Limits on Exotic Quarks in the SU(3)×U(1) Extension of the Standard Model from SUSY Search Data

Prashanta Das\textsuperscript{a}, Pankaj Jain\textsuperscript{a} and Douglas W. McKay\textsuperscript{b}

\textsuperscript{a}Physics Department, I.I.T. Kanpur, India 208016

\textsuperscript{b}Department of Physics & Astronomy
University of Kansas, Lawrence, KS 66045, USA

Abstract: We study the $p\bar{p}$ production and decay of exotic quarks that are predicted by the SU(3)×U(1) extension of the Standard Model. We show that recent experimental searches for SUSY particles at the Tevatron limit the mass of these quarks to be above 250 GeV. Run II will extend the reach to 320 GeV. This is one example of SUSY search signatures that apply directly to another, quite different, new physics model.

pdas@iitk.ac.in
pkjain@iitk.ac.in
mckay@kuark.phsx.ukans.edu
Among the “beyond the standard” models that offer plausible motivation and some attractive features, the “minimal” $SU(3)_{\text{Color}} \times SU(3)_L \times U(1)(3-3-1)$ model [1, 2, 3] distinguishes itself with a relatively low, $O(1 \text{ TeV})$ scale of new physics and some spectacular gauge boson and heavy quark decay patterns. Phenomenological studies [4, 5, 6, 7] to date have put the emphasis on searches for, and mass limits on, signals of the new gauge bosons at $e^+e^-$ and $pp$ colliders. In this note we focus instead on limits that $p\bar{p}$ collisions at the Tevatron have set or will set on the new heavy quarks.

The 3-3-1 models have the special twist that anomaly cancellation requires that there be three families of fermions, which is related to the fact that the color group is $SU(3)$. The new quarks (new compared to the Standard Model) are the third members of the fundamental representations of $SU(3)_L$ along with their right–handed $SU(3)_L$ singlet counterparts. The assignment of representations is not unique, and we choose the lepton $3^*$ triplet to be

$$\left(\begin{array}{c}
e \\
\nu_e \\
e^c
\end{array}\right)_L, \quad \left(\begin{array}{c}
\mu \\
\nu_\mu \\
\mu^c
\end{array}\right)_L, \quad \left(\begin{array}{c}
\tau \\
\nu_\tau \\
\tau^c
\end{array}\right)_L,$$

with $U(1)$ charge, or “strong” hypercharge, $Y_S = 0$. The “strong” refers to the fact that the physical vector boson that is predominantly the $U(1)$ gauge boson has a large coupling to matter fields. Our definition of $Y$ is: $Y \equiv \sqrt{3} \lambda_8 - Y_S 1_{3 \times 3}$, were $Q = T_3 + \frac{Y}{2}$ as usual. The question of the neutrino masses does not concern us here, so we do not consider the possibility of singlet, right-handed neutrinos. The three quark families consist in $SU(3)_L$ triplet and singlet choices as follows:

\begin{enumerate}
\item \begin{pmatrix} u \\ d \\ D \end{pmatrix}_L \begin{pmatrix} 3/3 \\ 2/3 \\ -4/3 \end{pmatrix}; \quad u_R \begin{pmatrix} 1/3 \\ -2/3 \end{pmatrix}; \quad d_R \begin{pmatrix} 1/3 \\ 2/3 \end{pmatrix}; \quad D_R \begin{pmatrix} 1/3 \\ 8/3 \end{pmatrix}
\item \begin{pmatrix} c \\ s \\ S \end{pmatrix}_L \begin{pmatrix} 3/3 \\ 2/3 \\ -4/3 \end{pmatrix}; \quad c_R \begin{pmatrix} 1/3 \\ -2/3 \end{pmatrix}; \quad s_R \begin{pmatrix} 1/3 \\ 2/3 \end{pmatrix}; \quad S_R \begin{pmatrix} 1/3 \\ 8/3 \end{pmatrix}
\item \begin{pmatrix} b \\ t \\ T \end{pmatrix}_L \begin{pmatrix} 2^* \\ -4/3 \\ 2/3 \end{pmatrix}; \quad b_R \begin{pmatrix} 1/3 \\ -2/3 \end{pmatrix}; \quad t_R \begin{pmatrix} 1/3 \\ -4/3 \end{pmatrix}; \quad T_R \begin{pmatrix} 1/3 \\ -10/3 \end{pmatrix}
\end{enumerate}
and it is understood that the leptons are SU(3)\textsubscript{color} singlets and all of the quarks are in triplet representations.

