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Search for the Neutral Current Top Quark Decay $t \to Zc$ Using the Ratio of Z-Boson + 4 Jets to W-Boson + 4 Jets Production

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We have used the Collider Detector at Fermilab (CDF II) to search for the flavor-changing neutral-current (FCNC) top quark decay $t \to Zc$ using a technique employing ratios of W and Z production, measured in $p\overline{p}$ data corresponding to an integrated luminosity of 1.52 fb^{-1}. The analysis uses a comparison of two decay chains, $p\bar{p} \to t\bar{t} \to WbWb \to \ell\nu bjjb$ and $p\bar{p} \to t\bar{t} \to ZcWb \to \ell\ell cjjb$, to cancel systematic uncertainties in acceptance, efficiency, and luminosity. We validate the modeling of acceptance and efficiency for lepton identification over the multi-year dataset using another ratio of W and Z production, in this case the observed ratio of inclusive production of W to Z bosons. To improve the discrimination against standard model backgrounds to top quark decays, we calculate the top quark mass for each event with two leptons and four jets assuming it is a $t\bar{t}$ event with one of the top quarks decaying to Zc. For additional background discrimination we require at least one jet to be identified as originating from a b-quark. No significant signal is found and we set an upper limit on the FCNC branching ratio $Br(t \to Zc)$ using a likelihood constructed from the $\ell\ell cjjb$ top quark mass distribution and the number of $\ell\nu bjjb$ events. Limits are set as a function of the helicity of the Z boson produced in the FCNC decay. For 100% longitudinally polarized Z bosons we find limits of 8.3% and 9.3% (95% C.L.) depending on the assumptions regarding the theoretical top quark pair production cross-section.

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1. Introduction

The standard model (SM) Lagrangian does not contain any flavor-changing neutral current (FCNC) terms such as $d \to s$, a consequence of its SU(2) structure [1]. In the SM the top quark is expected to decay via the charged weak current into a W boson and a bottom quark, $t \to W^+b$, with close to 100% branching ratio [2] and the FCNC decay $t \to Zc$ is highly suppressed [3]. However, some extensions of the SM (e.g. two-Higgs doublet models, models with extra quark singlets, technicolor models with a dynamical breakdown of the electroweak symmetry, etc.) predict measurable rates [1, 4, 5].

The production of top quark pairs, $t\bar{t}$, is the preferred channel to observe the FCNC transition $t \to c$ at the Tevatron. We have used data from an integrated luminosity of 1.52 fb^{-1} collected with the CDF II detector [6] to search for events in which one of the top quarks decays to Zc and the other one decays to Wb. In order to get a sample of high purity, we select the leptonic decays of the Z boson, $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$. In this scenario, the FCNC signature is most likely a pair of oppositely-charged leptons forming a Z boson, and four jets (the b and c jets from the t and $\bar{t}$, and two jets from $W \to q\bar{q}'$). To minimize the systematic uncertainties on the particle identification and trigger efficiencies, geometric acceptances, and luminosity, we rely on a technique based on the simultaneous comparison of two decay chains: $p\bar{p} \to t\bar{t} \to WbWb \to \ell\nu bjjb$ and $p\bar{p} \to t\bar{t} \to ZcWb \to \ell\ell cjjb$.

2. Control Regions: Inclusive Production of W and Z Bosons

The final states $\ell\nu bjjb$ and $\ell\ell cjjb$ used in this analysis contain products of the leptonic decays of $W \to \ell\nu$ and $Z \to \ell\ell$, for which there exist precise next-to-next-to-leading order (NNLO) predictions of inclusive cross-sections multiplied by branching fractions [7]. We use a comparison of the measured ratio of inclusive $W \to \ell\nu$ (see Fig. 1) to $Z \to \ell\ell$ (see Fig. 2) production to validate the lepton identification and trigger efficiencies in the Monte Carlo simulation predictions of signal and SM background to about 2%.

