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Search for Top Quark Flavor-Changing Neutral Currents at CMS

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Abstract

We present searches for the top quark flavor-changing neutral current (FCNC) interactions by the CMS experiment. The FCNC searches have been performed in the vertices of tqZ, tqg, and $tq\gamma$ in decay and production processes. The results are based on the data collected from proton proton collisions at the LHC at centre-of-mass energies of 7 and 8 TeV.

Keywords: Top quark, Flavor-Changing Neutral Currents

1. Introduction

Within the Standard Model (SM) framework, top quark decays around 100% of the time into a W boson and a bottom quark. While flavor-changing neutral currents (FCNC) decays are strongly suppressed in the SM because of the GIM (Glashow-Iliopoulos-Maiani) mechanism [1] with branching ratios of the order of $10^{-13,-14}$ [2]. Several extensions of the SM predict much larger branching ratios for the FCNC decays of the top quark. The quark-singlet model, the two-Higgs doublet model and the minimal supersymmetric model are examples of such models which can generate large FCNC in top quark decays [2]. The FCNC branching ratios of top quark decays in these models are typically greater than the SM branching ratios by several orders of magnitude. Depending on the model and its parameters, these branching ratios can grow up to the order of $10^{-4,-5}$ [2]. In this report, we report the results of the CMS experiment [3] on searches for FCNC couplings of $tq\gamma$, tqg and tqZ based on data collected at the center-of-mass energies of 7 TeV and 8 TeV at the LHC. In all searches, the effective Lagrangian approach has been used as a model independent way to search for the FCNC couplings. The searches have been performed either in single top or in top pair events. The most general Lagrangian describing the FCNC couplings has the following form [4],[5]:

$$\begin{aligned}\mathcal{L}_{eff} &= \sum_{q=u,c}\sqrt{2}g_s\frac{\kappa_{tqg}}{\Lambda}\bar{q}\sigma^{\mu\nu}T_a(f_LP_L+f_RP_R)tG^a_{\mu\nu} + \\ &+ \frac{g}{\sqrt{2}c_W}\frac{\kappa_{tqz}}{\Lambda}\bar{q}\sigma^{\mu\nu}(\hat{f}_LP_L+\hat{f}_RP_R)tZ_{\mu\nu} \\ &+ \frac{g}{4c_W}\zeta\bar{q}\gamma^{\mu}(\tilde{f}_LP_L+\tilde{f}_RP_R)tZ_{\mu} \\ &+ e\kappa_{tq\gamma}\bar{q}(\lambda_LP_L+\lambda_RP_R)\frac{\sigma_{\mu\nu}q^{\nu}}{m_t}A^{\mu} + h.c. \qquad (1)\end{aligned}$$

where $P_{L,R}$ are the chirality projection operators and $\sigma_{\mu\nu} = \frac{i}{4}[\gamma_\mu,\gamma_\nu]$. The new physics scales is denoted by Λ and $q^\nu = p^\nu_{top} - p^\nu_q$. The coefficients of the projection operators are in general complex and normalized to one.

2. Search for anomalous $tq\gamma$ FCNC couplings

The existence of anomalous FCNC couplings in $tq\gamma$ vertex would allow the production of a single top quark with a photon at the LHC. The main feature of the signal is the presence of an energetic photon in the final state because of the recoil against the heavy top quark. Another interesting feature of this channel is the sensitivity to both anomalous $tu\gamma$ and $tc\gamma$ couplings. The ratio of $\frac{\sigma_{t\gamma}}{\sigma_{\bar{t}\gamma}}$ is a powerful tool to distinguish between the $tu\gamma$ and $tc\gamma$ couplings [6]. The analysis is based on the LHC data in proton-proton collisions at 8 TeV collected with the CMS that corresponds to an integrated luminosity of 19.1 fb^{-1} [8]. The analysis is performed by requiring to have an isolated energetic photon, one isolated muon, at least one jet, and missing transverse energy. The signal events have been generated using PROTOS event generator at leading order [4]. A template fit method is used to estimate the contributions of two main background processes $W\gamma$+jets and W+jets. Other background contributions are estimated from simulation. Several kinematic variables together with the b-jet tagging information are combined using a Boosted Decision Tree (BDT) to extract the signal. The distributions of the BDT for $tu\gamma$ and $tc\gamma$ signal are presented in Fig.1.