Our representation of the covariant derivative for SU(3)\textsubscript{L} \times U(1) interactions with matter fields in the fundamental representation is

\[ D_\mu = \partial_\mu - igT^a W^a_\mu + i\frac{g_S}{2}Y_S V_\mu, \]

where \( T^a = \frac{\lambda^a}{2} \) in terms of the standard Gell–Mann Matrices \( \lambda^a \), and a 3 \times 3 unit matrix is understood in the \( V_\mu \), U(1) gauge field, interaction. The gauge field matrix in more detail reads

\[
T^a W^a = \frac{1}{\sqrt{2}} \begin{pmatrix}
\frac{W^3}{\sqrt{2}} & \frac{W^8}{\sqrt{6}} & Y^+ \\
\frac{W^-}{\sqrt{2}} & \frac{W^8}{\sqrt{6}} & Y^+
\end{pmatrix}
\]

The \( W^\pm \) are identified with the usual W-bosons of the standard model, while the \( Y \)'s, called dileptons, carry lepton number, \(|L| = 2\), and their interactions give rise to \( Y^{-+} \rightarrow e^-e^- \) and \( Y^- \rightarrow e^-\nu_e \) decays, for example. The heavy quarks \( D, S, T \), also with \(|L| = 2\), can decay through real or virtual \( Y \) emission to produce dilepton final states with a \(|\Delta L| = 2\) decay signature. These are the “spectacular” decay patterns referred to above.

Unless some special radiative mass generation effects are invoked, the minimal Higgs structure contains three \( 3 \)'s and one \( 6 \) of SU(3)\textsubscript{L}. In this minimal Higgs version of 3–3–1 models, the limited number of vacuum expectation values leads to the mass relation

\[
M_Y / M_{Z'} = [3g^2/(4g^2 + 12g_S^2)]^{1/2}.
\] (1)

Additional higgs multiplets allow one to relax this constraint. In addition, requiring that the SU(2)\textsubscript{L} \times U(1) couplings match the SU(3)\textsubscript{L} \times U_Y(1) couplings at the SU(3)_L breaking scale \( M_Y \) leads to the relationship

\[
g_S^2/g^2|_{M_Y} = \sin^2\theta_W/(1 - 4\sin^2\theta_W)|_{M_Y}.
\] (2)

This expression shows the “strong \( g_S \)” character of the model, since \( 4\sin^2\theta_W = 0.92 \) at the Z mass and it grows as the scale \( M_Y \) is increased \[8\]. Since the Higgs fields play a negligible role in the production and decay of the \( D, S \) and \( T \) quark fields, we do not review their properties here.

\[ \text{Analysis of } p\bar{p} \rightarrow Q\bar{Q} \text{ at 2 TeV.} \]
We are specifically addressing the bounds on new 3-3-1 quark properties that the Tevatron can set, so we assume that $M_Q < M_Y$ since previous studies [3] have set bounds $> 300$ GeV on $M_Y$ from $\mu -$ decay data. Heavy quark masses larger than this will exceed the Tevatron’s discovery reach even in run II, as we show below. For this study we do not require the minimal model relation, Eq. (1), between $M_Y$ and $M_{Z'}$. We fix $M_Y = 300$ GeV (the results are insensitive to $M_Y$) and $g_S(M_Y)$ and allow $M_{Z'}$ to range upward from one TeV. An expanded Higgs sector that introduces another vacuum expectation value not fixed by $SU(2)_L$ breaking allows $M_{Z'}$ and $M_Y$ to be chosen independently [6].

The parton level Feynman diagram relevant to the $Z'$ mediated production of exotic quark plus antiquark in hadron colliders is shown in Fig. 1, while the semi-leptonic decay diagram of a heavy quark is shown in Fig. 2. The QCD diagrams are the standard ones for heavy quark plus antiquark production. We use PYTHIA [10] to compute the contribution to the $Q \bar{Q}$ cross sections for both of these channels. The neutral $Z'$ spin-one boson is mixed with an angle $|\theta| < 5 \times 10^{-3}$ with the physical $Z$, so we do not include this tiny effect in the subsequent discussion. The relevant couplings beyond QCD then read:

