Resonance Production of Excited u-quark at FCC Based γp Colliders

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Received: date / Accepted: date

Abstract  Some Beyond the Standard Models suggested that fermions might have composite substructure. The existence of excited quarks is going to be the strong proof for the compositeness of Standard Model fermions. Therefore, the excited quarks have been investigated by the phenomenological and the experimental high energy physicists at various collider options for more than 40 years. The Future Circular Collider (FCC) is newly planned particle accelerator to be established at CERN. Beside the $\sqrt{s} = 100$ TeV proton-proton collisions, FCC includes electron-positron and electron-proton collision options. Construction of linear $e^-e^+$ colliders (or dedicated e-linac) tangential to the FCC will give opportunity to handle multi-TeV $ep$ and $γp$ collisions. We executed a simulation of the resonance production of the excited $u$ quark at FCC based $γp$ colliders with choosing both the polarized and unpolarized photon beams. It was showed that the Lorentz structure of the $q^* - q - γ$ vertex can be determined by the photon beam polarization. The attainable mass limits of excited $u$ quark reached the highest values when the polarized photon beam was chosen. The ultimate compositeness scale values, also, will be handled by appropriate choice of the photon beam polarization.

1 Introduction

The Standard Model (SM), the most reliable theory in particle physics, shows incredible consistency with experiments and reaches its last prediction after the CMS and the ATLAS collaborations, which both declared the detection of the Higgs boson \cite{1, 2} in 2012. Despite the marvelous success of the SM on wide range phenomena in particle physics, there are some unsolved mysteries that the SM does not explain. The quark-lepton symmetry, family replication, charge quantization, plenty numbers of elementary particles, parameters, etc. are unsolved issues in the SM frame. Therefore, numerous models are proposed to answer the mentioned problems. One of these approaches, compositeness, has an assumption that SM fermions are compound states of more fundamental particles called preons \cite{3–5}. Numerous preonic models have been suggested by particle physicists for more than forty years \cite{6–15}. Due to preonic interactions caused by preon models, plenty of new types of particles

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are expected, such as excited quarks and leptons, leptoquarks, leptogluons, diquarks, color sextet quarks, dileptons and so on.

Excited fermions are comprised of excited quarks ($q^*$) and leptons ($l^*$) that can be considered as the excited state of SM fermions. They could have spin-$1/2$ and spin-$3/2$ states and their masses are expected much heavier than the SM fermions. So, the discovery of excited fermions will be a direct proof of the SM quarks’ and leptons’ compositeness. After the first publication about the excited lepton which was written in 1965 [16], scores of theoretical, phenomenological [17–34] and experimental [35–47] researchers had been focused on proving the existence of excited fermions. The historical development of fundamental blocks of the matter [48] shows that new substructures of elementary particles are discovered by new experimental findings and this knowledge takes attention of particle physicists to do research on excited quarks and leptons.

Excited quarks decay into four final states with light jets ($q^* \rightarrow jj$), ($q^* \rightarrow j\gamma$), ($q^* \rightarrow jW$), and ($q^* \rightarrow jZ$). The most recent experimental results about excited quark mass are provided by CMS and ATLAS collaborations [41–47, 49]. $m_{q^*}$ mass exclusion limits are $m_{q^*} = 6.0$ TeV for $q^* \rightarrow jj$, $m_{q^*} = 5.5$ TeV for $q^* \rightarrow j\gamma$, $m_{q^*} = 3.2$ TeV for $q^* \rightarrow jW$, and $m_{q^*} = 2.9$ TeV for $q^* \rightarrow jZ$. For these experimental limits on excited quark mass, compositeness scale ($\Lambda$) is taken equal to $m_{q^*}$.

In this paper, we investigate resonant production of the up-type excited quark ($u^*$) with dijet final state at two different center of mass (CM) energies [50] of the Future Circular Collider (FCC) [51] based $\gamma p$-colliders [52]. We present the FCC based colliders options and their parameters, specifically $\gamma p$-colliders in the section 2, $q^*$ effective interaction Lagrangian and decay width in the section 3, and production cross sections and signal-background analysis using unpolarized and polarized photons in the section 4. Finally, outcomes of the $u^*$ mass limitations, the compositeness scale ($\Lambda$) searches and interpretation of our findings are presented in the last section.

