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Search for FCNC in top pair events in pp collisions (CMS)

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A search for flavor changing neutral currents in top quark decays $t \to Zq$ in events with a topology compatible with the decay chain $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$ are presented. The search is performed with a data sample corresponding to an integrated luminosity of $4.6\,fb^{-1}$ of proton-proton collisions at a center-of-mass energy of 7 TeV, collected with the CMS detector at the LHC. The observed number of events agrees with the standard model prediction and no evidence for flavor changing neutral currents in top quark decays is found.

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1. Introduction

The top quark decays with a branching fraction of nearly 100% to a bottom quark and a W boson, $\mathrm{t} \to \mathrm{Wb}$. However, some extensions of the standard model (SM) predict that the top quark can also decay through a neutral Z boson, $\mathrm{t} \to \mathrm{Zq}$, where q is a u or c quark. This decay is suppressed in the SM by the GIM mechanism [1] and occurs at the level of quantum loop corrections only. The branching fraction $\mathscr{B}(\mathrm{t} \to \mathrm{Zq})$ is predicted to be $\mathscr{O}(10^{-14})$ [2].Detection of this signal would therefore be an indication of a large enhancement in the branching fraction and clear evidence for violations of the SM prediction. There are several models that predict enhancements of the $\mathrm{t} \to \mathrm{Zq}$ decay where $\mathscr{B}(\mathrm{t} \to \mathrm{Zq})$ could be as large as $\mathscr{O}(10^{-4})$.

Previous searches for the flavor changing neutral currents in top quark decays performed at the Tevatron by CDF and D0 determined a $\mathscr{B}(\mathrm{t} \to \mathrm{Zq})$ upper limit of 3.7% [3] and 3.2% [4] at the 95% confidence level (CL), respectively. A recent search in the three-lepton channels performed at ATLAS with an integrated luminosity of 2.1 fb^{-1} reported a $\mathscr{B}(\mathrm{t} \to \mathrm{Zq})$ upper limit of 0.73% [5].

We look for $\mathrm{t\bar{t}} \to \mathrm{Zq} + \mathrm{Wb} \to \ell\ell\mathrm{q} + \ell\nu\mathrm{b}$ final state events, which produce three-lepton (eee, eeμ, $\mu\mu$e, $\mu\mu\mu$) final states with reduced background and fewer signal events. The analysis uses a data sample corresponding to an integrated luminosity of 4.6 fb^{-1} of proton-proton collisions at $\sqrt{s} = 7\,\mathrm{TeV}$, recorded by the Compact Muon Solenoid (CMS) [6] experiment during 2011.

2. Basic Selection

Events with two opposite-sign, isolated e or μ consistent with a Z-boson decay and an extra charged lepton are selected. All three leptons must be isolated and have transverse momentum $p_{\mathrm{T}} > 20\,\mathrm{GeV}$, and the electrons (muons) must have $|\eta| < 2.5$ ($|\eta| < 2.4$). Events are required to pass at least one of the ee or $\mu\mu$ high-p_{T} double-lepton triggers. Their efficiencies for events containing two leptons satisfying the analysis selection are measured to be 99%, 98%, 91% and 93% for the eee, eeμ, $\mu\mu$e and $\mu\mu\mu$ channels, respectively.

The invariant mass of at least one $\mathrm{e}^+\mathrm{e}^-$ or $\mu^+\mu^-$ pair is required to be between 60 GeV and 120 GeV and the one closest to Z-boson mass is taken. All leptons, which are used to select or reject events, must come from the same primary vertex. The $\mu^+\mu^-$ pair opening angle is required to differ from π radians by more than 0.05 radians to reject cosmic rays.

Electrons and muons from Z and W decays are expected to be isolated from other particles. A cone of size $\Delta\mathrm{R} \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ is constructed around the lepton momentum direction. The lepton relative isolation is quantified by summing the transverse energy (as measured in the calorimeters) and the transverse momentum of all objects within this cone respect to its transverse momentum. This requirement rejects misidentified leptons and background arising from hadronic jets. The third lepton in the event should be the result of a leptonic decay of a W boson. Events with a fourth lepton are rejected.

