Turkish Journal of Physics

http://journals.tubitak.gov.tr/physics/

Research Article

Turk J Phys
(2018) 42: 343 – 349
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doi:10.3906/fiz-1801-7

Single production of the excited muons at the SPPC-based ultimate μp collider

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Received: 09.01.2018 • **Accepted/Published Online:** 02.07.2018 • **Final Version:** 15.08.2018

Abstract: Single production potential of the excited muons at the SPPC-based ultimate muon-proton collider with center-of-mass energy of 116.6 TeV was analyzed. We calculated the production cross-sections and the decay widths of the excited muons with the process of $\mu p \to \mu^* X \to \gamma\mu X$. We obtained the normalized transverse momentum and pseudorapidity distributions of the final-state particles to attain the kinematical cuts for the discovery of the excited muons. With these cuts, we determined the mass limits. It was shown that the discovery limits on the mass of the excited muons are 19.6 and 10.1 TeV for $\lambda = m_{\mu*}$ and λ=50 TeV, respectively.

Key words: Excited muons, super proton-proton collider, muon-proton collider, mass limits

1. Introduction

The Standard Model (SM), the most persuasive theory in particle physics, provides excellent agreement with the results of various experiments. The detection of the Higgs boson in 2012 by the ATLAS and the CMS collaborations has also increased the reliability of the SM [1,2]. In spite of the outstanding success of being able to explain many phenomena in particle physics, there are some mysteries that the SM cannot explain. The family replication, quark-lepton symmetry, charge quantization, number of elementary particles, and dark matter are some of the unexplained issues. Therefore, many models beyond the SM (BSM) have been proposed to solve these issues. One of the most important of these models is the compositeness in which the SM fermions are made up of more fundamental particles called preons [3]. Within the scope of the revealed preonic models for many years, a lot of new particles such as excited leptons and quarks, color sextet quarks, leptoquarks, and dileptons have been suggested. As a result of the compositeness, it can be considered that the SM fermions are the ground states and the excited fermions are the excited states of these. The excited fermions may have spin-1/2 and spin-3/2 states, and their masses are expected to be heavier than those of the SM fermions. Thus, the discovery of the excited fermions will provide great evidence for the presence of the compositeness.

The most recent experimental results about the excited muon mass for pair and single production are provided by the OPAL and the ATLAS collaborations, respectively. $\mu*$ mass exclusion limits are $m_{\mu*} > 103.2$ GeV for $e^+e^- \to \mu * \mu*$, and $m_{\mu*} > 3000$ GeV for $pp \to \mu\mu * X$. For these limits on the excited muon mass, the compositeness scale (λ) is taken equal to$m_{\mu*}$, and the scaling factors are taken as $f = f' = 1$ [4].

Considerable phenomenological investigations have been recently carried out in the literature concerning the excited electron [5], muon [6], and neutrino [7]. In this paper, we investigated single production of the

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excited muons ($\mu*$) at the super proton-proton collider (SPPC)-based μp collider with center-of-mass energy of 116.6 TeV. We presented the SPPC-based ultimate μp collider option and its main parameters in Section 2, $\mu*$ effective interaction Lagrangian and decay width in Section 3, and production cross-sections and signal-background analysis in Section 4. Finally, we summarized our results in the last section.

2. SPPC-based ultimate μp colliders

The Large Hadron Collider (LHC) is the world's largest and most powerful particle collider built to date. Therefore, based on the LHC, we can consider the energy frontier colliders in three stages as prior-LHC ($<$2010), LHC era (2010–2030), and post-LHC ($>$2030). The LHC era, besides the LHC collider (pp, AA), includes important collider projects such as the International Linear Collider (ILC) [8] with a center-of-mass energy of 0.5 (1) TeV (e^-e^+), the low-energy muon collider ($\mu^-\mu^+$) [9], and the Large Hadron Electron Collider (LHeC) [10] with a center-of-mass energy of 1.3 TeV (ep, eA). The most important collider planned for the post-LHC era is the Future Circular Collider (FCC) [11] project with a center-of-mass energy of 100 TeV, proposed at CERN and supported by the European Union within the Horizon 2020 Framework Programme for Research and Innovation. The FCC collider will also provide the realization of FCC-based lepton-hadron (ep, μp) and photon-hadron (γp) collisions by constructing the appropriate accelerator structures tangentially to the FCC.

