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Searches for Fourth Generation Fermions

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Abstract

We present the results from searches for fourth generation fermions performed using data samples collected by the CDF II and D0 Detectors at the Fermilab Tevatron $p\overline{p}$ collider. Many of these results represent the most stringent 95% C. L. limits on masses of new fermions to-date.

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1 Introduction

A fourth chiral generation of massive fermions with the same quantum numbers as the known fermions is one of the simplest extensions of the SM with three generations. The fourth generation is predicted in a number of theories [1, 2, 3], and although historically have been considered disfavored, stands in agreement with electroweak precision data [3, 4, 5].

To avoid $Z \to \nu\overline{\nu}$ constraint from LEP I a fourth generation neutrino ν_4 must be heavy: $m(\nu_4) > m_Z/2$, where m_Z is the mass of Z boson, and to avoid LEP II bounds a fourth generation charged lepton ℓ_4 must have $m(\ell_4) > 101$ GeV/c^2. At the same time due to sizeable radiative corrections masses of fourth generation fermions cannot be much higher the current lower bounds and masses of new heavy quarks t' and b' should be in the range of a few hundred GeV/c^2 [5].

In the four-generation model the present bounds on the Higgs are relaxed: the Higgs mass could be as large as 1 TeV/c^2 [5, 6, 7]. Furthermore, the CP violation is significantly enhanced to the magnitude that might account for the baryon asymmetry in the Universe [8]. Additional chiral fermion families can also be accommodated in supersymmetric two-Higgs-doublet extensions of the SM with equivalent effect on the precision fit to the Higgs mass [3].

Another possibility is heavy exotic quarks with vector couplings to the W boson [9] Contributions to radiative corrections from such quarks with mass M decouple as $1/M^2$ and easily evade all experimental constraints.

At the Tevatron $p\overline{p}$ collider 4-th generation chiral or vector-like quarks can be either produced strongly in pairs or singly via electroweak production, where the latter can be enhanced for vector-like quarks. In the following we present searches for both pair and single production of heavy quarks performed by CDF and D0 Collaborations.

2 Search for pair production $t'\overline{t'}$ with subsequent decays $t' \to Wb$ and $t' \to Wq$

Due to preferred small mass splitting between fourth generation t' and b' quarks, $m(b') + m(W) > m(t')$, t' decays predominantly to Wq (a W boson and a down-type quark $q = d, s, b$) [5, 6]. CDF analyzed 5.6 fb^{-1} of $p\overline{p}$ collisions data [10] to search for both possibilities: q is a light (d, s), or heavy flavor quark (b). Analysis is performed using events characterized by a high-p_T lepton, large missing transverse energy $\not\!\!E_T$ and at least four hadronic jets. The data events were collected by triggers that identify at least one high-p_T electron or muon candidate or by a trigger requiring $\not\!\!E_T$ plus jets.

For the $t' \to Wb$ search at least one of the jets was required to be identified as

coming from a bottom quark (b-tagged) by a secondary vertex tagging algorithm. For the $t' \to Wq$ search instead, several additional kinematic event selection criteria were applied to suppress QCD background contributions. The main SM backgrounds for these searches are $t\bar{t}$ and $W+$ light- and heavy-flavor jets productions, that are modeled with PYTHIA and ALPGEN generators.

The t' events and mass of t' quark were fully reconstructed using a χ^2-based fit technique, used in top quark mass measurement analyses. The search for t' signal is performed by employing a 2D binned likelihood fit for the mass of t' quark (M_{reco}) and the $H_T = \sum_{jets} E_T + E_{T,\ell} + \not{E}_T$, a scalar sum of transverse energies for all objects in the event, which also serves as a good discriminator between SM and new physics signal. To further enhance a sensitivity for t', the events were split into four different sub-samples based on the number of jets (4 or ≥ 5) and based on good or poor mass reconstruction χ^2.

The kinematic distributions of H_T and M_{reco} for the $t' \to Wb$ analysis are shown in Fig. 1. The analysis fit on the data shows no significant excess due to $t'\overline{t'}$ production. The observed 95% C.L. limits along with expected limits bands are derived using Bayesian technique and are shown in Fig. 2. Assuming strong production mechanism we exclude t' quark with mass below 358 GeV/c^2 for $B(t' \to Wb) = 100\%$, and below 340 GeV/c^2 for $B(t' \to Wq) = 100\%$, where q is a light flavor quark, at 95% C.L.