The jets and the missing transverse energy vector ($-\Sigma\vec{p}_{\mathrm{T}}$) and its magnitude ($E_{\mathrm{T}}^{\mathrm{miss}}$) are reconstructed using a particle-flow technique [7]. An anti-k_{t} clustering algorithm [8] with a distance parameter of 0.5 is used for jet reconstruction. The charged constitutes of a jet which come from pileup is removed. Jets are required to have $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $|\eta| < 2.4$, and to be separated by $\Delta\mathrm{R} > 0.4$ from leptons passing the analysis selection. The missing transeverse energy vector is expected to be caused by the neutrinos from leptonic W-boson decays.We require the missing transverse energy to be larger than 30 GeV.

The samples of Drell–Yan events with invariant mass of lepton pairs $m_{\ell\ell}$ larger than 50 GeV, SM $t\bar{t}$, and WZ are generated using MADGRAPH [9]. The samples of WW and ZZ diboson events are simulated using PYTHIA [10], while single-top-quark events are generated using POWHEG [11, 12, 13]. The signal sample $pp \to t\bar{t} \to Zq + Wb \to \ell^+\ell^- q + \ell^\pm \nu b$ ($\ell = e, \mu, \tau$) is generated with MADGRAPH and the top quarks decay and hadronize through PYTHIA with helicity reweighted to SM prediction. The set of parton distribution functions used is CTEQ6L [14]. The CMS detector response is simulated using a GEANT4-based [15] model, and the events are reconstructed and analyzed using the same software used to process collision data. The simulated events are weighted so that the trigger efficiencies, reconstruction efficiencies and the distribution of reconstructed vertices observed in data are reproduced.

The observed and expected yields based on MC after the basic event selection described above are listed in Table 1. All entries in Table 1 also include the τ decay mode contributions. Single-top-quark production is dominated by the Wt channel. The total yields are dominated by diboson production and a reasonable agreement is observed between data and simulation.

Table 1: Event yields and background predictions based on simulated events for all three-lepton channels after the basic event selection, which includes the trigger, Z boson, third lepton, fourth-lepton veto and missing transverse energy requirements for an integrated luminosity of 4.6 fb^{-1}. The uncertainties include the statistical and systematic components separately (in that order).

Channel	$\mu\mu e$	$\mu\mu\mu$	eee	$ee\mu$
Drell–Yan	$2.0 \pm 1.4 \pm 0.3$	$0.9 \pm 1.0 \pm 0.1$	$2.8 \pm 1.7 \pm 0.4$	$0.9 \pm 1.0 \pm 0.1$
WZ	$46.1 \pm 6.8 \pm 6.1$	$60.3 \pm 7.8 \pm 8.0$	$40.9 \pm 6.4 \pm 5.4$	$48.6 \pm 7.0 \pm 6.4$
ZZ	$17.7 \pm 4.2 \pm 2.3$	$21.7 \pm 4.7 \pm 2.9$	$15.1 \pm 3.9 \pm 2.0$	$18.2 \pm 4.3 \pm 2.4$
WW	≤ 0.001	≤ 0.001	$0.2 \pm 0.3 \pm 0.0$	≤ 0.001
$t\bar{t}$	≤ 0.001	$0.5 \pm 0.7 \pm 0.1$	$0.9 \pm 0.9 \pm 0.1$	$0.9 \pm 0.9 \pm 0.1$
Single top	≤ 0.001	$0.1 \pm 0.4 \pm 0.0$	$0.0 \pm 0.2 \pm 0.0$	≤ 0.05
Total	$66 \pm 8 \pm 7$	$84 \pm 9 \pm 9$	$60 \pm 8 \pm 6$	$69 \pm 8 \pm 7$
Observed	73	87	85	61

3. Signal Reconstruction

For the $t \to Zq \to \ell^+\ell^- j$ signal, a full reconstruction of the top quark mass m_{Zj} is possible and straightforward, but there is no unambiguous way to pair multiple light-quark jets with the Z boson. Therefore all possible combinations are examined.

The invariant mass of the W and b jet system (m_{Wb}) can be reconstructed by assuming that the transverse components of the neutrino momentum are given by the E_T^{miss} vector information, while the longitudinal component could be resolved through a quadratic equation by assuming a nominal W mass. If the discriminant of the equation is found to be negative, it is set equal to zero. In events which there are two possible solutions for $p_{z\nu}$, the solution with the smaller magnitude of $p_{z\nu}$, is

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taken; studies with simulated signal events show that this solution is the correct one more than 60% of the time.