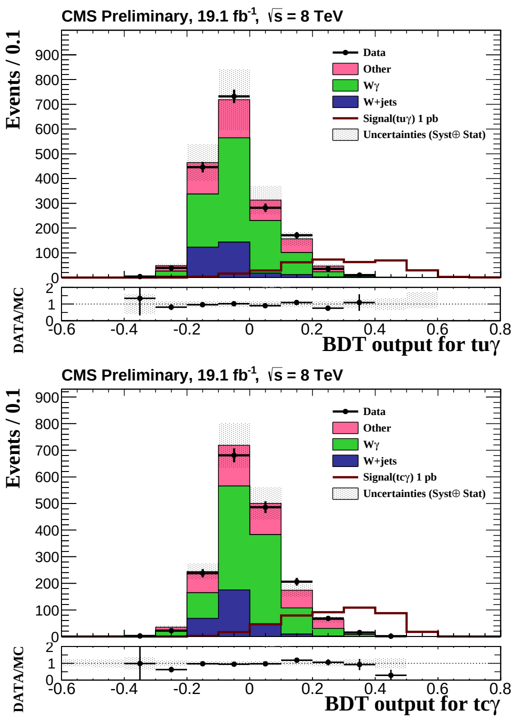

Figure 1: The BDT output distributions of $tu\gamma$ and $tc\gamma$. The signal distribution is normalized to a cross section of 1 pb [8].

No excess is observed over the SM expectation and upper limits are set on the signal cross sections considering all systematic uncertainties. The distributions of BDT in data together with estimated SM background are used to set upper limit on the production cross section of signal. The limit calculation is performed using the CLs technique that has been implemented in the Theta package [7]. The 95% CL upper limits on the signal cross sections are presented in Fig.2. The observed 95% CL upper limit at leading order on the signal cross sections times the leptonic branching ratio are 0.0234 pb and 0.0281 pb for $tu\gamma$ and $tc\gamma$ couplings,

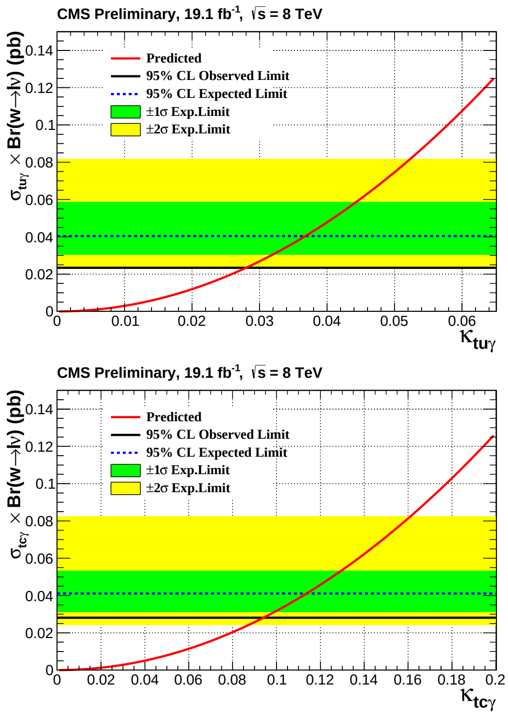

Figure 2: The 95% CL upper limit on the signal cross section as a function of the anomalous FCNC couplings $\kappa_{tu\gamma}$ and $\kappa_{tc\gamma}$ [8].

respectively. These limits are translated into the limits on the top quark decay into a photon plus a quark (up/charm) branching ratios, $BR(t \rightarrow u\gamma) < 0.0161\%$ and $BR(t \rightarrow c\gamma) < 0.182\%$. After including the full next-to-leading order QCD corrections to the signal cross section [9], the upper limits would improved to $BR(t \rightarrow u\gamma) < 0.0108\%$ and $BR(t \rightarrow c\gamma) < 0.132\%$. These limits are the most stringent limits on the anomalous $tq\gamma$ couplings. More details of the analysis can be found in [8].

3. Search for anomalous tqZ couplings

Anomalous FCNC interaction in tqZ vertex leads to production of a top quark in association with a Z boson at the LHC. The CMS experiment has searched for the anomalous tqZ in top quark decay in $t\bar{t}$ events [10] as well as in anomalous single top plus a Z boson production [11].

3.1. *tqZ in the decay of top quark in top pair events*

The analysis is based on 19.5 fb^{-1} of integrated luminosity of data at the center-of-mass energy at the LHC recorded by the CMS detector.