2 FCC based $\gamma p$-colliders

Throughout the last 40 years of the particle accelerator development, some groups and collaborations proposed linac-ring type colliders (see reviews [53–59]). Concerning energy frontier lepton-hadron options, VLEPP+UNK, THERA and LHeC were proposed in the 1980s, 1990s, and 2000s, respectively. The latter option [60] is planned to be established at CERN around the 2020s. Furthermore, after the Large Hadron Collider (LHC) physics program are completed, the FCC [61] will be seen as experimental particle physics frontier machine by the high energy physics community. The FCC is planned nearly 4 times bigger circumferences (Figure 1) and about 7 times higher center of mass energy than the LHC. The FCC is considered as three options, the electron-positron (FCC-ee) [62], the proton-proton (FCC-pp) [63] and the electron-proton (FCC-ep) [61] colliders. To measure new findings with high precision, FCC-ee is an appropriate option, notwithstanding, FCC-pp and FCC-ep are needed for deep investigation of interactions. For example, all properties of the Higgs boson can be measured by FCC-ee whose collision energy varies between 91 and 350 GeV however further measurements like top quark Higgs bosons interaction could be achieved by FCC-pp at 100 TeV center of mass energy. Besides, quark substructure discovery might be happen at FCC-ep collider.

In respect of our research on excited quark, we focus on the FCC based $\gamma p$ collider. There are several options for lepton-hadron collision but we chose the FCC based electron-proton colliders with using International Linear Collider (ILC) and Plasma Weak Field
Fig. 1  Schematic drawing of the Future Circular Collider and the Linear Collider

Accelerator-Linear Collider (PWFA-LC) [50]. Besides the FCC based \( e\pi \) colliders, \( \gamma p \) colliders could be utilized by exploiting Compton backscattering [52, 64]. Main parameters of the \( e\pi \) and \( \gamma p \) colliders which we used in our calculations are listed in Table 1.

### Table 1  Energy and luminosity parameters of the ILC\( \otimes \)FCC and PWFA-LC\( \otimes \)FCC based \( e\pi \) and \( \gamma p \) colliders

| Collider Name | \( E_e \) (TeV) | \( E_{\text{max}} \) (TeV) | \( \sqrt{s}_{e\pi} \) (TeV) | \( \sqrt{s}_{\gamma p} \) (TeV) | \( \mathcal{L}_{\text{int}} \) (fb\(^{-1}\)/year) |
|---------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| ILC\( \otimes \)FCC | 0.5 | 0.42 | 10 | 9.1 | 10-100 |
| PWFA-LC\( \otimes \)FCC | 5 | 4.15 | 31.6 | 28.8 | 1-10 |

3 Excited quark interaction Lagrangian and decay width

Interaction between excited quarks, SM quarks and gauge bosons is described by the magnetic type effective Lagrangian [18, 20, 23, 49]:

\[
L_{\text{eff}} = \frac{1}{2A} q^* \sigma^{\mu\nu} [g_s f_s \lambda^a \frac{1}{2} F_{\mu\nu}^a + g f \tau \frac{1}{2} W_{\mu\nu} + g' f' Y \frac{1}{2} B_{\mu\nu}] (\eta_L \frac{1}{2} - \eta_R \frac{1}{2}) q + H.c.,
\]

where, \( A \) denotes compositeness scale, \( q^* \) and \( q \) represent excited quark and ground state quark respectively, \( F_{\mu\nu}^a, W_{\mu\nu}, B_{\mu\nu} \) are the field strength tensors for gluon, SU(2) and U(1), \( \lambda^a \) are \( 3 \times 3 \) Gell-Mann matrices, \( \tau \) is the Pauli spin matrices, \( Y = 1/3 \) is weak hypercharge,
$g_s, g, g'$ are gauge coupling constants, $f_s, f, f'$ are free parameters that are chosen equal to 1. $\eta_L$ and $\eta_R$ are the left-handed and the right-handed chirality factors, respectively. The normalization of the coupling was chosen such that $\max(|\eta_L|, |\eta_R|) = 1$ and chirality conservation requires $\eta_L\eta_R = 0$ [49].

We implemented this interaction Lagrangian into CalcHEP software [65] by using LanHEP [66, 67]. As we mention in Section 1, there are four decay channels for $q^*$ and we plotted total decay width with respect to excited quark mass by taking compositeness scale equals to $q^*$ mass and $\Lambda = 30$ TeV in Figure 2. It is seen that excited quark mass values correlated with decay widths positively.

