Top Quark Properties at the Tevatron

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Top quark physics is currently one of the most exciting laboratories for looking for physics beyond the standard model (SM). Using integrated luminosity of 2 fb^{-1} from CDF and DØ, we present three searches for such new physics.

1. Introduction

Since the discovery of the top quark in Run I, CDF and DØ have recorded over thirty times the integrated luminosity. With this new data sample, we are now in the position to thoroughly test the SM predictions to see if we find any evidence for physics beyond the standard model. We present three such searches here: DØ's $t\bar{t}$ resonance search, CDF's top FCNC decay search, and CDF's invisible top decay search.

2. DØ $t\bar{t}$ Resonance Search

Heavy resonances may play a part in top quark pair production, adding structure to the spectrum expected by SM production. Many theories (*e.g.,* Kaluza Klein states of gluon or Z boson, axiglunons, top color) have such predictions. [1]

Using 2.1 fb^{-1} of integrated luminosity, DØ performed a search for a high mass resonance decaying into $t\bar{t}$ quarks in the lepton + jets channel requiring an identified electron or muon, missing transverse energy consistent with an undetected neutrino, and three or more jets with at least one jet being identified as coming from a b hadronic decay. We calculate the $t\bar{t}$ invariant mass by summing up all four-momenta of the (up to) four leading jets, the lepton and its neutrino. The neutrino four momentum is obtained from the transverse missing energy, $\not{E}_T$, and by solving $M_W^2 = (p_\ell + p_\nu)^2$. If there are two solutions, we use the one with smaller $|p_z^\nu|$; if no solutions exist, we use $p_z^\nu = 0$. As compared to a constrained kinematic fit, this method has been shown to give better sensitivity for high mass resonances with only a slight reduction in sensitivity at lower masses.

Table 1
Event yields from data and the SM expectation.

	3 **Jet**	≥ 4 **Jets**
$t\bar{t}$	364	344
W + jets	272	60
Multijet	62	22
Electroweak	72	20

Finding no significant excess from the standard model expectations (including backgrounds; see Figure 1 and Table 1), we calculate 95% C.L. upper limits on $\sigma_X \cdot B(X \to t\bar{t})$ for hypothesized values of M_X between 350 and 1000 GeV. Comparing this to the predicted top-color-assisted technicolor cross section for a Z' boson, we set a 95% C.L. limit of $M_{Z'} > 760\,\text{GeV}$ (see Figure 2). This beats the previous world's best limit from CDF $M_{Z'} > 725\,\text{GeV}$.

3. CDF Search for Top Flavor Changing Neutral Currents $t \to Zc$

In the SM, top quark flavor changing neutral current (FCNC) decays exist, but are very rare; $\mathcal{B}(t \to Zc)$ is predicted to be $\mathcal{O}(10^{-14})$, well below the sensitivity of the Tevatron or even the LHC. [4] There are several models (*e.g.,* two Higgs doublet, new quark singlets, SUSY, etc.) that boost this prediction by more than 10 orders of magnitude. Any evidence for this FCNC decay at the Tevatron would be a very strong indication of new physics.

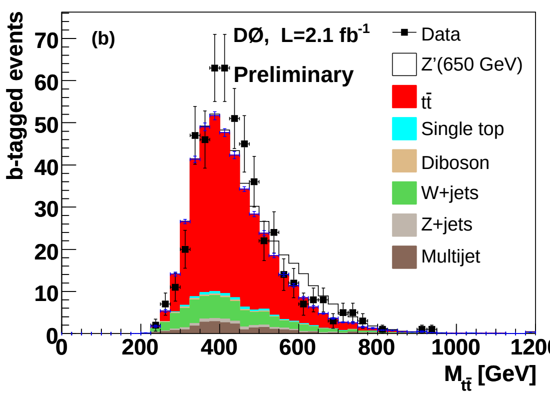

Figure 1. Expected and observed $t\bar{t}$ invariant mass distribution for the W + 4 or more jets channels, with at least one identied b-jet. The error bars drawn on top of the SM background indicate the statistical uncertainty. Superimposed as white area is the theory signal for a top-color-assisted technicolor Z^0 boson with M_{Z_0} = 650 GeV.