Following the discovery of the Higgs boson at CERN-LHC, new large colliders are being studied to explore Higgs physics in detail. In China, a two-stage circular collider project, called CEPC-SPPC (circular electron-positron collider – super proton-proton collider), is proposed for the post-LHC era. The first stage of the project is an electron-positron collider, the so-called Higgs factory, with a center-of-mass energy of 240 GeV to study the Higgs properties. The second stage is a proton-proton collider with center-of-mass energy of more than 70 TeV. The preliminary conceptual design report (Pre-CDR) of the project has been prepared and written [12] by the CEPC-SPPC study group. According to the Pre-CDR, the energy design goal of the SPPC is about 70 TeV using the same tunnel with the CEPC, which is about 54 km in circumference. Taking larger circumference options into consideration, different parameter sets of the SPPC collider are also evaluated [13,14]. Table 1 presents the main parameters of the SPPC collider including different design options.

Table 1. Main parameter options of the proton beam in the SPPC collider.

Parameters	SPPC-Pre-CDR	SPPC-54.7 km	SPPC-100 km	SPPC-100 km	SPPC-78 km
Beam energy (TeV)	35.6	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 (10^{35} cm^{-2} s^{-1})	1.1	1.2	1.52	1.02	1.52
Particles per bunch (10^{11})	2	2	2	2	2
Norm. RMS transverse emittance (μm)	4.10	3.72	3.65	3.05	3.36
Bunches per beam	5835	5835	10667	10667	8320
Bunches length (mm)	75.5	56.5	65	15.8	70.6
Beam-beam tune shift	0.006	0.0065	0.0067	0.008	0.0073

Various muon-proton colliders were proposed in the past. For example, construction of an additional 200 GeV energy muon ring in the Tevatron tunnel was proposed [15]. Similarly, it has recently been proposed to construct an additional muon collider ring with center-of-mass energy of 100 TeV in the SPPC tunnel [16]. Taking the energy option of 68 TeV into account, an ultimate muon-proton collider with center-of-mass energy of 116.6 TeV has been suggested. Main parameters of this collider are shown in Table 2. The present study intended to explore the production potential of the excited muons at this ultimate muon-proton collider.

Table 2. Main parameters of the SPPC-based ultimate muon-proton collider.

E_μ (TeV)	E_p (TeV)	$\sqrt{s}$ (TeV)	$L_{\mu p}$ ($cm^{-2}s^{-1}$)	L_{int} (fb^{-1})	ξ_μ	ξ_p
50	68	116.6	1.2×10^{33}	12	2.6×10^{-2}	3.5×10^{-2}

3. Effective Lagrangian and decay width

Excited leptons (and quarks) were first proposed by Terazawa and his team and have been discussed in detail since 1977 [17–19]. As a results of these studies, interaction between the excited muons, SM muons, and gauge bosons is described by the magnetic type effective Lagrangian [20] as:

$$L = \frac{1}{2\lambda}\bar{l}_R^{*}\sigma^{\mu\upsilon}\left[fg\frac{\vec{\tau}}{2}.\vec{W}_{\mu\upsilon} + f'g'\frac{Y}{2}B_{\mu\upsilon}\right]l_L + h.c \tag{1}$$

where λ denotes the compositeness scale or new physics scale; $l*$ and l represent the excited lepton and ground-state lepton, respectively; $\vec{W}_{\mu\upsilon}$ and $B_{\mu\nu}$ are the field strength tensors; $\vec{\tau}$ is the Pauli spin matrices; Y is hypercharge; g and g' are the gauge couplings; f and f' are the scaling factors for the gauge couplings of SU(2) and U(1); and $\sigma^{\mu\nu} = i(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)/2$ with γ^μ being the Dirac matrices.

The excited leptons decay into three channels: the γ-channel ($l* \to l\gamma$), Z-channel ($l* \to lZ$), and w-channel ($l* \to \nu w$). The branching ratios (BRs) of the excited muon for the coupling $f = f^{'} = 1$ and compositeness scale $\lambda = m_{\mu*}$ are given in Figure 1. The decay width of the excited leptons is expressed by the following formula:

$$(l^* \to lV) = \frac{\alpha m^{*3}}{4\ ^2} f_V^2 \left(1 - \frac{m_V^2}{m^{*2}}\right)^2 \left(1 + \frac{m_V^2}{2m^{*2}}\right), \tag{2}$$

where α is the electromagnetic coupling constant, m_v is the mass of the gauge boson, m^* is the mass of excited leptons, and f_v is the new electroweak coupling parameter corresponding to the gauge boson V, as $f\gamma = -(f+f)/2$, $fz = (-fcot\theta_w + f\tan\theta_w)/2$, $fw = f/\sqrt{2}sin\theta_w$, where θ_w is the weak mixing angle. We plotted the total decay width with respect to the excited muon mass by taking the compositeness scale equal to $m_{\mu*}$ and λ=50 TeV in Figure 2.