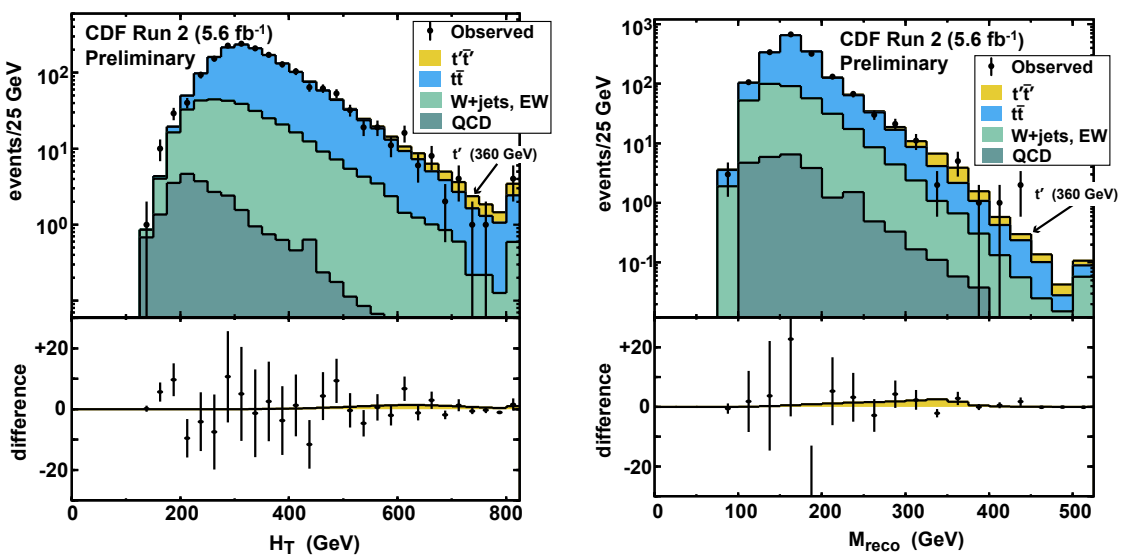

Figure 1: Distributions of H_T and M_{reco}. The contribution from t' events shown on the plot corresponds to t' mass of 360 GeV/c^2, assuming strong production mechanism.

Similar search for $t' \to Wq$ is done by D0 Collaboration [11], with the fit for $e+$ and $\mu+$ jets events performed separately. The kinematic distributions of H_T and M_{reco} are shown in Fig. 3. The data show no evidence for t', and the 95% C.L.

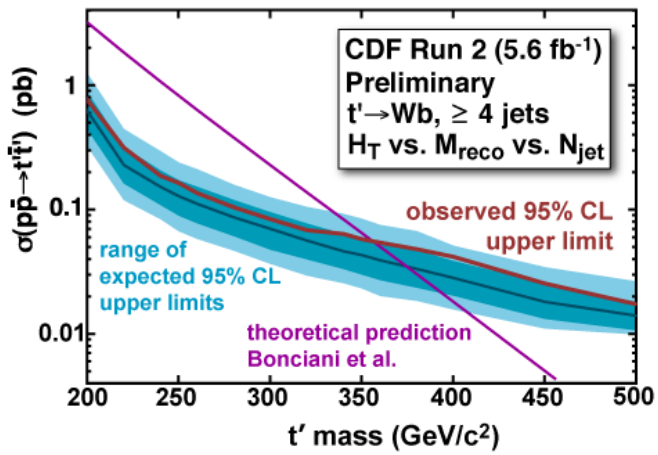

Figure 2: Observed and expected 95% C.L. upper limits as a function of the mass of the t' quark, for a t' decaying to Wb, obtained in CDF analysis.

observed and expected limits are presented in Fig. 4.

3 Search for pair production $b'\overline{b'}$ with subsequent decay $b' \to tW$

If the coupling of down-type fourth-generation quark b' to light quarks is small, then b' decays exclusively to tW. The limits on $b' \to Wq$ mode can be assessed from the t' analysis. CDF analyzed 4.8 fb^{-1} of data considering the mode $b'\overline{b'} \to WtW\overline{t} \to WWbWW\overline{b}$ in which one W boson decays leptonically [12]. Production and decay of b' pairs would appear as events with a charged lepton and missing transverse energy $\not\!\!E_T$ from leptonically decaying W, and a large number of jets from the two b quarks and the hadronic decays of the other three W bosons. Selected events are those with at least five jets, with at least one of them identified as due to b quark decay. SM backgrounds are primarily due to $t\bar{t}+$ and $W+$ jets, modeled with MADGRAPH and ALPGEN respectively, and interfaced with PYTHIA.

A b' signal is separated from the SM background both in the number of jets and the H_T. To take advantage of both of these characteristics, a variable "Jet-H_T" is introduced equal to $H_T + 1000$ GeV $\times(N_{jets} - 5)$, which is equivalent to a two-dimensional analysis in N_{jets} and H_T. The description of SM backgrounds is validated in low H_T regions. The CDF data distribution of Jet-H_T variable is shown in Fig. 6. In events with ≥ 7 jets a mild excess is observed at high-H_T region, however the total number of events in the ≥ 7 jets is consistent with expectation. The upper limits on $b'\overline{b'}$ production are derived using Feldman-Cousins likelihood-ratio ordering [13], and