$\begin{align*}
\Gamma(p^+ + u, d \to \bar{D}) &
\end{align*}$

$\begin{align*}
\Gamma(p^- + \bar{u}, \bar{d} \to D) &
\end{align*}$

Figure 1: $D \bar{D}$ production from $pp$ collision via $Z'$

$^{1}$Neutrino-oscillation “appearance” experiments set comparable limits of $> 340$ GeV.
\[ \mathcal{L}_{f\bar{f}Z'} = \sum_{f=u,d,D,t} \frac{g\delta}{\cos\theta_W} \bar{f} \gamma_\mu (a_f + b_f \gamma_5) f Z'\mu \]

(3)

and, with \( C \) the charge conjugation operator,

\[
\mathcal{L}_{f_1\bar{f}_2Y} = - \frac{g}{2\sqrt{2}} \sum_{\ell=e,\mu,\tau} Y^{--}_{\ell} \bar{\ell} \gamma_\mu \gamma_5 C \ell^T + \frac{g}{2\sqrt{2}} Y^{--}_\mu \bar{\ell} \gamma_\mu (1 - \gamma_5) u + h.c
+ \frac{g}{2\sqrt{2}} \sum_{\ell=e,\mu,\tau} Y^{--}_\mu \bar{\nu}_\ell \gamma_\mu (1 - \gamma_5) C \bar{\ell}^T + \frac{g}{2\sqrt{2}} Y^{--}_\mu \bar{D} \gamma_\mu (1 - \gamma_5) d + h.c,
\]

(4)

for the production and decay vertices. We assume for illustration that the \( D \) quark is the lightest of the new quarks in the model and concentrate our attention on its production and decay. Our bound on \( M_D \) will be the least lower bound in the sense that including one or both of the other exotic quarks to be active or choosing \( T \) as the lightest quark will yield larger lower bounds. The factors \( a_f \) and \( b_f \) in Eq. (3) are summarized in Table 1, and the coefficient \( \delta \) is defined as \( \delta \equiv (1 - \sin^2 \theta_W)/[3(1 - 4 \sin^2 \theta_W)]^{1/2} \).

| q  | u  | d  | D  | c  | s  | S  | t  | b  | T   |
|----|----|----|----|----|----|----|----|----|-----|
| \( a_f \) | \( \frac{1}{6} \) | \( -\frac{1}{3} \) | \( -\frac{5}{6} \) | \( \frac{1}{6} \) | \( -\frac{1}{3} \) | \( -\frac{5}{6} \) | \( \frac{2}{3} \) | \( \frac{1}{6} \) | \( \frac{7}{6} \) |
| \( b_f \) | \( \frac{1}{2} \) | 0  | \( -\frac{1}{2} \) | \( \frac{1}{2} \) | 0  | \( -\frac{1}{2} \) | 0  | \( -\frac{1}{2} \) | \( \frac{1}{2} \) |

Table 1

Figure 2: decay modes of \( D \) quark

In Fig. 3 we show the contribution to the \( p\bar{p} \rightarrow t\bar{t} + X \) cross-section from QCD \cite{11, 12, 13} plus the \( Z' \) graph in Fig. 1 as a function of \( M_{Z'} \). We have
used a fixed coupling $\delta = 1.89$ corresponding to a scale of 300 GeV, and the value $M_t = 175$ GeV, in making this estimate. Consistent with our remarks above, we also assume that besides $D$ the remaining exotic quarks are too heavy to constitute a decay mode of $Z'$. Requiring that QCD cross-section plus the $Z'$ contribution, which adds incoherently to the QCD cross section, lie within the experimental $1 - \sigma$ uncertainty, yields a lower bound on $M_{Z'}$ between 750 GeV and 1100 GeV. Our bound from $t\bar{t}$ production is independent of the details of the Higgs sector and, though weaker than the bound from the $Z'$ contribution to $\Gamma_b$ in $Z^0$ decay, it may become quite stringent as the experimental uncertainties in the $t\bar{t}$ cross-section are reduced. We should remark that the $2\sigma$ lower bound of 1.7 TeV found in [8] prevents us from suggesting that Fig. 3 shows evidence for $Z'$ in the mass range $750 \text{ GeV} < M_{Z'} < 1100 \text{ GeV}$.

Next we plot the cross section for $p\bar{p} \rightarrow D\bar{D} + X$ in Fig. 4 as a function of $M_D$ for $M_{Z'} = 1$ TeV and $M_{Z'} = \infty$; the latter is the pure QCD case which is the same as the top quark case, and it sets a minimum, or weakest, bound on the heavy quark mass $M_D$, as we discuss below.