Next, we add the requirements on jets, m_{Zj}, and m_{Wb} to the basic selection and search for $t\bar{t} \rightarrow Wb + Zq$ in two ways: One selection requires a minimum 250 GeV of S_T to reduce the combinatorials and loose requirements on m_{Zj} and m_{Wb} to be between 100 GeV and 250 GeV. The top candidate pair of the largest distance in azimuthal direction is chosen. The second selection is stricter, with tight requirements: m_{Zj} within 25 GeV of m_t and m_{Wb} within 35 GeV of m_t. Also one of the jets should be consistent with the hadronization of a b quark, namely a "b jet". The jet paired with Z which gives m_{Zj} closest to m_t is chosen. We refer to these two selections as the "S_T" and "b-tag" selections, respectively. Table 2 shows the estimates of the overall signal efficiency determined from simulated events.

Table 2: Signal selection efficiency for each three-lepton channels in percent. The efficiency is calculated as the fraction of events with leptonically (e, μ, τ) decaying W and Z bosons passing the selection. Only statistical uncertainties are shown.

Channel	S_T Selection [%]	b-tag Selection [%]
eee	(12.4 ± 1.1)	(3.8 ± 0.6)
eeμ	(13.8 ± 1.2)	(5.0 ± 0.7)
$\mu\mu$e	(14.8 ± 1.2)	(5.1 ± 0.7)
$\mu\mu\mu$	(14.7 ± 1.2)	(5.3 ± 0.7)

4. Background Estimation

Backgrounds are estimated from the yields of simulated events passing the full selection for WW, WZ, ZZ, $Wt\bar{t}$, $Zt\bar{t}$, and single-top-quark production, while estimates based on data are made for Drell–Yan and $t\bar{t}$ backgrounds. The uncertainties in the background estimation given below include, in order, the statistical and systematic components.

The WZ and ZZ production are the dominant diboson backgrounds. The production of W pairs has a higher cross section, but is unlikely to contain both an extra high-p_T lepton and to pass the Z requirement. The diboson background estimates are $13.6 \pm 3.7 \pm 2.6$ ($0.4 \pm 0.1 \pm 0.1$) and $1.1 \pm 0.1 \pm 0.2$ (≤ 0.03) for the WZ and ZZ processes in the S_T (b-tag) selection. These estimates are rescaled by 1.4 ± 0.1 to take into account the overall normalization difference observed between data and simulation for the zero jet events, after the basic event selection. The single-top-quark background is smaller than 0.01 at the 95% CL in both selections.

The Drell–Yan background is small due to the minimum 30 GeV requirement of missing transverse energy. Other backgrounds from QCD multijet events in which a jet could be misidentified as a lepton are negligible. It is possible for SM $t\bar{t}$ to satisfy the Z selection when both W bosons decay leptonically into the same flavor, but the third lepton and the top quark mass requirements will reject these events.

The Drell–Yan and $t\bar{t}$ or any other background having two leptons in an event are estimated based on two data samples. The first sample is composed of all events satisfying the basic event selection with two or more jets and loose requirements in S_T, The second sample also has the same requirements but it has a less stringent isolation criteria for the third lepton. Therefore, the second sample is an admixture of the purer three-lepton sample plus events with a misidentified lepton, originating from jets or heavy-flavor decays, or genuine three-lepton events that were lost in the signal sample due to the more stringent isolation requirement. The number of events in the two samples are then related by the efficiency of events with nominal lepton isolation and the probability of a jet to be misidentified as a lepton. Using the genuine and misidentified lepton efficiencies, which are both determined from data, the yield of genuine and misidentified three-lepton events is then found. This measurement is turned into an estimate of the Drell–Yan plus $t\bar{t}$ background after subtracting the contribution from dibosons and taking into account the change in acceptances and efficiencies (e.g. b-tagging) after the full signal selections are made. The total contribution of Drell-Yan plus $t\bar{t}$ events, after the S_T and b-tag selections are estimated to be $1.5 \pm 0.5 \pm 0.4$ and $0.06 \pm 0.02 \pm 0.01$, respectively. The statistical and systematic uncertainties are estimated from the amounts of the events of these two data samples and the uncertainty of the lepton isolation efficiencies measured with data. These estimates are compatible with the expectations based on simulated events. The total estimated backgrounds are given in Table 3.

