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Flavor Changing Neutral Current searches in the top quark sector

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Flavor changing neutral current (FCNC) interactions in top quark are highly suppressed in the Standard Model. Therefore, any measurable branching ratio for top FCNC decays would be an indication of new physics. In this article, searches for FCNC interactions in top quark production and decay by the ATLAS and CMS experiments at the LHC are presented. Searches in $t \to qH$, $t \to q\gamma$ and $t \to qZ$ decays, and in top quark production in $qg \to t$ or $q \to tg$ are summarized. None of the FCNC searches yielded positive results and exclusion limits on branching ratios, coupling strengths and cross-sections are obtained.

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1. Introduction

Flavor changing neutral current (FCNC) is a transition that changes the flavor of a fermion without changing its charge. These transitions are forbidden at tree level in the standard model (SM) and are suppressed at higher orders due to the GIM mechanism [8]. Therefore, the measurement of FCNC of the top quark provides a sensitive probe of physics beyond the SM.
Many models for new physics predict additional contributions to top FCNCs that are orders of magnitude in excess of SM expectations. Table 1 summarizes predictions for top FCNC branching ratios (BRs) in the SM and various new physics models [9]. Since the top quark decays before hadronizing, top flavor violation is ideally probed through direct FCNC production and decays of the top quark in experiments at the energy frontier.

Process	SM	2HDM-FV	2HDM-FC	MSSM	RPV	RS
$t \to u + H$	2×10^{-17}	6×10^{-6}	-	$\leq 10^{-5}$	$\leq 10^{-9}$	-
$t \to c + H$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$
$t \to u + \gamma$	4×10^{-16}	-	-	$\leq 10^{-8}$	$\leq 10^{-9}$	-
$t \to c + \gamma$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to u + g$	4×10^{-14}	-	-	$\leq 10^{-7}$	$\leq 10^{-6}$	-
$t \to c + g$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to u + Z$	7×10^{-17}	-	-	$\leq 10^{-7}$	$\leq 10^{-6}$	-
$t \to c + Z$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$

Table 1: SM and new physics model predictions for branching ratios of top FCNC decays. The predictions for SM, two-Higgs doublet model (2HDM) with flavor violating (FV) Yukawa couplings, the 2HDM flavor conserving (FC) case, minimal supersymmetric standard model (MSSM) with 1TeV squarks and gluinos, the MSSM for the R-parity violating case, and warped extra dimensions (RS) are taken from Ref. [9].

Among FCNC top-quark decays of the form $t \to qX$ with X = Z, H, γ, g, modes involving a Z or a Higgs boson or a photon are usually studied by searching for final states containing the corresponding decay particles, whereas anomalous single top-quark production ($qg \to t$) where a u- or c-quark and a gluon, originating from the colliding protons, interact to produce a single top quark are studied for better sensitivity.
The latest measurements by the ATLAS [10] and CMS [11] Collaborations are presented in this article.

2. $t \to u/c+H$

2.1 Results from ATLAS [1]

A search for FCNC decays of a top quark to an up-type quark ($q = u, c$) and the SM Higgs boson, where the Higgs boson decays to $b\bar{b}$ is presented. The analysis searches for top quark pair events in which one top quark decays to Wb, with the W boson decaying leptonically, and the other top quark decays to Hq. The search is based on pp collision data recorded at $\sqrt{s}$ = 8 TeV in 2012 with the ATLAS detector and uses an integrated luminosity of 20.3 fb^{-1}. The signal final

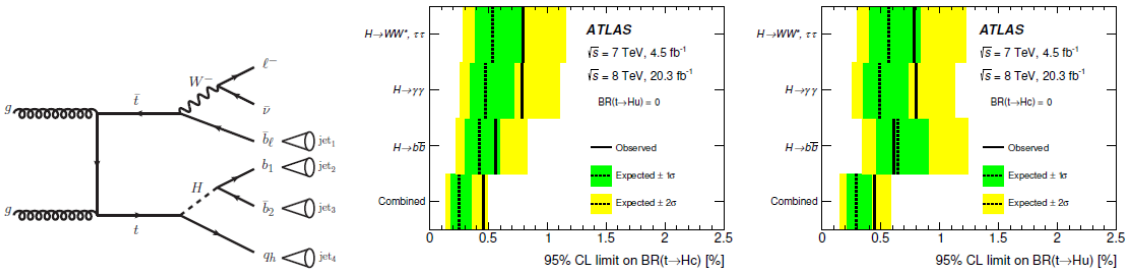

Figure 1: Feynman diagram (left), 95% CL upper limits on BR(t → Hc) (middle), BR(t → Hu) (right) [1]