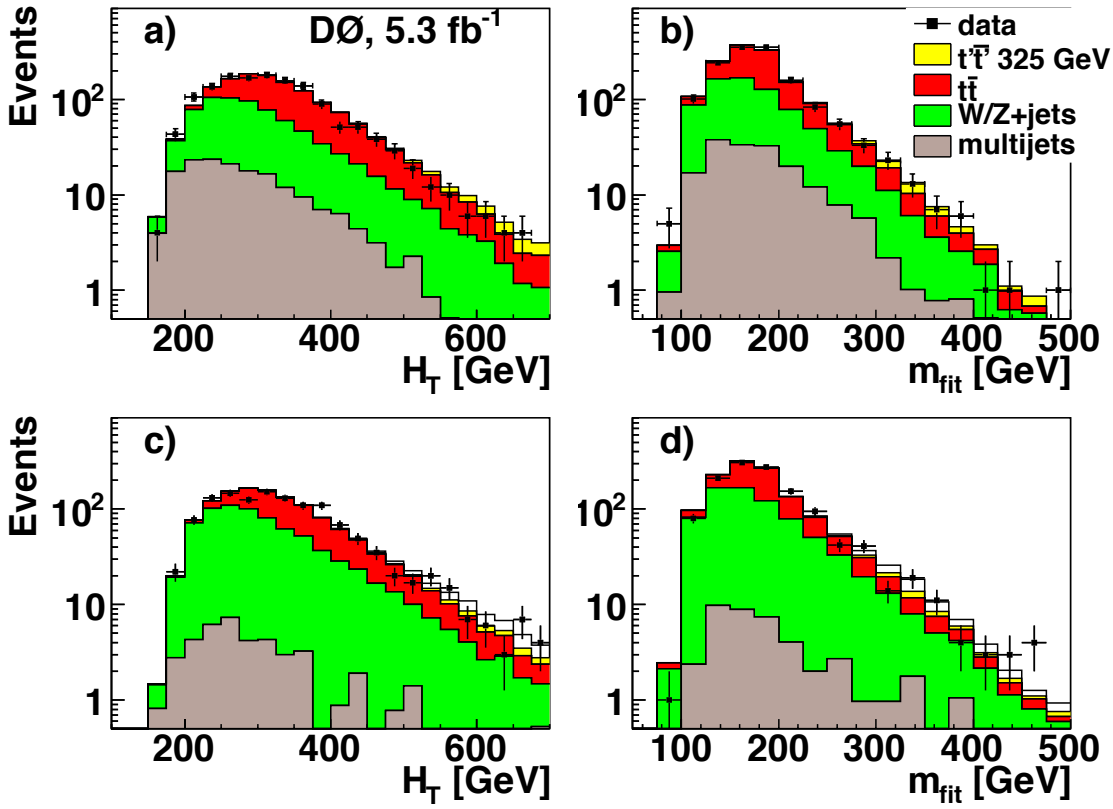

Figure 3: Distributions of H_T and t' reconstructed mass for $e+$ jets (top) and $\mu+$ jets events (bottom).

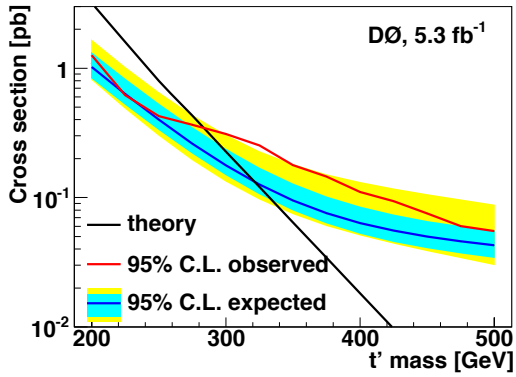

Figure 4: Observed and expected upper limits on $t'\overline{t'}$ production as a function of t' mass, obtained in D0 analysis.

are presented in Fig. 6.

CDF excludes a b' quark with mass below 372 GeV/c^2 at 95% C.L., assuming strong pair production mechanism and exclusive decay to tW.

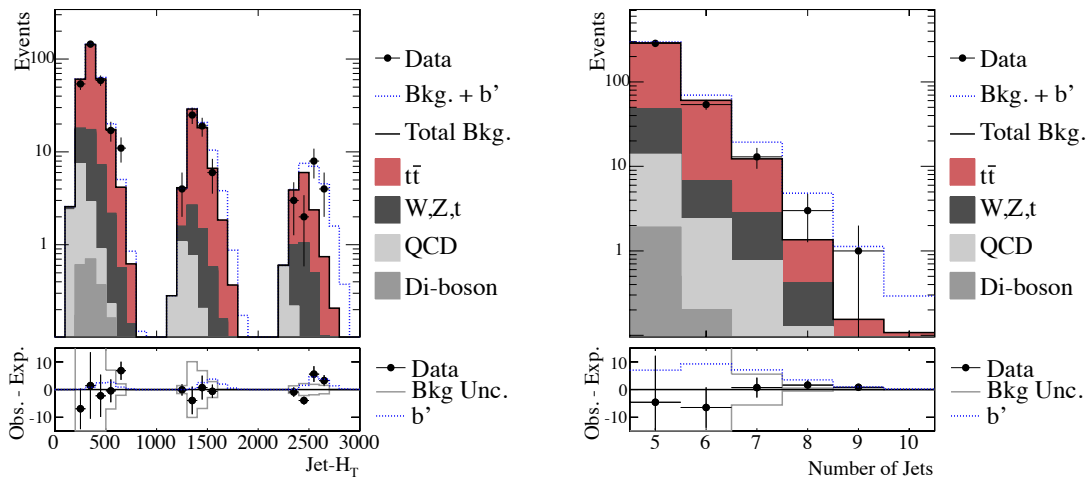

Figure 5: The distributions of "Jet-H_T" and jet multiplicity distributions in CDF b' search.

