Search for flavour-changing neutral currents with top quarks

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Abstract

Flavour-changing neutral currents are extremely rare processes in the standard model that can be sensitive to various new physics effects. A summary of the latest experimental results from the LHC experiments is given. Preliminary results of sensitivity studies for future colliders are also discussed.

Presented at TOP2017 10th International Workshop on Top Quark Physics
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PRESENTED AT

10\textsuperscript{th} International Workshop on Top Quark Physics
TOP2017
Braga, Portugal, September 17–22, 2017
1 Introduction

In the SM, flavor-changing neutral currents (FCNC) are forbidden at tree level and are strongly suppressed in higher orders by the Glashow-Iliopoulos-Maiani (GIM) mechanism [1]. The predicted branching fractions for top quark FCNC decays are expected to be $O(10^{-12}−10^{-16})$ [2, 3, 4]. In various extensions of the SM the FCNC effects are significantly enhanced and can be directly probed at the LHC [4, 5, 6]. Top quark FCNC interactions can be written with the following lagrangian:

$$\mathcal{L} = \sum_{q=u,c} \left[ \sqrt{2} g_s \frac{\kappa_{Xq}}{\Lambda} \bar{T}\sigma^{\mu\nu}(f_L^q P_L + f_R^q P_R)qG^a_{\mu\nu} + \frac{g}{\sqrt{2} c_W} \frac{\kappa_{Zq}}{\Lambda} \bar{T}\sigma^{\mu\nu}(f_L^q P_L + f_R^q P_R)qZ\mu - \frac{g}{4c_W} \kappa_{Zq} \bar{T}\gamma^\mu(f_L^q P_L + f_R^q P_R)qZ_\mu - \right] + \frac{g}{\sqrt{2}} \bar{T}K_{Hq}(f_L^q P_L + f_R^q P_R)qH + h.c.,$$

where $P_L$ and $P_R$ are chirality projectors in spin space, $\kappa_{Xq}$ is the effective coupling for $tXq$ vertex ($X = g, Z, \gamma, H$), $\zeta_{Zq}$ is the additional effective coupling for $tZq$ vertex, $f_L^q$ and $f_R^q$ are left and right-handed complex chiral parameters with a unitarity constraint of $|f_L^q|^2 + |f_R^q|^2 = 1$. The ATLAS [7] and CMS [8] experiments at the LHC study top FCNC anomalous interactions in the decays of top quarks in top quark pair production, as well as in singly produced top quarks.

2 Overview of results

The $tgq$ anomalous interactions are studied by CMS [9] and ATLAS [10] in single top quark events. The event signature considered by CMS in the analysis of data collected at 7 and 8 TeV includes the requirement of one isolated lepton, the presence of a significant amount of transverse missing energy ($E_{\text{miss}}^T$), exactly one $b$ and one non-$b$ jet. The dominant background is the $t\bar{t}$+jets production. A Bayesian neural network technique is used to separate signal from background events. The observed (expected) 95% confidence level (CL) upper limits are found to be $\mathcal{B}(t \to gu) < 2.0 \times 10^{-5}$ and $\mathcal{B}(t \to gc) < 4.1 \times 10^{-4}$. Selection criteria used in the analysis by ATLAS at 8 TeV include a veto on additional reconstructed jets with requiring only one $b$ jet to be present in the final state. The background is dominated by $W+$jets production. Separation between signal and background events is achieved with a neural network classifier. The resultant observed (expected) limits are $\mathcal{B}(t \to gu) < 4.0 \times 10^{-5}$ and $\mathcal{B}(t \to gc) < 2.0 \times 10^{-4}$. 


The $t \rightarrow Zq$ FCNC decays are probed by ATLAS in top quark pair events at 13 TeV [11]. The event topology includes the presence of three isolated leptons, $E_T^{\text{miss}} > 40$ GeV, exactly one $b$ jet and at least one non-$b$ jet. Several control regions are defined for each of the dominant background processes: $WZ+\text{jets}$, $ZZ+\text{jets}$, $ttZ$, and non-prompt leptons. Simultaneous maximum likelihood fit over control and signal regions is performed to extract the exclusion limits, $\mathcal{B}(t \rightarrow Zu) < 1.7 (2.4) \times 10^{-4}$ and $\mathcal{B}(t \rightarrow Zc) < 2.3 (3.2) \times 10^{-4}$. The analysis done by CMS with 8 TeV data explores a similar final state and additionally includes a single top associated FCNC production with a $Z$ boson in the simulation of signal events [12]. A boosted decision tree (BDT) discriminant is defined to suppress background events. The resultant limits are $\mathcal{B}(t \rightarrow Zu) < 2.2 (2.7) \times 10^{-4}$ and $\mathcal{B}(t \rightarrow Zc) < 4.9 (11.8) \times 10^{-4}$.