![Fig. 2 $u^*$ decay width correlations with excited quark mass at $u^*$ mass equals to compositeness scale and $\Lambda = 30$ TeV](image)

4 Excited $u$-quark production via proton collisions with unpolarized and polarized photon at $\sqrt{s}_{pp} = 9.1$ and 28.8 TeV

In our calculation, we used two types of particle beams, proton and photon (see Section 2). 50 TeV proton beam comes from the FCC and we chose CTEQ6L quark distribution function [68, 69] in numerical calculations. On the other side, we have polarized and unpolarized high energy photon beams [70, 71] which are obtained from Compton backscattering [72] of laser beam on ILC or PWFA-LC electrons. Feynman diagram for resonant production of $u^*$ in photon-proton collisions is presented in Figure 3.

![Fig. 3 Feynman diagram for signal.](image)
4.1 Cross Sections

In numerical calculations, we chose $\eta_L = 1$, $\eta_R = 0$ option for interaction Lagrangian (Eq. 1). Then, in CalcHEP framework, we insert corresponding electron and proton energies and choose laser photon option which corresponds to Compton backscattering photons.

Figure 4 shows the cross section values with respect to $u^*$ mass for polarized (helicity $\gamma_H$ equals to 1 and -1) and unpolarized ($\gamma_H = 0$) photon beams colliding with proton beam at 9.1 TeV center of mass energy. It is seen that excited quark could be produced with sufficiently high cross section up to roughly 8 TeV both for $\Lambda = 10$ TeV and $\Lambda = M_{u^*}$.

Figure 5 represents the same plots like the previous one but this time, center of mass energy is 28.8 TeV. It is seen that excited quark production could be achieved at higher mass values than previous collider option due to high center of mass energy in this collider option.
4.2 Signal and Background Analysis

4.2.1 Final State Distributions and Cut Determination

Our signal process is $\gamma + p \rightarrow u^* + X \rightarrow u + g + X$, therefore, background processes are represented by $\gamma + p \rightarrow j + j + X$, where $j$ denotes $u, \bar{u}, d, \bar{d}, c, \bar{c}, s, \bar{s}, b, \bar{b}$, and $g$ jets. To assign cuts for identifying signal from background, we looked at the both signal and background transverse momentum ($P_T$), the pseudo rapidity ($\eta$), and the invariant mass distributions for the final state particles. Only plots for polarized photon-proton collision are presented as examples because we observed very slight differences between polarized and unpolarized states. It should be noted that we normalized cross section values to plot $P_T$ and $\eta$ distributions for obtaining the cuts.

Figure 6 demonstrates $P_T$ distributions of the signal and the background final state particles for both two center of mass energy options. It is seen that when the applied $P_T$ cut was taken 500 GeV for the $\sqrt{s} = 9.1$ TeV and 1000 GeV for the $\sqrt{s} = 28.8$ TeV, the background was reduced almost completely but the signal was remained nearly unchanged.

![Fig. 6](image_url) Normalized $P_T$ distributions of background and signal processes for $\sqrt{s} = 9.1$ TeV at the left panel and for $\sqrt{s} = 28.8$ TeV at the right panel.

When the colliding beams have different energies, asymmetry occurs in signal and background distributions. So, we extracted $\eta$ cuts using signal and background final state jet distributions at their crossing point of their right side limits that are shown for both center of mass energies in Figure 7. On the other hand, we applied $\eta$ cuts -5.2 for the left hand side of the $\eta$ distributions (this value was taken from the CMS experiment forward sub-detector limits [73]). We summarized all $\eta$ cuts in Table 2.

Invaraint mass distributions for signal and background processes are presented in Figure 8. It is seen that signal peak values are above the background, so we determined invariant mass cut as $M_{u^*} - 2\Gamma_{u^*}$ and $M_{u^*} + 2\Gamma_{u^*}$ mass window, where $M_{u^*}$ is $u^*$ mass and $\Gamma_{u^*}$ is the decay width of the $u^*$.

4.2.2 Mass Limits Dependence on Integrated Luminosity and Photon Beam Polarization

To extract signal from background, we used the cuts that were determined by distribution plots in previous subsection. Then, Equation 2 was utilized to calculate statistical significance,
Fig. 7 Normalized $\eta$ distributions of background and signal processes for $\sqrt{s} = 9.1$ TeV at the left panel and for $\sqrt{s} = 28.8$ TeV at the right panel.