4 Search for $t'\bar{t}$ with $t' \to th$

If the t' quarks are produced via a new production mechanism, such as via new massive color-octet vector boson (G') exchange, the production cross section can be substantially higher than the one from QCD [15]. In these models it is possible that $G' \to t'\bar{t}$ with $t' \to th \to tb\bar{b}$ (see Fig. 7). This leads to event signatures with a large number of jets, three of which are expected to be from b-quarks.

D0 performed a search for $G' \to t'\bar{t} \to t\bar{t}h \to t\bar{t}b\bar{b}$ by using events with a least one high-p_T lepton, large missing transverse energy and at least 4 jets, with at least one of them identified as a b-jet. The events are further split depending on the number of jets (4 or ≥ 5), and the number of b-tagged jets (1, 2, or ≥ 3). Next, the simultaneous fit to the H_T distribution in all of these categories performed. The main background is from $t\bar{t}+$ jets, that is modeled with ALPGEN + PYTHIA, with a conservative 50% systematic uncertainty assigned to the process $t\bar{t}b\bar{b}$. The kinematic distributions of the H_T variable for different number of jets and tags are shown in Fig. 8.

The upper limits on G' production are set using a modified frequentist approach (CL_s) [14], and shown in Fig. 9 as a function of Higgs mass for different masses of t' quark. This can be interpreted as a 2D-limit in the phase space (m_H, m'_t) for a given

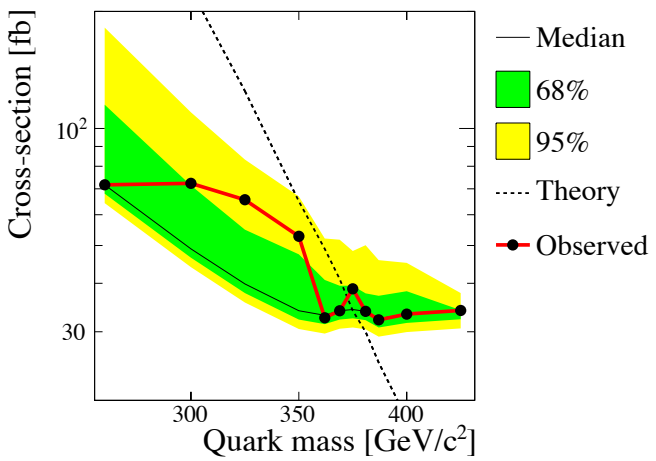

Figure 6: The CDF upper limits on the b' pair production, as a function of mass for b' quark.

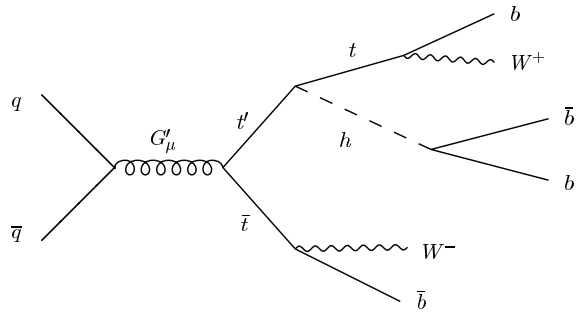

Figure 7: Feynman diagram for axi-gluon production.

