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A search for the fourth SM family quarks at the Tevatron

E. Arik[1], O. Çakır[2,a], S. Sultansoy[3,4]

[1] Boğaziçi University, Faculty of Arts and Sciences, Department of Physics, 80815 Bebek, Istanbul, Turkey
[2] Ankara University, Faculty of Science, Department of Physics, 06100 Tandoğan, Ankara, Turkey
[3] Gazi University, Faculty of Arts and Sciences, Department of Physics, 06500 Teknikokullar, Ankara, Turkey
[4] Azerbaijan Academy of Sciences, Institute of Physics, H. Cavid Avenue 33, Baku, Azerbaijan

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Abstract. It is shown that the fourth standard model (SM) family quarks can be observed at the Fermilab Tevatron if their anomalous interactions with known quarks have sufficient strength.

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It is known that flavor democracy [1] favors the existence of the fourth SM family fermions [2–4]. The masses of these fermions are expected to be nearly degenerate and lie between 300 GeV and 700 GeV. According to flavor democracy the fourth family neutrino should be heavy. In the framework of the democratic mass matrix approach, small masses for the first three neutrinos are compatible with large mixing angles assuming that the neutrinos are of the Dirac type [5]. Obviously, the existence of the fourth SM family leads to a lot of cosmological and astrophysical consequences (see for example [6]).

The experimental lower bounds on the fourth SM family fermions are as follows [7]: 100.8 GeV for the charged lepton, 45 (39.5) GeV for the Dirac (Majorana) neutrino and 199 (128) GeV for the "down" quark decaying via a neutral (charged) current. On the other hand, partial-wave unitarity at high energies leads to an upper limit of $m_4 < 1\,\mathrm{TeV}$ for heavy fermions [8].

The fourth family quarks will be copiously produced at the LHC [9,10] and the fourth family leptons will be observed at the future lepton colliders [11,12].

In principle, the Tevatron may also contribute to the subject. First, the fourth family quarks can manifest themselves indirectly due to the enhancement in the Higgs boson production [13,14]. Second, they can be produced directly via possible anomalous gqq_4 interactions. It should be noted that the arguments given in [15] for anomalous interactions of the top quark are more valid for u_4 and d_4 quarks since they are expected to be heavier than the top quark. In our previous papers [16,17] we have shown that the superjet events observed by the CDF [18–20] could be interpreted in relation to the latter mechanism if one assumes, in addition, the existence of a new light scalar particle, decaying dominantly to $\tau^+\tau^-$ and/or $c\bar{c}$.

[a] e-mail: Orhan.Cakir@science.ankara.edu.tr

In this work, we consider the anomalous production of u_4 and d_4 quarks at the Tevatron via the subprocesses $gu(c) \to u_4$ and $gd(s,b) \to d_4$, respectively, followed by either SM or anomalous decays into the SM particles.

We use the following effective Lagrangian for the anomalous interactions of the fourth SM family quarks [16]:

$$L = \frac{\kappa_\gamma^{q_i}}{\Lambda} e_q g_e \bar{q}_4 \sigma_{\mu\nu} q_i F^{\mu\nu} + \frac{\kappa_Z^{q_i}}{2\Lambda} g_Z \bar{q}_4 \sigma_{\mu\nu} q_i Z^{\mu\nu} + \frac{\kappa_g^{q_i}}{\Lambda} g_s \bar{q}_4 \sigma_{\mu\nu} T^a q_i G_a^{\mu\nu} + \text{h.c.}, \tag{1}$$

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 the Gell-Mann matrices; e_q is the charge of the quark; g_e, g_Z, and g_s are the electroweak and the strong coupling constants, respectively. $g_Z = g_e/\cos\theta_\mathrm{W}\sin\theta_\mathrm{W}$ where θ_W is the Weinberg angle. $\kappa^q_{\gamma,Z,g}$ define the strength of the anomalous couplings for the neutral currents with a photon, a Z boson and a gluon, respectively; Λ is the cutoff scale for the new physics.