4. Signal and background analysis

The SPPC-based ultimate μp collider will enable searching for the excited muons via the $\mu p \to \mu * X$ process with subsequent decay of the excited muon into a photon and a muon. Therefore, we consider the process $\mu p \to \gamma\mu X$ and the subprocesses $\mu q\,(q) \to \gamma\mu q\,(q)$. We implemented the excited muon interaction vertices into CALCHEP version 3.6.25 [21], a high-energy simulation software. The signal and background analyses

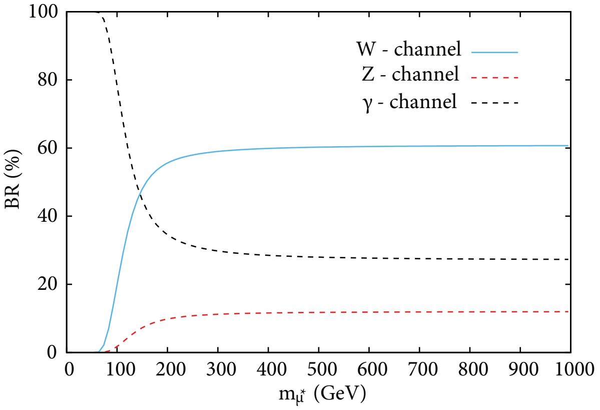

Figure 1. The branching ratios (%) depending on the mass of the excited muon for $f = f^{'} = 1$ and $\lambda = m_{\mu*}$.

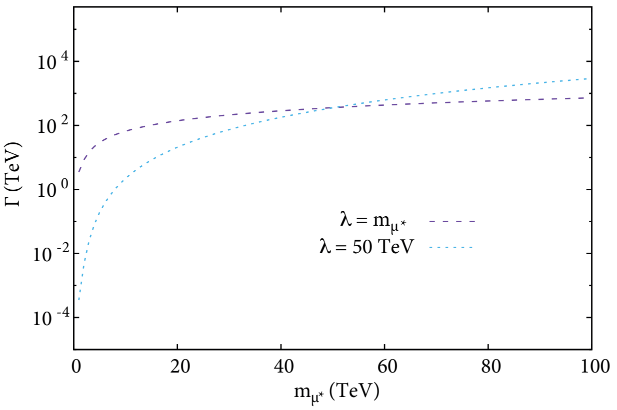

Figure 2. The total decay widths of the excited muons for $\lambda = \mathrm{m}_{\mu*}$ and $\lambda = 50$ TeV.

were done using this software. In our numerical calculations, we used the CTEQ6L1 [22] parton distribution functions.

Figure 3 shows the signal cross-section values with respect to $\mu*$ masses for the scale $\lambda = m_{\mu*}$ and $\lambda=$ 50 TeV, assuming the coupling parameter $f = f^{'} = 1$.

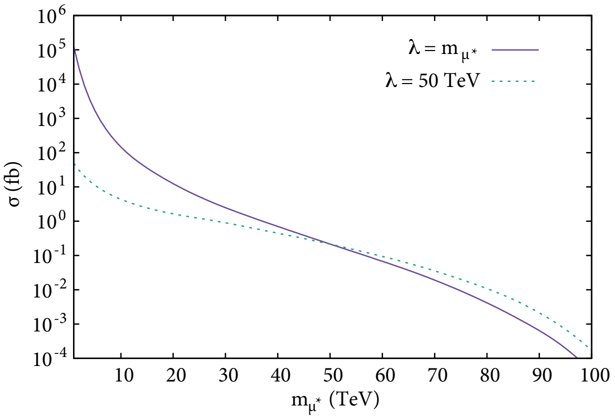

Figure 3. The total cross-sections of the excited muons for $\lambda = \mathrm{m}_{\mu*}$ and $\lambda = 50$ TeV.

