1080 850 655 515 400 315 246 |
4.2 $\mu_8$ is discovered by the FCC and observed at $\mu$-FCC

In this case, the value of cross section at $\mu p$ colliders, which is inversely proportional to $\Lambda^2$ gives the opportunity to determine the compositeness scale directly. As an example, let us consider the $\mu_{1500}$-FCC case. In Fig. 9 we present $\Lambda$ dependence of $\mu_8$ production cross section for $M_{\mu_8} = 2.5, 5, 7.5$ TeV. Supposing that FCC discovers $\mu_8$ with 5 TeV mass and $\mu_{1500}$-FCC measures cross section as $\sigma_{\text{exp}} \sim 100$ fb, one can derive the compositeness scale as $\Lambda_{\text{exp}} \lesssim 70$ TeV.

![Fig. 9. Cross section distributions with respect to compositeness scale for $\mu_{1500}$-FCC collider.](image)

4.3 $\mu_8$ is not discovered by FCC but observed at $\mu$-FCC

Another possibility is the failure of $\mu_8$ search at the FCC. This can be caused by the value of color-octet muon mass, $M_{\mu_8}$, which can be greater than the discovery limit of the FCC itself. In this case, the advantages of $\mu$-FCC colliders with quite large discovery limits manifest themselves.

5 Conclusion

Discovery mass limits for $\mu_8$ at the muon, proton and FCC based $\mu p$ colliders are shown in Fig. 10. It is obvious that discovery mass limits for pair production of $\mu_8$ at muon colliders are approximately half of CM energies. Discovery limit values for LHC and FCC are obtained by rescaling ATLAS/CMS second generation LQ results [23, 24] using the method developed by G. Salam and A. Weiler [26]. Following [27], integrated luminosity values 3 ab$^{-1}$ and 20 ab$^{-1}$ have been used for the High Luminosity LHC (HL-LHC) and the FCC-hh, respectively. As can be seen from Fig. 10, FCC based $\mu p$ colliders with a discovery limit up to 40 TeV are the most advantageous among the other collider options for $\mu_8$ searches. Moreover, FCC based $\mu p$ colliders will give the opportunity to probe compositeness up to the PeV scale.

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Fig. 10. Mass discovery limits ($SS = 5$) of the color octet muon regarding different type of colliders, i.e. proton, muon and muon-proton.

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