state is characterised by an isolated electron or muon and at least four jets. The search exploits the high multiplicity of b-quark jets, a characteristic of signal events, and employs a likelihood discriminant that uses the kinematic differences between signal and background, dominated by $t\bar{t} \to WbWb$ decays. No significant excess of events above the background expectation is found, and observed (expected) 95% confidence-level (CL) upper limits of 0.56% (0.42%) and 0.61% (0.64%) are derived for the $t \to Hc$ and $t \to Hu$ branching ratios, respectively. The combination of this search with other ATLAS searches in the $H \to \gamma\gamma$ and W decay modes significantly improves the sensitivity, yielding observed (expected) 95% CL upper limits on the t→Hc and t→Hu branching ratios of 0.46% (0.25%) and 0.45% (0.29%), respectively. The corresponding combined observed (expected) upper limits on the $|\lambda_{tcH}|$ and $|\lambda_{tuH}|$ couplings are 0.13 (0.10) and 0.13 (0.10), respectively. These are the most restrictive direct bounds on tqH interactions measured so far. A summary of the upper limits on the branching ratios obtained by the individual searches, as well as their combination, can be found in figure 1.

2.2 Results from CMS [2]

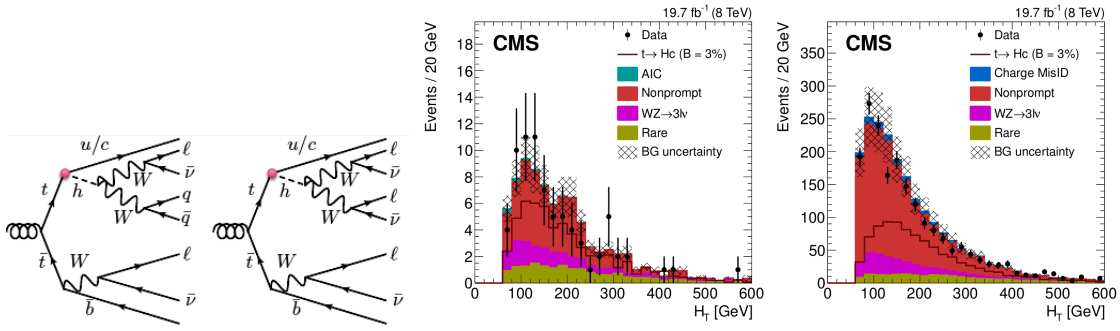

Figure 2: Feynman diagrams (left), H_T distributions in trilepton (middle) and same-sign dilepton (right) [2]

A search is performed for Higgs-boson-mediated FCNCs in the decays of top quarks. The search is based on pp collision data corresponding to an integrated luminosity of 19.7 fb^{-1} at a center-of-mass energy of 8 TeV collected with the CMS detector. Events in which a top quark pair is produced with one top quark decaying into a charm or up quark and a Higgs boson (H), and the other top quark decaying into a bottom quark and a W boson are selected. The Higgs boson in these

events is assumed to subsequently decay into either a pair of bosons or difermions. Figure 2 shows the H_T distributions for trilepton and same-sign dilepton events after applying the Z veto and jet requirement. No significant excess is observed above the expected SM background, and an upper limit at the 95% CL is set on the branching ratio $\mathscr{B}(t \to Hc)$ of 0.40% and $\mathscr{B}(t \to Hu)$ of 0.55%, where the expected upper limits are 0.43% and 0.40%, respectively. These results correspond to upper limits on the square of the flavor-changing Higgs boson Yukawa couplings $|\lambda^H_{tc}|^2 < 6.9 \times 10^{-3}$ and $|\lambda^H_{tu}|^2 < 9.8 \times 10^{-3}$.

