CDF Note 8888

Search for the Flavor Changing Neutral Current Decay $t \to Zq$ in $p\overline{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

The CDF Collaboration
URL `http://www-cdf.fnal.gov`
(Dated: July 13, 2007, Updated: February 18, 2008)

We present a search for the flavor changing neutral current decay of the top quark $t \to Zq$ with CDF Run II data corresponding to 1.12fb^{-1} of integrated luminosity. The decay $t \to Zq$ is extremely rare in the standard model and a signal at the Tevatron would be an indication of new physics. Using $Z+ \geq 4$ jet candidate events both with and without a loose secondary vertex b-tag, we observe data yields consistent with the background expectations. We set a 95% C.L. upper limit on the branching fraction $\mathcal{B}(t \to Zq)$ of 10.4% (expected limit: 6.8%). This is currently the world's best limit on $\mathcal{B}(t \to Zq)$ and improves the previous limit, which was inferred indirectly from the non-observation of $e^+e^- \to tq$, by approximately 25%.

Preliminary Result for Summer Conferences 2007

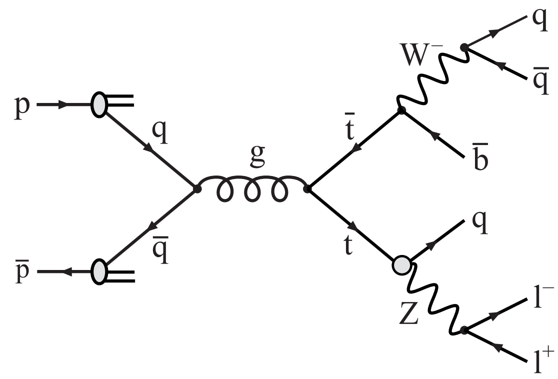


FIG. 1: Feynman diagram of $t\bar{t}$ production and a subsequent FCNC decay of one top quark into a Z boson and u or c quark, while the W boson from $t \to Wb$ decays hadronically. This results in a final state with two leptons and four jets.

I. INTRODUCTION

A. Theoretical Background and Previous Results

In the standard model of particle physics (SM), flavor changing neutral current (FCNC) decays are highly suppressed. They do not occur at tree level, and are only allowed at the level of quantum loop corrections at very small branching fractions. The branching fraction for the top quark decay $t \to Zq$ is predicted to be $\mathcal{O}(10^{-14})$, far below the experimental sensitivity of the Tevatron or even the Large Hadron Collider (LHC). As summarized by J.A. Aguilar-Saavedra [1], there exist new physics models that predict much higher branching fractions, up to $\mathcal{O}(10^{-2})$. Any detection of top's FCNC decay at the Tevatron would be an indication of new physics.

Previous searches for the FCNC $t \to Zq$ have been performed in CDF Run I and by the LEP experiments. The Run I analysis yielded an upper limit on the branching fraction $\mathcal{B}(t \to Zq)$ of 33% at 95% C.L. [2]. The best 95% C.L. upper limit on $\mathcal{B}(t \to Zq)$ prior to this analysis was inferred from the L3 experiment's non-observation of $e^+e^- \to tq$ to be 13.7% [3].

B. Analysis Method

We search for the FCNC decay $t \to Zq$ by examining $t\bar{t}$ events in which either top quark decays via an FCNC to a Z boson and a quark (u or c), and the other top quark undergoes the regular SM decay to a W boson and a b quark. We examine the decay channel in which the Z subsequently decays to a pair of charged leptons (e^+e^- or $\mu^+\mu^-$) and the W decays to two quarks. The final experimental signature of the FCNC comprises a reconstructed Z and four or more jets, one of which is a b-jet that can be identified by b-tagging algorithm. The signature does not include any neutrinos in the final state, and we are therefore able to fully reconstruct the event. See Fig. 1 for an illustration.