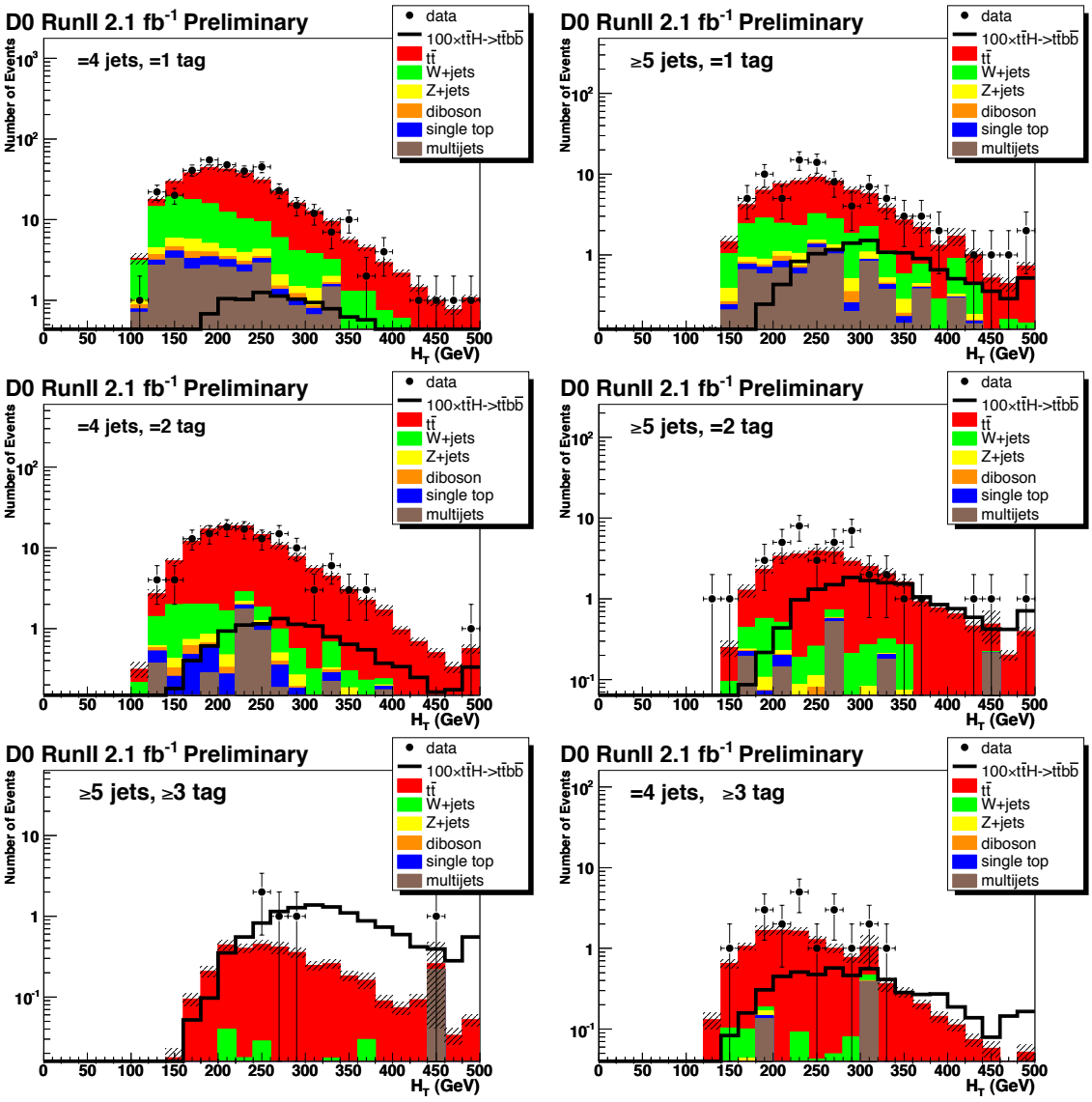

Figure 8: H_T distribution in various sub-samples of events, used in D0 search for $t't$.

coupling strength r and a mixing angle $\sin\theta_L \equiv s_L$ between the top and t' quark. The excluded region is shown in Fig. 9.

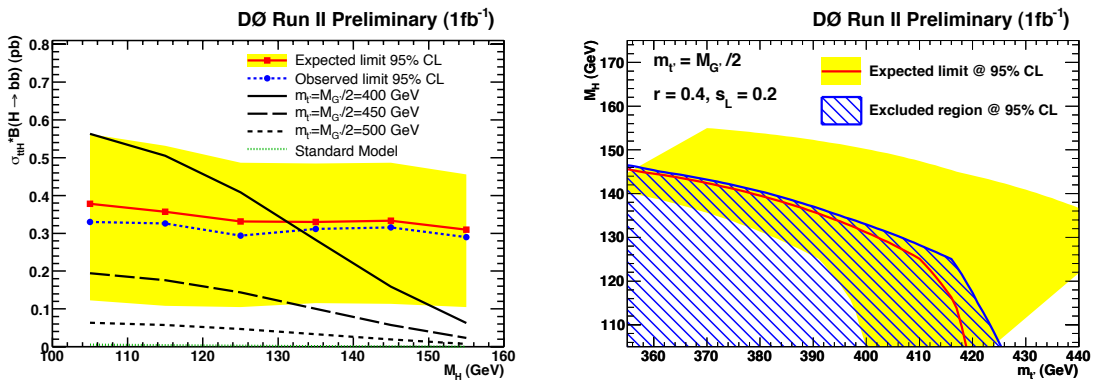

Figure 9: **LEFT:** The 95% C.L. upper limit on the cross section times SM branching ratio of $H \to b\bar{b}$, as a function of the SM Higgs mass. **RIGHT:** Excluded region as a function of the Higgs mass and the t' mass, assuming $m'_t = M_{G'}/2, r = 0.4$ and s_L .

5 Search for single new heavy quarks $Q \to Wq$ and $Q \to Zq$

Single production of heavy quarks can occur due to diagrams shown in Fig. 10. For vector-like quarks the production cross section can be enhanced with respect to SM-like fourth generation quarks, if the coupling strength κ_{qQ} to SM quarks is sufficiently large [16]. Depending on the couplings to u and d quarks the new heavy quarks can decay to either Wq or Zq.

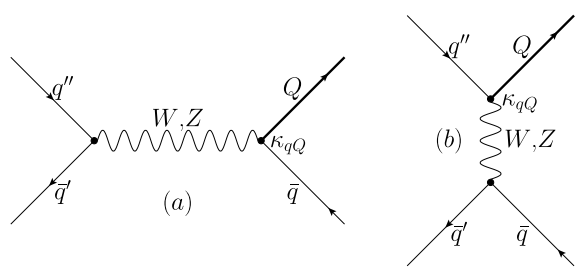

Figure 10: Feynmann diagrams for single vector-like quark production.