The SPPC-based ultimate μp collider with center-of-mass energy of 116.6 TeV can search for the excited muons in a very large mass range. Taking into account the experimental mass limit (3 TeV) of the excited muons, we explored the mass limits for the discovery of the excited muons in the mass range from 3 to 116 TeV. To separate the signal from the background, we applied a generic cut, $p_T > 20$ GeV, to final-state particles (muon, photon, and jets). The SM cross-section after the application of these generic cuts was calculated as $\sigma_B = 662.57$ pb. In order to assign the kinematical cuts best suited for the discovery, we considered both the signal and background transverse momentum (p_T) and the pseudorapidity (η) distributions of the final-state particles. Figures 4 and 5 show the normalized p_T distributions (left) and the normalized η distributions (right) of the final-state muons and photons, respectively, for the signals corresponding to the excited muon masses of 3, 30, 60, and 90 TeV, and the SM background. As can be seen from these figures, the kinematical cuts $p_T^{\mu,\gamma} > 700$ GeV, $-5 < \eta^{\mu} < 4.4$, and $-5 < \eta^{\gamma} < 4$ drastically reduce the background while keeping the signal almost unchanged. The invariant mass distributions of the $\mu\gamma$ system after the application of all kinematical cuts are shown in Figure 6. It is clearly seen that peak values of the signal are above the background.

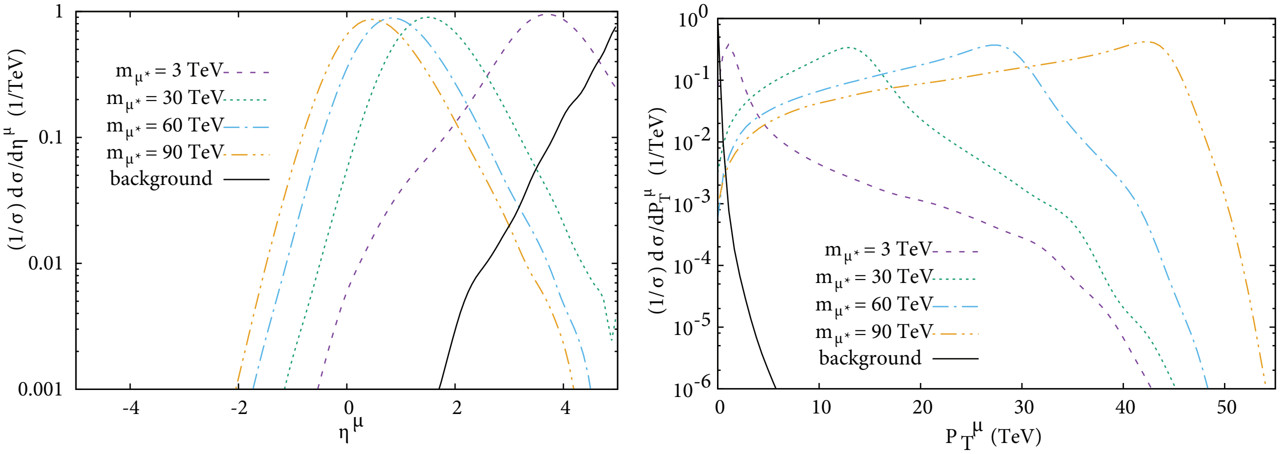

Figure 4. The normalized transverse momentum (left) and pseudorapidity distributions (right) of the final-state muons for $\lambda = \mathrm{m}_{\mu*}$ and $f = f^{'} = 1$.

