Anomalous production of fourth-family up-quarks
at future lepton hadron colliders

A. T. Alan\textsuperscript{1}, A. Senol\textsuperscript{1} and O. Çakır\textsuperscript{2}

\textsuperscript{1} Department of Physics, Abant Izzet Baysal University - 14280, Bolu, Turkey
\textsuperscript{2} Department of Physics, Ankara University, 06100 - Tandogan, Ankara, Turkey

(Received 16 March 2004; accepted 8 April 2004)

PACS. 12.60.-i – Models beyond the standard model.

Abstract. – We investigate the production of fourth-family up-type quarks using effective Lagrangian approach at future lepton-hadron colliders and study the kinematical characteristics of the signal with an optimal set of cuts. We obtain the upper mass limits 500 GeV at THERA and one TeV at Linac$\otimes$LHC.

Introduction. – As is well known, the Standard Model (SM) with three families is in excellent agreement with experimental data available today [1]. But it leaves some open questions. At the most fundamental level, the number of fermion generations and the origin of their mass hierarchy are not explained by the SM. For these reasons, and others, several models extending SM have been proposed [2–7]. Except the minimal $SU(5)$ GUT all these models accommodate extra fermion generations [8,9].

In the context of the search programs of future colliders, many analyses have been done for the production of fourth-generation quarks at the linear [10–12] and at hadron colliders [13]. The potentials of the future lepton-hadron colliders in the new physics searches are comparable to those of the linear and hadron colliders [14]. Thus, in this study, we investigate the possibility of a single production of a fourth-family up-quark ($u_4$) suggested by the effective Lagrangian approach. In this approach, the most general effective Lagrangian, which describes the Flavour Changing Neutral Current (FCNC) interactions between $u_4$ and ordinary quarks, involving electroweak boson and gluon, is given as follows [15,16]:

\begin{equation}
\mathcal{L}_{\text{eff}} = \sum_{U=u,c} \frac{i e e_U}{\Lambda} \kappa_{\gamma,u_4} \bar{u}_4 \sigma_{\mu\nu} q_{\nu} U A^\mu + \frac{g}{2 \cos \theta_W} \bar{u}_4 \left[ \gamma_\mu (v_{Z,U} - a_{Z,U} \gamma^5) + i \frac{\kappa_{Z,u_4}}{\Lambda} \sigma_{\mu\nu} q_{\nu} \right] U Z^\mu +
\end{equation}

\begin{equation}
+ i \frac{g_s}{\Lambda} \kappa_{g,u_4} \bar{u}_4 \sigma_{\mu\nu} q_{\nu} \frac{\lambda^i}{2} U G^{i\mu} + \text{H.c.},
\end{equation}

where $\sigma_{\mu\nu} = (i/2) [\gamma_\mu, \gamma_\nu]$, $\theta_W$ is the Weinberg angle, $q$ is the four-momentum of the exchanged boson; $e$, $g$ and $g_s$ denote the gauge couplings relative to $U(1)$, $SU(2)$ and $SU(3)$ symmetries, respectively; $e_U$ is the electric charge of up-type quarks, $A^\mu$, $Z^\mu$ and $G^{i\mu}$ the fields of the photon, $Z$-boson and gluon, respectively; and $\Lambda$ denotes the scale up to which the effective theory is assumed to hold. By convention, we set $\Lambda = m_{u_4}$, the mass of the fourth-family quark in the following.

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The anomalous production of fourth-family up-quark. – The parton level subprocess responsible for the \( u_4 \) production in ep collisions is \( eq \to eu_4 \). The kinematics of this process is the same as that of the single top quark production via FCNC interactions, which was presented in one of our earlier works [17]. Here, we present the total production cross-sections as functions of \( m_4 \) mass in figs. 1 and 2. In fig. 1, we display the cross-sections as functions of the mass of \( u_4 \), at future lepton-hadron collider THERA with the center-of-mass energy \( \sqrt{S} = 1 \text{ TeV} \) and with the luminosity of \( L = 4 \cdot 10^{30} \text{ cm}^{-2} \text{s}^{-1} \) [18]. Figure 2 shows the behaviour of the cross-section as a function of \( m_4 \) at Linac \( \otimes \) LHC with \( \sqrt{S} = 5.3 \text{ TeV} \) and with the luminosity of \( L = 10^{33} \text{ cm}^{-2} \text{s}^{-1} \) [19]. In these figures the lower lines correspond to the photonic channel only and the upper lines correspond to the sum of \( \gamma \) and \( Z \) exchange diagrams. Graphs in figs. 1 and 2 were computed by taking the illustrative anomalous coupling values \( \kappa_\gamma = \kappa_Z = 0.1 \). In obtaining the mentioned behaviour of the cross-sections we have taken into account both up and charm quark distributions [20,21]. The charm quark is present inside the proton as part of the quark-antiquark sea and gives considerable contribution to the cross-section.

