A Search for the Fourth SM Family Quarks through Anomalous Decays

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Abstract

The existence of fourth family follows from the basics of the Standard Model. Because of the high masses of the fourth family quarks, their anomalous decays could be dominant, if certain criteria are met. This will drastically change the search strategy at hadron colliders. We show that the fourth SM family down quarks with masses up to $400 - 450$ GeV can be observed (or excluded) via anomalous decays by Tevatron before the LHC.

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Recently, the search for the fourth SM family has drawn attention of both theoretical and experimental HEP community [1–3]. The existence of the fourth SM family is the outcome of the flavor democracy hypothesis and the actual spectrum of the third family fermion masses [4–6] (see, also review [7] and ref’s therein). Twenty years’ ongoing discussions on “precision data vs fourth SM family” have been concluded in favor of the fourth SM family (see [8, 9] and ref’s therein). Today, the mass and the mixing patterns of quarks and leptons are the most mysterious aspects of particle physics. Within the SM all these masses and mixings are put by hand and constitute the basic source of parameter inflation. The discovery of the fourth SM family could provide some systematics for SM fermion masses and mixings, which seems chaotic in the three family case.

Let us remind that flavour physics met a lot of surprises. The first example was discovery of $\mu$-meson (We were looking for $\pi$-meson predicted by Yukawa but discovered the “heavy electron”). The next example was represented by strange particles (later we understood that they contains strange quarks). The story was followed by $\tau$-lepton, c- and b-quarks discovered in 1970’s. Actually, c-quark was foreseen by GIM mechanism and quark-lepton symmetry and its mass was estimated in the few GeV region, whereas the discovery of $\tau$-lepton and b-quark was completely surprising for physicists. According to the Standard Model they are the members of the third fermion family, which was completed by the discovery of t-quark in 1995 at Tevatron. Actually, we need at least three fermion families in order to handle CP-violation within the SM [10]. CP violation is necessary for the explanation of Barion Asymmetry of the Universe (BAU). Unfortunately, SM with three fermion families does not provide actual magnitude for BAU. Fortunately, the fourth SM family could provide additional factor of order of $10^{10}$ and, therefore, solve the problem [11].

The existence of the fourth SM family could affect the Tevatron physics search program in two ways. First, it leads to essential enhancement of the Higgs production via gluon fusion (see, [12, 13] and ref’s therein). As a result, while in the case of three SM families (SM3) Tevatron data on $gg \to H \to WW \to ll' \, P_T^{mis}$ process excludes 162 GeV $< M_H < 166$ GeV [14] at 95% CL, the excluded region becomes 131 GeV $< M_H < 204$ GeV [15], if the Nature prefers four SM families case. Second, if the masses of the fourth family quarks are not so large, they could be directly observed by Tevatron.

Up to now, all searches for the fourth family quarks have been done by assuming that SM decay modes are dominant. Current lower limits on the fourth SM family quark masses
from direct searches at the Tevatron are:

a) \( M_{d_4} > 338 \) GeV at 95\% CL coming from the search for new bottom-like quark pair decays in same-charged lepton events with an integrated luminosity of 2.7 fb\(^{-1}\) \[16\].

b) \( M_{u_4} > 256 \) GeV at 95\% CL coming from the search for heavy top-like quarks, using lepton plus jets events with an integrated luminosity 0.76 fb\(^{-1}\) \[17\].

The heaviness of the t-quark has induced searches for its anomalous interactions \[18–22\]. For the same reason – new quarks are heavier than t-quark – in the search strategy the anomalous interactions for the fourth SM family quarks should be taken into account. These interactions may manifest themselves both in the production and decays of new quarks. If the anomalous decay modes of the fourth family quarks are dominant, lower limits on their masses given above are not valid and the search strategy should be changed drastically.

In this letter, we consider pair production of the fourth SM family down-type quarks with subsequent anomalous decays into photon+jet and jet+jet channels. More general consideration, including other manifestations, will be presented in the following publication \[23\].