In order to calculate the cross sections and the decay widths, we have implemented the new interaction vertices into the CompHEP [21] package. We have used the parton distribution functions CTEQ5L [22] at $Q^2 = m^2_{q_4}$. In addition to the dependence on the fourth family quark masses, the decay widths depend on $\kappa_V^{q_i}$ for anomalous decays and on CKM matrix elements $V_{q_4 q}$ for SM decay modes. This is demonstrated in Fig. 1a(b) for $m_{q_4} = 300\,\mathrm{GeV}$ (700 GeV). Since the u_4 and d_4 quarks are almost degenerate in mass, their anomalous s-channel production cross sections will be of the same order for equal anomalous couplings. If the SM decay modes of the fourth family quarks are dominant, an investigation of the u_4 quark is advantageous because of the clear $u_4 \to bW^+$ signature comparing to $d_4 \to tW^- \to bW^+W^-$. If the anomolaus decay modes

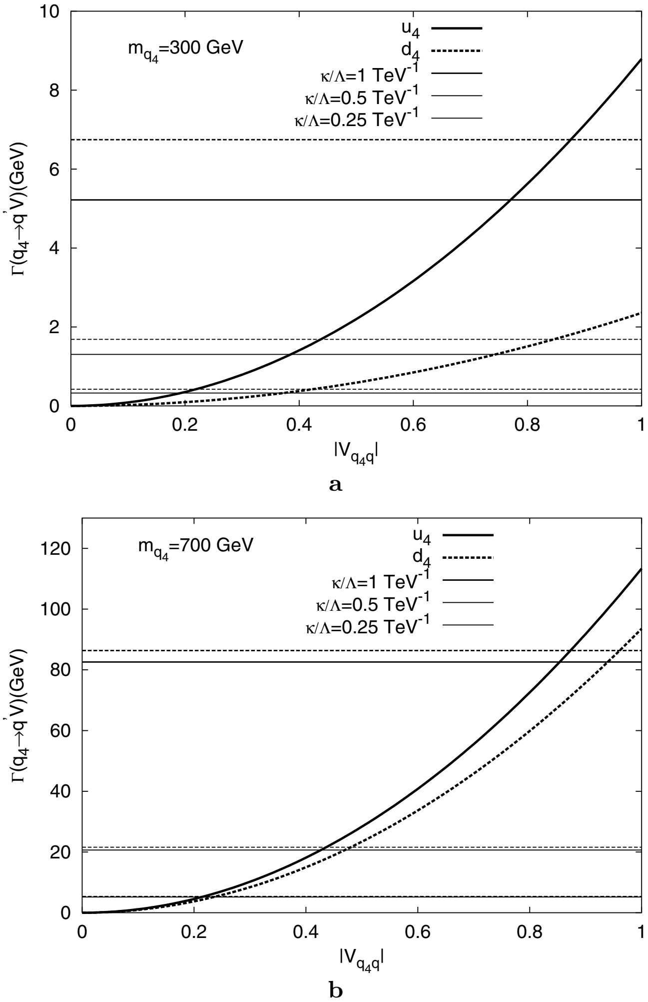

Fig. 1. The decay widths for the fourth family quarks with mass **a** $m_{q_4} = 300\,\text{GeV}$ and **b** $m_{q_4} = 700\,\text{GeV}$. Horizontal lines correspond to the anomalous decay modes

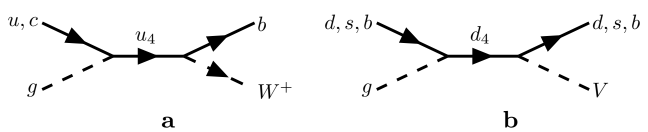

Fig. 2. Anomalous production of q_4 quarks followed by **a** SM decay of the u_4 quark and **b** anomalous decay of the d_4 quark where $V = g, Z, \gamma$

are dominant the d_4 quark has a clear signature, $d_4 \to bV$ ($V = \gamma, Z, g$), with b-tagging. The corresponding Feynman diagrams are shown in Fig. 2.