3. u/c $\to$ t+γ

3.1 Results from CMS [3]

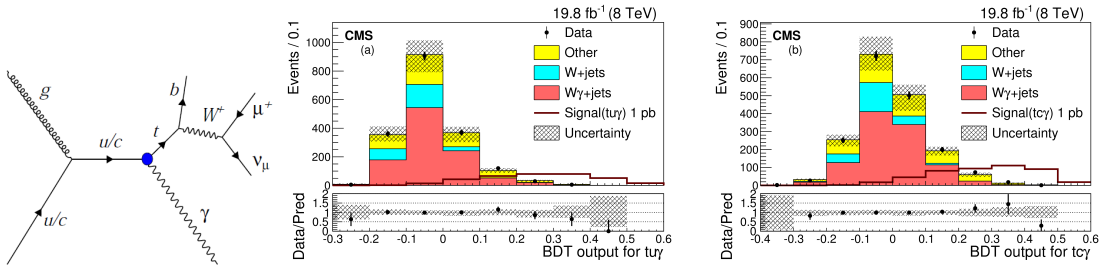

Figure 3: Feynman diagram (left), the BDT output distributions for tuγ (middle) and tcγ (right) [3]

A search for FCNC through single top quark production in association with a photon is performed. The study is based on pp collisions at a center-of-mass energy of 8 TeV using data collected with CMS, corresponding to an integrated luminosity of 19.8 fb^{-1}. The search for tγ events where $t \to Wb$ and $W \to \mu\nu$ is conducted in final states with a muon, a photon, at least one hadronic jet with at most one being consistent with originating from a bottom quark, and missing transverse momentum. No evidence of single top quark production in association with a photon through FCNC is observed as shown in the BDT output distribution in figure 3. Upper limits at the 95% CL are set on the tuγ and tcγ anomalous couplings and translated into upper limits on the branching fraction of the FCNC top quark decays: $\mathscr{B}(t \to u\gamma) < 1.3 \times 10^{-4}$ and $\mathscr{B}(t \to c\gamma) < 1.7 \times 10^{-3}$. Upper limits are also set on the cross section of associated tγ production in a restricted phase-space region. These are the most stringent limits currently available.

4. u/c+g $\to$ t and u/c $\to$ t+g

4.1 Results from ATLAS [4]

A search for single top-quark production via FCNC processes from gluon plus up- or charm-quark initial states in pp collisions at the LHC is presented. Data collected with the ATLAS detector in 2012 at a centre-of-mass energy of 8 TeV, corresponding to an integrated luminosity of 20.3 fb^{-1}, are used. Candidate events for a top quark decaying into a lepton, a neutrino and a jet are selected and classified into signal and background-like candidates using a neural network. No signal is observed and an upper limit on the production cross-section multiplied by

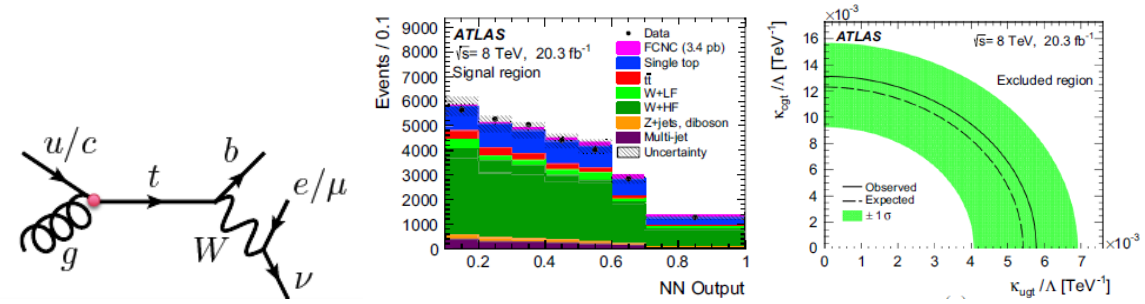

Figure 4: Feynman diagram (left), neural network (NN) output distribution in the signal region (middle) and upper limit on the coupling constants (right) [4].

