Has the anomalous single production of the fourth SM family quarks decaying into light Higgs boson been observed by CDF?

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Abstract  
Superjet events observed by the CDF Collaboration are interpreted as anomalous single production of the fourth SM family $u_4$ quark, decaying into a new light scalar particle. The specific predictions of the proposed mechanism are discussed.
Recently, CDF Collaboration has reported [1] the observation of an excess of events in $W + 2, 3$ jet topologies, the so called “superjet” events, in which a single jet has both a soft lepton and a secondary vertex. These events are interpreted in [2] as scalar quark $\tilde{b}$ with a mass of 3.6 GeV and a lifetime of 1 ps, decaying into $c\ell\bar{\nu}$ where scalar neutrino is assumed to be massless. In our opinion, this interpretation favors the MSSM scenario with superpartner of the right-handed neutrino as the LSP [3], because LEP experiments put the limit $m_{\tilde{\nu}} > 44$ GeV on the mass of superpartners of the left-handed neutrinos [4]. As mentioned in [5], at least some of these events could be explained as anomalous single production of the fourth SM family (see [6] and the references therein) quarks via the process $u_4 \rightarrow tg \rightarrow Wbg$. The superjet is associated with the normal $b$ quark decay. However, this interpretation leads to an essential excess in single tag events, which is several times larger than CDF observations [1].

In this letter, we give another interpretation to superjet events. Following our previous study [5], we still assume that the production is due to anomalous $q_4qg$ interaction but the decay chain is changed to $u_4 \rightarrow tx^0 \rightarrow Wb\tau^+\tau^-$. The new proposed particle $x^0$ must have a mass around 4$-5$ GeV. In this mechanism, superjet is formed by the decay of one $\tau$ leptonically and the other one hadronically. There are two possible identifications of $x^0$. One possibility is the lightest neutral Higgs boson in SM with extended Higgs sector. The other one is a light neutral dilepton which is expected in preonic models. 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:

$$
L = \frac{\kappa_\gamma}{\Lambda} e_q g_\gamma \bar{q}_4 \gamma_{\mu\nu}(A_{\gamma}^q + B_{\gamma}^q \gamma_5)q_4 F_{\mu\nu} + \frac{\kappa_Z}{2\Lambda} g_Z \bar{q}_4 \gamma_{\mu\nu}(A_Z^q + B_Z^q \gamma_5)q_4 Z_{\mu\nu} \\
+ \frac{\kappa_g}{\Lambda} g_s \bar{q}_4 \gamma_{\mu\nu}(A_g^{q\nu} + B_g^{q\nu} \gamma_5)T^a q_4 G_{\mu\nu} + h.c.
$$

(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. $g_Z = g_\gamma/\cos\theta_W \sin\theta_W$ where $\theta_W$ is the Weinberg angle. $A_{\gamma,Z,g}^q$ and $B_{\gamma,Z,g}^q$ are the magnitudes of the neutral currents; $\kappa_{\gamma,Z,g}$ 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 take all anomalous couplings as $\kappa_\gamma^q = \kappa_Z^q = \kappa_g^q = 1$. We have implemented the
new interaction vertices into the CALCHEP \[7\] package to calculate the cross sections and branching ratios.

\[x^0 \text{ as a light Higgs.}\] We require \(u_4 x^0\) coupling to be sufficiently large in order to provide significant \(\text{BR}(u_4 \rightarrow tx^0)\). On the other hand, the interaction of \(x^0\) with the intermediate vector bosons should be suppressed in order to avoid contradiction with the LEP data. So, we will denote this particle as a light Higgs boson \(h^0\). Naturally, the main decay mode of \(h^0\) should be into kinematically allowed heaviest fermions, namely \(\tau^+\tau^-\) and \(c\bar{c}\). In the case of \(h^0 \rightarrow \tau^+\tau^-\), the branching ratios into possible final states are 0.44 for superjet, 0.12 for all lepton mode, 0.43 for all hadron mode. Similar numbers are valid for \(h^0 \rightarrow c\bar{c}\). In order to have the lifetime of \(h^0\) to be less than 1 ps, the coupling constant \(a_\tau\) in the interaction term \(a_\tau h^0 \bar{u}_4\) should be larger than \(5 \times 10^{-7}\).

