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Search for Flavor Changing Neutral Current Decays of the Top Quark in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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Abstract

We search for the Flavor-Changing Neutral Current decays of the top quark $t \to q\gamma$ and $t \to qZ$ (here q represents the c and u quarks) in $\overline{p}p$ collisions at $\sqrt{s}$ = 1.8 TeV from a dataset with an integrated luminosity of approximately 110 pb^{-1} collected during the 1992-1995 run of the Collider Detector at Fermilab. We set limits on the branching fractions $BF(t \to q\gamma) < 2.9\%$ (at 95% CL) and $BF(t \to qZ) < 44\%$ (at 90% CL), consistent with the Standard Model.

Physics beyond the Standard Model can manifest itself by altering the expected rates of Flavor-Changing Neutral Current (FCNC) interactions. For example, the presence of the charm quark can be inferred from the small branching fraction $BF(K_L^0 \to \mu^+\mu^-)$. FCNC decays of the top quark are of particular interest[1, 2]. Because its mass is large, the top quark couples strongly to the electroweak symmetry breaking sector. Evidence for unusual decays of the top quark might provide insights into the mechanism of electroweak symmetry breaking. For the top quark, the FCNC decays $t \to qZ$ and $t \to q\gamma$ (where q denotes either a c- or a u-flavored quark) are expected to be exceedingly small[3] and any observation of these decays would indicate new physics.

We present results using approximately 110 pb^{-1} of data from proton-antiproton collisions at a center of mass energy of 1.8 TeV collected at the Collider Detector at Fermilab (CDF) during the 1992-1995 run of the Fermilab Tevatron. The CDF detector is described in detail elsewhere [4]; a brief discussion follows:

In the CDF detector, the momentum of charged particles is measured in the central tracking chamber (CTC), which sits inside a 1.4 T superconducting solenoidal magnet. Outside the CTC are electromagnetic and hadronic calorimeters, arranged in a projective tower geometry, covering the pseudorapidity region $|\eta| < 3.6$. In the central electromagnetic calorimeter, finely segmented proportional chambers (CES) used to measure transverse shower profiles are placed at a depth of approximately 6 radiation lengths. Surrounding the calorimeters, drift chambers in the region $|\eta| < 1.0$ provide muon identification. A 51 cm long silicon vertex detector (SVX) [5], located immediately outside the beampipe, provides precise track reconstruction in the plane transverse to the beam, and is used to identify secondary vertices that can be produced by b and c quark decays. A three level trigger selects the inclusive high transverse momentum electron and muon events used in this analysis.

At CDF, photons are detected as energy clusters in the electromagnetic calorimeter with no track (or one track with less than 10% of the photon energy, presumably from random overlap) pointing at the cluster. To reduce backgrounds from jets, the energy in a cone of $\Delta R = 0.4$ (where $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$) around the photon cluster be less than 15% of the photon energy, and the sum of the p_T of charged particles identified within this cone be less than 4.0 GeV. To reduce the background from neutral hadrons, the ratio of energy deposited in the hadronic calorimeter to that in the electromagnetic calorimeter was required to be less than $0.055 + 0.00045 \times E$, where E is the total energy of the candidate in GeV. To suppress π^0 and multiphoton backgrounds, the transverse shower profile in the CES and the energy sharing between the calorimeter towers must be consistent with an electromagnetic shower.

An electron is also identified as an energy cluster in the calorimeter, this time with a single track pointing to it. The energy of the cluster and the momentum of the track are required to be equal within measurement uncertainties, and the extrapolation of the track to the CES is required to match the measured position of the shower in the CES. In this analysis, we restrict ourselves to electrons in the central region ($|\eta| < 1.0$). Further details of the electron identification requirements can be found in Ref. [6].

A muon is identified by a track segment in the muon chambers with a track pointing at it. These muon candidates are required to have a match between the extrapolated track position and the measured muon position consistent with expectations from the multiple scattering of a muon, and energy deposition in the calorimeter consistent with a minimum ionizing particle. In this analysis, we restrict ourselves to muons in the central region ($|\eta| < 1.0$). Further details of the muon identification requirements can also be found in Ref. [6].

Jets are identified by energy deposited in the calorimeters in a cone of $R < 0.4$. Details of the CDF jet reconstruction algorithm can be found in Ref. [7].

At Tevatron energies, the dominant source of top quarks is $t\bar{t}$ pair production from $q\bar{q}$ annihilation. In the search for FCNC decays we assume that the other top quark in the pair decays via the Standard Model decay $W + b$. We then normalize to the observed number of events where both top quarks decay to $W + b$. Such events in which one W decays leptonically and the other W decays hadronically are identified by a high p_T electron or muon, missing energy from the undetected neutrino, and three or more jets, at least one of which must be identified as containing a b hadron from the presence of secondary vertex from a long lived particle. [6] In a 100 pb^{-1} sample, we observe $23.1 \pm 5.7 \pm 2.8$ $t\bar{t}$ candidates over background, which extrapolates to $25.5 \pm 6.2 \pm 3.1$ $t\bar{t}$ events in 110 pb^{-1}.