The recently published results of searches for SUSY particles at the Tevatron [15, 16] allow us to put limits on the exotic quarks and illustrate that SUSY searches can be applied with little cost to other new physics processes. These studies conducted by the DØ and CDF detector groups use trilepton final states [15, 16] that could arise from the decay of the charginos and neutralinos $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$. $\tilde{\chi}_1^\pm$ decays into a charged lepton, a neutrino and LSP and the $\tilde{\chi}_2^0$ decays into two charged leptons plus an LSP. Simulating the same lepton isolation cuts as used in these experiments we may apply their results directly to a search for the exotic 3-3-1 quarks, which decay into a jet plus two like charged leptons or a jet plus a charged lepton and a neutrino. The $D\bar{D}$ final state lepton products are $\ell\ell\bar{\ell}$ or $\bar{\ell}\ell\ell$, just as the SUSY case.

The search for gauginos was conducted by considering the $eee, e\mu\mu, \mu\mu\mu$ and $\mu\mu\mu$ trilepton channels. The DØ experiment [16] turned out to provide the more stringent limit on the exotic quark mass, so we present some details of that case here. For the $eee$ channel two different cuts were imposed in the experimental search corresponding to two different mass, so we present some details of that case here. For the $eee$ channel two different cuts were imposed in the experimental search corresponding to two different triggers $eE_T$ and $2eE_T$. The first trigger $eE_T$ required that at least one electron is detected with transverse energy $E_T$ greater than 20 GeV and the missing energy $E_T$ is greater than 15 GeV. The second trigger $2eE_T$ required detection of at least one electron with $E_T > 12$ GeV and at least one more electron with $E_T > 7$ GeV and missing energy $E_T > 7$ GeV. The minimum lepton transverse energies $E_{T1}, E_{T2}$ and $E_{T3}$ (GeV) are required to be 22.5, 5 and 14.9, 5 for
the two triggers $e\slash E_T$ and $2e\slash E_T$ respectively. Similar cuts are placed for the channels $e\mu, e\mu\mu$. For case of three muons the corresponding values are 17, 5, 5 and 5, 5, 5 with the trigger $\mu$ and $\mu\mu$ respectively.

If $DD$ is light enough to be produced at the Tevatron, it will also contribute to the cross-section for trilepton plus missing energy signal used to search for charginos and neutralinos. We consider a specific channel in which the trilepton final state consists of three electrons. Integrating over the produced jets, there are six decay modes available to the $D$ quark, namely $\ell_i\ell_i$ and $\ell_i\nu$ where $i = 1, 2, 3$ corresponds to the three generations and $\ell_i$ represents the charged leptons. With the corresponding six decay modes of $D$ we get a total of 36 decay channels for $DD$. Since either $D$ or $\bar{D}$ can decay into two electrons the total for production of the final state $eee\nu$ is 1/18 of the total cross section of $DD$ production. We determine the number of such trilepton events expected from the $DD$ final state putting the cuts as prescribed by the experimental search [15].

In brief, we take the PYTHIA generated events from both QCD and $Z'$ production and decay of $DD$ and require the lepton $E_T$ cuts described above and $E_T > 15$ GeV and $|\eta| < 3.5$ for electrons and $|\eta| < 1.0$ for muons. A lepton isolation cut is applied to all events: if a nominal jet has $P_T > 15$ GeV, then $R \equiv \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} > 0.4$, is required where $\Delta \eta = |\eta_{\text{jet}} - \eta_{\text{lepton}}|$ and $\Delta \phi = |\phi_{\text{jet}} - \phi_{\text{lepton}}|$. An efficiency factor of 1/4 is applied in order to summarize the lepton identification efficiencies and electron tracking efficiency. The ratio of total efficiency to kinematic plus trigger efficiencies roughly accounts for these experimental effects [13].

For our purpose it suffices to consider the channels $eee$ and $\mu\mu\mu$. We impose the appropriate cuts and efficiency factor as just described to estimate the number of $3l + E_T$ events expected in a 95 pb$^{-1}$ sample. Noting that the experiment showed no events after the full cuts were applied and that the backgrounds are less than 0.5 events, we require that fewer than 0.5 events are obtained in the simulated sample for each pair of $M_D$, $M_{Z'}$ values at the $M_Y$ value chosen. Overall the $eee$ cuts are looser (the $\eta$ cuts are the determining factors), so the $M_D$ value for a given $M_{Z'}$ is higher, than for the $\mu\mu\mu$ case. In Fig. 5 we show that resulting exclusion boundary in $M_D - M_{Z'}$ space for $M_Y = 300$ GeV. The region below the curve is excluded, and the $M_{Z'} \rightarrow \infty$ limit gives the (QCD determined) lowest bound $M_D > 250$ GeV, which is our main result.