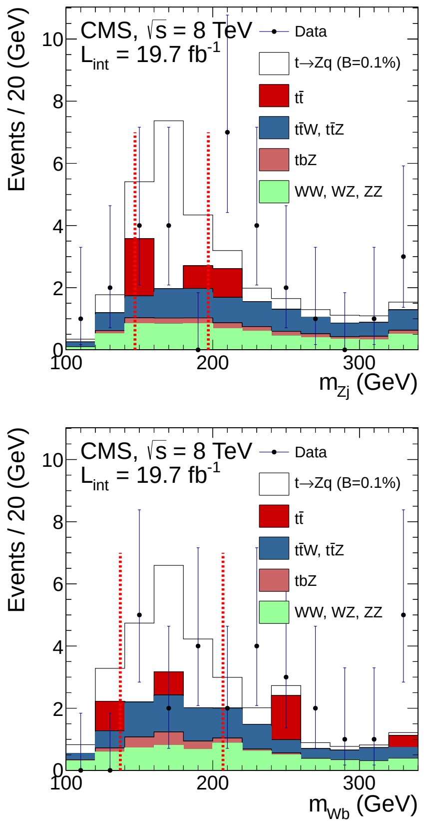

Figure 3: The distributions of m_{Zj} (left), m_{Wb} after the event selection before the top quark mass requirements [10].

The analysis is performed in top pair events with one top quark decays into a W boson and a bottom quark and another one decays anomalously into a Z boson and an up-type quark. Only the leptonic decay of the W and Z bosons are considered in the analysis. Therefore, to select the signal event candidates, it is required to have three isolated leptons, large missing transverse energy, and at least two jets in the final state. Exactly one of the jets is required to be a b-tagged jet. The signal events are generated with a MadGraph [12] event generator and the contributions of the background processes are estimated using a data-driven technique. The dominant backgrounds contributions are coming from diboson and $t\bar{t} + X$. The data-driven background estimation relies on the b-tagging information of the jets. In order to reconstruct the top quarks, the reconstructed Z boson and the un-tagged jet are paired to reconstruct one of the top quarks and the W boson and b-tagged jet are paired to reconstruct the other top quark. The signal region is defined as the region where the reconstructed masses of Wb and Zj reside at mass windows of 35 GeV and 25 GeV around the top quark mass. The distributions of signal and background together with data distributions are depicted in Fig.3. Inside the signal region, there is only one data event and the SM background prediction is 3.1 ± 5.1. As no excess of events over the SM prediction is observed upper limit is set on the signal cross section and then translated into limits on the anomalous couplings and branching ratios. The upper limits on the branching ratio $B(t \to Zq)$ is found to be 0.06% at 95% CL. The combination of the 8 TeV analysis and the 5 fb^{-1} of data at 7 TeV leads to an upper limit of 0.05% at 95% CL. The main systematic uncertainties in this analysis are originating from the factorization and renormalization scales, parton distribution functions (PDFs) and the top pair production rate. This upper bound is the most stringent bound obtained on $B(t \to Zq)$ so far.

3.2. *tqZ in single top+Z events*

As mentioned previously, the search for FCNC processes in tqZ and tqg vertices can be performed in single top quark production in association with a Z boson. The CMS experiment has performed this search based on 5 fb^{-1} of integrated luminosity of data at the center-of-mass energy of 7 TeV [11]. This channel provides the possibility to probe both tqg and tqZ couplings simultaneously. The signal signature consistes of three isolated leptons and a b-tagged jet in the final state. The signal events have been generated with MadGraph. Several kinematic variables as well as the b-jet tagging information are combined using BDT to extract the signal events. The Z+jets process with fake leptons is the main source of backgrounds. There are also background contributions from ZZ+jets, top pair, and single top plus a Z boson process. To estimate the shapes of BDT for Z+jets events, the third lepton isolation criterion is inverted while other background processes are based on simulation. No indication of signal is observed therefore exclusion limits at 95% CL on the anomalous couplings are calculated from the BDT output distributions and then translated into limits on the branching ratios. The observed upper limits on the branching ratios are found to be $BR(t \to ug) < 0.56\%$, $BR(t \to cg) < 7.12\%$, $BR(t \to uZ) < 0.51\%$, $BR(t \to cZ) < 11.40\%$ [11].

