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Prospects for top-prime quark discovery at the Tevatron

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Abstract

We show that a top-prime quark as heavy as 600 GeV can be discovered at the Tevatron, provided it is resonantly pair-produced via a vector color octet. If the top-prime originates from a vectorlike quark, then the production of a single top-prime in association with a top may also be observable, even through its decay into a Higgs boson and a top. A color octet with mass of about 1 TeV, which decays into a top-prime pair, may account for the CDF excess of semileptonic $(Wj)(Wj)$ events.

1 Introduction

The top-quark discovery at the Tevatron [1], made more than a decade ago, has completed the quark sector of the standard model. It is imperative to ask whether physics beyond the standard model includes additional quarks, and in particular, whether there are any heavier quarks with collider signatures similar to those of the top quark.

All standard model fermions are chiral (*i.e.*, their left- and right-handed components have different gauge charges). Additional chiral quarks could exist, although a variety of nontrivial constraints need to be satisfied [2, 3, 4]. Most importantly, electroweak observables are highly sensitive to the presence of chiral fermions [5].

A simpler possibility would be the existence of vectorlike (*i.e.*, non-chiral) fermions. These can easily evade all experimental constraints because their effects decouple in the limit of large fermion masses. Given that the masses of vectorlike fermions are not protected by the electroweak symmetry, they are likely to be larger than the electroweak scale. As a result, even if vectorlike fermions exist, it is natural that they have not been discovered so far.

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A vectorlike quark that mixes with the top quark may decay into Wb with a sizable branching fraction, appearing in collider experiments as a heavier copy of the top quark [2, 6, 7, 8]. For a region of parameter space, the same is true for an up-type quark belonging to a chiral 4th generation [4]. The CDF Collaboration has searched for t' pair production, where t' is a hypothetical quark assumed to decay to a W boson and a jet, with 760 pb^{-1} of data in Run II of the Tevatron, setting a lower mass limit of 256 GeV at the 95% CL [9]. More recently, with 2.8 fb^{-1}, the CDF limit on the t' mass has been raised to 311 GeV [10]. Given the record luminosities achieved recently at the Tevatron, and various improvements of the search techniques, the CDF and D0 experiments may become sensitive to t' pairs produced via QCD for t' masses up to roughly 350 GeV.

Here we show that the top-prime production cross section at hadron colliders could be substantially higher than the QCD prediction if a "gluon-prime", *i.e.* a massive color-octet vector boson, is present in the theory. This provides motivation for the search of significantly heavier t' quarks, and in particular allows the interpretation of some excess events observed by the CDF Collaboration [10] in terms of a t' with mass of about 450 GeV. Specifically, we consider an extension of the standard model which includes a vectorlike fermion that has the same gauge charges as the right-handed top quark, and a gluon-prime arising from an $SU(3) \times SU(3)$ extension of QCD similar to those presented in [11] (the gluon-prime in that case is referred to as a "coloron"). We find that this model predicts several interesting collider signatures, and propose further ways of testing the origin of the CDF excess.

The two hypothetical particles discussed here are part of various models for TeV scale physics. In the top-quark seesaw model [12, 13, 14], the vectorlike quark binds to the top-quark forming a Higgs boson, with binding provided by the coloron. In certain models with a flat [15] or warped [16] extra dimension, the vectorlike quark and the gluon-prime appear as Kaluza-Klein modes. Rather than imposing here any of the constraints among parameters present in these models, we consider a generic renormalizable theory that includes these two particles.

In Section 2 we review the properties of the vectorlike quark, in the absence of a gluon-prime. We then analyze the t'+G'_μ model in Section 3, and present its implications for Tevatron searches in Section 4. A concluding discussion is given in Section 5.

2 Vectorlike origin of the top-prime quark

Let us start with the standard model plus a single vectorlike quark, labelled by χ, which transforms as $(3, 1, 2/3)$ under the $SU(3)_c \times SU(2)_W \times U(1)_Y$ gauge group. This up-type vectorlike quark, having electric charge $+2/3$, may mix with the top quark. The mixings of χ with the first two generations of quarks are expected to be small, and we will neglect them. The Lagrangian includes two gauge invariant quark mass terms and two Yukawa interactions of χ and u^3 to the Higgs doublet, where u^3 is the standard model up-type quark of the third generation in the gauge eigenstate basis. Given that $SU(2)$ transformations that mix χ_R and u^3_R are not physically observable, we can choose one of the Yukawa couplings to vanish. Thus, after electroweak symmetry breaking, the quark mass matrix and interactions with the Higgs boson are given by

$$\mathcal{L} = -\left(\overline{u}^3_L \ , \ \overline{\chi}_L\right) \begin{pmatrix} \lambda_t \left(v_H + h^0/\sqrt{2}\right) & 0 \\ M_0 & M_\chi \end{pmatrix} \begin{pmatrix} u^3_R \\ \chi_R \end{pmatrix} + \text{H.c.} \ , \tag{2.1}$$

where h^0 is the Higgs boson and $v_H \simeq 174$ GeV is the VEV of the Higgs doublet. The two mass parameters, M_0 and M_χ, and the λ_t Yukawa coupling are taken to be real parameters, as their complex phases can be absorbed by $U(1)$ transformations of the quark fields.

To relate these three real parameters of the Lagrangian to physical observables, we transform the gauge eigenstates $u^3_{L,R}$ and $\chi_{L,R}$ to the mass eigenstates $t_{L,R}$, $t'_{L,R}$, where t is the top quark observed at the Tevatron, of mass $m_t \approx 173$ GeV, and t' is a new quark of mass $m_{t'}$, which remains to be discovered. The relation between the two bases depends on two angles, θ_L and θ_R,

$$\begin{pmatrix} t_{L,R} \\ t'_{L,R} \end{pmatrix} = \begin{pmatrix} c_{L,R} & -s_{L,R} \\ s_{L,R} & c_{L,R} \end{pmatrix} \begin{pmatrix} u^3_{L,R} \\ \chi_{L,R} \end{pmatrix} \ , \tag{2.2}$$

where $s_{L,R}$ and $c_{L,R}$ are short-hand notations for $\sin\theta_{L,R}$, and $\cos\theta_{L,R}$, respectively. As explained above, no physical observable depends on θ_R (the situation changes in the model presented in the next section). The mixing angle θ_L affects the electroweak interactions of the top quark as well as the Yukawa couplings of the Higgs boson. The relations between the physical parameters m_t, m'_t, θ_L and the initial parameters λ_t, M_χ, M_0 are given by

$$m^2_{t,t'} = \frac{1}{2}\left(M^2_\chi + M^2_0 + \lambda^2_t v^2_H\right)\left[1 \mp \sqrt{1 - \left(\frac{2\lambda_t v_H M_\chi}{M^2_\chi + M^2_0 + \lambda^2_t v^2_H}\right)^2}\,\right] \tag{2.3}$$

for the masses, and by

$$\tan 2\theta_L = \frac{2M_0\lambda_t v_H}{M^2_\chi + M^2_0 - \lambda^2_t v^2_H} \ , \tag{2.4}$$

for the θ_L mixing angle, which is taken to be between 0 and $\pi/2$. The θ_R mixing angle is given in terms of $m_t, m_{t'}$ and θ_L by

$$s_R^2 = \frac{s_L^2 m_{t'}^2}{s_L^2 m_{t'}^2 + c_L^2 m_t^2} \ . \tag{2.5}$$

Although s_L and $m_{t'}$ are independent parameters, s_L cannot vary over the entire range 0 to 1 when $m_{t'}$ is large enough. To see this, it is useful to express s_L in terms of $\lambda_t v_H$, m_t, and $m_{t'}$:

$$s_L = \sqrt{\frac{\lambda_t^2 v_H^2 - m_t^2}{m_{t'}^2 - m_t^2}} \ . \tag{2.6}$$