the $t \to Wb$ branching ratio is set. The observed 95% CL limit is $\sigma_{qg\to t} \times \mathscr{B}(t \to Wb) < 3.4$ pb and the expected 95% CL limit is $\sigma_{qg\to t} \times \mathscr{B}(t \to Wb) < 2.9$ pb. To visualise the observed upper limit in the neural-network output distribution, the FCNC signal process scaled to 3.4 pb stacked on top of all background processes is shown in figure 4 (middle). The observed limit can be interpreted as upper limits on the coupling constants of FCNC interactions divided by the scale of new physics $k_{ugt}/\Lambda < 5.8 \times 10^{-3}\text{TeV}^{-1}$ and $k_{cgt}/\Lambda < 13 \times 10^{-3}\text{TeV}^{-1}$ and on the branching ratios $\mathscr{B}(t \to ug) < 4.0 \times 10^{-5}$ and $\mathscr{B}(t \to cg) < 20 \times 10^{-5}$. Distributions of the upper limits on the coupling constants for combinations of cgt and ugt channels are shown in figure 4 (right).

4.2 Results from CMS [5]

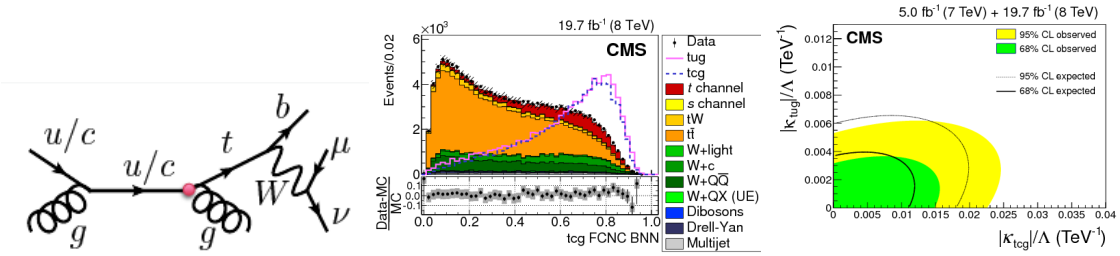

Figure 5: Feynman diagram (left), BNN discriminant distributions for tcg (middle) and upper limit on the coupling constants (right) [5].

Single top quark events produced in the t channel are used to set limits on anomalous Wtb couplings and to search for top quark FCNC interactions. The data taken with the CMS detector at the LHC in proton-proton collisions at $\sqrt{s}$ = 7 and 8 TeV correspond to integrated luminosities of 5.0 and 19.7 fb^{-1}respectively. The analysis is performed using events with one muon and two or three jets. A Bayesian neural network (BNN) technique, used to discriminate between the signal and backgrounds, is found to be consistent with the SM prediction. The comparison of the neural network output for the data and model is shown in figure 5 (middle). The 95% confidence level (CL) exclusion limits on anomalous right-handed vector, and left- and right-handed tensor Wtb couplings are measured to be $|f_V^R| < 0.16$, $|f_T^L| < 0.057$, and $0.049 < f_T^R < 0.048$, respectively. For the FCNC couplings k_{tug} and k_{tcg} , the 95% CL upper limits on coupling strengths

are $|k_{tug}|/\Lambda < 4.1 \times 10^{-3}\text{TeV}^{-1}$ and $|k_{tug}|/\Lambda < 1.8 \times 10^{-2}\text{TeV}^{-1}$, where Λ is the scale for new physics, and corrspond to upper limits on the branching fractions of 2.0×10^{-5} and 4.1×10^{-4} for the decays $t \to ug$ and $t \to cg$, respectively. The combined $\sqrt{s}$ = 7 and 8 TeV observed and expected exclusion limits at 68% and 95% CL on the anomalous FCNC parameters in the form of two-dimensional contours are shown in figure 5 (right).

