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RAL-94-045

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Singlet quarks beyond the top at the Tevatron?

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Abstract

The first evidence for the top quark at the Tevatron may indicate a cross section higher than the QCD expectation. We consider the possibility that isosinglet heavy quarks may be contributing to the signal and discuss ways of testing this possibility. For example, a charge $\frac{2}{3}$ singlet quark, approximately degenerate and mixing with the top quark, would effectively double the standard top signals. A charge $-\frac{1}{3}$ singlet quark mixing with the bottom quark would not affect top signals but would generate excess $Z +$ multijet events with a b-tag. [hep-ph/9405224]

The first evidence for a top-quark signal has just been presented by the CDF experiment at the Fermilab Tevatron $p\bar{p}$ collider [1], indicating a mass $m_t = 174 \pm 10^{+13}_{-12}$ GeV. An excess of multijet events is found, containing either two W-bosons or a W-boson and at least one b-jet, where these W-bosons are identified by $W \to \ell\nu$ leptonic decays. The observed signal rate is somewhat higher than the standard QCD expectations for $p\bar{p} \to t\bar{t}X$ production [2]. Although this higher rate may be attributed to statistical fluctuations or background uncertainties, it has already encouraged theoretical speculation about possible enhancements of the $t\bar{t}$ cross section, such as a color singlet and octet resonances coupled strongly to top quarks [3] or a techni-eta resonance [4]. A different new-physics possibility is not that $t\bar{t}$ production itself is enhanced but that other heavy quarks are produced and contribute to the observed signals. A fourth-generation quark (mentioned as a possibility in Ref. [1]) is not particularly attractive, since a fourth light sequential neutrino is excluded by Z decay data [5]. However, a theoretically interesting possibility is the existence of isosinglet quarks that occur for example in superstring-inspired E_6 models [6–9] or other exotic quarks outside the Standard Model [10,11]. Isosinglet quarks are among the few classes of new particle that could exist near the electroweak mass scale without much perturbing the standard analysis of electroweak radiative corrections. In the present letter we concentrate on the isosinglet options, the phenomenologies of which have been considered in other contexts [6–10,12].

In addition to the fermions of the Standard Model (SM), we address the possibility that each generation includes either a singlet charge $-\frac{1}{3}$ quark $Q = x_d, x_s, x_b$ or a singlet charge $\frac{2}{3}$ quark $Q = x_u, x_c, x_t$. These new singlet quarks are color-triplets and are produced by standard QCD subprocesses; their production rates are exactly those for SM quarks of the same masses. They decay via mixing with SM quarks of the same charge into qW, $q'Z$ and $q'H$ channels, where $q(q')$ is a lighter quark and H is the SM Higgs boson; if the mixing is small the decay interactions and branching fractions are simply related [6–10]:

$$B(Q \to qW) : B(Q \to q'Z) : B(Q \to q'H) \simeq 2 : 1 : 1 \, , \tag{1}$$

apart from kinematic factors that are $\simeq 1$ for $m_Q >> M_W, M_Z, m_H$. We assume for simplicity that the mixing occurs mostly within the same generation, in which case $q(q')$ is the corresponding light quark: $x_d \to uW, dZ, dH$, etc. The Higgs considerations generalize somewhat beyond the SM; in the minimal supersymmetric extension [13], for example, if there is only one light Higgs boson (the charged and other neutral Higgses comparatively heavy) then its couplings are close to those of the SM. For present purposes we shall assume $m_H \lesssim M_Z$; if H is very much heavier than this, it will be suppressed in decays of singlet quarks near the top mass.

Since these new quarks introduce new decay modes, it may be pertinent now to mention some further aspects of the CDF top search [1]. Compared to standard expectations and the measured top production rate, CDF reports a deficit of a few events in the $W + 4$jets background rate (that might be explained by fewer top events) and an excess of 2 events in the tagged $Z + 4$jets channel compared with 0.64 ± 0.06 expected. Both effects could be statistical fluctuations [1].