The effective Lagrangian for anomalous magnetic type interactions of the fourth family quarks is given as \[24–26\]:

\[
L = \sum \frac{\kappa_q}{\Lambda} q \gamma \bar{q} \gamma \sigma_{\mu \nu} q_i F^{\mu \nu} + \sum \frac{\kappa_Z}{2 \Lambda} g_Z \bar{q} q_4 \sigma_{\mu \nu} q_i Z^{\mu \nu} + \sum \frac{\kappa_g}{\Lambda} g_s \bar{q} q_4 \sigma_{\mu \nu} T^a q_i G^{\mu \nu}_a + H.c. \tag{1}
\]

where \( F^{\mu \nu} \), \( Z^{\mu \nu} \) and \( G^{\mu \nu} \) are the field strength tensors of the gauge bosons, \( \sigma_{\mu \nu} \) is the anti-symmetric tensor, \( T^a \) are Gell-Mann matrices, \( e_q \) is electric charge of quark, \( g_e, g_Z \) and \( g_s \) are electromagnetic, neutral weak and strong coupling constants, respectively. \( g_Z = g_e / \cos \theta_W \sin \theta_W \) where \( \theta_W \) is the Weinberg angle. \( \kappa_q, \kappa_Z \) and \( \kappa_g \) are the strength of anomalous couplings with photon, \( Z \) boson and gluon, respectively. \( \Lambda \) is the cutoff scale for new physics. This type of gauge and Lorentz invariant effective Lagrangian have been proposed in the framework of composite models for interactions of excited fermions with ordinary fermions and gauge bosons \[25, 26\].

For numerical calculations we implement the Lagrangian (1), as well as fourth family SM Lagrangian into the CalcHEP package \[27\]. The partial decay widths of \( d_4 \) for SM (\( d_4 \rightarrow W^- q \) where \( q = u, c, t \)) and anomalous (\( d_4 \rightarrow \gamma q, d_4 \rightarrow Z q, d_4 \rightarrow g q \) where \( q = d, s, \))
b) modes are given below:

\[ \Gamma(d_4 \rightarrow W^- q) = \frac{|V_{qd_4}|^2 \alpha_s M_{d_4}^3}{16 M_W^2 \sin^2 \theta_W} \chi_w \sqrt{x_w} \]  

(2)

where \( \chi_w = (1 + x_4^W + x_4^2 - 2x_4 + 2x_4^2 + x_4^2) \), \( \chi_0 = (1 + x_4^W + x_4^2 - 2x_4 + 2x_4^2 + x_4^2) \), \( x_q = (M_q/M_{d_4}) \) and \( x_w = (M_W/M_{d_4}) \).

\[ \Gamma(d_4 \rightarrow Zq) = \frac{\alpha_s M_{d_4}^3}{16 \cos^2 \theta_W \sin^2 \theta_W} \left( \frac{\kappa_q}{\Lambda} \right)^2 \chi_z \sqrt{x_z} \]  

(3)

where \( \chi_z = (2 - x_4^W - x_4^2 - 4x_4^2 - x_4^2 - 2x_4^2 - 6x_4 x_4^2 + 2x_4^2) \), \( \chi_1 = (1 + x_4^W + x_4^2 - 2x_4 + 2x_4^2 + x_4^2) \) and \( x_Z = (M_Z/M_{d_4}) \).

\[ \Gamma(d_4 \rightarrow gq) = \frac{2 \alpha_s M_{d_4}^3}{3} \left( \frac{\kappa_q}{\Lambda} \right)^2 \chi_2 \]  

(4)

where \( \chi_2 = (1 - 3x_4^2 + 3x_4^4 - x_4^6) \),

\[ \Gamma(d_4 \rightarrow \gamma q) = \frac{\alpha_s M_{d_4}^3 Q_q^2}{2} \left( \frac{\kappa_q}{\Lambda} \right)^2 \chi_2 \]  

(5)