Fig. 8 Signal and background invariant mass distributions for $\sqrt{s} = 9.1$ TeV (the left panel) and $\sqrt{s} = 28.8$ TeV (the right panel) with $\gamma_{H} = -1$.

Table 2 List of the pseudo rapidity cut limits for both center of mass energy options.

| $\sqrt{s}$ (TeV) | 9.1 | 28.8 |
|-----------------|-----|-----|
| $\gamma_{H}$    | -1  | 0   | -1  | 0   |
| Cut Limits      | Min | Max | Min | Max | Min | Max | Min | Max |
| $\eta_j$        | -5.2| 0.0 | -5.2| -0.2| -5.2| 2.1 | -5.2| 2.0 |

\[ S = \frac{\sigma_1}{\sqrt{\sigma_1 + \sigma_B}} \sqrt{\mathcal{L}_{\text{int}}} \quad (2) \]

where, $\sigma_1$ and $\sigma_B$ are signal and background cross section values, respectively, and $\mathcal{L}_{\text{int}}$ is the integrated luminosity. Obtained $u^*$ mass limits were listed in the Table 3 and 4 for both center of mass energies 9.1 TeV and 28.8 TeV colliders, respectively. According to Table 1, integrated luminosity values are 10-100 fb$^{-1}$ for ILC⊗FCC and 1-10 fb$^{-1}$ for PWFA-LC⊗FCC options. As expected, higher integrated luminosity increased mass limits for $u^*$. Besides, it is seen from Table 3 and 4 that photon beam polarization enhanced $u^*$ mass limits 0.21 TeV for 9.1 TeV CM and approximately 1.5 TeV for 28.8 TeV CM at their upper luminosity values if compared to unpolarized photon beam-proton collisions. In addition, the attainable best $u^*$ mass limits could be achieved when the $\Lambda = M_{u^*}$. 
Table 3  Excited u quark mass limits for 9.1 TeV center of mass energy γp collider.

| $\sqrt{s}$         | 9.1 TeV | 28.8 TeV |
|---------------------|---------|----------|
| $\mathcal{L}_{int}$ | 1 fb$^{-1}$ | 1 fb$^{-1}$ |
| $\Lambda$           | $M_{u^*}$ | $M_{u^*}$ |
| $5\sigma$           | 6.97     | 13.8     |
| $3\sigma$           | 7.41     | 17.4     |
| $2\sigma$           | 7.82     | 19.5     |
| $\gamma_{se}$       | 6.58     | 8.94     |
| Mass Limits (TeV)   | 7.27     | 14.2     |
| $M_{u^*}$           | 7.60     | 16.8     |
| $M_{u^*}$           | 7.99     | 14.9     |
| $M_{u^*}$           | 7.78     | 19.7     |
| $M_{u^*}$           | 7.78     | 19.7     |
| $M_{u^*}$           | 8.00     | 20.3     |
| $M_{u^*}$           | 8.00     | 20.3     |
| $M_{u^*}$           | 7.82     | 17.9     |
| $M_{u^*}$           | 8.00     | 20.3     |

In Figure 9, we scanned luminosity values needed for discovery ($5\sigma$), observation ($3\sigma$) and exclusion ($2\sigma$) of $u^*$ as a function of its mass. It is seen that photon beam polarization enhanced attainable mass limits of $u^*$.

Fig. 9  The first row represents luminosity and $u^*$ mass relations for $\sqrt{s} = 9.1$ TeV and the second row shows the same relations for $\sqrt{s} = 28.8$ TeV with $\Lambda = M_{u^*}$ at three different significance values. The left column corresponds to $\gamma_{se} = -1$ and the right panel corresponds to $\gamma_{se} = 0$. 
4.2.3 Attainable Compositeness Scale

We took compositeness scale equals to \( \alpha^* \) mass or some specific values as 10, 15, and 30 TeV until this subsection. Here, we scanned both the compositeness scale values and \( \alpha^* \) mass for discovery (5\( \sigma \)), observation (3\( \sigma \)) and exclusion (2\( \sigma \)) mass limits. It is seen from Figures 10 and 11 that the higher compositeness scales correspond to the lower \( \alpha^* \) mass values. As it was expected, when the center of mass energy reached the 28.8 TeV with the highest luminosity value, the compositeness scale values had risen to the high level for all \( \alpha^* \) mass spectra. Furthermore, the photon beam polarization will give opportunity to probe bigger compositeness scale values than the unpolarized photon beam-proton collision.

