Search for excited $u$ quark in dijet final states at future pp Colliders

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Abstract

Resonant production of excited $u$ quark at the Future Circular Collider and Super proton-proton Collider have been researched. Dominant jet-jet decay mode has been considered. It is shown that FCC and SppC have great potential for discovery of excited $u$ quark: up to 44 and 58 TeV masses, respectively. This discovery will also give an opportunity to determine the compositeness scale up to multi-PeV level.

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I. INTRODUCTION

Standard Model (SM) contains plenty of elementary particles and their parameters that are not completely explained. To overcome these unsolved problems that the SM does not give answers, new models have been developed beyond the Standard Model (BSM) such as supersymmetry, extra dimensions, string theory and composite models. These BSM theories require higher energy level than SM energy domain to bring solutions for unanswered problems. So, the SM is considered as low energy configuration of the more fundamental theory.

Numbers of particles and parameters in the SM are reduced in the frame of the composite models [1–16]. According to composite models, while SM quarks and leptons are predicted as composite particles, preons are considered as the most fundamental particles. If excited states of the SM fermions are experimentally observed, this observation will be clear proof of quarks and leptons’ compositeness.

Excited fermions are known as much more heavier particles than the SM fermions and they could be split into two classes: excited quarks (q*) and excited leptons (l*). These heavy particles could also have spin-1/2 and spin-3/2 states. From the first publication about excited leptons in 1965 [17] until today there have been plenty of phenomenological [18–38] and experimental [39–51] works performed on excited fermions.

Excited states of SM quarks might be shown in four possible final states with light jets, \( q^* \rightarrow jj, q^* \rightarrow \gamma j, q^* \rightarrow W j \) and \( q^* \rightarrow Z j \). Currently, the LHC puts experimental mass limits for all four final state cases [47, 51, 52] that are \( m_{q^*} = 6.0, 5.5, 3.2, \) and 2.9 TeV, respectively. Like SM fermions, excited fermions also have three families and we focused on \( u^* \) production which decays to dijet final states.

After the LHC physics mission is over, a new and more powerful collider will take place as an energy frontier discovery machine for the high energy physics. At CERN, Geneva, Future Circular Collider (FCC) [53] is planned for the next step with \( \sqrt{s} = 100 \) TeV. The other project, Super Proton Proton Collider (SppC) is planned in China at multi TeV center of mass (CM) energies [54], we chose \( \sqrt{s} = 136 \) TeV option in this work. Both projects promise very high luminosity. The FCC will be expected to reach 2500 \( fb^{-1} \) integrated luminosity in ten years (Phase I) and 15000 \( fb^{-1} \) integrated luminosity in 15 years (Phase II) [55–57]. Over all in 25 years, total integrated luminosity will be 17500 \( fb^{-1} \). On the other side, the
SppC will deliver \( pp \) collisions with 22500 \( fb^{-1} \) integrated luminosity in 15 years (See Tab. I).

| Collider Name | FCC | SppC |
|---------------|-----|------|
| \( \sqrt{s} \) (TeV) | 100 | 136 |
| Integrated Luminosity \( (fb^{-1}) \) | Phase I (10 Years) | Phase II (15 Years) |
| | 2500 | 15000 |
| | | 22500 |
| | 17500 | |

In this work, we explored spin-1/2 excited \( u \) quark \( (u^*) \) at the FCC and the SppC. In the following, we stated spin-1/2 excited quark interaction Lagrangian, decay widths and cross section values in section II, signal-background analysis to determine cuts in section III and attainable mass and compositeness scale \( (\Lambda) \) limits and conclusions in section IV.