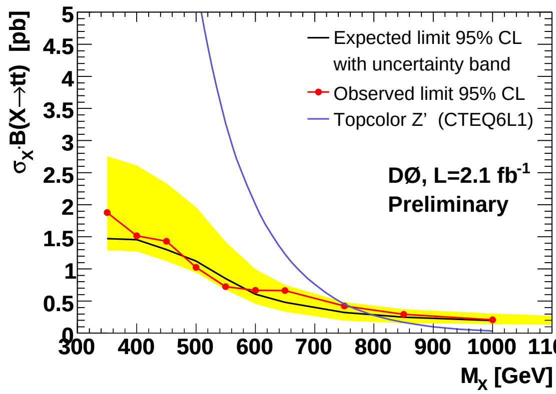

Figure 2. Expected and observed Expected and observed 95% C.L. upper limits on $\sigma_X \cdot B(X \to t\bar{t})$ compared with the predicted top-color-assisted technicolor cross-section for a Z^0 boson with a width of $\Gamma_{Z^0} = 0.012 \cdot M_{Z^0}$ as a function of the resonance mass M_X. The shaded band gives the $\pm 1\sigma$ uncertainty in the SM expected limit.

Using 1.9 fb^{-1}, CDF searches for the FCNC decay $t \to Zc$ by looking for events where one top quarks decays to a Z boson and a charm quark while the other top quark decays to a W boson and a bottom quark. We look for Z bosons that decay to two light charged leptons (e^+e^- or $\mu^+\mu^-$) and the W boson decays hadronically. Our signal therefore consists of a reconstructed Z candidate and four jets (the two W daughters, the bottom quark, and the charm quark; see Figure 3). Instead of requiring two well-identified leptons, we double our signal acceptance by requiring a single well-identified lepton and an isolated charged track.

The smaller backgrounds include dibosons (WZ and ZZ) with associated jets and SM $t\bar{t}$ where the two leptons from the W decays are consistent with a Z boson. The largest and most difficult background in this channel is SM production of a Z boson with associated jets. We do not have any absolute constraints on this background; instead we let its normalization float in our fit to data.

We start with a base selection of a Z candidate and four or more jets. To be able to estimate the size the dominant background, we apply event selection criteria (a transverse mass requirement and four tiered transverse energy requirement for the leading four jets). Events that fail any of these requirements are placed in to the *Control* region (thus named because it has little signal acceptance, but over two-thirds of the background events). Events that pass these requirements are further subdivided based on whether any of the four leading jets are identified as having a bottom quark (*Tagged*) or not (*Anti-Tagged*).

To distinguish signal from background, we create a χ^2 that uses the kinematic constraints of the $t \to Zc$ decay (see Equation 1). Since we do not know which jet is associated with which quark, we loop over all permutations and take the lowest χ^2 value.

$$\chi^2 = \left(\frac{m_{W,\mathrm{rec}} - m_{W,\mathrm{PDG}}}{\sigma_{W,\mathrm{rec}}}\right)^2 + \qquad (1)$$

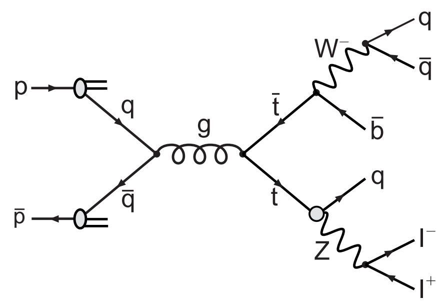

Figure 3. Feynman diagram of $t\bar{t}$ production and a subsequent FCNC decay of one top quark into a Z boson and u or c quark, while the W boson from $t \to Wb$ decays hadronically. This results in a final state with a Z and four jets.

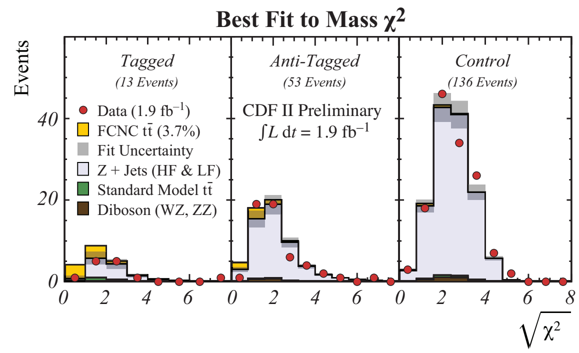

Figure 4. Mass χ^2 distribution for b-tagged and non-b-tagged signal regions and the control region. The data points as a function of $\sqrt{\chi^2}$ are compared to the SM background prediction and the expected FCNC yield at the observed 95% C.L. upper limit on the branching fraction $\mathcal{B}(t \to Zc) < 3.7\%$. The data are consistent with the background prediction.

