Anomalous single production of the fourth SM family quarks at Tevatron

E. Arik\textsuperscript{a}, O. Cakır\textsuperscript{b}, S. Sultansoy\textsuperscript{c,d}

\textsuperscript{a}) Boğaziçi University, Faculty of Arts and Sciences, Department of Physics, 80815, Bebek, Istanbul, Turkey
\textsuperscript{b}) Ankara University, Faculty of Science, Department of Physics, 06100 Tandoğan, Ankara, Turkey
\textsuperscript{c}) Gazi University, Faculty of Arts and Sciences, Department of Physics, 06500, Teknikokullar, Ankara, Turkey
\textsuperscript{d}) Azerbaijan Academy of Sciences, Institute of Physics, H. Cavid Av., 33, Baku, Azerbaijan

Abstract

Possible single productions of fourth family $u_4$ and $d_4$ quarks via anomalous $q_4 q V$ interactions at Tevatron are studied. Signature of such processes are discussed and compared with the recent results from Tevatron.

The flavor democracy enforces the existence of the fourth Standard Model (SM) family \cite{1, 2}. The masses of the fourth family quarks are expected to be degenerate and lie between 300 GeV and 700 GeV (see \cite{3} and references therein).

It is clear that the pair production of the fourth family quarks will be copious at CERN LHC \cite{4, 5}. In addition, extra SM generations will yield an essential enhancement in Higgs production at LHC and Tevatron \cite{6, 7, 8}. Furthermore, the future lepton colliders will be the best place to observe the fourth SM family leptons \cite{9, 10}.
Together with the indirect manifestation of the fourth SM family via enhancement of the Higgs boson production, the fourth family quarks can also be observed at Tevatron if anomalous $q_4 V$ interactions exist. The arguments given in [11] for anomalous interactions of the top quark are more valid for $u_4$ and $d_4$ since they are expected to be heavier than the top quark.

In this work, we present a preliminary analysis of the anomalous single production of $u_4$ and $d_4$ quarks at Tevatron. The recent observation of excess of events with the final state containing $W + 2, 3$ jets [12, 13, 14] can be interpreted as the signature of these processes.

The effective Lagrangian for the anomalous interactions between the fourth family quarks, ordinary quarks and the gauge bosons $V$ ($V = \gamma, Z, g$) can be written as follows:

$$L = \frac{\kappa_{\gamma}^{q_i}}{\Lambda} e_q g_{\gamma} \bar{q}_4 \sigma_{\mu\nu}(A_{\gamma}^{q_i} + B_{\gamma}^{q_i} \gamma_5) q_i F^{\mu\nu} + \frac{\kappa_{Z}^{q_i}}{2\Lambda} g_Z \bar{q}_4 \sigma_{\mu\nu}(A_{Z}^{q_i} + B_{Z}^{q_i} \gamma_5) q_i Z^{\mu\nu}$$

$$+ \frac{\kappa_{g}^{q_i}}{\Lambda} g_s \bar{q}_4 \sigma_{\mu\nu}(A_{g}^{q_i} + B_{g}^{q_i} \gamma_5) T^a q_i G_a^{\mu\nu} + h.c. \quad (1)$$

where $F^{\mu\nu}$, $Z^{\mu\nu}$, and $G^{\mu\nu}$ are the field strength tensors of the photon, $Z$ boson and gluons, respectively; $T^a$ are Gell-Mann matrices; $e_q$ is the charge of the quark; $g_{\gamma}, g_Z$, and $g_s$ are the electroweak, and the strong coupling constants respectively. $g_{Z} = g_{e}/ \cos \theta_W \sin \theta_W$ where $\theta_W$ is the Weinberg angle. $A_{\gamma,Z,g}^{q_i}$ and $B_{\gamma,Z,g}^{q_i}$ are the magnitudes of the neutral currents; $\kappa_{\gamma,Z,g}^{q_i}$ define the strength of the anomalous couplings for the neutral currents with a photon, a $Z$ boson and a gluon, respectively; $\Lambda$ is the cutoff scale for the new physics.

We assume all the neutral current magnitudes in Eq. (1) to be equal, satisfying the constraint $|A|^2 + |B|^2 = 1$ and redefine all anomalous couplings:

$$\kappa_{\gamma}^{q_i} = \kappa_{Z}^{q_i} = \kappa_{g}^{q_i} = \lambda^{(4-i)} \quad (2)$$

where generation number $i = 1, 2, 3, 4$. We have implemented the new interaction vertices into the CALCHEP [15] package. Two values of $\lambda$ are considered ($\lambda = 1, 0.5$) as an example. Table 1 and 2 (3 and 4) present the branching ratios and the total decay widths of the $u_4$ ($d_4$) quark via anomalous interactions. Note that the branching ratios are independent of $\Lambda$ whereas total decay width is proportional to $\Lambda^{-2}$. SM decay modes are negligible for $\lambda/\Lambda > 0.01$ TeV due to the small magnitude of the extended Cabibbo-Kobayashi-Maskawa matrix elements $V_{ub}$ and $V_{dt}$ [16].
Table 1: Branching ratios (%) and total decay widths for $u_4$ ($\lambda = 1, \Lambda = 1$ TeV).