We perform the search for the FCNC decay $t \to Zq$ as a blind search, with the blinded region defined as events with a reconstructed Z in the mass range of $76\,\mathrm{GeV}/c^2$ to $106\,\mathrm{GeV}/c^2$, four or more jets, and mass χ^2 (constructed from reconstructed W, SM top, and FCNC top masses, as described in Section II) less than 9. To increase the sensitivity of our search, we split the data sample into two subsamples that are analyzed separately, a b-tagged and an anti-b-tagged sample, using the "loose" flavor of the standard CDF secondary vertex b-tagging algorithm (SECVTX). We take the signal acceptances and efficiencies from a Monte Carlo (MC) simulation and correct for known differences between the MC simulation and the CDF data. We normalize the expected event yield to the measured $t\bar{t}$ production cross section in the lepton+jets channel of $\sigma_{t\bar{t}} = (8.8 \pm 1.1(\mathrm{stat.} + \mathrm{syst.}))$ pb [4].

We estimate the background for the FCNC signal coming from SM processes using a combination of data-driven and MC techniques. The dominant background process is the production of Z bosons in association with jets. Other background contributions include SM $t\bar{t}$ production and diboson production (WZ, ZZ). Contributions from W production in association with jets and from WW production are negligible.

The event selection criteria for the b-tagged and the anti-b-tagged data samples are optimized for the best combined expected limit for the branching fraction $\mathcal{B}(t \to Zq)$. The framework for calculating limits takes systematic uncertainties into account. After the final selection criteria have been chosen, we derive a limit on $\mathcal{B}(t \to Zq)$ from

TABLE I: The optimized event selection criteria.

Kinematic Variable	**Optimized Cut**
Z Mass	$\in$ [76, 106 GeV/c^2]
Leading Jet E_T	$\geq$ 40 GeV
Second Jet E_T	$\geq$ 30 GeV
Third Jet E_T	$\geq$ 20 GeV
Fourth Jet E_T	$\geq$ 15 GeV
Transverse Mass	$\geq$ 200 GeV
$\sqrt{\chi^2}$	$<$ 1.6 in b-tagged sample,
	$<$ 1.35 in the anti-tagged sample

the number of events observed in the signal region and the number of expected background events.

II. DATA SAMPLE AND EVENT SELECTION

For this analysis, we use data collected with the CDF II detector between March 2002 and September 2006, which corresponds to an integrated luminosity of 1.12 fb^{-1}. We require that the data from the silicon detector, from the electromagnetic calorimeter, and from muon chambers are marked "good" in the data quality assessment. The data for this analysis was collected with inclusive lepton triggers that require transverse energies of $E_T > 18$ GeV for electrons and transverse momenta of $p_T > 18\,\mathrm{GeV}/c$ for muons.

For the base event selection we reconstruct a Z and four or more jets. The Z selection requires exactly one lepton pair of the same flavor and opposite charge. One of the leptons must pass tight selection and lepton identification criteria, the other lepton can be formed from an isolated track in the drift chamber. The invariant mass of the lepton pair must fall into the range between $76\,\mathrm{GeV}/c^2$ and $106\,\mathrm{GeV}/c^2$. We correct the energies of reconstructed jets to the parton level and require jets to have corrected $E_T \geq 15\,\mathrm{GeV}$ and to fall into the pseudorapidity range of $|\eta| < 2.4$ [5].

We optimize the final event selection for the best expected limit, defined as

$$\text{Expected Limit} = \sum_{n_{\text{obs}}} P(n_{\text{obs}}|n_{\text{back}}) \cdot \text{Lim}(n_{\text{obs}}|A, n_{\text{back}}), \tag{1}$$

where n_{obs} represents the number of events observed, n_{back} is expected background, A is the signal acceptance convolved with efficiency, $P(n_{\text{obs}}|n_{\text{back}})$ is the Poisson probability that n_{back} background events fluctuated to n_{obs}, and Lim is any upper limit calculation. For the optimization, we apply additional cuts on the event kinematics. Our strongest discriminant to distinguish signal from background is a mass χ^2 variable, see Fig. 3 (a). In a signal event, there is one decay of the type $t \to Wb$. Two jets in the event form a W, which in turn forms a top quark together with a third jet. There is also one decay of the type $t \to Zq$, in which the Z has to be paired with the fourth jet to form the second top quark. The mass χ^2 is defined as