The number of superjet events can be estimated as
\[
N_s = \sigma(gq \rightarrow u_4) \cdot \text{BR}(u_4 \rightarrow th^0) \cdot \text{BR}(t \rightarrow bW) \\
\cdot \text{BR}(h^0 \rightarrow \text{superjet}) \cdot \text{BR}(W \rightarrow e\nu + \mu\nu) \cdot \epsilon \cdot L_{int}
\] (2)
where \(\epsilon\) stands for detection efficiency. In Table 1, we present production cross section, branching ratios and total decay width for \(u_4\) at different mass values, assuming \(\text{BR}(u_4 \rightarrow th^0) = 10\%\). This assumption corresponds to \(b_{tu_4} \approx 0.1\) where \(b_{tu_4}\) is the coupling in the interaction term \(b_{tu_4} h^0 u_4\). By taking \(\epsilon = 0.25\), \(\text{BR}(t \rightarrow bW) = 1\) and \(\text{BR}(W \rightarrow e\nu + \mu\nu) = 0.21\), we obtain from Eq. (2) number of superjet events \(N_s = 6\) for \(m_{u_4} = 300\) GeV and the integrated luminosity \(L_{int} = 106\) pb\(^{-1}\).

\[x^0 \text{ as a light dilepton.}\] Second candidate for the identification of \(x^0\) is a neutral dilepton with zero lepton number [8]. So, we denote this particle as \(D_0^0\). The difference between \(D_0^0\) and \(h^0\) decay modes is that \(D_0^0\) decays into \(\tau^+\tau^-\) only. \(D_0^0\) can be produced in \(u_4\) decays via the mixing with a diquark \(D_q^0\), interacting with \(u_4\) and \(t\) (for classification of diquarks see [9]):
\[
D_1^0 = D_\tau^0 \cdot \cos \theta + D_q^0 \cdot \sin \theta \\
D_2^0 = -D_\tau^0 \cdot \sin \theta + D_q^0 \cdot \cos \theta
\] (3) (4)
where \(\theta\) is the mixing angle. Therefore, \(u_4\) decay chain becomes \(u_4 \rightarrow tD_1^0 \rightarrow Wb \tau^+\tau^-\), where we identify \(x^0\) as \(D_1^0\), and \(D_2^0\) is assumed to be heavy. In order to obtain \(\text{BR}(u_4 \rightarrow t D_1^0) = 10\%\), one needs \(b \sin \theta = 0.1\) where \(b\) is the coupling constant of the \(D_0^0 u_4 t\) interaction.
TABLE I: Branching ratios (%), total decay widths for $u_4$ and production cross section $\sigma(p\bar{p} \to u_4X)$ with $\Lambda = 2$ TeV.

| Mass (GeV) | $gu(c)$ | $gt$ | $Zu(c)$ | $Zt$ | $\gamma u(c)$ | $\gamma t$ | $\Gamma$ (GeV) | $\sigma$ (pb) |
|------------|---------|------|---------|------|---------------|-------------|---------------|--------------|
| 200        | 42      | 0.54 | 2.0     | -    | 0.90          | 0.028       | 0.39          | 33.4         |
| 250        | 40      | 5.2  | 2.2     | -    | 0.83          | 0.11        | 0.81          | 25.9         |
| 300        | 37      | 11   | 2.2     | 0.41 | 0.77          | 0.23        | 1.50          | 24.8         |
| 400        | 32      | 17   | 2.1     | 1.0  | 0.69          | 0.37        | 3.96          | 21.8         |
| 500        | 31      | 21   | 2.0     | 1.4  | 0.66          | 0.44        | 8.20          | 15.2         |
| 600        | 30      | 23   | 2.0     | 1.5  | 0.64          | 0.49        | 14.67         | 9.4          |
| 700        | 30      | 24   | 2.0     | 1.6  | 0.62          | 0.51        | 23.80         | 5.1          |

To test the proposed mechanism, we have reconstructed the invariant mass of the $W + j$ system where $j$ denotes the ordinary jet accompanying the superjet, using the $W + 2$ jet events in Table XVI of [1]. The resulting mass values are 159, 175, 600, 159, 178, 228, 172, 149 GeV. The third and the sixth events do not reproduce the expected top quark mass value and probably they are due to SM background.

Another prediction of our mechanism is the occurrence of spectacular events with collinear $e\mu$ tracks originating from $x^0$ when both $\tau$ leptons decay leptonically. Ratio of the number of events of this type to the number of superjet events should be $1 : 15$ for $h^0$ and $1 : 8$ for $D_{\tau}^0$. Therefore, we expect the observation of a number of collinear $e\mu$ tracks at the upgraded Tevatron with integral luminosity $1\,\text{fb}^{-1}$.

In conclusion, CDF superjet events seem to indicate very exciting physics at TeV scale. Namely, existence of the fourth SM family, anomalous interactions, extended SM Higgs sector etc. The scale $\Lambda = 2$ TeV can be a hint of relatively low scale compositeness which will lead to a rich zoo of new particles at the LHC.

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