$$\left(\frac{m_{t\to Wb,\mathrm{rec}} - m_t}{\sigma_{t\to Wb}}\right)^2 + \left(\frac{m_{t\to Zq,\mathrm{rec}} - m_t}{\sigma_{t\to Zq}}\right)^2$$

Using the χ^2, we fit the data in our three regions to templates from our signal $t \to Zc$, as well as our backgrounds. The smaller backgrounds are constrained to their theoretical values while the dominant SM Z + jets background has no absolute constraints (only a loose 20% constraint between the *Control* region and the two signal regions). The fit is consistent with the background only hypothesis (See Figure 4). We use a Feldman-Cousins limit technique and set a 95% C.L. upper limit $\mathcal{B}(t \to Zc) < 3.7\%$. This upper limit is more than 3.5 times better than the previous world's best limit of 13.7%. [4]

4. CDF Search for Invisible Top Decays

In the standard model (SM), top almost always decays to a W boson and a b quark. In this analysis, we will search for the possibility of alternative top decays using 1.9 fb^{-1}. The general idea is to consider the yield of our standard lepton + jet selection and look for a deviation from expected as defined by the theoretical $t\bar{t}$ production cross section.

In order for this analysis to be sensitive to a non $t \to Wb$ decay, the relative acceptance of $t\bar{t} \to Wb\ XY$ (where XY is the non-standard decay) must be significantly different than that of $t\bar{t} \to Wb\ Wb$ (we denote the ratio of this acceptance as $\mathcal{R}_{\mathrm{wx}/\mathrm{ww}}$).

We consider $t\bar{t}$ candidate events in the lepton + jets channel, this time requiring two or more jets be identified as a bottom quark jet. By comparing the expected number of events for the theoretical $t\bar{t}$ production cross section, we can place limits on several processes (see Table 3). Because there is a very strong dependence of the top mass on the theoretical cross section, we complete the analysis using three different top masses. (see Table 2). For this analysis, CDF considered the non-SM decays of $t \to Zc$, $t \to \gamma c$, $t \to gc$, and $t \to$ *invisible*. [2] By *invisible*, we mean a decay that does not get incorrectly reconstructed as a double b-tagged lepton + jet event.

With the background estimate and the theoretical $t\bar{t}$ cross section, we generated Feldman-Cousins acceptance bands to calculate a 95%

Table 3
The measured upper limits for (a) $t \to Zc$, (b) $t \to gc$, (c)$t \to \gamma c$, and (d) $t \to$ invisible for top masses of 175 GeV/c^2, 172.5 GeV/c^2, and 170 GeV/c^2.

Decay	$\mathcal{R}_{\mathbf{wx/ww}}$ (%)	**Upper Limit (%)** (175 GeV)	**Upper Limit (%)** (172.5 GeV)	**Upper Limit (%)** (170 GeV)
$\mathcal{B}(t \to Zc)$	32	13	15	18
$\mathcal{B}(t \to gc)$	27	12	14	17
$\mathcal{B}(t \to \gamma c)$	18	11	12	15
$\mathcal{B}(t \to \text{invisible})$	0	9	10	12

Table 2
Theoretical predictions of $t\bar{t}$ production cross section at $\sqrt{s} = 1.96$ TeV from Cacciari *et al.*. [3] Uncertainties shown are the sum in quadrature of the scale and PDF systematic uncertainties.

Top Mass (GeV)	Theory Xsec (pb)
170.0	$7.85^{+0.63}_{-0.67}$
172.5	$7.26^{+0.57}_{-0.62}$
175.0	$6.73^{+0.52}_{-0.57}$

limit. Using the total number of observed signal event candidates, we calculated the limits shown in Table 3. This is the world's first limit on the invisible decay of the top quark.

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5. Conclusions

We have presented three of the worlds best limits on searches for new physics in top quark physics. Although all three measurements are consistent with SM expectations, both CDF and DØ are still hard at work looking for any evidence of physics beyond the standard model.

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