| Mass (GeV) | $gu(c)$ | $gt$ | $ Zu(c)$ | $ Zt$ | $\gamma u(c)$ | $\gamma t$ | $\Gamma$ (GeV) |
|-----------|---------|------|---------|------|--------------|------------|-------------|
| 200       | 47      | 0.6  | 2.2     | -    | 0.99         | 0.031      | 1.39        |
| 250       | 44      | 5.8  | 2.4     | -    | 0.93         | 0.12       | 2.91        |
| 300       | 41      | 12   | 2.4     | 0.46 | 0.86         | 0.25       | 5.41        |
| 400       | 36      | 19   | 2.3     | 1.1  | 0.77         | 0.41       | 14.26       |
| 500       | 34      | 23   | 2.2     | 1.5  | 0.73         | 0.49       | 29.53       |
| 600       | 33      | 25   | 2.2     | 1.7  | 0.71         | 0.54       | 52.82       |
| 700       | 33      | 27   | 2.2     | 1.8  | 0.69         | 0.57       | 85.69       |

Table 2: The same as Table 1, but for $\lambda = 0.5$.

| Mass (GeV) | $gu$ | $gc$ | $gt$ | $ Zu$ | $ Zc$ | $ Zt$ | $\gamma u$ | $\gamma c$ | $\gamma t$ | $\Gamma$ (GeV) |
|-----------|------|------|------|------|------|------|------------|------------|------------|-------------|
| 200       | 18   | 72   | 3.7  | 0.86 | 3.4  | -    | 0.38       | 1.5        | 0.079      | 0.06        |
| 250       | 13   | 53   | 28   | 0.73 | 2.9  | -    | 0.28       | 1.1        | 0.6        | 0.15        |
| 300       | 9.7  | 39   | 45   | 0.58 | 1.3  | 1.7  | 0.21       | 0.83       | 0.95       | 0.35        |
| 400       | 6.9  | 27   | 58   | 0.43 | 1.7  | 3.4  | 0.15       | 0.58       | 1.2        | 1.18        |
| 500       | 5.8  | 23   | 63   | 0.38 | 1.5  | 4.0  | 0.12       | 0.49       | 1.3        | 2.72        |
| 600       | 5.3  | 21   | 69   | 0.35 | 1.4  | 4.3  | 0.11       | 0.45       | 1.4        | 5.15        |
| 700       | 5.1  | 20   | 67   | 0.34 | 1.4  | 4.4  | 0.11       | 0.43       | 1.4        | 8.62        |

Table 3: Branching ratios (%) and decay widths for $d_4$ ($\lambda = 1, \Lambda = 1$ TeV).

| Mass (GeV) | $gd(s, b)$ | $Zd(s, b)$ | $\gamma d(s, b)$ | $\Gamma$ (GeV) |
|-----------|------------|------------|------------------|-------------|
| 200       | 32         | 1.5        | 0.17             | 2.05        |
| 250       | 31         | 1.7        | 0.17             | 4.04        |
| 300       | 31         | 1.9        | 0.17             | 7.01        |
| 400       | 31         | 2.0        | 0.17             | 16.68       |
| 500       | 31         | 2.0        | 0.17             | 32.64       |
| 600       | 31         | 2.1        | 0.16             | 56.46       |
| 700       | 31         | 2.1        | 0.16             | 89.71       |
Table 4: Same as Table 2 but for $\lambda = 0.5$.

| Mass (GeV) | $gd$ | $gs$ | $gb$ | $Zd$ | $Zs$ | $Zb$ | $\gamma d$ | $\gamma s$ | $\gamma b$ | $\Gamma$ (GeV) |
|-----------|------|------|------|------|------|------|-----------|-----------|-----------|----------------|
| 200       | 4.5  | 18   | 72   | 0.22 | 0.86 | 3.4  | 0.024     | 0.096     | 0.38      | 0.22          |
| 250       | 4.5  | 18   | 72   | 0.25 | 0.99 | 4.0  | 0.024     | 0.095     | 0.38      | 0.44          |
| 300       | 4.5  | 18   | 72   | 0.26 | 1.1  | 4.2  | 0.024     | 0.095     | 0.38      | 0.76          |
| 400       | 4.5  | 18   | 71   | 0.28 | 1.2  | 4.5  | 0.024     | 0.095     | 0.38      | 1.82          |
| 500       | 4.4  | 18   | 71   | 0.29 | 1.2  | 4.6  | 0.024     | 0.094     | 0.38      | 3.57          |
| 600       | 4.4  | 18   | 71   | 0.29 | 1.2  | 4.7  | 0.024     | 0.094     | 0.38      | 6.17          |
| 700       | 4.4  | 18   | 71   | 0.3  | 1.2  | 4.8  | 0.024     | 0.094     | 0.38      | 9.81          |