$$\chi^2 = \left(\frac{m_{W,\text{rec}} - m_{W,\text{PDG}}}{\sigma_{W,\text{rec}}}\right)^2 + \left(\frac{m_{t\to Wb,\text{rec}} - m_{t,\text{PDG}}}{\sigma_{t\to Wb}}\right)^2 + \left(\frac{m_{t\to Zq,\text{rec}} - m_{t,\text{PDG}}}{\sigma_{t\to Zq}}\right)^2, \tag{2}$$

where we assume a top mass of 175 GeV/c^2 and the resolutions $\sigma_{W,\text{rec}} = 15$ GeV, $\sigma_{t\to Wb} = 24$ GeV, and $\sigma_{t\to Zq} = 21$ GeV. We evaluate χ^2 for all permutations of the leading four jets in the event and select the permutation with the lowest χ^2. In addition, we cut on transverse mass of the the four leading jets and the Z,

$$m_T = \sqrt{\left(\sum E_T\right)^2 - \left(\sum \vec{p}_T\right)^2}, \tag{3}$$

and on the transverse energies of the four leading jets. The final cut values shown in Table I are determined by a multidimensional scan of the expected limit on the branching fraction $\mathcal{B}(t \to Zq)$ that takes into account the correlations among the variables.

III. ACCEPTANCE CALCULATION

The acceptance calculation for this analysis is based on detailed MC simulations. All FCNC signal samples have been created with the PYTHIA event generator, version 6.216 [6], assuming a top quark mass of 175 GeV/c^2. We re-weight the samples such that the helicity of the Z boson from the $t \to Zq$ decay is 65% longitudinal and 35% left-handed, where the magnitude of the longitudinal component has been chosen such that it matches the prediction of the SM Higgs mechanism. We assign a systematic uncertainty of 3.5% due to this unknown aspect of the tZc interaction, corresponding to half the total possible deviation in acceptance.

The event yield expected from the FCNC decay $t \to Zq$ is normalized to the measured $t\bar{t}$ cross section in the lepton+jets channel. The acceptance calculation accounts for the overlap between the two channels and all contributions to the total FCNC event yield: The $t\bar{t}$ cross section is re-interpreted assuming the presence of FCNC decays. The acceptance for the FCNC decay is composed of events in which one of the top quarks decays via the FCNC and events in which both tops decay via the FCNC. These considerations result in an acceptance formula in which the acceptance depends on variable to be measured, in our case the branching fraction limit on the decay $t \to Zq$. This dependence is accounted for in the limit calculation. The number of expected FCNC signal events $N_{\rm signal}$ is given by the probabilities $\mathcal{P}$ for one or both of the top quarks decaying via an FCNC, the $t\bar{t}$ cross section $\sigma_{t\bar{t}}$, and the integrated luminosity $\int \mathcal{L}{\rm d}t$:

$$
\begin{aligned}
N_{\rm signal} &= \left[\left(\mathcal{P}(t\bar{t} \to WbZq) \cdot \mathcal{A}_{WZ}\right) + \left(\mathcal{P}(t\bar{t} \to ZqZq) \cdot \mathcal{A}_{ZZ}\right)\right] \cdot \sigma_{t\bar{t}} \cdot \int \mathcal{L}{\rm d}t \\
&= \mathcal{B}_Z \cdot (N_{LJ} - B_{LJ}) \cdot \frac{\mathcal{A}_{WZ}}{\mathcal{A}_{LJ{\rm ww}}} \cdot \frac{\left(2 \cdot (1 - \mathcal{B}_Z) + K_{ZZ/WZ} \cdot \mathcal{B}_Z\right)}{(1-\mathcal{B}_{\rm z})^2 + 2\mathcal{B}_{\rm z} \cdot (1-\mathcal{B}_{\rm z}) \cdot \mathcal{R}_{\rm wz/ww} + \mathcal{B}_{\rm z}^2 \cdot \mathcal{R}_{\rm zz/ww}},
\end{aligned}
\tag{4}
$$