When $\lambda_t \gg 1$ the above relation implies

$$s_L = \frac{\lambda_t v_H}{m_{t'}} \left[1 + O\left(\frac{m_t^2}{m_{t'}^2}\right) + O\left(\frac{m_t^2}{\lambda_t^2 v_H^2}\right) \right] \ . \tag{2.7}$$

The Yukawa coupling λ_t is limited by perturbativity, so that Eq. (2.7) gives an upper limit on s_L. For $m_{t'} \to \infty$, we see that the mixing vanishes ($s_L \to 0$) so that the new physics decouples from the standard model. For top-prime masses accessible at the Tevatron, however, the upper limit from (2.7) can be ignored because it is above 1.

The interactions of t and t' with the electroweak bosons depend on θ_L [8]. The charged-current interactions are

$$\frac{g}{\sqrt{2}} W_\mu^+ \, \overline{b}_L \gamma_\mu \left(c_L t_L + s_L t'_L \right) + \text{H.c.} \tag{2.8}$$

where $g \equiv e/\sin\theta_W$ is the $SU(2)_W$ gauge coupling. Given that the measurement of single-top production at the Tevatron sets a limit on the coefficient of the t-W-b coupling[1] $c_L \simeq V_{tb} \lesssim 0.82$, we find a nontrivial constraint:

$$s_L < 0.57 \ . \tag{2.9}$$

The Z boson has modified interactions with the left-handed quarks, including a flavor-changing t-t' current:

$$\frac{g}{\cos\theta_W} Z_\mu \left[\left(\frac{c_L^2}{2} - \frac{2}{3}\sin^2\theta_W \right) \overline{t}_L \gamma_\mu t_L + \left(\frac{s_L^2}{2} - \frac{2}{3}\sin^2\theta_W \right) \overline{t'}_L \gamma_\mu t'_L \right.$$
$$\left. + \frac{s_L c_L}{2} \left(\overline{t'}_L \gamma_\mu t_L + \text{H.c.} \right) \right] \ . \tag{2.10}$$

[1]The D0 measurement [17] is $|V_{tb}| = 1.07 \pm 0.12$, and the CDF one [18] is $|V_{tb}| = 0.91 \pm 0.11 \pm 0.07$. Combining these two measurements in quadrature gives $|V_{tb}| > 0.82$ at the 95% CL. We use this result only as a rough estimate for the combined limit; a proper combination of measurements, which takes into account correlations, would need to be performed by the CDF and D0 Collaborations. Note that the D0 measurement by itself gives almost the same limit: $|V_{tb}| > 0.83$ at the 95% CL.

The interactions of t_R and t'_R with the Z boson are identical with those of the right-handed top quark in the standard model. The Higgs interactions with t and t' can be expressed in terms of θ_L, m_t/v_H and m'_t/v_H:

$$\frac{-1}{v_H\sqrt{2}} h^0 \left(c_L^2 m_t \, \bar{t}_L t_R + s_L^2 m_{t'} \, \overline{t'}_L t'_R + c_L s_L m_{t'} \, \bar{t}_L t'_R + c_L s_L m_t \, \overline{t'}_L t_R \right) + \text{H.c.} \tag{2.11}$$

The modified electroweak couplings of the t quark as well as the new couplings of the W and Z bosons to the t' quark have an impact on electroweak observables. Most notably, the W and Z masses get one-loop corrections such that the T parameter, which measures weak-isospin violation, is given by [13]

$$T = \frac{3}{16\pi \sin^2\theta_W} \frac{m_t^2 s_L^2}{M_W^2} \left(s_L^2 \frac{m_{t'}^2}{m_t^2} + \frac{4 c_L^2 m_{t'}^2}{m_{t'}^2 - m_t^2} \ln \frac{m_{t'}}{m_t} - 1 - c_L^2 \right) - \Delta(M_h) \quad . \tag{2.12}$$

Here $\Delta(M_h) \geq 0$ is the contribution due to Higgs loops, and depends only on the Higgs mass. Using the standard model with $M_h = 115$ GeV as the reference point, the 95% confidence limit (assuming an optimal contribution to the S parameter) is $T \lesssim 0.36$ [3], and Δ varies from 0 to 0.15 as M_h varies from 115 to 500 GeV. Fixing $m_{t'} = 450$ GeV, we find that the limit on the $t - t'$ mixing ranges from $s_L \lesssim 0.32$ for $M_h = 115$ GeV to $s_L \lesssim 0.38$ for $M_h = 500$ GeV. Although this limit is more stringent than Eq. (2.9), it is less robust: new physics may relax the electroweak fit without being discovered at the Tevatron or LHC. For example, leptophobic Z' bosons or complex Higgs triplets can give negative contributions to T, allowing larger values for s_L. For this reason we will not use the electroweak constraints in what follows.

The charged-current interactions induce the $t' \to W^+ b$ decay, while the flavor-changing neutral-current interactions induce the $t' \to Z^0 t$ decay, assuming $m_{t'} \gtrsim 264$ GeV. The tree-level decay widths are given by

$$\begin{aligned} \Gamma(t' \to W^+ b) &= \frac{s_L^2 m_{t'}^3}{32\pi v_H^2} \left(1 - \frac{M_W^2}{m_{t'}^2}\right)^2 \left(1 + \frac{2M_W^2}{m_{t'}^2}\right) \ , \\ \Gamma(t' \to Z^0 t) &= \frac{c_L^2 s_L^2 m_{t'}^3}{64\pi v_H^2} \left[\left(1 - \frac{m_t^2}{m_{t'}^2}\right)^3 + O\left(\frac{M_Z^4}{m_{t'}^4}\right) \right] \ . \end{aligned} \tag{2.13}$$

The Higgs interactions allow the $t' \to h^0 t$ decay, provided $m_{t'} > M_h + m_t$:

$$\Gamma(t' \to h^0 t) = \frac{c_L^2 s_L^2 m_{t'}^3}{64\pi v_H^2} \left(1 + \frac{6m_t^2 - M_h^2}{m_{t'}^2} + \frac{m_t^4 - m_t^2 M_h^2}{m_{t'}^4} \right) \beta\left(\frac{m_t^2}{m_{t'}^2}, \frac{M_h^2}{m_{t'}^2} \right) \quad , \tag{2.14}$$