5. $t \to u/c+Z$

5.1 Results from ATLAS [6]

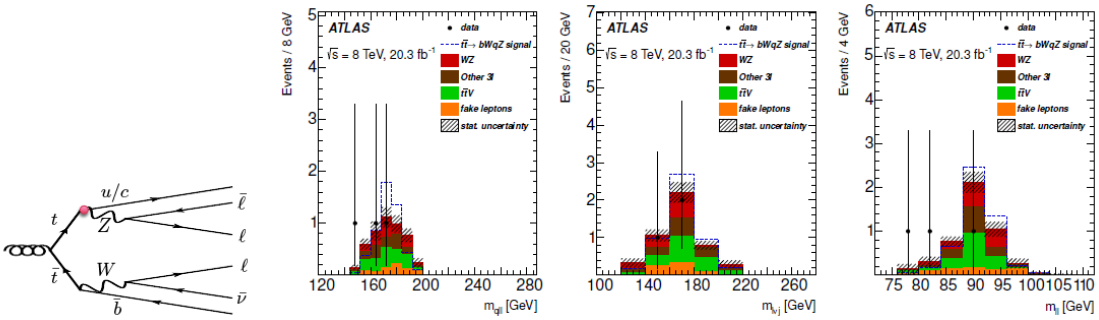

Figure 6: Feynman diagram (left), reconstructed masses of the top quark from the FCNC decay, top quark from the SM decay and Z boson [6].

A search for the FCNC decay $t \to qZ$ is presented. Data collected by the ATLAS detector during 2012 from proton proton collisions at the Large Hadron Collider at a centre-of-mass energy of $\sqrt{s}$ = 8 TeV, corresponding to an integrated luminosity of 20.3 fb^{-1}, are analysed. Top-quark pair-production events with one top quark decaying through the $t \to qZ$ ($q = u, c$) channel and the other through the dominant SM mode $t \to bW$ are considered as signal. Only the decays of the Z boson to charged leptons and leptonic W boson decays are used. Figure 6 shows the reconstructed masses of the top quarks and Z boson after the final selection. No evidence for a signal is found and an observed (expected) upper limit on the $t \to qZ$ branching ratio of $7 \times 10^{-4}(8 \times 10^{-4})$ is set at the 95% CL.

5.2 Results from CMS [7]

A search for the production of a single top quark in association with a Z boson is presented, both to identify the expected SM process and to search for FCNC interactions. The data sample corresponds to an integrated luminosity of 19.7 fb^{-1} recorded by the CMS experiment at the LHC in proton-proton collisions at $\sqrt{s}$ = 8 TeV. Final states with three leptons, electrons or muons, and at least one jet are investigated. The post-fit data-to-prediction distributions, including the post-fit uncertainties, are presented in figure 7 (middle) for the four channels combined. A moderate excess of events compatible with SM tZq production is observed, and the corresponding cross section is measured to be $\sigma(tZq \to l\nu bl^+l^-q) = 10^{+8}_{-7}$ fb with a significance of 2.4σ. No presence of FCNC production of tZ(q) is observed and exclusion limits at 95% CL on the branching ratios of a top

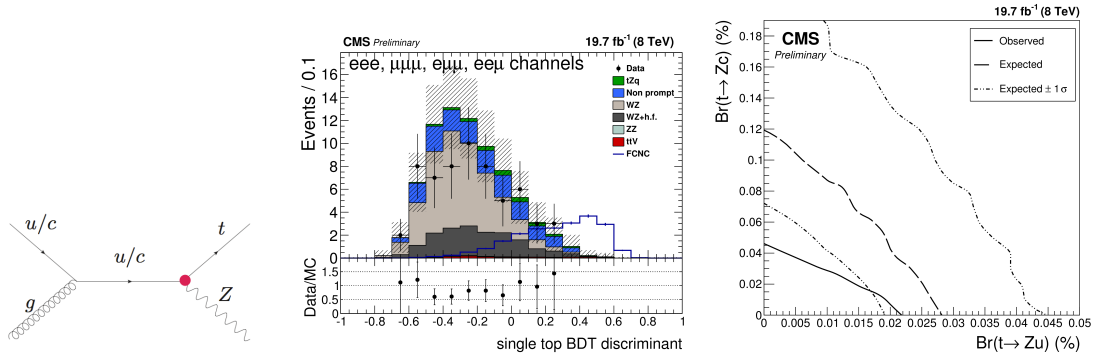

Figure 7: Feynman diagram (left), the BDT responses (middle), exclusion limits at the 95% CL (right) [7]