where

$$
\begin{aligned}
\mathcal{B}_Z &\equiv \mathcal{B}(t \to Zq) = 1 - \mathcal{B}(t \to Wb), \\
N_{LJ} &\equiv \text{Lepton+Jets Event Yield}, \\
B_{LJ} &\equiv \text{Lepton+Jets Background}, \\
\mathcal{A}_{WZ} &\equiv \text{FCNC Acceptance for } t\bar{t} \to Zq\,Wb, \\
\mathcal{A}_{ZZ} &\equiv \text{FCNC Acceptance for } t\bar{t} \to Zq\,Zq, \\
\mathcal{A}_{LJ_{WW}} &\equiv \text{Lepton+Jets Acceptance for SM } t\bar{t}, \\
\mathcal{A}_{LJ_{WZ}} &\equiv \text{Lepton+Jets Acceptance for } t\bar{t} \to Zq\,Wb, \\
\mathcal{A}_{LJ_{ZZ}} &\equiv \text{Lepton+Jets Acceptance for } t\bar{t} \to Zq\,Zq, \\
K_{ZZ/WZ} &\equiv \mathcal{A}_{ZZ}/\mathcal{A}_{WZ}, \\
\mathcal{R}_{WZ/WW} &\equiv \mathcal{A}_{LJ_{WZ}}/\mathcal{A}_{LJ_{WW}}, \\
\mathcal{R}_{ZZ/WW} &\equiv \mathcal{A}_{LJ_{ZZ}}/\mathcal{A}_{LJ_{WW}}.
\end{aligned}
$$

We chose the $t\bar{t}$ production cross section measurement that requires a double b-tag as the normalization because it results in the best expected limit. The event selection of the double b-tag analysis is similar enough to the FCNC selection for parts of the systematics to cancel. At the same time, the sensitivity of the analysis is enhanced because the lepton+jets acceptance of the FCNC signal ($\mathcal{R}_{WZ/WW}$ and $\mathcal{R}_{ZZ/WW}$ in the denominator of the acceptance correction of Eq. (4)) is reduced. Note that the integrated luminosity cancels in the above equation.

IV. BACKGROUND PROCESSES

There are several physics processes that have signatures consistent with the FCNC event selection. The dominant background contribution for this analysis comes from Z bosons produced in association with jets (Z+jets). On a much smaller level, the SM decay $t\bar{t} \to W^+bW^-\bar{b}$ contributes to the background when the invariant mass of two leptons in the dilepton decay mode or a lepton and a jet misidentified as a lepton in the lepton+jets decay mode falls within the Z mass window. A contribution similar in size to SM $t\bar{t}$ decays comes from diboson production with a real Z in the event (WZ and ZZ). Very small contributions come from Ws produced in association with jets (W+jets), and from the WW diboson process. In both of those cases, the events do not have a Z in the final state, and a lepton from the W decay and a misidentified jet from the event are needed to form a Z candidate.