Consider first the case of charge $-\frac{1}{3}$ ("down-type") singlet quarks and suppose that at least one of them has mass near m_t and is pair produced at the Tevatron at a rate comparable with $t\bar{t}$. Its decay branching fractions [6–10] are then approximately

$$\begin{aligned} B(x_d \to uW, dZ, dH) &\simeq \tfrac{1}{2},\ \tfrac{1}{4},\ \tfrac{1}{4}\,, \\ B(x_s \to cW, sZ, sH) &\simeq \tfrac{1}{2},\ \tfrac{1}{4},\ \tfrac{1}{4}\,, \\ B(x_b \to tW, bZ, bH) &\simeq 0,\ \tfrac{1}{2},\ \tfrac{1}{2}\,, \end{aligned} \tag{2}$$

with $x_b \to tW$ forbidden by kinematics. It follows immediately that only the x_d and x_s options yield large qW decay fractions. These additional singlet $Q \to qW$ contributions are superficially similar to $t \to bW$ decays, but differ in important ways.

(i) The untagged single-W signal rate is only about half of that for $t\bar{t}$ production with the same mass (where bW decays are 100 %), assuming that the qZ and qH hadronic decays look passably like hadronic qW.

(ii) The untagged two-W signal rate is only about a quarter of that for $t\bar{t}$.

(iii) The final quark $q = u$ or c is not a b-quark; however c-quarks can sometimes satisfy the lepton or vertex criteria used in b-tagging and therefore masquerade as b.

(iv) The charged lepton in the subsequent $W \to \ell\nu$ decay has a different kinematical distribution relative to the initial and final quark momenta [12] (to be precise, it corresponds to the neutrino distribution in $t \to bW \to b\ell\nu$); however, in small data samples this distribution cannot be accurately determined.

There is therefore some potential for $x_s \to cW$ decays to mimic b-tagged top signals, but at rates reduced by the $x_s \to cW$ branching fraction and by the tag-factor for c-jets. Thus the tendency would be to increase the untagged $W + 4$jets background much more than the apparent top signal; but in the CDF data this background seems already too low, so to this extent the $Q = x_s$ hypothesis is disfavored. On the other hand, the equally populated $x_s \to sZ, sH$ modes give rise to $x_s\bar{x}_s \to s\bar{s}WZ(WH, ZZ, HH, ZH)$ final states, with no counterparts in top decays. As noted above, WZ and WH can contribute to the single-W top signal, since $Z \to q\bar{q}$ or $H \to b\bar{b}$ dijet decays can mimic $W \to q\bar{q}'$. But in cases where Z is identified by $Z \to \ell\bar{\ell}$ or $Z \to \nu\bar{\nu}$ (missing p_T), excess $csWZ$ events with two extra hard quark jets could be seen. Also the $s\bar{s}ZZ$ and $s\bar{s}ZH$ modes contribute excess $Z+$multijets events with high b-tag probability (from $Z, H \to b\bar{b}$); the CDF excess of tagged $Z + 4$jet events might be explained in this way. However, each $(Z \to \ell\bar{\ell})jjjj$ event implies approximately six $(W \to \ell\nu)jjjj$ events from other $x_s\bar{x}_s$ decay modes, so explaining the $Z + 4$jet excess in this way would make the $W + 4$jets deficit more acute.

Alternatively, if we address the Z+4jets excess alone, the case $Q = x_b$ becomes attractive. It generates no top-like signal nor unwanted $W+$multijets background, but gives new $b\bar{b}ZH$, $b\bar{b}ZZ$ and $b\bar{b}HH$ final states, of which the first two could easily provide tagged $Z + 4$jets events (and incidentally a possible Higgs signal [8–10]).

Consider next the case of charge $\frac{2}{3}$ ("up-type") singlet quarks and suppose that at least one of them has mass near m_t and is pair produced at the Tevatron at a rate comparable with $t\bar{t}$. Its decay branching fractions [10] are then approximately

$$
\begin{aligned}
B(x_u \to dW, uZ, uH) &\simeq \tfrac{1}{2},\ \tfrac{1}{4},\ \tfrac{1}{4}\,, \\
B(x_c \to sW, cZ, cH) &\simeq \tfrac{1}{2},\ \tfrac{1}{4},\ \tfrac{1}{4}\,, \\
B(x_t \to bW, tZ, tH) &\simeq 1,\ 0,\ 0
\end{aligned}
\tag{3}
$$

with $x_t \to tZ$, tH forbidden by kinematics. Each of these options yields large qW decay fractions, but the capacity to mimic top decays depends on the particular case.