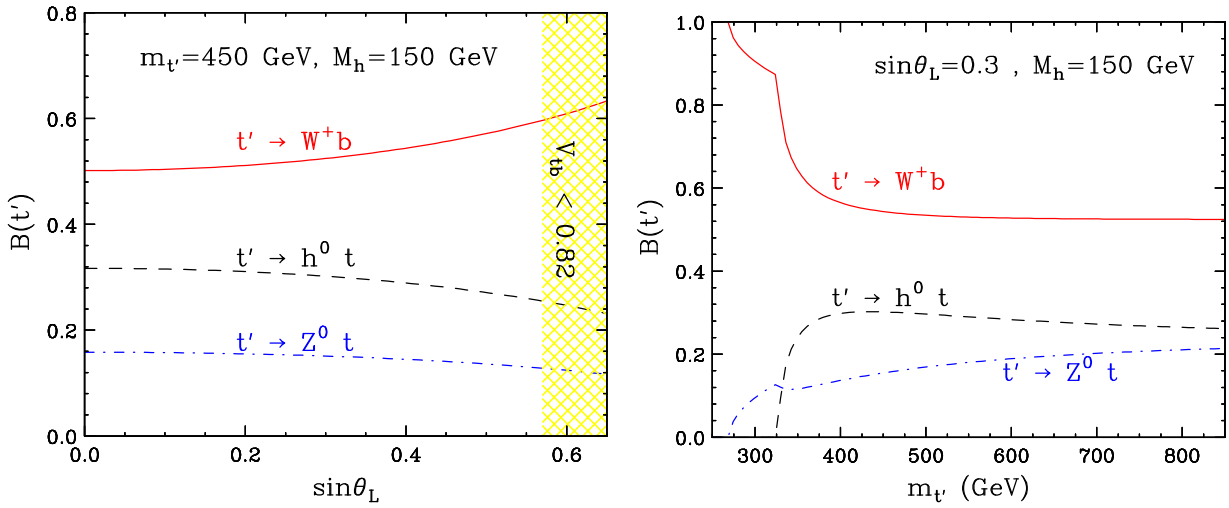

Figure 1: Branching fractions of t' for a Higgs mass $M_h = 150$ GeV, as a function of either $s_L \equiv \sin\theta_L$ or $m_{t'}$. The shaded region on the first plot is excluded by Eq. (2.9).

where β is the relative velocity of the decay products:

$$\beta(x_1, x_2) = \left[(1 - x_1 - x_2)^2 - 4x_1x_2\right]^{1/2} \quad . \tag{2.15}$$

Eqs. (2.13) and (2.14) agree with the results given in [19].

In the limit of $m_{t'} \gg m_t + M_h$ the branching fractions for the t' decays are

$$B(t' \to W^+b) = \frac{1}{1 + c_L^2} \geq 50\% \ ,$$

$$B(t' \to Z^0t) = B(t' \to h^0t) = \frac{c_L^2}{2\,(1 + c_L^2)} \leq 25\% \ . \tag{2.16}$$

Given that the t' quark compensates for a heavier Higgs boson in the electroweak fits (see Eq. (2.12) and Refs. [14, 20]), allowing even $M_h \sim 500$ GeV, the $t' \to h^0t$ decay could be strongly phase-space suppressed for $m_{t'}$ as large as ~ 700 GeV. If $m_{t'} < m_t + M_h$, then the $t' \to W^+b$ branching fraction becomes even larger: $B(t' \to W^+b) > 2/(2 + c_L^2) > 2/3$, where the first inequality is due to the phase-space suppression of the $t' \to Z^0t$ decay. As an example, the branching fractions of t' for $M_h = 150$ GeV are shown in Figure 1 as a function of s_L for fixed $m_{t'}$, and as a function of $m_{t'}$ for fixed s_L.

It is interesting that the top-prime lifetime can be long in the $s_L \to 0$ limit [2]. The decay length for a top-prime moving at the speed $\beta_{t'}$ is given by:

$$L = 3\,\text{cm}\left(\frac{10^{-8}}{s_L}\right)^2\left(\frac{450\ \text{GeV}}{m_{t'}}\right)^3 \beta_{t'} \ . \tag{2.17}$$

Therefore the top-prime decay is prompt for $s_L \gtrsim 10^{-7}$. Nevertheless the limit of very small s_L is natural in a theory where a symmetry imposes $M_0 = 0$, motivating searches for displaced top-prime vertices.

3 A model with gluon-prime and top-prime

We now extend the model of Section 2 by including a $SU(3)_1 \times SU(3)_2$ gauge symmetry which is spontaneously broken down to the diagonal group $SU(3)_c$, identified with the gauge symmetry of QCD. This symmetry breaking pattern is due to the vacuum expectation value of a field Σ transforming as a bilinear under the two $SU(3)$ groups. Σ may be an elementary scalar so that the theory presented here is renormalizable and simple, but the radial degrees of freedom within Σ do not play a role in what follows. The quarks transform under the extended gauge group as shown in Table 1.

When Σ gets a VEV proportional to the 3×3 unit matrix, the two $SU(3)$ gauge bosons G^1_μ and G^2_μ mix [11]. One linear combination of the two $SU(3)$ gauge bosons is the massless gluon of QCD, G_μ, while the orthogonal combination G'_μ is a color-octet boson of spin 1 and mass M_G:

$$\begin{pmatrix} G^1_\mu \\ G^2_\mu \end{pmatrix} = \frac{1}{\sqrt{h_1^2 + h_2^2}} \begin{pmatrix} h_2 & -h_1 \\ h_1 & h_2 \end{pmatrix} \begin{pmatrix} G_\mu \\ G'_\mu \end{pmatrix} ,$$

where h_1 and h_2 are the $SU(3)_1 \times SU(3)_2$ gauge couplings.

In the mass eigenstate basis for the fermions and gauge bosons, the gluon interactions with all quarks are vectorlike and have a strength set by the QCD gauge coupling

$$g_s = \frac{h_1 h_2}{\sqrt{h_1^2 + h_2^2}} . \tag{3.1}$$

	$SU(3)_1$	$SU(3)_2$	$SU(2)_W$	$U(1)_Y$
SM quarks: q^i_L, u^i_R, d^i_R	3	1	2, 1, 1	+1/6, +2/3, −1/3
vectorlike quark: χ_L, χ_R	1	3	1	+2/3
scalar with VEV: Σ	3	$\overline{3}$	1	0

Table 1: Fields charged under the $SU(3)_1 \times SU(3)_2$ gauge group, and their electroweak charges. The i upper index of the standard model quarks labels the three generations.