D0 performed a search for vector-like quarks in both $(W \to \ell\nu)$+ jets and $(Z \to \ell\ell)$ + jets channels in 5.4 fb^{-1} of data [17], using events with either single lepton + missing transverse energy (W), or events with exactly two electrons or muons forming an

invariant mass consistent with that of a Z boson. In addition, in both cases at least two high-E_T jets are required to be present in the event.

In the single lepton channel the highest-E_T jet expected to be from vector-like quark decay, and required to have $E_T > 100$ GeV. The second-highest E_T jet is expected to be from the SM quark produced in association with the vector-like quark. It is expected to be in one of the forward regions of the detector with direction strongly correlated with the charge of the produced vector-like quark, and thus also with the charge of the lepton from its decay. It is therefore required that $Q_\ell \times \eta_{j_2} > 0$, where Q_ℓ is the lepton charge and η_{j_2} is the pseudorapidity of the second jet in the event. Similarly, in the dilepton channel additional selection requirements characteristic of a heavy resonance decay to a Z boson and a jet are applied, such as the p_T of the dilepton system to be greater than 100 GeV, and the leading jet E_T to be above 100 GeV.

Fig. 11 shows the reconstructed vector-like transverse mass for the single lepton channel (left), and the vector-like quark mass in the dilepton channel, reconstructed as the invariant mass of the dilepton + leading jet system (right). No significant excess of data over the background prediction in either channel is observed. Upper limits on vector-like quark production cross sections are extracted using a modified frequentist approach (CL_S) [14], and are shown in Fig. 12.

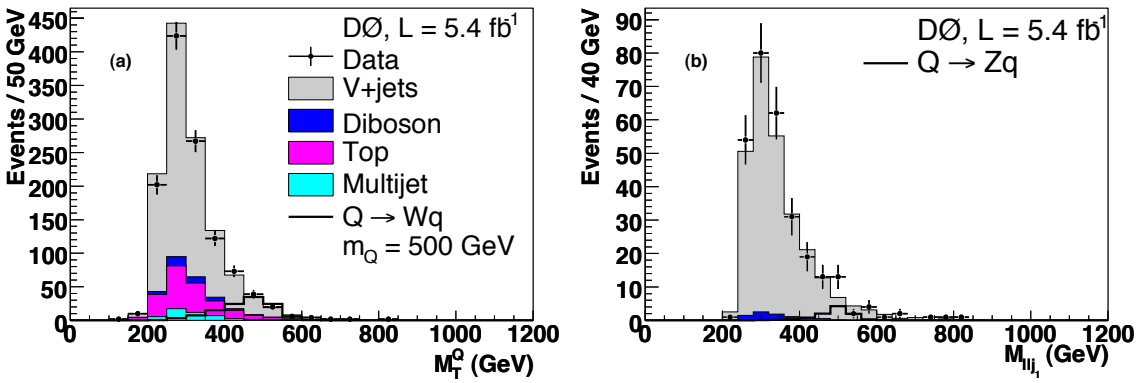

Figure 11: **LEFT:** Vector-like quark transverse mass for the single lepton channel. **RIGHT:** Vector-like quark mass for the dilepton channel (right).

CDF Collaboration performed a similar search for singly-produced vector-like quarks decaying to Wq using 5.7 fb^{-1} of data. The distribution of transverse mass of the vector-like quark is presented in Fig. 13. No significant deviation from the SM predictions is observed and the limits on the production cross section of new heavy quarks and the size of the couplings are set, that are shown in Fig. 14.

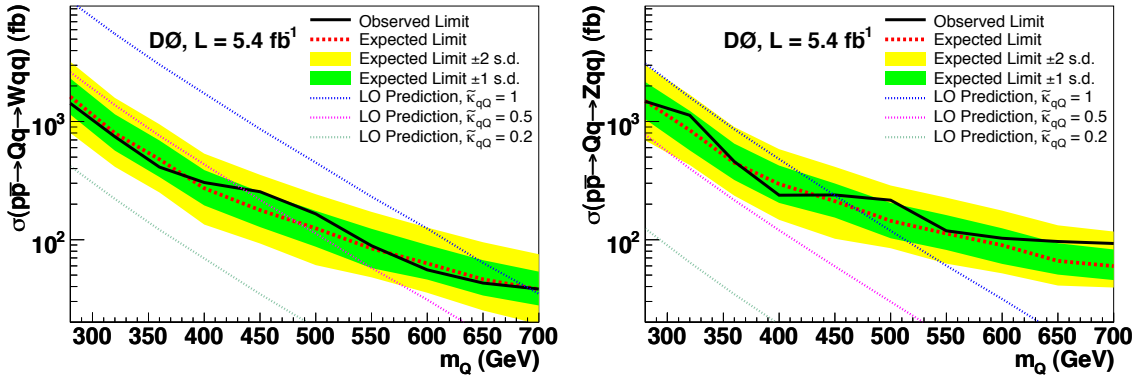

Figure 12: D0 observed and expected upper limits on production cross section for a vector-like quark Q decaying to $W+$ jet (left) and $Z+$ jet (right), as a function of m_Q for different values of couplings κ_{qQ}.