Table 3: Background composition, observed and expected yields, and limits at the 95% CL for all three-lepton channels combined for the S_T and b-tag selections for an integrated luminosity of $4.6\,\mathrm{fb}^{-1}$. The uncertainties in the background estimation include the statistical and systematic components separately (in that order).

Selection	S_T	b-tag
WZ background	$13.6 \pm 3.7 \pm 2.6$	$0.4 \pm 0.1 \pm 0.1$
ZZ background	$1.1 \pm 1.0 \pm 0.2$	≤ 0.03
Drell-Yan and $t\bar{t}$ background	$1.5 \pm 0.5 \pm 0.4$	$0.2 \pm 0.1 \pm 0.1$
Total background prediction	$16.2 \pm 3.9 \pm 2.6$	$0.6 \pm 0.1 \pm 0.1$
Observed events	11	0
Expected limit at the 95% CL	$\mathscr{B}(t \to Zq) < 0.42\%$	$\mathscr{B}(t \to Zq) < 0.34\%$
Observed limit at the 95% CL	$\mathscr{B}(t \to Zq) < 0.39\%$	$\mathscr{B}(t \to Zq) < 0.34\%$

5. Systematics Uncertainties

The major contributions of systematic uncertainties come from the trigger efficiency, choice of parton distribution functions, lepton selection, pileup modeling, missing transverse energy resolution, uncertainty on the $t\bar{t}$ cross section, b-tagging efficiency for high-p_T b jets [16], and jet energy scale [17]. The prescription given in [18] is used to determine the uncertainty from the choice of parton distribution functions. The uncertainty on the luminosity measurement is 4.5% [19]. All these sources combine to give a 21% (23%) relative uncertainty on the signal acceptance times efficiency in the S_T (b-tag) selection. The systematic uncertainties are summarized in Table 4. The systematic uncertainty of the background estimation is listed with the total background prediction given in Table 3.

Table 4: Summary of the systematic uncertainties for the three-lepton signal selection in percent for the S_T and b-tag selections.

Source	S_T selection [%]	b-tag selection [%]
Trigger efficiency	4	4
Luminosity	5	5
Parton distribution functions	6	6
Lepton selection	7	7
Pileup events	7	7
Missing transverse energy resolution	8	8
b tagging	—	9
Jet energy scale	10	10
Cross sections	11	11
Total	21	23

6. Results and Summary

In the S_T (b-tag) selection, we expect 16.2 ± 3.9 (0.6 ± 0.1) events from the SM background processes and we observe 11 (0) events for all four channels combined. No excess beyond the SM background is observed and a 95% CL upper limit on the branching fraction of $t \to Zq$ is determined using the modified frequentist approach (CLs method [20, 21]). A summary of the observed and predicted yields and limits are presented in Table 3.

The calculation of the upper limit is based on the information provided by the observed event count combined with the values and the uncertainties of the luminosity measurement, the background prediction, and the fraction of all $t\bar{t} \to Zq + Wb \to \ell\ell q + \ell b$ events expected to be selected. The signal event yield is obtained from the efficiency times acceptance and branching fraction for simulated events.

The best observed and expected 95% CL upper limits on the branching fraction $\mathscr{B}(t \to Zq)$ are 0.34% and 0.34%, respectively, obtained in the b-tag selection from the combined three-lepton analyses. The corresponding observed and expected upper limits for the S_T selection are 0.42% and 0.39% , respectively. The one with better expected limit is taken as the final result.

We report a search for flavor changing neutral currents in top quark decays in $t\bar{t}$ events produced in proton-proton collisions at $\sqrt{s} = 7\,\text{TeV}$ is presented. A sample of three-lepton events is selected from data recorded by CMS during 2011 corresponding to an integrated luminosity of $4.6\,\text{fb}^{-1}$. These events are compatible with a $pp \to t\bar{t} \to Zq + Wb \to \ell\ell q + \ell\nu b\,(\ell = e, \mu)$ topology. No excess of events over the SM background is observed and a $\mathscr{B}(t \to Zq)$ branching fraction larger than 0.34% is excluded at the 95% confidence level.

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