The gluon-prime interaction with light quarks is also vectorlike, but of different strength:

$$g_s r \, G'^a_\mu \, \overline{q}\gamma^\mu T^a q \ , \tag{3.2}$$

where T^a are the $SU(3)_c$ generators and

$$r \equiv \frac{h_1}{h_2} \ . \tag{3.3}$$

If $r \ll 1$ ($r \gg 1$), then the gauge coupling h_2 (h_1) is large and the theory becomes nonperturbative. Imposing some loose perturbative condition, h_2 (h_1) $< 4\pi/\sqrt{N_c}$ with $N_c = 3$, and using Eq. (3.1) with $\alpha_s \equiv g_s^2/(4\pi) \approx 0.1$, we derive the range of values for r where our tree-level results can be trusted:

$$0.15 \lesssim r \lesssim 6.7 \ . \tag{3.4}$$

The gluon-prime interactions with the t and t' quarks are chiral, and include flavor-diagonal terms,

$$g_s G'^a_\mu \left[\overline{t}\gamma^\mu \left(g_L P_L + g_R P_R \right) T^a t + \overline{t'}\gamma^\mu \left(g''_L P_L + g''_R P_R \right) T^a t' \right] \ , \tag{3.5}$$

as well as flavor-changing terms,

$$g_s G'^a_\mu \, \overline{t}\gamma^\mu \left(g'_L P_L + g'_R P_R \right) T^a t' + \text{H.c.} \tag{3.6}$$

The left- and right-handed projection operators are given as usual by $P_{L,R} = (1 \mp \gamma_5)/2$, the couplings of the left-handed quarks are

$$g_L = r c_L^2 - \frac{s_L^2}{r} \quad , \quad g''_L = r s_L^2 - \frac{c_L^2}{r} \quad , \quad g'_L = \left(r + \frac{1}{r} \right) s_L c_L \ , \tag{3.7}$$

while the right-handed couplings, g_R, g''_R and g'_R, are analogous to the left-handed ones except for the replacements $s_L \to s_R$ and $c_L \to c_R$.

Altogether, the model discussed here has 5 free parameters: the masses $m_{t'}$ and M_G of the top-prime and gluon-prime, the mixing parameter s_L from the top sector, the ratio r of the $SU(3)_1$ and $SU(3)_2$ gauge couplings, and the standard model Higgs mass M_h.

Given the couplings shown in Eqs. (3.2), (3.5) and (3.6), we can compute the decay widths of G'_μ. Summing over the standard model quarks other than top, we find

$$\Gamma \left(G'_\mu \to \sum q\bar{q} \right) = \frac{5}{6} \alpha_s r^2 M_G \ . \tag{3.8}$$

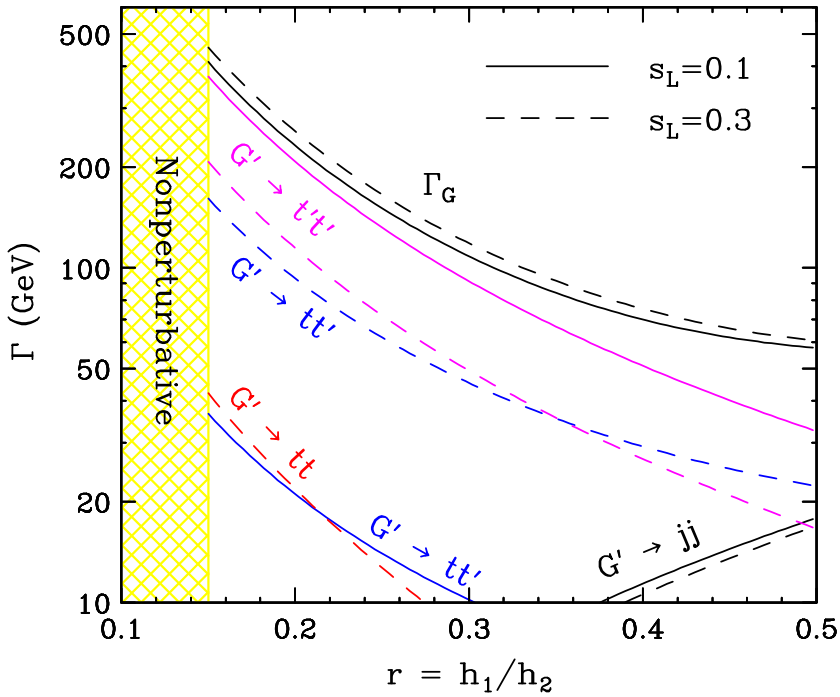

Figure 2: Decay widths of G'_μ as shown in Eqs. (3.8)-(3.11) for its four decay modes, as a function of the ratio r of gauge couplings, for $M_G = 1$ TeV, $m_{t'} = 450$ GeV, and $s_L = 0.1$ (solid lines) or 0.3 (dashed lines). The top two lines represent the total width.

The decay width into $t\bar{t}$, for $M_G \gg m_t$, is given by:

$$\Gamma\left(G'_\mu \to t\bar{t}\right) = \frac{\alpha_s}{12}\left(g_L^2 + g_R^2\right) M_G \ . \tag{3.9}$$

Including the exact phase-space suppression, the decay width into $t'\bar{t}'$ is

$$\Gamma\left(G'_\mu \to t'\bar{t}'\right) = \frac{\alpha_s}{12}\left[\left(g_L''^2 + g_R''^2\right)\left(1 - \frac{m_{t'}^2}{M_G^2}\right) + 6 g_L'' g_R'' \frac{m_{t'}^2}{M_G^2}\right]\left(1 - \frac{4m_{t'}^2}{M_G^2}\right)^{1/2} M_G \ . \tag{3.10}$$

Finally, the gluon-prime may decay into a top and a top-prime quark, with a width

$$\Gamma\left(G'_\mu \to t\bar{t}' + t'\bar{t}\right) = \frac{\alpha_s}{6}\left[\left(g_L'^2 + g_R'^2\right) F\left(\frac{m_{t'}^2}{M_G^2}, \frac{m_t^2}{M_G^2}\right) + 6 g'_L g'_R \frac{m_{t'} m_t}{M_G^2}\right] \beta\left(\frac{m_{t'}^2}{M_G^2}, \frac{m_t^2}{M_G^2}\right) M_G \ , \tag{3.11}$$

where $\beta(x_1, x_2)$ is given in Eq. (2.15) and

$$F(x_1, x_2) = 1 - \frac{1}{2}\left(x_1 + x_2\right) - \frac{1}{2}\left(x_1 - x_2\right)^2 \ . \tag{3.12}$$

In Figure 2 we plot the tree-level partial widths of the gluon-prime as a function of r for fixed s_L.

The total width of G'_μ, Γ_G, is the sum of the above four decay widths. For small r the total width is large, as shown in Figure 2, but for $r \gtrsim 0.3$ the gluon-prime becomes a narrow resonance, with Γ_G less than 10% of M_G. Note that for $M_G \gg 2m_{t'}$, the total width is independent of the quark mixing angles:

$$\Gamma_G = \frac{\alpha_s}{6}\left(6r^2 + \frac{1}{r^2}\right) M_G \ . \tag{3.13}$$

4 Resonant production of top-prime quarks

Let us now compute the cross sections for quark pair production at hadron colliders. We are primarily interested in the case where the $t'\bar{t}'$ production via an s-channel gluon-prime is substantially larger than the QCD production. A large G'_μ coupling to light quarks would be in conflict with the limits on dijet resonances, but the $t'\bar{t}'$ cross section can still be substantially enhanced if the G'_μ width is small. In that case we can ignore the interference between the gluon-prime and gluon. The partonic cross section for $t'\bar{t}'$ production as a function of the center-of-mass energy of the collision $\hat{s}$ is

$$\sigma\left(q\bar{q} \to G'_\mu \to t'\bar{t}'\right) = \frac{\sigma_0}{2}\left(1 - \frac{4m_{t'}^2}{\hat{s}}\right)^{1/2}\left[\left(g_L''^2 + g_R''^2\right)\left(1 - \frac{m_{t'}^2}{\hat{s}}\right) + 6g_L''g_R''\frac{m_{t'}^2}{\hat{s}}\right] . \tag{4.1}$$