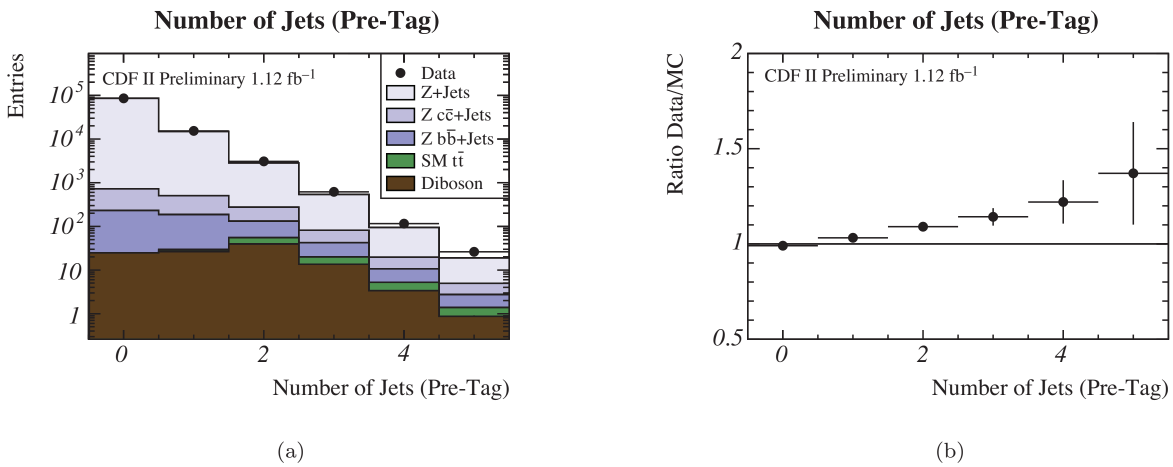


FIG. 2: Data-MC comparison of the number of jets in events with a reconstructed Z. (a) Distribution of the number of jets before b-tagging. (b) Ratio of data over MC. The Z+jets MC samples are normalized to the 0-jet bin, and contributions from SM $t\bar{t}$ and diboson productions are added according to their predicted cross sections.

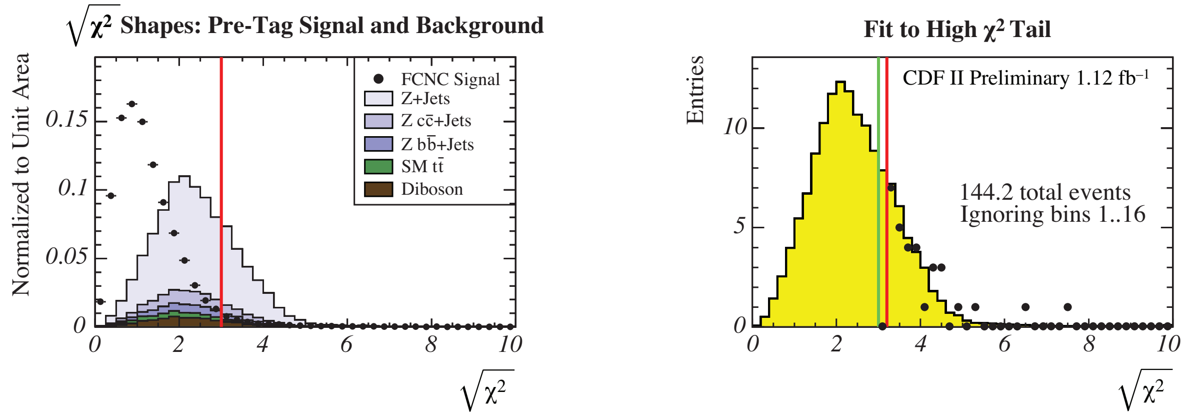
A. Z+jets Production

We estimate the background from Z+jets production from a combination of data-driven and MC methods. For our studies we use MC samples of the production of $Z + n$ partons ($n = 0 \ldots 4$), $Z + b\bar{b} + n$partons ($n = 0 \ldots 2$), and $Z + c\bar{c} + n$ partons ($n = 0 \ldots 2$) generated with the ALPGEN v2.10 MC generator [7]. ALPGEN utilizes Pythia for parton showers and features a built-in mechanism to remove the phase space overlap between matrix element and parton shower jets. As ALPGEN is a leading order generator, we normalize the event yield to the number of events with a reconstructed Z and no additional jets in the data. From a data-MC comparison of the jet multiplicities in events with a reconstructed Z we find that ALPGEN systematically underestimates higher jet multiplicities, see Fig. 2. We therefore rely on ALPGEN MC only for the shapes of kinematic distributions and extract the expected number of Z+jets background events from the data.

To determine the total background we normalize the number of events in the tail of the mass χ^2 distribution to the data and predict the total number of events using the shape of the χ^2 distribution, as illustrated in Fig. 3 (b). We average the predictions of the number of events with $\sqrt{\chi^2} > 3.0$ and $\sqrt{\chi^2} > 3.2$ and take the difference between the two results into account for the uncertainty of the prediction. The predicted number of background events is 130 ± 28. The Z+jets background is then obtained by subtracting backgrounds from SM $t\bar{t}$ and diboson production. We have determined that the fraction of events with one or more b-tags is $(15 \pm 4)\%$. This number is derived from the fraction of events with $\sqrt{\chi^2} > 3.0$ that are b-tagged and double-checked with a MC template method that fits the number of tags in individual jet bins. The expected numbers of background events in 1.12 fb^{-1} are summarized in Table II.

