New Physics in Top Quark Events at the Fermilab Tevatron Collider

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Abstract. We present two new measurements from the Fermilab Tevatron Collider: the CDF collaboration presents a search for flavor changing neutral currents in top quark pair decay, and the D0 collaboration presents the first measurements of the integrated forward-backward charge asymmetry in top quark pair production. The later is used as a probe for resonant production.

1. Introduction
The top quark was discovered at the Fermilab Tevatron proton-antiproton (p$\bar{p}$) collider in 1995. It is by far the heaviest fundamental particle. Suggestively, its Yukawa coupling to the Higgs field is of order unity. This raises the possibility that the top quark has a special role in electroweak symmetry breaking, and motivates the search for new physics signatures in top quark events.

Both analyses presented here use roughly 1 fb$^{-1}$ data samples collected at $\sqrt{s} = 1.96$ TeV during Run II of the Fermilab Tevatron Collider. Top quarks are mostly produced in pairs, and both measurements study this production channel.

2. A Search for the Flavor Changing Neutral Current Decay $t \to Zq$ at CDF
In the standard model (SM) flavor changing neutral current (FCNC) decays are suppressed by the GIM mechanism. In particular, the branching ratio $B(t \to Zq)$ is $\approx O(10^{-14})$ so that any observation of this process is a clear indication of new physics. Branching fractions as high as $O(10^{-2})$ are possible in beyond the SM (BYSM) scenarios [1].

We search for events where one of the top quarks decayed into a $Z$ boson and a quark ($u$ or $c$), while the other decays to a $W$ boson and a $b$ quark. We look for subsequent decays $Z \to l^+l^-$ and $W \to q\bar{q}$, where $l$ is an electron or a muon and $q$ is a light quark. This decay chain allows us to fully reconstruct the event, and background is strongly suppressed by requiring that the invariant mass of the leptons is consistent with a $Z$ boson decay. We further suppress background using a mass $\chi^2$ based on how well the rest of the event fits the desired decay channel

$$\chi^2 = \left( \frac{m_{W,rec} - m_W}{\sigma_W} \right)^2 + \left( \frac{m_{l-Wb,rec} - m_l}{\sigma_{l-Wb}} \right)^2 + \left( \frac{m_{l-Zq,rec} - m_l}{\sigma_{l-Zq}} \right)^2, \quad (1)$$

where the resolutions are $\sigma_W = 15$ GeV, $\sigma_{l-Wb} = 24$ GeV, and $\sigma_{l-Zq} = 21$ GeV, and we assume $m_t = 175$ GeV and $m_W = 80.4$ GeV.

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We perform a blind search in two disjoint signal regions, with and without a $b$-tag. Jets are tagged as $b$-jets when found to contain a secondary vertex. Both signal regions have $76 < M_{t\bar{t}} < 106$ GeV, four or more jets, and $\chi^2 < 9$. The dominant background is $Z$ boson production in association with jets. Its shape is estimated using matched ALPGEN \cite{2} and its amount is normalized to data in a high $\chi^2$ sample. Standard model top pair production and decay is a non negligible background in the $b$-tagged sample. Its shape is estimated using PYTHIA \cite{3} and its production cross section is taken from a dedicated measurement \cite{4}.

The acceptance for signal decays is taken from detailed Monte Carlo (MC) simulation. Samples are generated with PYTHIA and reweighted so that the helicity of the $Z$ boson is 65% longitudinal and 35% left handed. Systematic uncertainties were assigned to the acceptance due to other possible polarizations. The expected yield of signal events is calculated as a function of $B_{Z} = B(t \rightarrow Zq)$,. It is based on the $t\bar{t}$ production cross section measured under SM assumptions, taking into account the overlap between the two samples and the signal acceptance’s dependence on $B_{Z}$. The overlap is minimized by using a cross section measurement that uses only double $b$-tagged events \cite{4}.

We apply a frequentist limit calculation \cite{5} for the two signal regions including full systematic uncertainties on the size of the signal samples, their acceptance, their background, and on the inputs taken from the SM cross-section measurement. We set a 95% C.L. upper limit $B(t \rightarrow Zq) < 10.6\%$ (illustrated in Figure 1), consistent with the expected limit of $(7.1 \pm 3.0)\%$. When assuming a $m_t = 170$ GeV we obtain $B(t \rightarrow Zq) < 11.2\%$.

![Figure 1. Mass $\chi^2$ distributions for the tagged and anti-tagged data samples. The data points are compared to the background prediction and to the expected FCNC yield at the observed 95% C.L. upper limit. The green arrows indicate the upper edges of the signal regions.](image1)

![Figure 2. Forward-backward top charge asymmetry from MC@NLO as a function of the fourth-highest jet $p_T$.](image2)

### 3. Charge Asymmetry in Top Quark Pair Production at D0
At tree level, the SM predicts charge symmetric top quark pair production. But this is merely an accident as the initial $p\bar{p}$ state is not a charge conjugation eigenstate. Next-to-leading order (NLO) calculations predict forward-backward asymmetries of $(5–10)\%$ \cite{6, 7}, but recent next-to-next-to-leading order (NNLO) calculations predict significant corrections for $t\bar{t}j$ production \cite{8}. The asymmetry arises from several interference between contributions symmetric
and antisymmetric under the exchange $t \to \bar{t}$ [6], and depends strongly on the region of phase space being probed, as demonstrated in Figure 2. The small asymmetries expected in the standard model make this a sensitive probe for new physics.