First, let us consider the process $p\bar{p} \to u_4 X \to bW^+X$. Table 1 lists the cross sections for signal (with couplings $\kappa/\Lambda = 0.5\,\text{TeV}^{-1}$ and $0.25\,\text{TeV}^{-1}$) and the main background $p\bar{p} \to bW^+X$. We consider two cases: without any cuts and with $p_T^b > 50\,\text{GeV}$ for b-jets for two limiting m_{u_4} mass values, namely, 300 GeV and 700 GeV. Numerical calculations were performed for $|V_{u_4 b}| = (\kappa/\Lambda)\cdot\text{TeV}$. This yields the dominance of SM decay mode (see Fig. 1). In order to estimate the observability limits for anomalous couplings κ/Λ, we use the definition of significance

$$\text{SS} = \frac{\sigma_{\text{S+B}} - \sigma_{\text{B}}}{\sqrt{\sigma_{\text{B}}}} \sqrt{\epsilon \cdot \text{BR} \cdot L_{\text{int}}} \qquad (2)$$

where $\epsilon = 0.5$ is the detection efficiency including b-tagging and BR $= 0.2$ is the branching ratio of $W^+ \to e^+\nu_e + \mu^+\nu_\mu$. We also require the minimum number of signal events to be 10 and SS ≥ 5. Assuming $L_{\text{int}} = 10\,\text{fb}^{-1}$ for the integrated luminosity. We obtain, following the lower limits on the anomalous coupling: $\kappa/\Lambda = 0.03\,\text{TeV}^{-1}$ without cuts and $\kappa/\Lambda = 0.01\,\text{TeV}^{-1}$ with $p_T^b > 50\,\text{GeV}$ for $m_{u_4} = 300\,\text{GeV}$. Corresponding numbers for $m_{u_4} = 700\,\text{GeV}$ are $\kappa/\Lambda = 0.33\,\text{TeV}^{-1}$ and $\kappa/\Lambda = 0.12\,\text{TeV}^{-1}$, respectively.

Table 1. The cross sections for the process $p\bar{p} \to u_4 X \to bW^+X$ with $\kappa/\Lambda = 0.5$ and $0.25\,\text{TeV}^{-1}$, and the corresponding background $p\bar{p} \to bW^+X$ without and with p_T cuts

	$m_{u_4} = 300$ (700) GeV			
	no cut		with cut	
κ/Λ, TeV^{-1}	0.5	0.25	0.5	0.25
$\sigma_{\text{S+B}}$, pb	22.1 (0.62)	5.7 (0.21)	20.4 (0.34)	5.2 (0.082)
σ_B, pb	0.184		6.8×10^{-4}	

Table 2. Branching ratios (BR) and decay widths Γ for the d_4 quark with the anomalous coupling $\kappa/\Lambda = 0.5$ and $0.25\,\text{TeV}^{-1}$. The last row presents the cross section for the main background process

m_{d_4}, GeV		300		700	
κ/Λ, TeV^{-1}		0.5	0.25	0.5	0.25
BR(%)	$gd(s,b)$	31	31	31	31
	$Zd(s,b)$	1.9	1.9	2.1	2.1
	$\gamma d(s,b)$	0.17	0.17	0.16	0.16
Γ, GeV		1.75	0.44	22.4	5.6
$\sigma(p\bar{p} \to d_4 X)$, pb		21.4	5.19	0.18	0.077
$\sigma(p\bar{p} \to b\gamma X)$, pb		2.72×10^{-3}			2.25×10^{-6}

The next process we consider is $p\bar{p} \to d_4 X \to qVX$ where $q = d, s, b$ and $V = g, Z, \gamma$. The condition $|V_{d_4 t}| < (\kappa/\Lambda)\cdot\text{TeV}$ ensures the anomalous decay mode of d_4 to be dominant. In Table 2, branching ratios and total decay widths of the d_4 quark with $m_{d_4} = 300$ and 700 GeV are given for the anomalous coupling $\kappa/\Lambda = 0.5\,\text{TeV}^{-1}$ and $\kappa/\Lambda = 0.25\,\text{TeV}^{-1}$. The calculated signal cross sections for the d_4 quark are presented in Table 2.