We consider two FCNC event signatures, depending on whether the W (from the decay $t \rightarrow Wb$) decayed leptonically or hadronically. If the W decayed leptonically, we search for events with a high E_T photon ($E_T > 20$ GeV), an identified W (via a high p_T lepton and missing transverse energy carried by the neutrino) and at least 2 jets. If the W decayed hadronically, we search for events with a high E_T ($E_T \geq 50$ GeV) photon and at least 4 jets, one of which must contain a secondary vertex, identifying it as containing a b hadron. In both cases, there must be a jet-photon mass combination between 140-210 GeV, consistent with $m(t)$. In the non-leptonic case, the remaining jets must have $\Sigma E_T \geq 140$ GeV, consistent with the decay of a second top quark in the event. The b-tagged jet must be associated with the second top combination.

Because we are interested in the relative number of events with Standard Model and FCNC signatures, we use the ISAJET [8] Monte Carlo and a parametric simulation of the CDF detector to determine the acceptances and efficiencies relative to the Standard Model signal, shown in Table 1. These efficiencies include branching fractions. The first uncertainty is the uncertainty in the relative acceptance; the second is the effect of the b-tagging efficiency of $45 \pm 7\%$ per b jet contained in the SVX fiducial region.

40% of our $t \rightarrow q\gamma$ acceptance is in our photon plus multijet mode, and 60% is in the lepton plus photon mode.

In our data, zero events are seen in the non-leptonic channel and one event is observed in the leptonic channel. We expect a background of less than half an event

$t\bar{t}$ Decay	Identified As	Relative Efficiency
$WbWb$	Standard Model	1 (exact)
$Wb\gamma q$	Standard Model	$0.46 \pm 0.03 \pm 0.04$
$Wb\gamma q$	FCNC	$7.92 \pm 0.34 \mp 0.79$

Table 1: Efficiencies and acceptances for $t \to \gamma q$ decays, normalized to Standard Model top decays.

in each channel. To set a conservative limit, we assume any events passing cuts are signal and do not subtract this background.

The single event that passes all selection requirements has a 77 GeV muon, an 88 GeV photon, 3 jets, and a missing transverse energy of 24 GeV. While it is selected into the FCNC decay candidate sample, this event is also kinematically consistent with the decay $t \to W^+b$, $\bar{t} \to W^-\bar{b}\gamma$, followed by $W^+ \to \mu^+\nu$ and $W^- \to$ jets. However, the photon E_T is exceptionally large for this decay. The event could conceivably be interpreted in the framework of supersymmetry.

Observation of one event passing cuts implies a 95% confidence limit of fewer than 6.45 (including systematic uncertainties) which corresponds to a branching fraction limit of:

$$BF(t \to c + \gamma) + BF(t \to u + \gamma) < 2.9\%$$

The statistical uncertainty in the number of events in the normalization sample is the dominant source of systematic uncertainty. The uncertainty in b-quark identification efficiency also contributes to the overall systematic uncertainty. The uncertainties on acceptance and photon identification are negligible by comparison.

We also search for $t \to qZ$ events using the channel where the Z decays to e^+e^- or $\mu^+\mu^-$, and the other t-quark decays to 3 jets. The expected signature is therefore an event with four jets and with two leptons that reconstruct to a Z. Because the Z branching fraction to leptons is small, this analysis is less sensitive than the $t \to q\gamma$ search. Candidate $Z \to l^+l^-$ events were selected using criteria described in detail in [9]. Z bosons are identified as opposite-charge same-flavor lepton pairs inside the range $75 < M_{l^+l^-} < 105$ GeV/c^2. We require each of the 4 jets to have $E_T > 20$ GeV and be contained in the region $|\eta| < 2.4$.

A version of this analysis that duplicates the technique of the $t \to q + \gamma$ search is in progress. This preliminary result sets a limit on the cross section times branching fraction, and by comparing to our measured cross section, calculates a branching fraction. Using ISAJET [8] and a parametric trigger efficiency, we determine that our acceptance times efficiency for $t \to Zq$ events is 0.144 ± 0.004.

There are two comparable sources of background to the $t \to qZ$ signal. One is ordinary Z+multijet production, and 0.5 background Z+4 jet events are expected. The second source of background is from real Standard Model $t\bar{t}$ events where both W's decay leptonically, and the two leptons have an invariant mass that falls within the Z window. (0.6 events) Diboson (WZ or ZZ) + 2 or more jet events add an additional background of 0.1 events, for a total of approximately 1.2 events. As before, to set a conservative limit, we assume any events passing cuts are signal and do not subtract this background.

A single $Z \to \mu^+\mu^-$ event passes all cuts. The event kinematics better fit the Z+multijet hypothesis than the FCNC decay hypothesis. Observation of one event passing cuts implies a 90% confidence limit of fewer than 4.9 (including systematic uncertainties) events. Folding in the measurement of the top cross section in the dilepton channel of $9.3^{+4.4}_{-3.4}$ pb^{-1} allows us to set the limit:

$$BF(t \to c + Z) + BF(t \to u + Z) < 44\%$$

The systematic uncertainties are similar to those in the $t \to c\gamma$ search.

In summary, we search for the Flavor-Changing Neutral Current decays $t \to q\gamma$ and $t \to qZ$ in $\overline{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. No statistically significant excess of these events is seen, although one candidate event survives all cuts in each mode. Both events have interpretations outside of the FCNC decay hypothesis. In order to set conservative limits, we treat these events as FCNC candidates and set limits on the branching fractions $BF(t \to q\gamma) < 2.9\%$ (at 95% CL) and $BF(t \to qZ) < 44\%$ (at 90% CL), consistent with Standard Model expectations.

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