The resonant part of the above cross section is contained in

$$\sigma_0 = \frac{8\pi}{27}\alpha_s^2 r^2 \, \frac{\hat{s}}{\left(\hat{s} - M_G^2\right)^2 + M_G^2\Gamma_G^2} \ , \tag{4.2}$$

where Γ_G, the total width of the gluon-prime, was computed at the end of Section 3. Similarly, the $t\bar{t}$ production cross section due to an s-channel gluon-prime is given by replacing $m_{t'} \to m_t$, $g_L'' \to g_L$ and $g_R'' \to g_R$ in the above expression for $\sigma\big(q\bar{q} \to G'_\mu \to t'\bar{t}'\big)$. The cross section for producing a top and a top-prime is:

$$\sigma\left(q\bar{q} \to G'_\mu \to t\bar{t}' + t'\bar{t}\right) = \sigma_0\,\beta\left(\frac{m_{t'}^2}{\hat{s}}, \frac{m_t^2}{\hat{s}}\right)\left[\left(g_L'^2 + g_R'^2\right)F\left(\frac{m_{t'}^2}{\hat{s}}, \frac{m_t^2}{\hat{s}}\right) + 6g_L'g_R'\frac{m_t m_{t'}}{\hat{s}}\right] , \tag{4.3}$$

with the functions β and F given in Eqs. (2.15) and (3.12), respectively. The dijet cross section, including 5 quark flavors and neglecting the t-channel exchange, is simply

$$\sigma\big(q\bar{q} \to G'_\mu \to jj\big) \simeq 5r^2\sigma_0 \ . \tag{4.4}$$

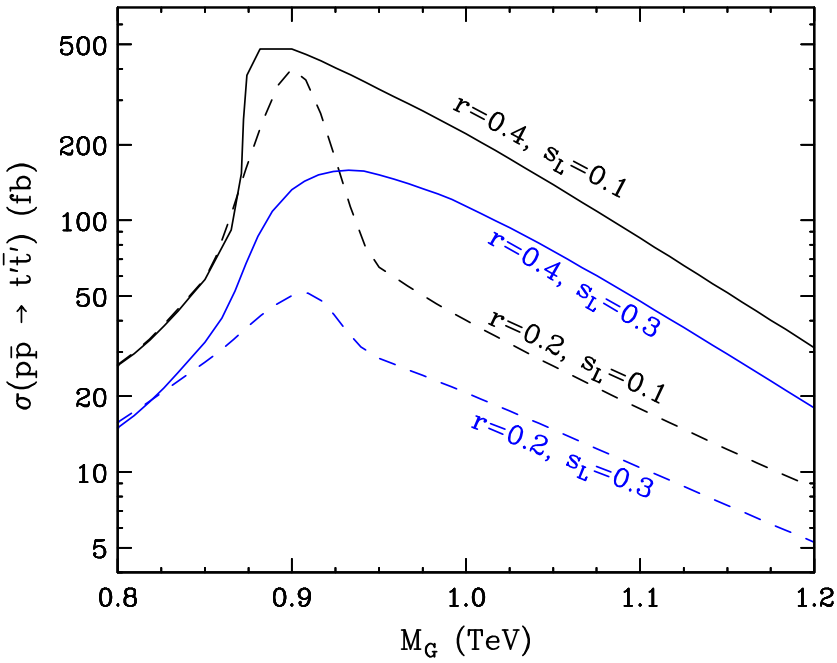

Figure 3: Cross section for t' pair production at the Tevatron as a function of the G'_μ mass M_G, for $m_{t'} = 450$ GeV, $r = 0.2$ or 0.4, and $s_L = 0.1$ or 0.3.

Convoluting these partonic cross sections with the CTEQ6L [21] parton distribution functions, one can obtain the leading-order cross sections at hadron colliders. We have also implemented the interactions shown in Eqs. (3.2), (3.5) and (3.6) in CalcHEP [22] and MadGraph [23], allowing us to more efficiently compute the hadronic cross sections [24]. The $p\bar{p} \to G' \to t'\bar{t}'$ cross section in Run II of the Tevatron is shown in Figure 3, for a renormalization and factorization scale of $\sqrt{\hat{s}}$. The threshold behavior close to $M_G \sim 2m_{t'}$ results in regions where a given cross section is consistent with two different G'_μ masses. We do not include any next-to-leading order corrections because they have not been computed for this process.

4.1 The t' search in the $(Wj)(Wj)$ final state at the Tevatron

We now have the tools needed to discuss the existing Tevatron t' searches. The CDF Collaboration [10] has searched for t' pair production in the $\ell + \nu + 4j$ channel, where the lepton and neutrino reconstruct a W. They then imposed that two of the jets reconstruct a second W, and paired the remaining jets with the hadronic and leptonic Ws in such a way as to minimize the difference between the invariant mass of the jet+W systems. The latter constraint determines $m_{t'}$. In 2.8 fb^{-1} of data they found 7 candidate $t'\bar{t}'$

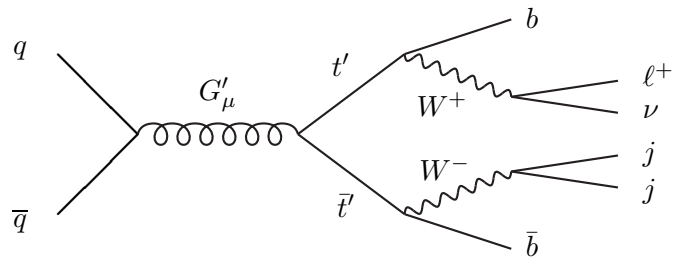

Figure 4: Resonant $t'\bar{t}'$ production followed by $t' \to Wb$ decays, with one W decaying leptonically and the other W decaying to jets.

events with reconstructed $m_{t'}$ between 375 and 500 GeV. The standard model predicts a background of 2.1 events. Although the excess events may be due to a fluctuation of the background, it is intriguing that they can be interpreted as due to the decays of a t' pair with $m_{t'} \approx 450$ GeV. Taking into account the resolution, any value of $m_{t'}$ between about 400 and 500 GeV would probably fit the data.

However, the cross section that can account for the observed events is at least an order of magnitude larger than the QCD production of a t' pair at that mass [10]. We propose that this discrepancy is due to the resonant enhancement of the cross section when the gluon-prime is produced in the s-channel, as shown in Figure 4.