II. INTERACTION LAGRANGIAN, DECAY WIDTHS and CROSS SECTIONS

As an effective interaction Lagrangian [20, 22, 25, 52], Equation 1 was utilized for the spin-1/2 excited quarks:

\[
L_{\text{eff}} = \frac{1}{2\Lambda} q_R^* \sigma^{\mu\nu} [g_s f_s \frac{\lambda_a}{2} G_{\mu\nu}^a + g f \frac{\tau^\rho}{\sqrt{2}} W_{\mu\nu}^\rho + g' f' \frac{Y}{2} B_{\mu\nu}] q_L + \text{h.c.} \tag{1}
\]

where, compositeness scale is represented as \( \Lambda \), \( q_R^* \) denotes right-handed excited quark, \( q_L \) depicts ground state left-handed quark, field strength tensors are \( G_{\mu\nu}^a \) for gluon, \( W_{\mu\nu}^\rho \) for SU(2), and \( B_{\mu\nu} \) for U(1). \( \lambda_a \), \( \frac{\tau^\rho}{\sqrt{2}} \), and \( Y \) are color parameters for gluon-quark interaction, Pauli spin matrices and weak hyper-charge, respectively. Gauge coupling constants are \( g_s \), \( g \), and \( g' \); and \( f_s \), \( f \), \( f' \) are free parameters that are taken as equal to 1 in numerical calculations. Interaction Lagrangian (Eq. 1) was implemented into CalcHEP [58] software by using LanHEP interface [59, 60]. In our calculations, CTEQ6L1 [61, 62] parton distribution function was used and factorizations and renormalization scale were taken equal to \( M_{q^*} \).
Partial decay widths of different channels are

$$\Gamma(u^* \rightarrow dW) = \frac{1}{32\pi} g_W^2 f_W^2 \frac{M_{u^*}^3}{\Lambda^2} \left(1 - \frac{m_W^2}{M_{u^*}^2}\right)^2 \left(2 + \frac{m_W^2}{M_{u^*}^2}\right)$$  \hspace{1cm} (2)$$

$$\Gamma(u^* \rightarrow uZ) = \frac{1}{32\pi} g_Z^2 f_Z^2 \frac{M_{u^*}^3}{\Lambda^2} \left(1 - \frac{m_Z^2}{M_{u^*}^2}\right)^2 \left(2 + \frac{m_Z^2}{M_{u^*}^2}\right)$$ \hspace{1cm} (3)$$

$$\Gamma(u^* \rightarrow ug) = \frac{1}{3} \alpha_s f_s^2 \frac{M_{u^*}^3}{\Lambda^2}$$ \hspace{1cm} (4)$$

$$\Gamma(u^* \rightarrow u\gamma) = \frac{1}{4} \alpha f_\gamma^2 \frac{M_{u^*}^3}{\Lambda^2}$$ \hspace{1cm} (5)$$

with \(f_Z = f T_3 \cos^2 \theta_W - f' (Y/2) \sin^2 \theta_W\), \(f_W = f/\sqrt{2}\), \(f_\gamma = f T_3 + f' Y/2\), \(g_W = \sqrt{4\pi\alpha/\sin \theta_W}\), and \(g_Z = g_W/\cos \theta_W\) here \(T_3\) is the third component of the weak isospin of \(u^*\). In Fig. 1, total decay widths were given for \(\Lambda = M_{u^*}\) and \(\Lambda = 100\) TeV by scanning excited quark mass from 6 TeV to 100 TeV. It is obviously seen that while \(u^*\) mass value is risen, decay widths are increased.

\[\text{Figure 1. Decay widths versus } u^* \text{ mass for both } \Lambda = M_{u^*} \text{ and } \Lambda = 100 \text{ TeV}\]

Basically, \(pp \rightarrow u^* + X \rightarrow ug + X\) is a signal process and 6 Feynman diagrams (Fig. 2) emerge with \(u^*\) that make contributions to signal cross section calculations.

In Fig. 3, excited \(u\) quark cross section values are plotted for the FCC (\(\sqrt{s} = 100\) TeV) and the SppC (\(\sqrt{s} = 136\) TeV) with \(\Lambda = M_{u^*}\) and \(\Lambda = 100\) TeV. When the compositeness
scale value is taken as equal to excited $u$ quark mass, cross section values are about 300 times higher at $M_{u^*} = 6$ TeV for both collider options. Indeed, it seems that $u^*$ could be produced at very high mass values for both collider options.