We assume the anomalous decays of \( u_4 \) quark to be dominant, which is different from the case of top-quark decays where the SM decay mode is dominant. In table I, we present the branching ratios and the total decay widths of \( u_4 \) quark via anomalous interactions. SM decay modes are negligible for \( \kappa/\Lambda > 0.01 \text{ TeV}^{-1} \) due to the small magnitude of the extended CKM matrix elements \( V_{u_4b} \) [22,23].

In order to enrich the statistics for the experimental observations of the signal, we also take

| Mass (GeV) | \( gu(c) \) | \( gt \) | \( Zu(c) \) | \( Zt \) | \( \gamma u(c) \) | \( \gamma t \) | \( \Gamma(\text{GeV}) \) |
|------------|-------------|---------|-------------|---------|--------------|--------------|----------------|
| 300        | 3.1         | 0.9     | 70.5        | 25.2    | 0.1          | 0.04         | 7.15           |
| 400        | 1.4         | 0.8     | 61.1        | 36.6    | 0.07         | 0.04         | 20.12          |
| 500        | 0.8         | 0.6     | 57.3        | 41.2    | 0.04         | 0.03         | 42.31          |
| 600        | 0.5         | 0.4     | 55.2        | 43.8    | 0.03         | 0.02         | 76.29          |
| 700        | 0.4         | 0.3     | 53.9        | 45.4    | 0.02         | 0.02         | 124.45         |
into account $\bar{u}_4$ production through the subprocess $e\bar{q} \rightarrow e\bar{u}_4$. The contribution of this process is relatively small when compared with the $u_4$ production due to the sea quark distribution in the proton. Tables II and III present the total production cross-sections of $u_4$ and $\bar{u}_4$ in addition to the number of signal and background events in various decay channels of $u_4$ at THERA and Linac $\otimes$ LHC, respectively.

When the fourth-family $u_4$ (or $\bar{u}_4$) quarks are produced, they will decay via FCNC interactions giving rise to the signal $e^-qV$, where $q = u, c, t$ (or $\bar{u}, \bar{c}, \bar{t}$) and $V$ denotes the neutral gauge bosons $\gamma$, $Z$, $g$.

We consider the relevant backgrounds from the following subprocesses:

$$
eq \rightarrow e\gamma,$$

$$
eq \rightarrow e\gamma Z,$$

$$
eq \rightarrow e\gamma g,$$

where $q = u, c$ (or $\bar{u}, \bar{c}$). The cross-sections for these backgrounds are shown in table II (at THERA) and table III (at Linac $\otimes$ LHC) for the minimal cuts $p_T^{e\gamma} > 10$ GeV and optimal cuts $p_T^{e\gamma} > 20$ GeV and $M_{\gamma V} > 250$ GeV on the final-state particles. From table II we conclude that the number of signal events for $u_4 \rightarrow gq$ and $u_4 \rightarrow Zq$ ($q = u, c$) channels is promising, which makes it possible to observe a $u_4$ production signal at the THERA, especially for low-lying $u_4$-quark mass values (300–500 GeV). As can be seen from table III, it will be possible to observe the anomalous production of $u_4$ quark in all decay channels if the corresponding background is kept at a low level at Linac $\otimes$ LHC collider. We found that $u_4$

### Table II – Number of signal and background events in various decay channels of $u_4$-quark at THERA with $\sqrt{S} = 1$ TeV and $L = 40$ pb$^{-1}$ with corresponding total cross-section in pb. $B_1$ and $B_2$ denote the number of background events with the cuts $(p_T^{e\gamma} > 10$ GeV) and $(p_T^{e\gamma} > 20$ GeV, $M_{\gamma V} > 250$ GeV), respectively.