One worry about the s-channel resonance interpretation is that, in order to be produced at the Tevatron, the new particle must couple to quarks or gluons and hence would give rise to a dijet resonance that would already have been observed. The CDF search for dijet resonances in 1.1 fb^{-1} of data has ruled out a gluon-prime of mass up to 1.25 TeV [26], assuming that it couples to all quarks as the usual gluon. In our model, though, the branching fraction into jets is parametrically smaller by a factor r^4: one factor of r^2 coming from the width to dijets, and another coming from the total width (dominated by the width to t' pairs) which is proportional to $1/r^2$ for $r \ll 1$. Furthermore, the production of the gluon-prime is suppressed by r^2, due to the smaller coupling to standard model quarks. As a result, $\sigma(p\bar{p} \to G' \to jj)$ decreases as r^6, and the limit of 120 fb set by dijet resonance searches can be satisfied for a nontrivial range of parameters: for $M_G = 1$ TeV, we find $r \lesssim 0.4$. Note that the dijet cross section, given in Eq. (4.4), is only weakly dependent on s_L through Γ_G.

Searches for $t\bar{t}$ resonances also impose a constraint on our model. The partonic cross

section, ignoring terms of order $m_t^2/\hat{s}$, may be written as

$$\sigma\left(q\bar{q} \to G'_\mu \to t\bar{t}\right) \approx \frac{\sigma_0}{2r^2}\left[\left(s_L^2(1+r^2)-r^2\right)^2 + \left(\frac{s_L^2 m_{t'}^2(1+r^2)}{m_t^2+s_L^2(m_{t'}^2-m_t^2)} - r^2\right)^2\right] , \quad (4.5)$$

where we used the expression for s_R given in Eq. (2.5). The above square bracket is maximized when $s_L \to 1$ as long as $r < 1$, while for r too small Γ_G is large so that σ_0 is small. Hence, $t\bar{t}$ resonance searches are sensitive to the region of large s_L and large r. The current best limit on the cross section of a $t\bar{t}$ resonance is 570 fb for a resonance of 900 GeV [27].

A similar analysis applied to Eq. (4.1) shows that $\sigma\left(q\bar{q} \to G'_\mu \to t'\bar{t'}\right)$ is maximized for $s_L \to 0$. In this limit, the product of the G'_μ couplings to light quarks and to t' becomes independent of r, but for small r the $t'\bar{t'}$ cross section still decreases when r decreases because the G'_μ becomes broader. We display the cross section for t' pair production at the Tevatron in Figure 5 as contours (solid lines) in the s_L-r plane. Given that the $t' \to Wb$ branching fraction is approximately 70% for large Higgs mass (see Section 2), the cross section for $(W^+b)(W^-\bar{b})$ is around half the $t'\bar{t'}$ cross section.

This should be compared with the observed $(Wj)(Wj)$ cross section, which must be around 20 fb in order to give rise to 5 excess events for an 8.8% acceptance [25], corresponding to a $t'\bar{t'}$ cross section of 40 fb. Thus, values $r \gtrsim 0.2$ are preferred within the allowed (unshaded) region in Figure 5. With this restriction, the G' width is less than 20% of its mass (see Figure 2), justifying our neglect of interference with the gluon in computing the $t'\bar{t'}$ and $t\bar{t}$ cross sections[2].

The top-prime production in association with a top quark is also of interest. Its partonic cross section, given in Eq. (4.3), vanishes in the $s_L \to 0$ limit, while for $m_{t'}^2 \gg m_t^2$ it is proportional to $s_L^2 c_L^2$. Thus, the $t\bar{t'} + t'\bar{t}$ cross section reaches its maximum for s_L close to 1/2, away from the maxima of both the $t'\bar{t'}$ and $t\bar{t}$ cross sections. In Figure 5 we show the $t\bar{t'} + t'\bar{t}$ cross section contours (dashed lines) in the s_L-r plane. Strikingly, in the region where the CDF excess events may be explained and $0.3 \lesssim s_L \lesssim 0.5$ and $0.3 \lesssim r \lesssim 0.4$, the $(W^+b)(W^-\bar{b})$ cross section from associated t' production may be up to 5 times larger than that from t' pair production.

It is important to note that there are searches for '$t\bar{t}$ resonances' from both the CDF

[2]The $t'\bar{t'}$ contours in the lower part of the allowed region ($r \lesssim 0.2$) in Figure 5 are only approximate, since the width of the G'_μ is large here. The interference with the gluon may easily be included using CalcHEP or MadGraph, but may complicate the comparison to the data because experimental plots often assume a narrow width and no interference.

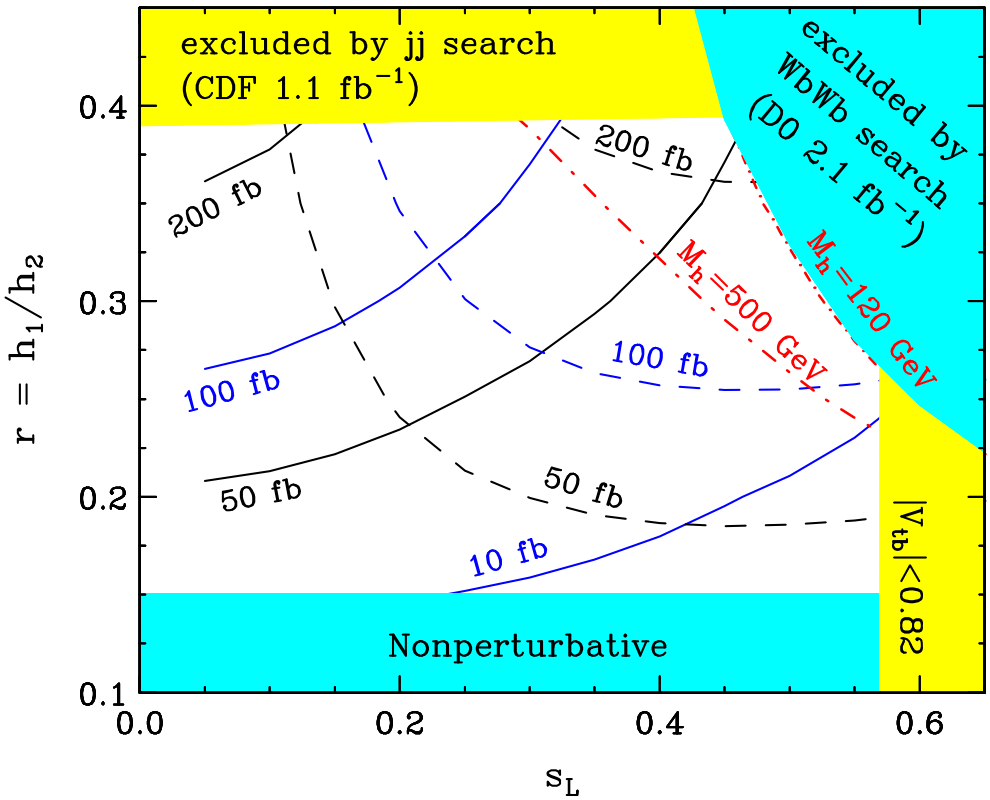

Figure 5: Production cross sections for $t'\bar{t}'$ (solid lines) and $t\bar{t}' + t'\bar{t}$ (dashed lines) at the Tevatron, for $M_G = 1$ TeV and $m_{t'} = 450$ GeV. The shaded regions for $s_L > 0.57$ and $r < 0.15$ are excluded by Eqs. (2.9) and (3.4). The shaded region from the upper side of the plot is excluded by the search for dijet resonances [26]. The search for $(Wb)(Wb)$ resonances [29] excludes the upper-right corner: the shaded region for $M_h = 120$ GeV, and everything above the dot-dashed line for $M_h = 500$ GeV.