(i) $x_u\bar{x}_u$ and $x_c\bar{x}_c$ production give untagged single-W and two-W signals similar to $t\bar{t}$, with reduced rates (like down-type singlets) but similar lepton distribution to t decay (unlike down-type singlets). However, the associated quarks are d and s, so these signals would only get into a b-tagged sample via mis-tagging. There would be b-tagged $Z+4$jet contributions but the $W+$ multijets background deficit would get worse. There is little to recommend these cases.

(ii) $x_t\bar{x}_t$ production however gives signals almost identical to $t\bar{t}$. The x_t decays to Z and H are suppressed (but could proceed at some level via mixing with other generations). A major difference between $x_t\bar{x}_t$ and standard $t\bar{t}$ signals is in the lifetime [14]: the t decays before hadronization can happen, so effects like spin depolarization and quarkonia formation are suppressed for $t\bar{t}$; x_t lives much longer, due to the small $t-x_t$ mixing, so such effects are allowed for $x_t\bar{x}_t$ states.

(iii) x_t-onia are an interesting subject in themselves. Quarkonium states can be produced via gluon fusion at hadron colliders. Their single-quark decay modes would be suppressed by the small $x_t - t$ mixing and hence various annihilation decays, such as ZZ, $Z\gamma$, ZH, HH and $H\gamma$ [15], might be detectable.

To summarize, the central question is whether singlet quarks Q with mass near m_t may be contributing a significant part of the CDF top signals. We conclude as follows.

(a) The cases $Q = x_d, x_b, x_u, x_c$ cannot contribute significantly to the CDF top signals; their single-W and two-W signals are reduced by the $Q \to qW$ branching fraction (that vanishes for x_b) and further suppressed by b-tagging.

(b) The case $Q = x_s$ is less suppressed by b-tagging and can contribute a small fraction of the top signal. E_6 models can accommodate such charge $-\frac{1}{3}$ singlets.

(c) The case $Q = x_b$ is interesting for a different reason; it contributes nothing to the CDF top signals nor $W +$ multijets backgrounds, but it can provide tagged $Z + 4$jets events as seen by CDF, most of which would be $b\bar{b}ZH$ events containing a Higgs signal [8–10]. E_6 models can accommodate this case too.

(d) This $Z+$ multijet production could be important in other contexts, e.g. as an extra source of events with high missing transverse energy $\not{E}_T$, that might be confused with supersymmetry signals. Two events with high $\not{E}_T$ were reported in early CDF data [16].

(e) The case $Q = x_t$ can almost exactly duplicate the top signals; for mass $m_{x_t} = m_t$ it would double the top signal rate. However, we know of no popular models containing this case.

(f) We recall that all heavy singlet scenarios imply heavy quarkonium possibilities [15].

(g) Event ratios in the more interesting cases may be summarized approximately:

$$
\begin{aligned}
x_s\bar{x}_s &\Rightarrow ccWW : csWZ : csWH : ssZH : ssZZ : ssHH \simeq 4:4:4:2:1:1 \\
x_b\bar{x}_b &\Rightarrow bbZH : bbZZ : bbHH \simeq 8:4:4 \\
x_t\bar{x}_t &\Rightarrow bbWW \simeq 16
\end{aligned}
\tag{4}
$$

(h) In all these down-type and up-type singlet scenarios, it is understood that the combined $t\bar{t}$ plus $Q\bar{Q}$ events would not simply be distributed like a standard top signal alone. Beside the questions of lepton momentum and decay width mentioned above, the presence of two (generally different) masses would broaden many distributions such as the reconstructed top mass and the apparent $t\bar{t}$ invariant mass.

ACKNOWLEDGMENTS

This research was supported in part by the U.S. Department of Energy under Contract No. DE-AC02-76ER00881 and in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation.

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