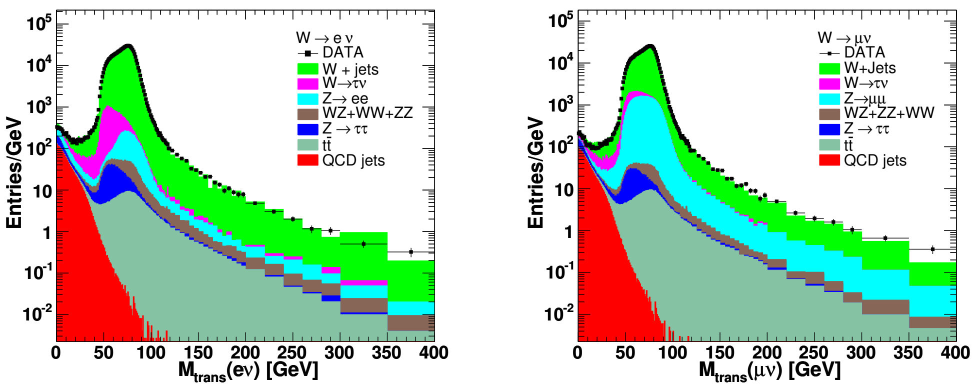

Figure 1: The observed (points) and expected (histogram) distributions in transverse mass of $e + \not{E}_T$ (left figure) and $\mu + \not{E}_T$ (right figure). The contribution from $t\bar{t}$ production is calculated for the SM case. The order of stacking in the histograms is the same as in their legends.

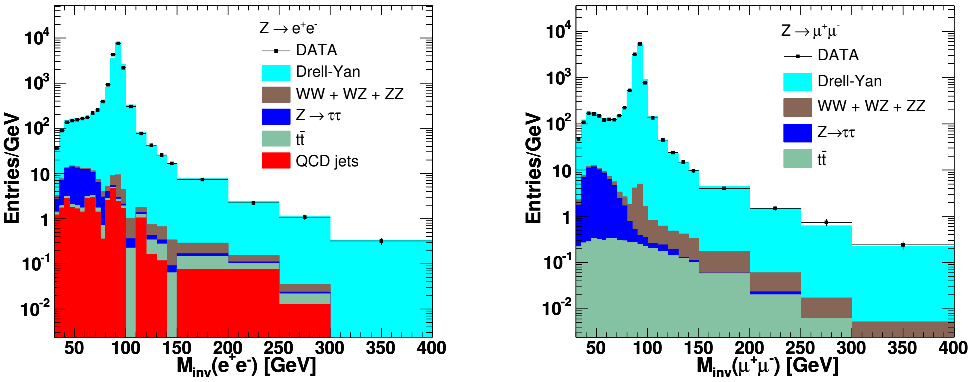

Figure 2: The observed (points) and expected (histogram) distributions in the invariant mass of e^+e^- (left figure) and $\mu^+\mu^-$ (right figure) lepton pairs. The order of stacking in the histograms is the same as in their legends.

3. Signal Regions: W + 4 Jets and Z + 4 Jets

The measurement of the FCNC branching ratio relies on two datasets: $\ell\ell + 4$ jets and $\ell\,\not{E}_{\mathrm{T}} +$ 4 jets, where $\ell\ell$ and $\ell\,\not{E}_{\mathrm{T}}$ are consistent with decays of a Z boson or a W boson, respectively. At least one of the four jets in the final state is required to be identified as heavy flavor decay, "b-tagged", by the secondary vertex identification algorithm. The H_T-distribution for the W + 4 jets events agree well with those of top quark pair decays (see Fig. 3). The total transverse energy, H_T, is a scalar sum of E_T of all reconstructed objects (electrons, muons, photons, jets, missing transverse energy, and unclustered energy).