4. Search for *tqg* FCNC anomalous couplings

The presence of the anomalous FCNC couplings in tug and tcg vertices lead to production of a single top quark plus a jet at the LHC. The final state is similar to the t-channel SM single top production. The final state consists of exactly one isolated muon, one light-flavor jet in the forward region, one b-tagged jet from the top quark decay, and large missing transverse momentum. The analysis is performed using 5 fb^{-1} of data taken at the center-of-mass energy of 7 TeV [13]. The FCNC signal events have been generated using the CompHEP event generator [14]. All the FCNC samples are normalized to the next-to-leading order cross sections. The main background contribution is coming from W+jets events. The QCD multijet background is estimated by a data-driven method while other backgrounds are estimated from simulation. The QCD background control region is obtained by reversing the isolation criterion of the muon. The FCNC signal and background separation is done by BNNs. Many kinematic variables are used as the input variables of BNN. Two FCNC BNNs have been trained independently. One for the FCNC in *tug* vertex and another one for the FCNC *tcg* processes. Fig. 4 shows the distributions of the FCNC BNN discriminants. The hashed band corresponds to systematic uncertainty. As it can be seen, data and SM expectation is in a good agreement in Fig. 4. Output distributions of two FCNC BNNs with discrimination from the SM backgrounds are used as a basis for the statistical analysis to set the exclusion limits. Fitting of histogram shapes and normalization provides the posterior distributions of the anomalous couplings. The 2D contour plot of FCNC parameters is shown in Fig. 5. The limits are translated into the upper limits on the branching ratios [13]:

$$BR(t \to ug) < 3.55 \times 10^{-4},$$
$$BR(t \to ug) < 3.44 \times 10^{-3}. \quad (2)$$

These limits will be significantly improved after including the data taken at the center-of-mass energy of 8 TeV.

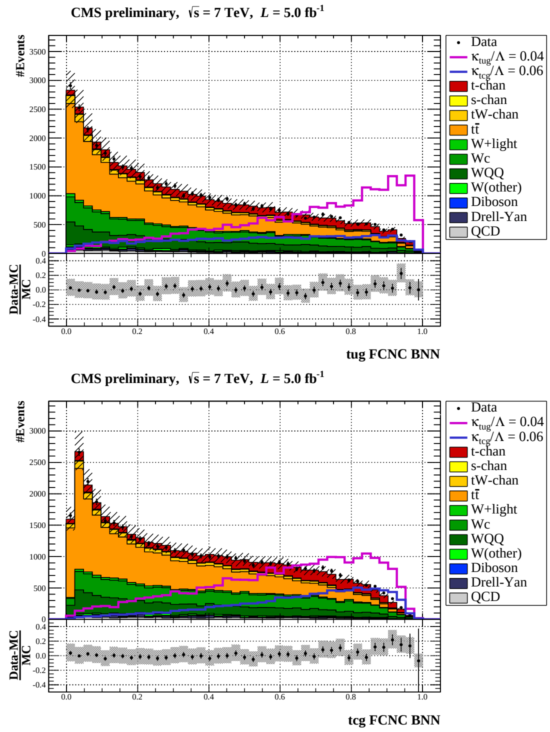

Figure 4: Data and model agreement for the FCNC BNN discriminants.The hashed band corresponds to systematic uncertainty [13].

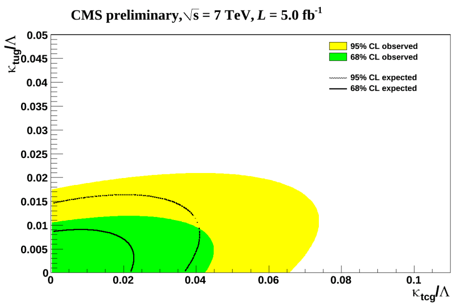

Figure 5: Exclusion upper limits in two-dimensions on the anomalous *tug* and *tcg* couplings at 68% and 95% CL [13].

5. Summary

The CMS experiment has performed searches for flavor-changing neutral currents in $tq\gamma$, tqZ and tqg vertices in top pair and single top processes. No indication of the FCNC processes have been observed in the LHC data at the center-of-mass energies of 7 anf 8 TeV. Therefore, upper limits are set on the anomalous couplings and the branching ratios at 95% CL. Figure 6 shows the observed upper limits at 95% CL on the $BR(t \to qZ)$ versus $BR(t \to q\gamma)$ for the DELPHI, ZEUS, H1, D0, CDF, ATLAS and CMS collaborations [8]. The experimental sensitivity are becoming close to the predictions some extensions of the SM.

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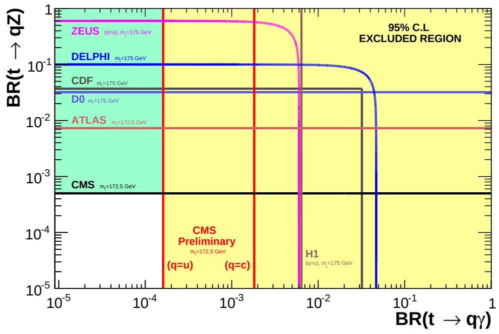

Figure 6: The observed 95% CL upper limit on on $BR(t \to qZ)$ versus $BR(t \to q\gamma)$ for the LEP, ZEUS, H1, D, CDF, ATLAS and CMS collaborations [8].

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