One can wonder what is the criteria for the dominance of anomalous decay modes over SM ones. It is seen from Eq. (2)-(5) that the anomalous decay modes of the fourth SM family quarks are dominant, i.e. \( \Gamma(d_4 \rightarrow gq) + \Gamma(d_4 \rightarrow Zq) + \Gamma(d_4 \rightarrow \gamma q) > \Gamma(d_4 \rightarrow W^- q) \), if the relation \( (\kappa/\Lambda) \gtrsim 1.2(V_{ud_4}^2 + V_{cd_4}^2 + V_{td_4}^2)^{1/2} \) TeV\(^{-1} \) is satisfied (hereafter \( \kappa_Z = \kappa_g = \kappa_1 = \kappa \) is assumed). The experimental upper bounds for the fourth family quark CKM matrix elements are \( |V_{ud_4}| \leq 0.063, \ |V_{us_4}| \leq 0.46, \ |V_{ub_4}| \leq 0.47, \ |V_{ud_4}| \leq 0.044, \ |V_{ct_4}| \leq 0.46, \ |V_{td_4}| \leq 0.47 \) [28]. On the other hand, the predicted values of these matrix elements are expected to be rather small in the framework of flavor democracy hypothesis. For example, the mass matrix parametrization proposed in [29], which gives correct predictions for CKM and MNS mixing matrix elements through use of SM fermion mass values as input, predicts \( |V_{u_4d}| = 0.0005, \ |V_{u_4s}| = 0.0011, \ |V_{u_4b}| = 0.0014, \ |V_{ud_4}| = 0.0002, \ |V_{ct_4}| = 0.0012, \ |V_{td_4}| = 0.0014 \). In this case, the anomalous decay modes are dominant, if \( (\kappa/\Lambda) > 0.0022 \) TeV\(^{-1} \). The latter correspondens to upper limit 500 TeV for new physics scale \( \Lambda \), assuming \( \kappa = O(1) \).

The cross-section for the \( d_4\overline{d}_4 \) pair production at the Tevatron is shown in Fig. 1. We have used CalcHEP [27] with CTEQ6L [30] parton distribution functions for numerical
Table I: Signal and background cross sections values for various cuts. All cuts include $p_T > 50 \text{ GeV}$, $|\eta| < 2$, $|M_{inv}(\gamma j) - M_{d_4}| < 20 \text{ GeV}$, $|M_{inv}(jj) - M_{d_4}| < 20 \text{ GeV}$.

| $M_{d_4}$ | 200 GeV | 300 GeV | 400 GeV |
|-----------|---------|---------|---------|
| cuts      | $\sigma_S$, fb | $\sigma_B$, fb | $\sigma_S$, fb | $\sigma_B$, fb |
| $p_T > 20\text{GeV}$ | 39.2 | $5.4 \times 10^5$ | 2.92 | $5.4 \times 10^5$ | 0.23 | $5.4 \times 10^5$ |
| $p_T > 50\text{GeV}$ | 24.5 | $2.7 \times 10^3$ | 2.40 | $2.7 \times 10^3$ | 0.21 | $2.7 \times 10^3$ |
| all cuts  | 21.8 | 3.63 | 2.27 | 0.091 | 0.20 | 0.006 |

We propose $p\bar{p} \rightarrow d_4 \bar{d}_4 \rightarrow \gamma qg\bar{q}$ (where $q = d, s, b$) process to analyze the Tevatron search potential to discover $d_4$ quark via anomalous decays. In detector this process is seen as $\gamma + 3j$ events. We use CalcHEP [27] and MADGRAPH [31] packages with CTEQ6L [30] parton distribution functions for the calculation of the signal and background processes, respectively. In order to extract the $d_4$ signal and to suppress the background, following cuts are applied: $p_T > 50 \text{ GeV}$ and $|\eta| < 2$ for all final state partons and photon, as well as invariant mass within $\pm 20 \text{ GeV}$ around $d_4$ mass. The effects of these cuts can be seen from Table I.

Statistical significance has been calculated by using following formula [32]:

Figure 1: Cross section for $d_4\bar{d}_4$ pair production at the Tevatron.
Summary and Outlook. – Keeping in mind the LHC status, the Tevatron has about 2 more years for new physics discovery. The fourth SM family quarks are among the most prominent candidates for beyond the SM3 physics and possible dominance of their anomalous decay modes should not be ignored. If these modes are dominant, the fourth SM family down quarks with masses up to 400-450 GeV can be observed (or excluded) via anomalous decays.
by Tevatron before the LHC.

Acknowledgments

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