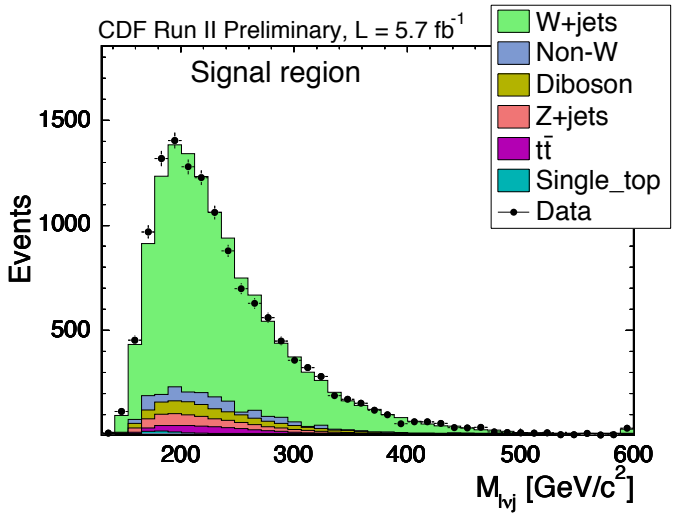

Figure 13: Vector-like quark transverse mass in CDF search.

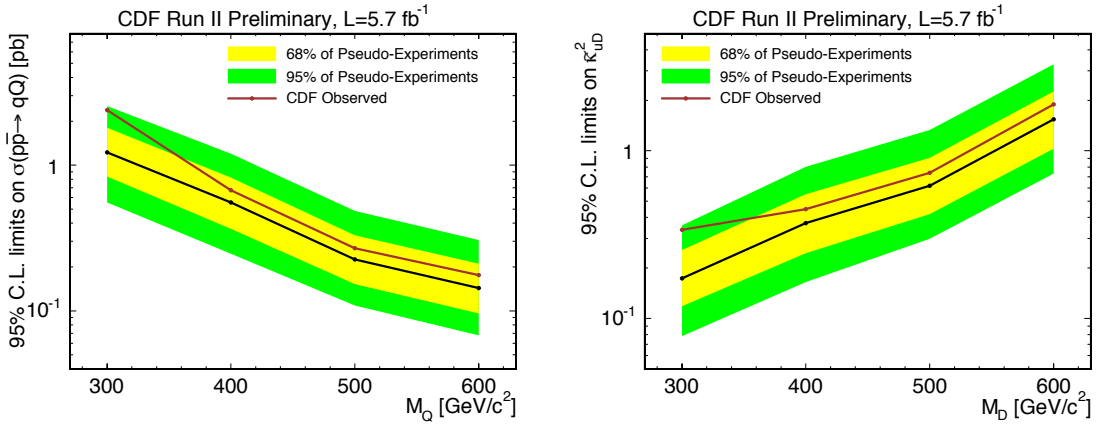

Figure 14: CDF 95% C.L. limit on production cross section of new heavy quarks (assuming $\kappa_{uQ} = 1$) , and the limit on the size of the coupling as functions of the heavy quark mass.

6 Search for Exotic $T'\overline{T'}$ with $T' \to tX$

In some of the exotic fourth-generation scenarios T' quark can decay to the top quark t and a dark matter candidate [18]. The pair production of such quarks results in a signature $t\bar{t}XX$ with an extra missing energy due to both of X. CDF performed the search in 4.8 fb^{-1} of data using events $\ell + 4$ jets $+\not\!\!E_T$, requiring a large missing transverse energy $\not\!\!E_T > 100$ GeV.

The SM background due $t\bar{t}$ and $W+$ jets is validated in two control regions. High $\not\!\!E_T$ control region: events with $N_{jets} = 3, \not\!\!E_T > 100$ GeV, which validates modeling of the large $\not\!\!E_T$ events, and low $\not\!\!E_T$ control region: events with $N_{jets} \geq 4, \not\!\!E_T < 100$ GeV, which validates the modeling of events with 4 jets. The signal region is defined as $N_{jets} \geq 4$, and $\not\!\!E_T > 100$ GeV. The transverse W mass distributions corresponding to these regions are shown in Fig. 15. The event yields corresponding to different regions are listed in Table I.

No significant excess that could be attributed to production of T' quarks is observed, and the limits are obtained by performing a log-likelihood fit to the transverse W boson mass. The observed and expected 95% C.L. limits as a function of the mass of T' quark and mass of dark matter candidate X are shown in Fig. 16.