B. Other Backgrounds

We obtain the background contributions from the SM $t\bar{t}$ production and from diboson production from Pythia MC simulations of these processes. For SM $t\bar{t}$ production we use a top mass of 175 GeV/c^2 and scale the expected event yield to the measured SM $t\bar{t}$ cross section of $\sigma_{t\bar{t}} = (8.8 \pm 1.1(\text{stat.} + \text{syst.}))$ pb [4]. The background prediction for diboson production assumes production cross sections of 13 pb for WW production, 3.96 pb for WZ production, and 1.56 pb for ZZ production with two on-shell Z bosons [8]. Diboson, WZ, and ZZ production is the larger contribution before b-tagging; however, the two b jets in the final state make SM $t\bar{t}$ production the larger contribution in the b-tagged sample. The contribution from WW production is negligible. We have estimated the contribution from W+jets production from the number of events in the data with an $e\mu$ pair coming from a $W \to \mu\nu$ decay and a jet misidentified as an electron. We have found the contribution to be negligible.



(a) (b)

FIG. 3: (a) Mass χ^2 distribution of signal and background events, with the vertical line showing the cut of $\sqrt{\chi^2} = 3$. The signal and background samples are normalized to unit area. (b) Mass χ^2 distribution, showing the fit to data in the high χ^2 tail. Vertical lines show cuts at $\sqrt{\chi^2} = 3$ and $\sqrt{\chi^2} = 3.2$.

TABLE II: Summary of all background contributions to the search for the FCNC decay $t \to Zq$. Given are the expected numbers of background events in 1.12 fb^{-1}.

Source	**Without b-tag**	**Loose SECVTXb-tag**
Z+Jets	122.7±28	17.3±6
Standard Model $t\bar{t}$	2.6±0.3	1.9±0.2
Diboson (WZ, ZZ)	4.7±0.2	0.8±0.1
WW, W+Jets	< 0.1	negligible
Total Backgrounds:	130±28	20±6

V. SYSTEMATIC UNCERTAINTIES

A. Signal Systematics

We study the signal acceptance systematics for three selections, our base selection, and for our two signal regions (anti-tagged and loose SECVTX tagged) after the final event selection. The two signal regions are deliberately disjoint because of their complementary b-tagging requirements. Our limit calculation takes into account the correlations among the systematic uncertainties across the signal regions; therefore, we will distinguish systematic uncertainties that are fully correlated among the regions (e.g. lepton scale factors) and systematic uncertainties that are fully anti-correlated among the regions (e.g. b-tagging scale factors).

Our final acceptance formula given in Eq. (4) shows that the main figure of interest for the signal acceptance is the ratio $\mathcal{A}_{WZ}/\mathcal{A}_{LJ_{\mathrm{ww}}}$, i.e. the ratio of acceptances for the FCNC signal, using the FCNC selection criteria, and the acceptance for SM $t\bar{t}$, using the selection criteria for $t\bar{t}$ cross section analysis to which we normalize our search. We quote our signal acceptance systematics as the relative change in $\mathcal{A}_{WZ}/\mathcal{A}_{LJ_{\mathrm{ww}}}$. A summary of the results is given in Table III.

We attribute correlated systematic uncertainties to Monte Carlo correction factors (lepton scale factors for lepton identification efficiencies and separate trigger efficiencies), the correction on the jet energy as identified by the calorimeter, and the amount of initial state radiation (ISR) and final state radiation (FSR) from the event. Since our signal Monte Carlo sample is generated flat in $\cos\theta^*$, the angle between the top boost and the positive lepton in the Z rest frame, we must re-weight it to the appropriate handedness: 65% longitudinal, 35% left-handed. We apply a systematic uncertainty on this helicity re-weighting of the signal FCNC Monte Carlo sample. We also include a correlated systematic uncertainty on the parton distribution functions. We attribute an anti-correlated systematic uncertainty on the b-tagging scale factors applied to the Monte Carlo simulation. We also include an anti-correlated systematic uncertainty for the difference in event tagging rate between $ZuWb$ and $ZcWb$ final states.