Conclusions

The $SU(3) \times U(1)$ extension of the standard model has reasonable moti-
vation \cite{L} and strong, easily testable predictions that have some features in common with the predictions of supersymmetry. We applied the results of recent DØ and CDF searches for gauginos in $3\ell \not{E}_T$ final states to put a new, lower bound of 250 GeV/$c^2$ on the mass of exotic quarks in the $SU(3) \times U(1)$ model. The increased luminosity and energy at run II should be able to push this bound up to about 320 GeV.

The statement of our result can be turned around. Had DØ obtained a signal above background, it could have been interpreted as a signal for neutralino and a chargino production or for exotic $SU(3) \times U(1)$ quark production. Further study of the jet activity in the events would have been necessary to discriminate between the two. We suggest that it would be useful to include a survey of such alternatives to SUSY interpretations in the analysis of “SUSY signal” searches.

![Graph](image)

**Fig. 3:** Top cross section including the Standard Model and the $Z'$ contribution as a function of the $Z'$ mass. The two horizontal lines show the upper and lower limits of the current experimental result obtained by combining CDF and DØ data \cite{14}.
Fig. 4 The $D$ exotic quark cross section as a function of its mass. The lower curve corresponds to pure QCD production and the upper curve includes QCD plus the $Z'$ contribution with $M_{Z'} = 1$ TeV.
Fig. 5 The lower bound on the exotic quark as a function of its mass $M_D$ and the $Z'$ mass. The vertical line corresponds to the limit obtained by excluding the $Z'$ contribution to the $D\bar{D}$ cross section.

Acknowledgements: We thank Phil Baringer for discussions about backgrounds and Marc Paterno and Sarah Eno for communications that patiently explained the cuts and efficiencies in [15]. Computational facilities of the Kansas Institute for Theoretical Science were used in this work, which was supported in part by U.S. DOE Grant No. DE-FG02-85ER40214.

References

[1] F. Pisano and V. Pleitez, *Phys. Rev. D* **46**, 410 (1992).

[2] R. Foot, O. Hernandez, F. Pisano, and V. Pleitez, *Phys. Rev. D* **47**, 4158 (1993).
[3] P.H. Frampton, *Phys. Rev. Lett.*, 69, 2889 (1992).

[4] D. Ng, *Phys. Rev. D* 49, 4805 (1994).

[5] P.H. Frampton, J.T. Liu, B.C. Rasco and D. Ng, *Mod. Phys. Lett. A* 9, 1975 (1994).

[6] B. Dutta and S. Nandi, *Phys. Lett. B* 340, 86 (1994).

[7] K. Sasaki, K. Tokoshuka, S. Yamada, Y. Yamazaki, *Phys. Lett. B* 345, 495 (1995).

[8] P. Jain and S. Joglekar, *Phys. Lett. B* 407, 151 (1997). This reference argues that the $SU(3)_L$ breaking scale $M_Y$ is the one appropriate to the matching condition.

[9] L. Johnson and D. W. McKay, (unpublished).

[10] T. Sjöstrand, *Comput. Phys. Commun.* 82, 74 (1994).

[11] E. Berger and H. Contopanagos, *Phys. Lett. B.* 361, 115 (1995).

[12] E. Laenen et al. *Phys. Lett. B* 321, 254 (1994); *Nucl. Phys. B* 369, 543 (1992).

[13] S. Catani et al. CERN-TH/96-21, [hep-ph/9602208](http://arxiv.org/abs/hep-ph/9602208) (1996).

[14] We show the combined CDF and DØ number $\sigma_{tt} = 6.7 \pm 1.3pb$ (preliminary). See G. Velev “CDF Findings of the Top Quark”, and B. Klina “DØ Findings on the Top Quark”, available on the web pages of the collaborations.

[15] B. Abbott et al., *Phys. Rev. Lett.* 80, 1591 (1998).

[16] F. Abe et al, *Phys. Rev. Lett.* 80, 5275 (1998).

[17] For recent work on aspects and extensions of this model, see C.A. de S. Pires and O.P. Ravinez, *Phys. Rev. D* 58, 035008 (1998); M.B. Tully and G.C. Joshi, [hep–ph/9807201](http://arxiv.org/abs/hep-ph/9807201); V. Pleitez and M. Tonasse, *Phys. Lett. B* 430, 174 (1998).