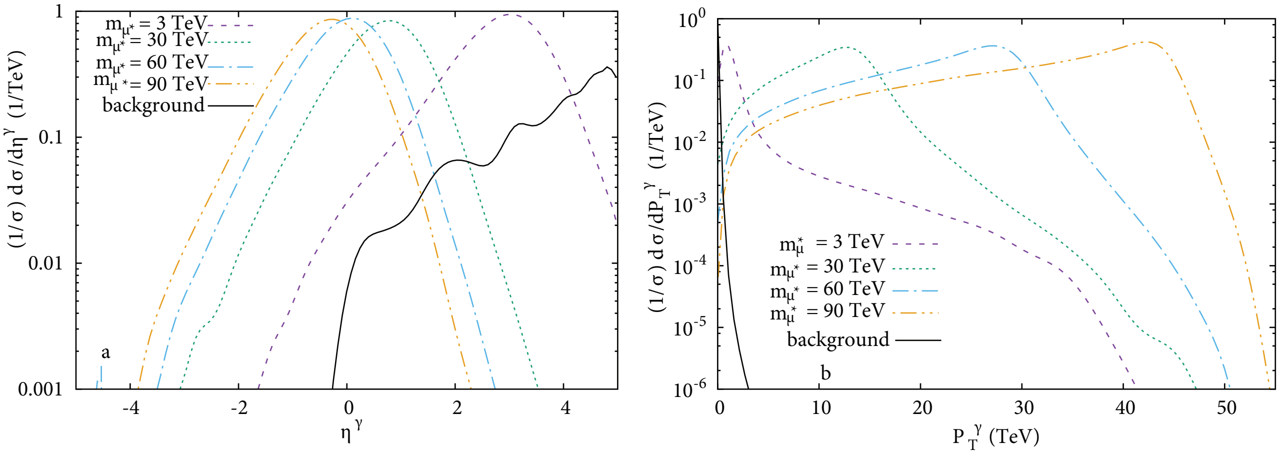

Figure 5. The normalized transverse momentum (left) and pseudorapidity distributions (right) of the final-state photons for λ= $\mathrm{m}_{\mu*}$ and $f = f^{'} = 1$.

In addition to kinematical cuts, we also applied a cut on the $\mu\gamma$ invariant mass as $m_{\mu*} - 2\;{}_{\mu*} < m_{\mu\gamma} < m_{\mu*} + 2\;{}_{\mu*}$, where ${}_{\mu*}$ is the decay width of the excited muon. We defined statistical significance (SS) of the expected signal as

$$SS = \sqrt{2[(S+B)\ln\left(1+\left(\frac{S}{B}\right)\right) - S]}, \tag{3}$$

where S and B denote event numbers of the signal and background, respectively. We calculated the mass limits for exclusion (2σ), observation (3σ), and discovery (5σ) of the excited muons for both $\lambda = m_{\mu*}$ and λ=50 TeV, assuming the coupling parameter $f = f^{'} = 1$. Our results are summarized in Table 3.

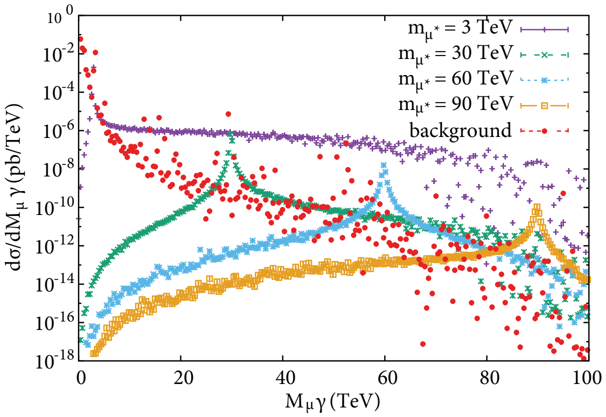

Figure 6. The invariant mass distributions, including the statistical errors of the excited muon signal and the background for $\lambda = m_{\mu*}$ and $f = f^{'} = 1$.

Table 3. The mass limits for the exclusion (2σ), the observation (3σ), and the discovery (5σ) of the excited muons at the SPPC-based muon-proton collider, assuming the coupling $f = f^{'} = 1$ and the energy scale $\lambda = m_{\mu*}$.

SS criteria	$\lambda = m_{\mu*}$	$\lambda =$ 50 TeV
2σ	32.5 TeV	13.2 TeV
3σ	24.3 TeV	11.7 TeV
5σ	19.6 TeV	10.1 TeV

5. Conclusion

It has been shown that the SPPC-based ultimate muon-proton collider has a significant potential for excited muon searches. We studied the excited muon signal and corresponding background at the SPPC-based ultimate muon-proton collider with center-of-mass energy of 116.6 TeV. In the simulations, we assumed the energy scale as $\lambda = m_{\mu*}$ and the coupling parameter as $f = f^{'} = 1$. Our analysis showed that the SPPC-based muon-proton collider can discover the excited muons up to 19.6 TeV for $\lambda = m_{\mu*}$ and 10.1 TeV for $\lambda =$ 50 TeV. As a result, the SPPC-based muon-proton collider offers the possibility to search for excited muons over a very large mass range.

Acknowledgments

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

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