The top quark charge asymmetry is well suited to measurement in proton-antiproton collisions where it can be directly observed as a forward-backward asymmetry. The signed difference between the rapidities of the $t$ and $\bar{t}$, $\Delta y \equiv y_t - y_{\bar{t}}$, measures the asymmetry in $t\bar{t}$ production. We define the integrated asymmetry to be $A_{\bar{t}t} = \frac{N_{\bar{t}} - N_t}{N_{\bar{t}} + N_t}$, where $N_{\bar{t}}$ ($N_t$) is the number of events with a positive (negative) $\Delta y$. We use the lepton+jets decay mode of the $t\bar{t}$ quark pair, where one of the two $W$ bosons from the $t\bar{t}$ pair decays into hadronic jets and the other decays into leptons. This mode combines a large branching fraction ($\approx 34\%$) with high signal purity, as a consequence of requiring an isolated electron or muon with large transverse momentum ($p_T$). We further enhance the sample with a loose $b$-tagging requirement. This channel allows accurate reconstruction of the $t$ and $\bar{t}$ directions in the collision rest frame, which we perform using a kinematic fitter, and the charge of the electron or muon provides an excellent tag for the $t$ or $\bar{t}$ quark.

The measurement is not corrected for acceptance and reconstruction effects. Instead, a prescription is given [10] which allows one to describe the acceptance at the particle level to an accuracy of $2\%$ (absolute). Misreconstruction of the sign of $\Delta y$ dilutes the observed asymmetry. The dilution’s effect on the integrated asymmetry depends on the asymmetry’s dependence on $|\Delta y|$, which is still uncertain for SM production and unknown for BYSM production. The dilution is parametrized as a function of the generated $|\Delta y|$, and can be applied to any model allowing a comparison with the data [10].

The main background sources are $W$+jets production and multijet production. The asymmetry of the $W$+jets background is taken from the ALPGEN MC, to estimate its amount we define a likelihood discriminant, $D$, using variables that are well described in our simulation, provide separation between signal and $W$+jets background, and do not bias $|\Delta y|$ for the selected signal. The amount of multijet background and its asymmetry are estimated from data. We extract the sample composition and the asymmetry simultaneously using a maximum likelihood fit to the distribution of events. The signal $D$ distribution used in the fit is taken from PYTHIA MC. The measured (uncorrected) asymmetry is $(12 \pm 8 \text{ (stat.)} \pm 1 \text{ (syst.)}) \%$, which is consistent with the MC@NLO prediction of $(0.8 \pm 0.2 \text{ (stat.)} \pm 1.0 \text{ (accept.)}) \%$.

**Figure 3.** Comparison of data and its fitted model as a function of the likelihood discriminant for forward events (left) and backward events (right). The number of events from each source is listed in the legend with its statistical uncertainty.

To demonstrate the measurement’s sensitivity to new physics, we study possible $t\bar{t}$ production via massive electrically neutral gauge bosons, generically referred to as $Z'$. We study the scenario where the coupling between the $Z'$ boson and quarks is proportional to that between the $Z$ boson and quarks, which yields an asymmetry of $(13-35)\%$. Hence this measurement provides a unique
probe for wide asymmetric resonances. We translate the measured asymmetry into measure of
the fraction of $t\bar{t}$ pairs produced via such a resonance $f$, and then set upper limits at 95% C.L.
on $f$. As both the measured asymmetry and that expected from production via a $Z'$ resonance
are larger than the asymmetry expected in the SM, the observed limits (e.g. $f < 0.79$ at $M_{Z'} = 650$ GeV) are weaker than the expected ones (e.g. $f < 0.40$ at the same mass).

[1] Aguilar-Saavedra J A 2004 Acta Phys. Polon. B 35 2695-710.
[2] Mangano M L et al 2003 JHEP 0307 1; Höche S et al 2006 hep-ph/0602031.
[3] Sjöstrand T et al 2001 Comput. Phys. Commun. 135 238.
[4] The CDF Collaboration 2007 CDF Public Note 8792.
[5] Feldman G and Cousins R 1998 Phys. Rev. D 57 3873.
[6] Kühn J H and Rodrigo G 1999 Phys. Rev. D 59 054017.
[7] Bowen M T et al 2006 Phys. Rev. D 73 14008.
[8] Dittmaier S et al 2007 Phys. Rev. Lett. 98 262002.
[9] Frixione S and Webber B R 2002 JHEP 0206 29; Frixione S et al 2003 JHEP 0308 7.
[10] The D0 Collaboration 2007 D0 Note 5393-CONF.
[11] Abazov V M et al (D0 Collaboration) 2004 Phys. Rev. Lett. 92 221801; Aaltonen T et al (CDF Collaboration) 2007 arXiv:0709.0705.