quark decaying to a Z boson and an up or a charm quark are found to be $\mathrm{BR}(\mathrm{t} \to \mathrm{Zu}) < 0.022\%$ and $\mathrm{BR}(\mathrm{t} \to \mathrm{Zc}) < 0.049\%$, respectively. The limits are calculated for different combinations of tZu and tZc anomalous couplings, as shown in figure 7 (right).

6. Summary

A review on FCNC searches in the top quark sector has been presented with the results from the ATLAS and CMS experiments, covering all known types of FCNC couplings of top quark with various final states. These processes play an important role as a test for the SM as well as to search for new physics. No signs of FCNCs in the decays of $\mathrm{t\bar{t}}$ or single top quark processes have been observed. The ATLAS and the CMS experiments have significantly improved the exclusion limits for FCNC couplings with Run 1 data. The exclusion limits are getting closer to the predictions from specific new physics models. Figure 8 presents the summary of limits by the ATLAS and CMS Collaborations. The higher center of mass energy and luminosity of Run 2 will allow us to study FCNC processes with an unprecedented precision.

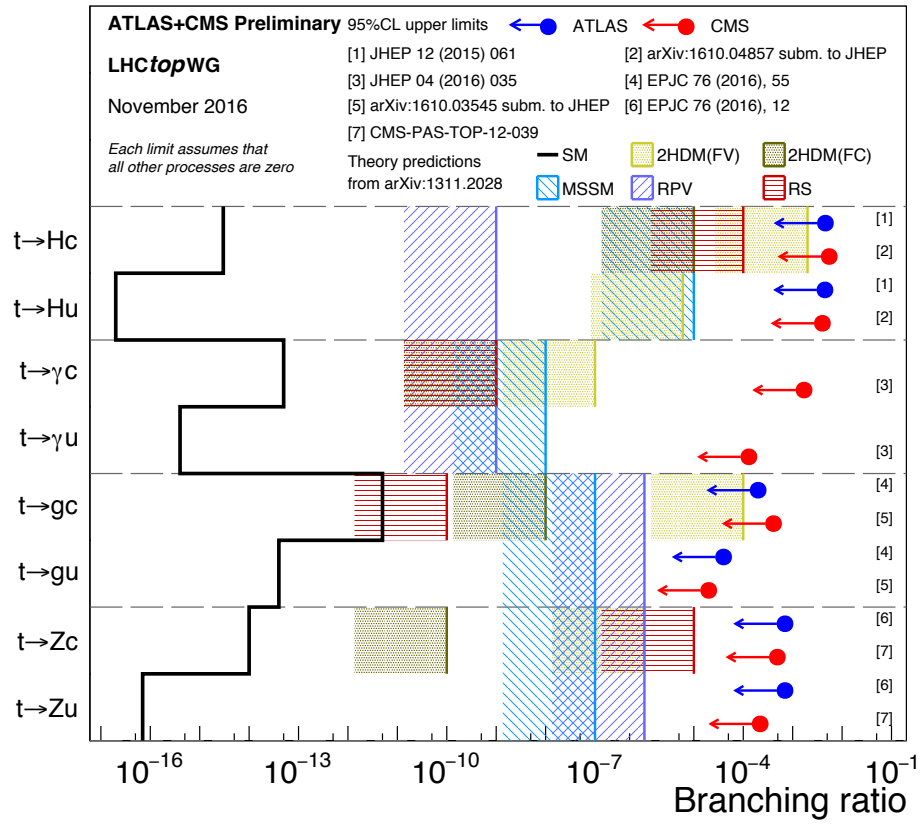

Figure 8: Summary of the current 95% confidence-level observed limits on the branching ratios of the top quark decays via flavour changing neutral currents to a quark and a neutral boson t→Xq (X=g, Z, γ or H; q=u or c) by the ATLAS and CMS Collaborations compared to several new physics models [12]

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