Keeping in mind the assumptions for the decays of the u_4 and d_4 quarks, one can differentiate between u_4 and $\bar{u}_4$ quarks by identifying the charge of the lepton from W decay. However, d_4 and $\bar{d}_4$ quarks have the same final state signatures. For this reason we will double the number of signal events in our estimations below. The decay modes of d_4 and $\bar{d}_4$ quarks consist of two-jet, $Z +$ jet and $\gamma +$ jet. Even though the dijet mode is dominant, the extraction of the signal does not seem to be promising due to the huge SM background. For the $Z +$ jet mode, again $Z \to q\bar{q}$ is not promising due to the large back-

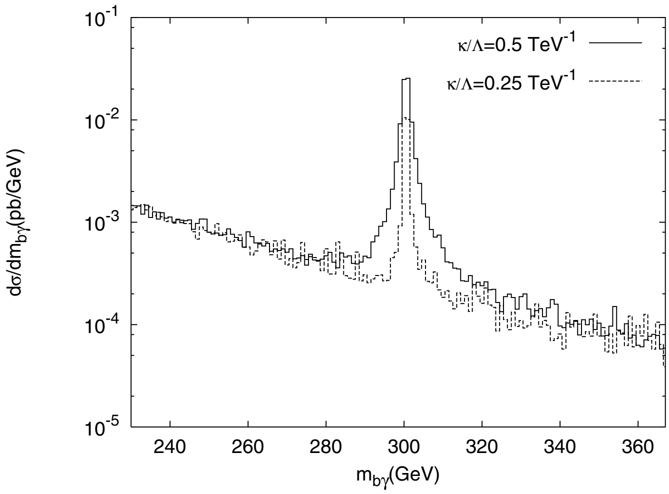

Fig. 3. Invariant mass distribution of b-tagged jet and photon for signal ($m_{d_4} = 300\,\text{GeV}$, $\kappa/\Lambda = 0.5$ and $0.25\,\text{TeV}^{-1}$) and background

ground; $\text{BR}(Z \to l^+l^-)$ reduces the number of events a lot; $Z \to \nu\bar{\nu}$ results in monojet final states but one cannot reconstruct m_{d_4}. Hence, the optimum final state is $\gamma+$jet. The background for this process is also large, but it can be reduced if one uses the advantage of b-tagging. For this reason we consider the signal process $p\bar{p} \to d_4X \to b\gamma X$ with the main background $p\bar{p} \to b\gamma X$.

For illustration, in Fig. 3 we present the invariant mass distribution of the background and signal events for $m_{d_4} = 300\,\text{GeV}$, and two values of κ/Λ (0.5 and $0.25\,\text{TeV}^{-1}$). Obviously, from Fig. 3 the signal is quite observable. As κ/Λ decreases and/or m_{d_4} increases the situation gets worse. In order to observe at least 10 signal events with $\text{SS} \geq 5$ at $L_{\text{int}} = 10\,\text{fb}^{-1}$, the anomalous coupling should satisfy $\kappa/\Lambda \geq 0.08$ (0.9) TeV^{-1} for $m_{d_4} = 300\,\text{GeV}$ ($m_{d_4} = 700\,\text{GeV}$).

Obviously, the fourth family quarks contribute to the rare B decays as well as B–$\bar{B}$ mixing via loop diagrams. These contributions are studied in a lot of papers [23–25]. However, according to flavor democracy they are suppressed due to very small CKM mixings between the fourth family and known quarks [26]. There are also similar loop diagrams coming from the effective Lagrangian (1). In principle, the contributions at the loop level from SM and anomalous interactions can compensate each other. On the other hand, there could be anomalous interactions between light quarks, too. In this case, rare decays such as $b \to sl^+l^-$ could be realized at tree level. However, the strength of the anomalous couplings for light quarks are expected to be much smaller than those for the fourth family quarks [15]. Concerning the recent rare B decay data [27], a rough estimation leads to $\kappa/\Lambda < 3 \times 10^{-5}\,\text{TeV}^{-1}$ for the $b \to s\gamma$ transition.

In conclusion, the fourth SM family quarks could be observed at the upgraded Tevatron depending on the anomalous coupling and the mass values. For $L_{\text{int}} = 10\,\text{fb}^{-1}$, the u_4 quark with mass 300 GeV and SM decay mode can be observed if $\kappa/\Lambda > 0.01\,\text{TeV}^{-1}$. For $m_{u_4} = 700\,\text{GeV}$, the lower limit on κ/Λ is $0.12\,\text{TeV}^{-1}$. On the other hand, the d_4 quark with mass 300 (700) GeV and anomalous decay mode can be observed if $\kappa/\Lambda > 0.08$ (0.9) TeV^{-1}.

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