![Graphs showing compositeness scale and mass limits](image)

Fig. 10 The first row represents attainable \( \Lambda \) dependence on \( M_{\alpha^*} \) for \( \mathcal{L}_{\text{int}} = 10 \text{ fb}^{-1} \) and \( \sqrt{s} = 9.1 \text{ TeV} \). The second row shows the same relations for the same center of mass energy and \( \mathcal{L}_{\text{int}} = 100 \text{ fb}^{-1} \).

In Table 5 and 6, we summarize the highest attainable compositeness scale quantities for various \( M_{\alpha^*} \) values at the highest integrated luminosity values for both \( \gamma p \) collider options. It is clearly seen that when the photon beam polarization is in charge, compositeness scale values are increased for whole \( M_{\alpha^*} \) values. For instance, when we looked at the compositeness scale values for \( \sqrt{s} = 9.1 \text{ TeV} \) collider option with \( M_{\alpha^*} = 6 \text{ TeV} \), the \( \Lambda \) value increased to 70.5 TeV from 48.7 TeV at the 5\( \sigma \) significance. Similarly, the compositeness scale value rose to 77.9 TeV from 51.9 TeV for \( \sqrt{s} = 28.8 \text{ TeV} \) collider option with the same \( \alpha^* \) mass values at the 5\( \sigma \) significance.

4.2.4 Determination of the Lorentz Structure of the \( q^*-q-\gamma \) Vertex

The FCC-pp collider option will give opportunity to investigate \( M_{\alpha^*} \) up to 50 TeV mass limit [74] which essentially exceeds potential capacity of \( \gamma p \) collider options. However, the \( q^*-q-\gamma \) vertex could not be determined because the proton beams are unpolarized. The FCC based \( \gamma p \) colliders have capability to handle polarized photon beam which will allow to determine Lorentz structure of the excited quark interactions. Then, we executed asymmetry
Fig. 11 The first row represents attainable \( \Lambda \) dependence on \( M_{u^*} \) for \( \mathcal{L}_{\text{int}} = 1 \text{ fb}^{-1} \) and \( \sqrt{s} = 28.8 \text{ TeV} \). The second row shows the same relations for the same center of mass energy and \( \mathcal{L}_{\text{int}} = 10 \text{ fb}^{-1} \).

Table 5  Attainable top \( \Lambda \) limits for \( M_{u^*} \) with the \( \mathcal{L}_{\text{int}} = 100 \text{ fb}^{-1} \).

| CM (TeV) | 9.1 |
|----------|-----|
| \( M_{u^*} \) (TeV) | 6 | 7 | 6 | 7 |
| \( \Lambda \) (TeV) | 5\( \sigma \) | 70.5 | 30.8 | 48.7 | 21.2 |
| | 3\( \sigma \) | 117 | 51.3 | 81.2 | 35.4 |
| | 2\( \sigma \) | 176 | 76.9 | 122 | 53.1 |

Table 6  Attainable top \( \Lambda \) limits for \( M_{u^*} \) with the \( \mathcal{L}_{\text{int}} = 10 \text{ fb}^{-1} \).

| CM (TeV) | 28.8 |
|----------|-----|
| \( M_{u^*} \) (TeV) | 6 | 10 | 15 | 6 | 10 | 15 |
| \( \Lambda \) (TeV) | 5\( \sigma \) | 77.9 | 65.6 | 40.5 | 51.9 | 44.8 | 27.7 |
| | 3\( \sigma \) | 130 | 109 | 67.4 | 86.5 | 74.7 | 46.2 |
| | 2\( \sigma \) | 195 | 164 | 101 | 130 | 112 | 69.4 |

Calculations taking compositeness scales equals to \( u^* \) mass for \( \eta_L = 1 \), \( \eta_R = 0 \) and \( \eta_L = 0 \), \( \eta_R = 1 \) choices (\( \eta_L \) and \( \eta_R \) are chirality factors in Equation 1). Lorentz structure of the \( q^*-q-\gamma \) vertex are distinguished by looking at the asymmetry numbers given in the Table 7. Asymmetry calculation is done by Equation 3:

\[
\text{Asymmetry} = \frac{\sigma(\gamma_{\mathcal{H}} = 1) - \sigma(\gamma_{\mathcal{H}} = -1)}{\sigma(\gamma_{\mathcal{H}} = 1) + \sigma(\gamma_{\mathcal{H}} = -1)}
\]  

(3)
where $\alpha$ denotes asymmetry, $\sigma(\gamma_H = -1)$ corresponds to cross section numbers with helicity equals to -1, and $\sigma(\gamma_H = 1)$ represents to cross section numbers with helicity equals to 1.