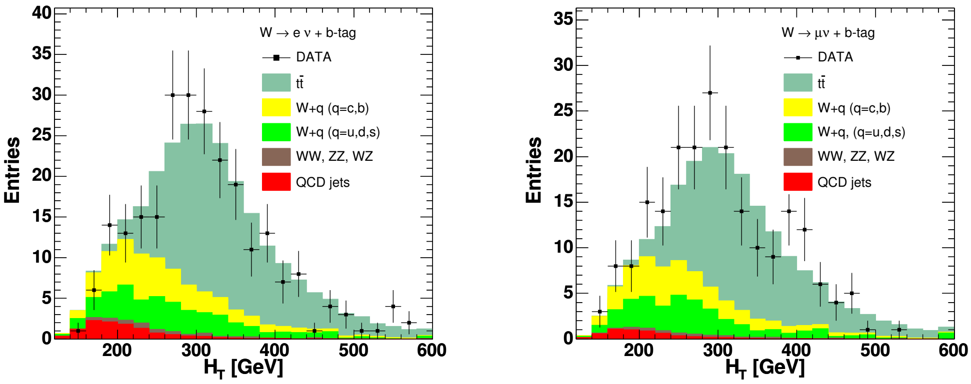

Figure 3: The measured distribution (points) in H_T in events with a W and four jets, compared to SM expectations (histogram), for the electron channel (left figure) and muon channel (right figure). The order of stacking in the histograms is the same as in their legends.

The top quark mass M_{top} is used as a discriminating variable against the SM backgrounds to estimate the number of $t\bar{t}$ events decaying into a Z boson and four jets via FCNC (see Fig. 4). The value of M_{top} is calculated by minimizing the χ^2 distribution, which is based on the assumption that the event is $p\bar{p} \to t\bar{t} \to Z + 4$ jets $\to \ell\ell + 4$ jets.

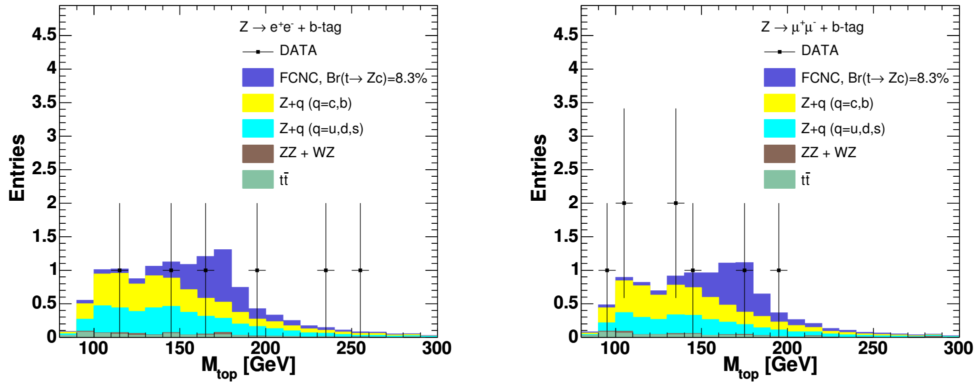

Figure 4: The measured distribution (points) in the fitted top quark mass in events with a Z and four jets with at least one b-tagged jet, compared to the SM expectations and an FCNC signal (stacked histogram), for the electron channel (left figure) and muon channel (right figure). The order of stacking in the histograms is the same as in their legends.

4. Conclusions and Results

Taking into account systematic uncertainties we find an upper limit at 95% C.L. on the branching ratio of $t \to Zc$. To be assumption-independent we parametrize the limit on $Br(t \to Zc)$ as a function of the fraction of longitudinally polarized Z bosons. The parametrization allows us to cover the full range of all possible helicity structures of the $t \to Zc$ vertex. The upper limits calculated for five fractions of longitudinally polarized Z's are presented in Table 1 for both the Gaussian and the flat priors. The result is primarily statistics-limited.

Longitudinal Fraction	0.00	0.25	0.50	0.75	1.0
Gaussian prior	9.0%	8.8%	8.6%	8.5%	8.3%
Flat prior	10.2%	10.0%	9.7%	9.5%	9.2%

Table 1: The upper limits on the FCNC branching ratio $Br(t \to Zc)$ in % as a function of the longitudinal fraction of the Z bosons in the FCNC coupling ($t \to Zc$) at 95% CL. The limits labeled Gaussian prior use as input the theoretical cross-section of $\sigma(p\bar{p} \to t\bar{t})$; the limits labeled Flat prior are theory-independent.

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