and D0 Collaborations that do not attempt to reconstruct the top mass. These are in fact searches for $WbWb$ resonances, and in the context of our model, they are sensitive to the *sum* of the $t\bar{t}$, $t'\bar{t}'$, $t'\bar{t}$ and $t\bar{t}'$ resonances. The CDF search of this type [28], with 680 pb^{-1} of data, yielded 13 events with $WbWb$ invariant masses in the 750 - 1000 GeV range, while the estimated background is approximately 5 events. The D0 search [29], with 2.1 fb^{-1}, set a 95% confidence level upper limit of 210 fb on a $WbWb$ resonance of 1 TeV. This limit excludes a region in the s_L-r plane, which depends on the Higgs mass because of the $t' \to Wb$ branching fraction. For $M_h = 120$ GeV the shaded region in the upper right corner of Figure 5 is excluded; for larger Higgs masses the excluded region grows, reaching the dot-dashed line for $M_h = 500$ GeV.

Figure 5 shows that a sizable region of parameter space is consistent with the $(Wj)(Wj)$

events observed at CDF when $M_G = 1$ TeV. Larger values of M_G, up to about 1.2 TeV, can also give a $t'\bar{t}'$ cross section above 40 fb, especially for small s_L. Values of M_G below 1 TeV are also fine, but the constraint on r from dijet resonance searches becomes more stringent. For M_G as low as 850 GeV, the $t'\bar{t}'$ cross section remains above 40 fb, with the small r and small s_L region satisfying the dijet constraint (see the $r = 0.2$ and $s_L = 0.1$ line on Figure 3).

Should the potential t' pair signal at CDF grow with luminosity, and also be confirmed by the D0 Collaboration, then its large cross section will point to an s-channel resonance. If this is the case, the invariant mass distribution of the full $(Wj)(Wj)$ final state should have a peak, representing the observation of a new particle (the gluon-prime in our model) as well as a measurement of its mass (M_G). Even if the current excess turns out to be only a fluctuation of the background, searching for a peak in the distribution of the total invariant mass in each event may uncover a top-prime signal that is otherwise swamped by background. It is thus important for the CDF and D0 Collaborations to impose a mass constraint on the $(Wj)(Wj)$ sample where one W and one jet have a mass peak at $m_{t'}$ and the other W and the remaining jet have a mass peak at either m_t or $m_{t'}$.

In addition, detailed studies of the t' can be carried out. Its spin and couplings to standard model particles may be measured by adapting current Tevatron analyses for the top quark, such as W-helicity measurements. Moreover, the invariant mass distribution of the lepton and b-jet from the same t' decay, which differs from that of the t due to the larger mass of the t', allows the measurement of the chiral structure of the t'-W-b coupling and t' spin [30]. Also, the measurement of the $t'\bar{t}'$ forward-backward asymmetry will probe the chiral structure of the G'_μ couplings.

Given the large enhancement of $t'\bar{t}'$ production in the presence of the G'_μ, it is instructive to estimate the ultimate $m_{t'}$ reach of the Tevatron. At the $M_G = 2m_{t'}$ threshold the G'_μ width becomes very small because the $t'\bar{t}'$ decay is no longer kinematically available. For small s_L, we get $\Gamma_G \approx \alpha_s r^2 M_G$, so that the width is smallest for small r. As a consequence, at threshold the $p\bar{p} \to G'_\mu \to t'\bar{t}'$ cross section becomes large for small r, in contrast with the small r region in Figure 5. Taking $M_G = 1.2$ TeV, $m_{t'} = 600$ GeV, $s_L = 10^{-2}$ and $r = 0.2$ we find $\sigma(p\bar{p} \to G'_\mu \to t'\bar{t}') \approx 35$ fb. For $M_h > m_{t'} - m_t$, the branching fraction into Wb is 72%, so that the $(W^+b)(W^-\bar{b})$ signal has a cross section of 18 fb. This is huge compared to the QCD pair production, of approximately 0.1 fb at $m_{t'} = 600$ GeV. Assuming a $\sim 9\%$ acceptance for a semileptonic $(Wj)(Wj)$ event at $m_{t'} = 600$ GeV, we find that there will be approximately 10 events in 10 fb^{-1} of data,

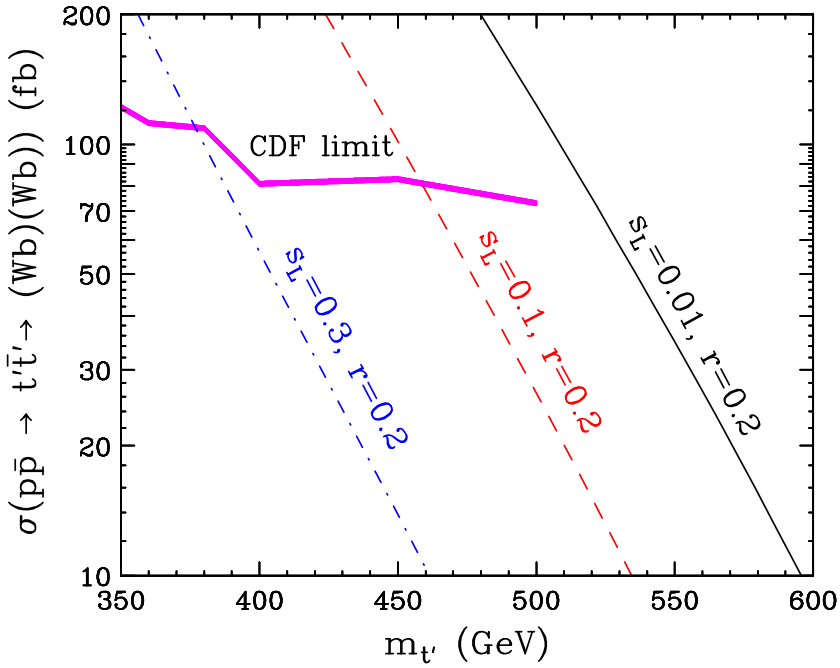

Figure 6: Cross section for $p\bar{p} \to G' \to t'\bar{t}' \to (Wb)(Wb)$ at the Tevatron as a function of t' mass, for $M_G = 2m_{t'}$, $M_h = 120$ GeV, $r = 0.2$, and $s_L = 0.01$, 0.1 or 0.3. Also shown is the CDF limit, taken from [10].

while the background is likely to be very small. We conclude that $m_{t'} = 600$ GeV will be within the reach of the Tevatron if enough data is analyzed. For a lighter Higgs boson, the smaller $t' \to Wb$ branching fractions leads to a decrease in the $(Wb)(Wb)$ signal. The $(Wb)(Wb)$ cross section is plotted in Figure 6 as a function of t' mass for $M_h = 120$ GeV.