Table 7 The polarization asymmetry for the excited $u$ quark

| CM (TeV) | $M_{u^*}$ (TeV) | $\gamma_H$ | $\eta_L = 1, \eta_R = 0$ | $\eta_L = 0, \eta_R = 1$ |
|----------|-----------------|------------|------------------------|------------------------|
|          | $\sigma$ (pb)   | $\alpha$   | $\sigma$ (pb)          | $\alpha$               |
| 9.1      | 6               | -1         | 4.15 $\times$ 10^{-5}  | -0.99                  | 8.07 $\times$ 10^{-5}  | 0.99 |
|          | -1              | 1.71 $\times$ 10^{-7} | 2.29 $\times$ 10^{-4}  | 2.78 $\times$ 10^{-4}  | 3.54 $\times$ 10^{-3}  | 0.98 |
| 28.8     | 10              | -1         | 1.39 $\times$ 10^{-1}   | -0.99                  | 4.34 $\times$ 10^{-4}  | 0.99 |
|          | -1              | 9.20 $\times$ 10^{-4} | 7.61 $\times$ 10^{-5}  | 7.61 $\times$ 10^{-5}  | 1.23 $\times$ 10^{-2}  | 0.99 |

5 Conclusion

In this work, we analyzed resonance production of the excited $u$ quark at the FCC based $\gamma p$ colliders that offers two possibilities: $\sqrt{s}_{\gamma p}^{\text{max}} = 9.1$ TeV with $\mathcal{L}_{\text{int}} = 10-100$ fb$^{-1}$ (ILC$\otimes$FCC) and $\sqrt{s}_{\gamma p}^{\text{max}} = 28.8$ TeV with $\mathcal{L}_{\text{int}} = 1-10$ fb$^{-1}$ (PWFA-LC$\otimes$FCC).

We did calculation of the $u^*$ mass limits for discovery (5$\sigma$), observation (3$\sigma$) and exclusion (2$\sigma$) confidence levels at the 10, 15, 30 TeV compositeness scales and at $\Lambda = M_{u^*}$, but the highest mass limits is achieved by taking $M_{u^*}$ equals to $\Lambda$. As seen from Table 3 and 4, the photon beam polarization increases the mass limits for all confidence levels. For $\gamma_H = -1$, $\Lambda = M_{u^*}$ and $\mathcal{L}_{\text{int}} = 100$ fb$^{-1}$, attainable mass limits are 7.99 TeV for 5$\sigma$, 8.23 TeV for 3$\sigma$ and 8.40 TeV for 2$\sigma$ at $\sqrt{s} = 9.1$ TeV collider option. Concerning the highest center of mass energy collider option ($\sqrt{s} = 28.8$ TeV), the biggest attainable mass limits become 19.4 TeV for 5$\sigma$, 21.1 TeV for 3$\sigma$ and 22.2 TeV for 2$\sigma$ confidence levels.

Besides the specific values of the compositeness scale, we scanned the compositeness scale with respect to $M_{u^*}$. Our calculation results show that the highest compositeness scale value is provided by the photon beam polarization (see Table 5 and 6). Compositeness scale values are evaluated as 77.9 TeV for 5$\sigma$, 130 TeV for 3$\sigma$ and 195 TeV for 2$\sigma$ at $\sqrt{s} = 28.8$ TeV with $\mathcal{L}_{\text{int}} = 10$ fb$^{-1}$, $M_{u^*} = 6$ TeV and $\gamma_H = -1$.

Certainly, if excited quarks mass lies in the region mention above, the FCC-pp collider will discover $u^*$ before the construction of FCC based $\gamma p$ colliders. However, latter ones will provide unique opportunity to determine Lorentz structure of $u^*-u\gamma$ vertex by using polarized photon beams.

Acknowledgements This study is supported by TÜBİTAK under the grant No 114F337. We thank Professor Yasar Onel for his support and contribution to form this work.
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