Anomalous single production cross sections for $u_4$ and $d_4$ quarks at Tevatron are plotted in Figure 1. The upper curves are obtained with $\lambda = 1, \Lambda = 2$ TeV and the lower ones with $\lambda = 0.5, \Lambda = 1$ TeV. The excess of events with a $W$ and a superjet in $W + 2$ jet sample, observed by the CDF collaboration at Tevatron, can be explained as anomalous single production of $u_4$ with subsequent decay chain $u_4 \rightarrow tg \rightarrow Wbg$. Let us estimate the number of events expected in both scenarios mentioned above. In the case of $\lambda = 0.5$, $\sigma(pp \rightarrow u_4X) \times BR(u_4 \rightarrow tg) = 0.31$ pb for $m_{u_4} = 400$ GeV. Assuming 40% detector efficiency and $BR(W \rightarrow e\nu + \mu\nu) \approx 0.21$, one obtains $2 - 3$ such events for $106$ pb$^{-1}$ integrated luminosity. In addition, the same number of events are expected from $pp \rightarrow \bar{u}_4X$. CDF collaboration has observed 8 events while the SM prediction is $2.69 \pm 0.41$ [12]. In the case of $\lambda = 1$, one needs to set $\Lambda = 4$ TeV in order to obtain similar number of events (for $\lambda = 1$, $\sigma \sim \Lambda^{-4}$).

The other main decay modes, namely $gu$ and $gc$ will give rise to dijet final states. For $m_{u_4} = 400$ GeV, $\sigma \times BR(u_4 \rightarrow jj) \approx 0.18$ pb with $\lambda = 0.5$ and $\Lambda = 1$ TeV and $\sigma \times BR(u_4 \rightarrow jj) \approx 1.1$ pb with $\lambda = 1$ and $\Lambda = 4$ TeV. The CDF dijet analysis [17] lead to an upper limit of 16 pb at this mass. The contribution of $d_4$ to the dijet events is estimated to be 0.6 pb with $\lambda = 0.5$ and $\Lambda = 1$ TeV and 0.75 pb with $\lambda = 1$ and $\Lambda = 4$ TeV.

Finally, if we allow the SM decay modes of $d_4$ to be comparable to anomalous ones, the superjet events in $W + 3$ jet sample can be explained through the following decay chain: $d_4 \rightarrow Wt \rightarrow WWb$, where one $W$ decays leptonically and the other decays into two jets. CDF collaboration has observed 5 events while the SM prediction is $1.71 \pm 0.40$ [12].

In conclusion, the upgraded Tevatron reaching integrated luminosity 15 fb$^{-1}$ can observe the fourth SM family quarks before the LHC, provided that the
anomalous single production is dominant.

Figure 1: Anomalous single production cross section for $u_4$ (solid curves), $d_4$ (dashed curves) quarks. Upper (lower) curves correspond to $\lambda = 1$, $\Lambda = 2$ TeV ($\lambda = 0.5$, $\Lambda = 1$ TeV).

Acknowledgments

This work is partially supported by Turkish State Planning Organization under the Grant No 2002K120250.

References

[1] A. Datta and S. Raychaudhuri, Phys. Rev. D 49, 4762 (1994).
[2] A. Celikel, A. K. Ciftci and S. Sultansoy, Phys. Lett. B 342, 257 (1995).
[3] S. Sultansoy, hep-ph/0004271 (2000).
[4] E. Arik et al., Phys. Rev. D 58, 117701 (1998).
[5] ATLAS Technical Design Report, CERN/LHCC/99-15, Volume 2, Chapter 18 (1999).
[6] O. Cakir and S. Sultansoy, Phys. Rev. D 65, 013009 (2002).

[7] E. Arik et al., CERN-ATLAS Scientific Note SN-ATLAS-2001-006 (2001), hep-ph/0109037 (2001).

[8] E. Arik et al., hep-ph/0203257, to be published in Phys. Rev. D 66 (2002).

[9] A. K. Cifıtcı, R. Cifıtcı and S. Sultansoy, Phys. Rev. D 65, 055001 (2002).

[10] R. Cifıtcı, A. K. Cifıtcı, E. Recepoglu and S. Sultansoy, hep-ph/0203083 (2002).

[11] H. Fritzsch, D. Holtmannspötter, Phys. Lett. B 457, 186 (1999).

[12] D. Acosta et al., Phys. Rev. D 65, 052007 (2002).

[13] G. Apollinari et al., Phys. Rev. D 65, 032004 (2002).

[14] G. Apollinari et al., FERMILAB-Pub-01/265-E February 2002.

[15] A. Pukhov et al., hep-ph/9908288 (1999).

[16] S. Atag et al., Phys. Rev. D 54, 5745 (1996).

[17] F. Abe et al., Phys. Rev. D 55, R5263 (1997).