III. SIGNAL and BACKGROUND ANALYSIS

As mentioned in previous section signal process is defined as $pp \rightarrow u^* + X \rightarrow ug + X$. Background process which is used in calculation is $pp \rightarrow jj + X$, here $j$ denotes
$u, \bar{u}, d, \bar{d}, c, \bar{c}, s, \bar{s}, b, \bar{b}$ and $g$. It is important to determine transverse momentum ($P_T$), pseudo rapidity ($\eta$) and invariant mass ($M_{jj}$) cut values for selecting clear signal. To do so, final state particles distribution plots were checked (see Fig. 4). According these figures, $P_T$ cuts were applied as 2 TeV, $\eta$ cuts were determined as $|\eta| < 2.5$; the cone angle radius was chosen as $\Delta R > 0.5$ for both colliders. Additionally, invariant mass cuts were applied as $M_{u^*} - 2\Gamma_{u^*} < M_{jj} < M_{u^*} + 2\Gamma_{u^*}$ mass window for again both collider options, here $M_{u^*}$ denotes excited $u$ quark mass and $\Gamma_{u^*}$ is total decay widths of the $u^*$.

![Transverse momentum and $\eta$ distribution plots for FCC (left column) and SppC (right column).](image)

In order to calculate statistical significance, Eq. 6 is used:

$$SS = \frac{\sigma_S}{\sqrt{\sigma_S + \sigma_B}} \sqrt{L_{int}}$$

where, $\sigma_S$ and $\sigma_B$ denote signal and background cross section values, respectively and $L_{int}$ represents integrated luminosity. Using Eq. 6, we have calculated $u^*$ mass’ discovery ($5\sigma$), observation ($3\sigma$) and exclusion ($2\sigma$) limits on prospective frontier machines, namely FCC and SppC.
IV. RESULTS and CONCLUSIONS

Discovery, observation and exclusion limits on the mass of excited $u$ quark depending on integrated luminosity of the FCC and SppC for $\Lambda = M_{u^*}$ case were plotted in Fig. 5. It is seen that FCC-Phase I will give an opportunity to discover, observe or exclude $u^*$ up to $M_{u^*} = 38.2, 41.3$ or $43.8$ TeV, respectively. At the end of the FCC-Phase II, these values become $M_{u^*} = 44.1$ TeV ($5\sigma$), $M_{u^*} = 47.1$ TeV ($3\sigma$) and $M_{u^*} = 49.5$ TeV ($2\sigma$). On the other hand, corresponding values for SppC are $M_{u^*} = 58.4$ TeV ($5\sigma$), $M_{u^*} = 62.5$ TeV ($3\sigma$) and $M_{u^*} = 65.7$ TeV ($2\sigma$) that essentially exceed the FCC limits.

![Figure 5. Mass dependence on luminosity at all confidence levels for the FCC and SppC.](image)

In principle, compositeness scale might be quite higher than excited quark mass. If excited $u$ quark is not discovered at FCC or SppC, one can evaluate lower limits on compositeness scale. For illustration, we plot achievable compositeness scale depending on $u^*$ mass for ultimate luminosity values at both colliders were plotted in Fig. 6. Let us assume $u^*$ mass equals 20 TeV and it is not seen at FCC in resonant channel. Then, according to Fig. 6, this means that compositeness scale is larger than 12 PeV ($5\sigma$), 20 PeV ($3\sigma$) and 30 PeV ($2\sigma$).

In Fig. 7, necessary luminosities for observation and discovery of 20 TeV mass excited $u$ quark depending on compositeness scale were plotted for both energy-frontier colliders. As can be seen that if $\Lambda = 1000$ TeV, FCC will observe $u^*$ with 4500 $fb^{-1}$ integrated luminosity and $L_{int} = 12000$ $fb^{-1}$ is needed for discovery, which correspond to 12 and 19.5 operation years, respectively. Concerning the SppC, it will observe $u^*$ with 20 TeV mass within first year and discover it in 2 years if compositeness scale is equal to 1000 TeV.
In conclusion, FCC and SppC have great potential for discovery of excited $u$ quark: up to 44 and 58 TeV masses, respectively. This discovery will also give an opportunity to determine the compositeness scale up to multi-PeV level.

Figure 7. Compositeness scale - luminosity correlation plots for the FCC and SppC.

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