| Mass (GeV) | $g u(c)$ | $g t$ | $Z u(c)$ | $Z t$ | $\gamma u(c)$ | $\gamma t$ | $\sigma_{tot}(e u(c) \rightarrow e u_4)$ | $\sigma_{tot}(e \bar{u}(c) \rightarrow e \bar{u}_4)$ | $B_1$ | $B_2$ |
|------------|----------|-------|----------|-------|---------------|------------|----------------------------------|---------------------------------|------|------|
| 300        | 12.4     | 3.6   | 280.1    | 100.3 | 0.56          | 0.17       | 6.67                             | 3.26                            |      |      |
| 400        | 4.1      | 2.2   | 176.6    | 105.8 | 0.20          | 0.10       | 4.57                             | 2.66                            |      |      |
| 500        | 1.7      | 1.2   | 117.8    | 84.6  | 0.08          | 0.06       | 3.02                             | 2.12                            |      |      |
| 600        | 0.7      | 0.6   | 75.9     | 60.1  | 0.04          | 0.03       | 1.88                             | 1.55                            |      |      |
| 700        | 0.3      | 0.3   | 43.3     | 36.4  | 0.02          | 0.01       | 1.05                             | 0.96                            |      |      |
| $B_1$      | 17440    |       | 6.7      |       | 1152          |            |                                  |                                 |      |      |
| $B_2$      | 20.3     |       | 1.3      |       | 41.2          |            |                                  |                                 |      |      |

### Table III – Number of signal and background events in various decay channels of $u_4$-quark at Linac $\otimes$ LHC with $\sqrt{S} = 5.3$ TeV and $L = 10^4$ pb$^{-1}$ with corresponding total cross-section in pb. $B_1$ and $B_2$ denote the number of background events with the cuts $(p_T^{e\gamma} > 10$ GeV) and $(p_T^{e\gamma} > 20$ GeV, $M_{\gamma V} > 250$ GeV), respectively.

| Mass (GeV) | $g u(c)$ | $g t$ | $Z u(c)$ | $Z t$ | $\gamma u(c)$ | $\gamma t$ | $\sigma_{tot}(e u(c) \rightarrow e u_4)$ | $\sigma_{tot}(e \bar{u}(c) \rightarrow e \bar{u}_4)$ | $B_1$ | $B_2$ |
|------------|----------|-------|----------|-------|---------------|------------|----------------------------------|---------------------------------|------|------|
| 300        | 6423.1   | 1835.2| 144692.4 | 51786.5| 286.7         | 86.0       | 13.97                            | 6.54                            |      |      |
| 400        | 2696.1   | 1423.3| 115137.5 | 68945.8| 131.1         | 65.5       | 13.06                            | 5.78                            |      |      |
| 500        | 1459.8   | 984.3 | 101194.3 | 72720.7| 70.9          | 50.0       | 12.36                            | 5.29                            |      |      |
| 600        | 890.8    | 681.2 | 91990.9  | 72926.4| 45.8          | 34.9       | 11.74                            | 4.92                            |      |      |
| 700        | 592.3    | 488.3 | 85088.9  | 71614.7| 30.4          | 25.4       | 11.15                            | 4.63                            |      |      |
| $B_1$      | $1.9 \times 10^7$ |   | $1.2 \times 10^4$ |   | $1.4 \times 10^6$ | |                                 |                                 |      |      |
| $B_2$      | $6.5 \times 10^4$ |   | $3.3 \times 10^3$ |   | $5.1 \times 10^3$ | |                                 |                                 |      |      |
production signal at this machine is observable down to the anomalous coupling $\kappa_{V,u_4} = 0.01$ at the mass of $u_4$-quark about 700 GeV. For the channels including top quark in the final state ($e^-Vt$) we obtain very low number of background events, therefore we have not shown them in tables II and III.

Assuming Poisson statistics, we use the significance formula $S/\sqrt{B} \geq 3$ for signal observation at the 95% CL, where the number of signal and background events $S$ and $B$ are calculated by multiplying the cross-section with corresponding branching ratios depending on the decay channels and the integrated luminosities of the colliders considered.

Conclusion. – In this study, we have considered the anomalous single production of fourth-family up-quarks via the FCNC couplings at future ep colliders. We have shown that the reaction $eq \rightarrow eu_4$ can take place at an observable rate at these colliders. Hence, the fourth-family up-quark will manifest itself at THERA and Linac $\otimes$ LHC with masses below 500 GeV and 1 TeV, respectively. Thus the future lepton-hadron colliders have promising potential in searching for manifestations of non-standard physics.

This work is partially supported by Abant Izzet Baysal University Research Found.

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