4.2 Other signatures at hadron colliders

Also interesting for both t' pair production and associated production are the decays $t' \to Z^0 t$ and $t' \to h^0 t$. In particular, the $t' \to h^0 t$ decay may allow the discovery of the standard model Higgs boson. Processes with large branching fractions include

$$p\bar{p} \to G'_\mu \to t'\bar{t} \to \ (tZ^0)\,\bar{t} \ / \ (t\,h^0)\,\bar{t} \ / \ (W^+b)\,\bar{t} \ ,$$

$$p\bar{p} \to G'_\mu \to t'\bar{t}' \to \ (tZ^0)(W^-\bar{b}) \ / \ (t\,h^0)(W^-\bar{b}) \ ,$$

as well as the charge-conjugated processes. The parentheses here indicate that the two particles form a mass peak. Any of the $h^0 \to b\bar{b}, W^+W^-, Z^0Z^0$ decay modes may be important depending on the Higgs boson mass.

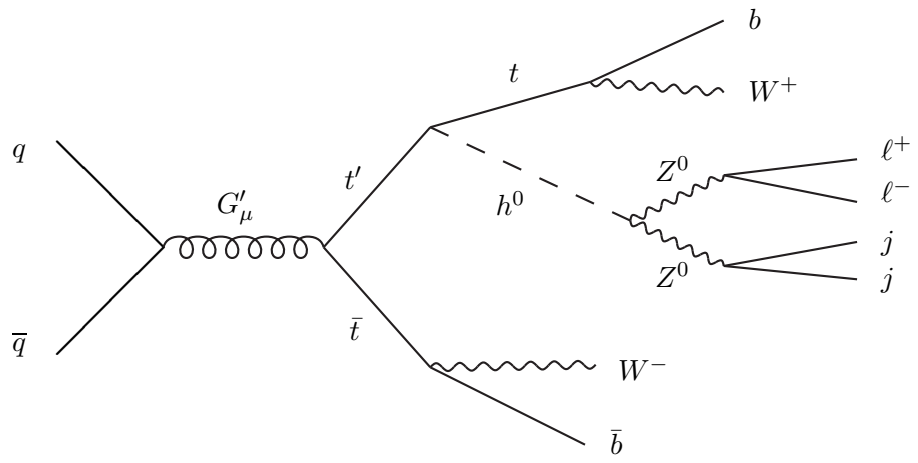

Figure 7: Resonant $t'\bar{t}$ production followed by $t' \to h^0 t$ and $h^0 \to Z^0 Z^0$ decays.

For example, with M_h in the 200 - 230 GeV range, the standard model predicts a branching fraction of approximately 2.8% for $h^0 \to Z^0 Z^0$ with one Z^0 decaying to e^+e^- or $\mu^+\mu^-$ and the other Z^0 decaying to jets. Taking into account that $B(t' \to h^0 t) \approx 20\%$ for $m_{t'} = 450$ GeV, and that $\sigma(p\bar{p} \to G'_\mu \to t't)$ can be as large as 200 fb for $M_G = 1$ TeV (see Figure 5), we find that the process shown in Figure 7 can have a cross section of about 1 fb at the Tevatron, which is more than an order of magnitude larger than the corresponding $t\bar{t}h$ cross section in the Standard Model. Thus, the CDF and D0 experiments could each observe several $t\bar{t}h^0$ events with $h^0 \to Z^0 Z^0 \to (\ell^+\ell^-)(jj)$. The background for this process is likely to be small, given that the two Z's form a mass peak at M_h.

Single-t' production from W exchange is rather small at the Tevatron. Compared to the standard model single-t production [32], single-t' production is suppressed due to the larger t' mass, and also by s_L^2 arising from the t'-W-b vertex given in Eq. (2.8). We find $\sigma(p\bar{p} \to t'j) \approx 4$ fb $(s_L/0.4)^2$ without cuts, for $m_{t'} = 450$ GeV. It would be difficult to distinguish this signature from the large $W + 2j$ background, which is estimated in Ref. [31].

At the LHC, by contrast, single-t' production is the main production mechanism for a heavy vectorlike t' [7, 32]. The $t' \to h^0 t$ decay followed by $h \to b\bar{b}$ has been studied in Ref. [33], while the more promising case $h^0 \to Z^0 Z^0$ with one of the Z^0 bosons decaying leptonically has been discussed in Ref. [8]. The LHC signals arising from QCD $t'\bar{t}'$ production are discussed in [33, 19, 34].

The LHC phenomenology in the presence of both the t' and the gluon-prime has not been studied yet. The small parton distribution for antiquarks within the proton reduces the gluon-prime production in pp collisions compared to $p\bar{p}$ collisions (gauge invariance forbids the gluons to couple at tree level to a single G'_μ). Nevertheless, the large center-of-mass energy planned for the LHC will significantly extend the reach in $m_{t'}$ and M_G.

5 Conclusions

We have shown that the pair production of top-prime quarks at the Tevatron may be increased by up to two orders of magnitude compared to the QCD process if it occurs via an s-channel resonance. In the case where this resonance is a gluon-prime particle, the Tevatron searches may be sensitive to top-primes as heavy as 600 GeV. Such a gluon-prime arises in gauge extensions of QCD, while the top-prime can arise from a vectorlike quark that has a mass mixing with the standard top quark.

It is intriguing that the simple renormalizable model for new physics presented here, which includes only two particles beyond the standard model, fits the noticeable CDF excess in the semileptonic $(Wj)(Wj)$ channel without fine-tuning. Fixing the top-prime mass at 450 GeV, we can match the CDF excess for any gluon-prime mass in the 850 - 1200 GeV range. A $Z' \to t'\bar{t}'$ interpretation of this excess would be problematic, because the large coupling to t' would require the embedding of the associated gauge symmetry in a non-Abelian gauge group at a scale near the Z' mass.

Independent of the CDF excess, our $t' + G'_\mu$ model motivates new ways of analyzing existing Tevatron data. Single production of a t' in association with a top quark may have a large cross section. This process, as well as $t'\bar{t}'$ production, with a top-prime subsequently decaying to $h^0 t$ imply that the Tevatron may be sensitive to Higgs masses as large as 230 GeV. A possible discovery channel is resonant $t'\bar{t}$ production followed by $t' \to h^0 t$ and $h^0 \to Z^0 Z^0$ decays.

On a more general note, the $t' + G'_\mu$ model presented here underscores the importance of reconstructing the invariant mass of the entire event, even for complicated final states such as $WjWj$ or $t\bar{t}h^0$. Furthermore, the rich phenomenology predicted in this simple extension of the standard model (including, for example, the displaced t' decays mentioned in Section 2, or the $WbtZ$ signature mentioned in Section 4) illustrates that the Tevatron may discover new physics provided that searches are extended to cover as many signatures as possible.

Note added: Subsequent to the completion of this paper, the D0 search for resonances in the $WbWb$ final state was updated with 3.6 fb^{-1} of data [35]. The new result includes 17 events in the 800 - 1000 GeV range, with a background of approximately 6.4 events. The extra events may arise from a G'_μ resonance with $M_G \approx 900$ GeV which decays into a t' pair or into a t' and a t quark. A set of parameters consistent with this scenario is $m_{t'} \approx 430$ GeV, $r \approx 0.2$, $s_L \approx 0.1$, $M_h \approx 120$ GeV.

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