TABLE III: Summary of systematic shifts of the acceptance ratio $\mathcal{A}_{WZ}/\mathcal{A}_{LJ\mathrm{ww}}$. Note that the upper grouping contains those systematics that are correlated, and the lower grouping are those that are anti-correlated between the anti-tagged and the loosely tagged selection.

Systematic Uncertainty	**Base Selection (%)**	**Anti-Tagged (%)**	**Loose Tag (%)**
Lepton Scale Factor	0.5	0.5	0.5
Trigger Efficiency	0.2	0.2	0.2
Jet Energy Scale	3.1	2.6	1.9
ISR/FSR	1.3	2.6	6.5
Helicity Re-Weighting	3.5	3.4	3.2
Parton Distribution Functions	0.9	0.9	0.9
Total Correlated	5.0	5.1	7.5
b-Tagging Scale Factor	10.2	16.3	5.5
Mistag $\alpha\beta$ Correction	0.6	1.0	0.4
$\mathcal{B}(t \to Zc)$ versus $\mathcal{B}(t \to Zu)$	0.0	4.0	4.0
Total Anti-Correlated	10.2	16.8	6.8

TABLE IV: Summary of systematic shifts of the ratio of events with $\sqrt{\chi^2} < 1.6$ to events with $\sqrt{\chi^2} > 3$.

Systematic Uncertainty	**Anti-Tagged (%)**	**Loose Tag (%)**
Lepton Scale Factor	< 0.1	< 0.1
Trigger Efficiency	< 0.1	< 0.1
Jet Energy Scale	5.1	2.1
B-Tagging Scale Factor	< 0.1	0.3
Mistag $\alpha\beta$ Correction	0.2	0.4
ALPGEN MC Generator	10.0	5.9
Total Uncertainty	11.2	6.3

B. Background Systematics

The main systematic uncertainties in the background estimate come from the estimates of the Z+jets event yield in the signal region and the tagging rate for Z+jets events. Additional uncertainties arise from the shape of the χ^2 distribution predicted in the MC simulation. We estimate this uncertainty by varying the same parameters of interest as for the signal systematics. In addition we examine the effect of different settings for the ALPGEN MC generator. For a given parameter, we quote the systematic uncertainty as the shift in the ratio of the number of events predicted for $\sqrt{\chi^2} < 1.6$ to the number of events predicted for $\sqrt{\chi^2} > 3$. The results are summarized in Table IV.

C. Normalization to Top Production Cross Section

We normalize our measurement to the measured $t\bar{t}$ production cross section. As shown in Eq. (4), the number of FCNC events depends on signal yield and the number of expected background events of the $t\bar{t}$ cross section analysis. Hence we add the statistical uncertainty of the signal yield and the total uncertainty of the background for that analysis to the systematic uncertainty of our result. The total normalization uncertainty amounts to 9.8%.

VI. RESULTS AND CONCLUSIONS

The final numbers of expected and observed events are summarized in Table V. The data in the signal region is consistent with the expected background. We apply a Feldman-Cousins limit calculation for the two signal regions including the full systematic uncertainties. We set a 95% C.L. upper limit on the $t \to Zq$ branching fraction, $\mathcal{B}(t \to Zq) < 10.4\%$,[9] consistent with the expected limit of $6.8 \pm 3.0\%$. Our result is illustrated in Fig. 4. The above limit has been obtained using a top mass of 175 GeV/c^2. When we assume a top mass of 170 GeV/c^2, we obtain $\mathcal{B}(t \to Zq) < 11.0\%$ at 95% C.L.

This measurement improves the previous world's best limit, 13.7% set by L3 [3], by almost 25% and improves the CDF Run I limit, 33% [2], by more then a factor of three.

TABLE V: Observed and expected numbers of events in the base selection and the optimized anti-tagged and tagged selections.