7 Summary

We presented recent searches for fourth-generation quarks performed by CDF and D0 Collaborations using $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. No evidence for fourth-

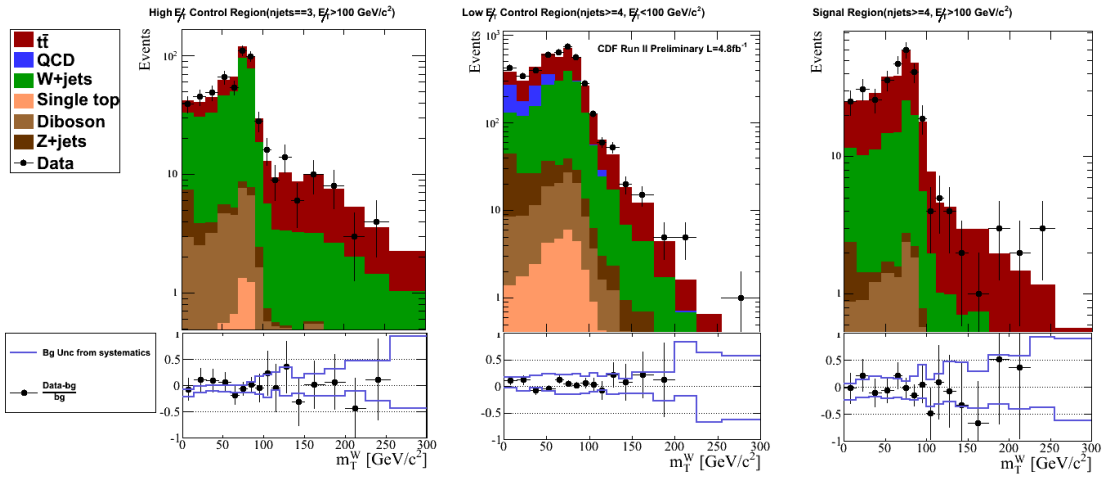

Figure 15: Transverse W mass distribution in the control and the signal regions.

TABLE I: Number of events with uncertainty due to systematics for various signal points compared to backgrounds and data for three different cuts.

Cut Flow:	1 lepton, $N_{Jets} \geq 1, \not\!\!E_T \geq 20$ GeV/c	$N_{Jets} \geq 4$	$\not\!\!E_T \geq 100$ GeV/c
$T'T' \to ttXX$			
$m_{T'} = 300, m_X = 90$ [GeV/c^2]	$146.7^{+0.18}_{-0.17}(syst)$	$69.1^{+5.5}_{-6.2}$	$22.8^{+3.4}_{-2.9}$
$m_{T'} = 310, m_X = 90$ [GeV/c^2]	$115.8^{+0.25}_{-0.51}$	$55.3^{+4.3}_{-4.5}$	$22.2^{+2.3}_{-2.3}$
$m_{T'} = 330, m_X = 90$ [GeV/c^2]	$116.3^{+0.11}_{-0.05}$	$56.4^{+4.6}_{-5.0}$	$27.5^{+4.2}_{-3.8}$
$m_{T'} = 360, m_X = 1$ [GeV/c^2]	$111.3^{+0.33}_{-0.45}$	$54.9^{+3.1}_{-4.4}$	$37.9^{+2.5}_{-3.4}$
$t\bar{t}$	4367^{+527}_{-435}	1957^{+304}_{-274}	189^{+54}_{-50}
W+jets	478268^{+56117}_{-48003}	1738^{+838}_{-260}	105^{+31}_{-14}
Single top	882.16 ± 8.8	30.8 ± 3.1	1.86 ± 0.2
Diboson	5057.7 ± 506	112.5 ± 11	9.69 ± 0.1
Z+jets	20624 ± 2062	135.4 ± 13	4.00 ± 0.4
QCD	78244 ± 7824	590.9 ± 59	0.04 ± 0.0
Total Background	587255^{+56500}_{-48400}	4566^{+1090}_{-540}	310^{+80}_{-64}
Data	591400	4571	309

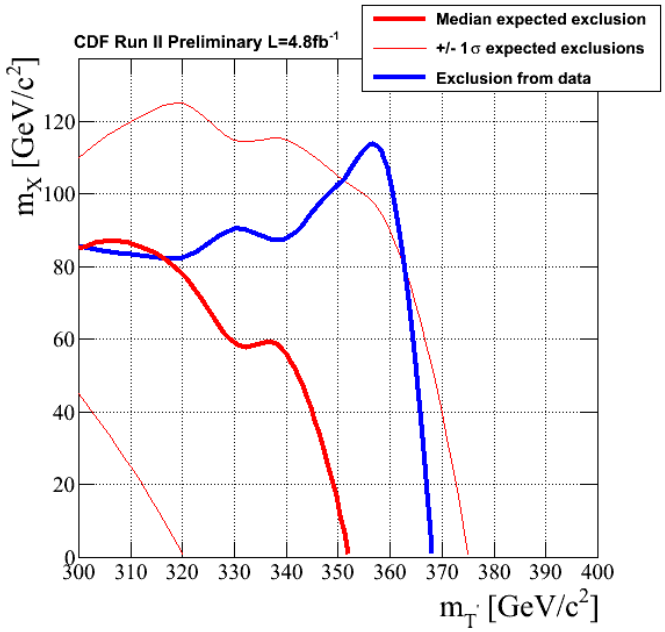

Figure 16: Excluded region on the 2D- $(m_{T'}, m_X)$ - plane.

generation fermions has been observed and 95% C.L. limits on masses and production cross section of these quarks have been set.

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