Selection	Observed	Expected
Base Selection	141	130±28
Base Selection (Tagged)	17	20±6
Anti-Tagged Selection	12	7.7±1.8
Tagged Selection	4	3.2±1.1

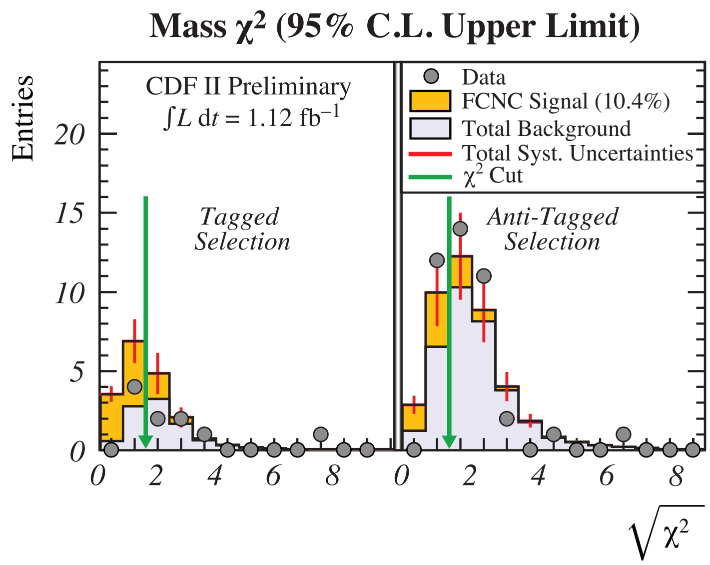


FIG. 4: Mass χ^2 distributions for the tagged and anti-tagged data samples. The data points are compared to the the background prediction and the expected FCNC yield at the observed 95% C.L. upper limit of $\mathcal{B}(t \to Zq) = 10.4\%$. The vertical lines indicate the upper edges of the signal regions. The data is consistent with the background prediction.

Acknowledgments

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Comisión Interministerial de Ciencia y Tecnología, Spain; the European Community's Human Potential Programme; the Slovak R&D Agency; and the Academy of Finland.

---

[1] J. A. Aguilar-Saavedra, *Top flavour-changing neutral interactions: Theoretical expectations and experimental detection*, Acta Phys. Polon. **B35** (2004), 2695–2710, hep-ph/0409342.

[2] F. Abe et al. (CDF Collaboration), *Search for Flavor-Changing Neutral Current Decays of the Top Quark in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV*, Phys. Rev. Lett. **80** (1998), 2525–2530.

[3] P. Achard et al. (L3 Collaboration), *Search for Single Top Production at LEP*, Phys. Lett. **B549** (2002), 290–300, hep-ex/0210041.

[4] CDF Collaboration, *Measurement of the $t\bar{t}$ Production Cross Section in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV using Lepton+Jets Evetns with Secondary Vertex b-Tagging*, CDF Public Note 8795, 2007.

[5] CDF uses a right-handed coordinate system such that the positive z-direction aligns with the direction of the proton beam. The other rectangular coordinates x and y are defined pointing outward and upward. We can then work in a polar geometry

with $r = \sqrt{x^2 + y^2 + z^2}$ and $\phi = \arctan(y/x)$. From $\theta = \arccos(z/r)$ we define pseudo-rapidity $\eta = -\ln\tan\theta/2$ to complete the CDF coordinate system (r, ϕ, η).

[6] T. Sjöstrand, L. Lönnblad, and S. Mrenna, PYTHIA *6.2: Physics and manual*, (2001), hep-ph/0108264.

[7] M. L. Mangano, M. Moretti, F. Piccinini, R. Pittau, and A. D. Polosa, *ALPGEN, a generator for hard multiparton processes in hadronic collisions*, JHEP **07** (2003), 001, hep-ph/0206293.

[8] J. M. Campbell and R. K. Ellis, *An update on vector boson pair production at hadron colliders*, Phys. Rev. **D60** (1999), 113006.

[9] We have previously reported a limit of $\mathcal{B}(t \to Zq) < 10.6\%$ at 95% C.L. We have updated the limit together with the new result based on $1.9\,\mathrm{fb}^{-1}$ of data, which supersedes the result presented in this note, see CDF Public Note 9202.