The $tqg$ anomalous interactions are probed by CMS at 8 TeV in events with single top quarks produced in association with a photon [13]. Event selection criteria includes the presence of one isolated lepton, one isolated photon, $E_T^{\text{miss}} > 30$ GeV, and up to one $b$ jet. The dominant $W\gamma$ background along with $W+\text{jets}$ events are suppressed with a BDT discriminant. The resultant exclusion limits are $\mathcal{B}(t \rightarrow \gamma u) < 1.3 (1.9) \times 10^{-4}$ and $\mathcal{B}(t \rightarrow \gamma c) < 2.0 (1.7) \times 10^{-3}$.

The $tHq$ FCNC processes are studied by ATLAS in top quark pair events with $t \rightarrow qH, H \rightarrow \gamma\gamma$ at 13 TeV [14]. The analysis explores the final state with two isolated photons. For leptonic top quark decays the selection criteria includes the requirement of one isolated lepton, exactly one $b$ jet, and at least one non-$b$ jet. In case of hadronic top quark decays the analysis selects events with no isolated leptons, at least one $b$ jet, and at least three additional non-$b$ jets. The dominant background processes are associated with the production of non-resonant $\gamma\gamma+\text{jets}$, $t\bar{t}+\text{jets}$ and $W+\gamma\gamma$ events. The analysis is done in the diphoton mass window of $100 < m_{\gamma\gamma} < 160$ GeV. The resultant limits are found to be $\mathcal{B}(t \rightarrow Hu) < 2.4 (1.7) \times 10^{-3}$ and $\mathcal{B}(t \rightarrow Hc) < 2.2 (1.6) \times 10^{-3}$. The $tHq$ anomalous couplings are probed by CMS in $H \rightarrow b\bar{b}$ channel in top quark pair events, as well as in single top associated production with a Higgs boson, at 13 TeV [15]. The event selection includes the requirement of one isolated lepton, at least two $b$ jets, and at least one additional non-$b$ jet. The dominant $t\bar{t}$ background is suppressed with a BDT discriminant to set the exclusion limits of $\mathcal{B}(t \rightarrow Hu) < 4.7 (3.4) \times 10^{-3}$ and $\mathcal{B}(t \rightarrow Hc) < 4.7 (4.4) \times 10^{-3}$. The combination of results obtained by CMS at 8 TeV results in $\mathcal{B}(t \rightarrow Hu) < 5.5 (4.0) \times 10^{-3}$ and $\mathcal{B}(t \rightarrow Hc) < 4.0 (4.3) \times 10^{-3}$ [16], while a similar combination of ATLAS results yields $\mathcal{B}(t \rightarrow Hu) < 4.5 (2.9) \times 10^{-3}$ and $\mathcal{B}(t \rightarrow Hc) < 4.6 (2.5) \times 10^{-3}$ [17].

The upcoming upgrade of the LHC, the High-Luminosity LHC (HL-LHC) project, is expected to introduce a substantial increase in the peak luminosity with accumulating a larger data set to reach $\gtrsim 3 ab^{-1}$ by the end of the data taking. Preliminary sensitivity studies for the HL-LHC suggest the expected 95% CL upper limit of $\mathcal{B}(t \rightarrow Zq) < 2.4 \times 10^{-5}$ [18]. Similar studies for $tqg$ and $tHq$ yield $\mathcal{B}(t \rightarrow \gamma u) < 2.7 \times 10^{-5}$, $\mathcal{B}(t \rightarrow \gamma c) < 2.0 \times 10^{-4}$ [19], and $\mathcal{B}(t \rightarrow Hq) <$
\( \mathcal{O}(10^{-4}) \) [18, 20]. A proposed experiment with the focus on the study of deep inelastic lepton-hadron scattering, a Large Hadron electron Collider (LHeC), is expected to provide a competitive sensitivity to \( t\gamma q \) and \( tZq \) searches with the expected limits of 
\[ \mathcal{B}(t \to \gamma u) < 1.62 \times 10^{-5} \quad \text{and} \quad \mathcal{B}(t \to \gamma c) < 1.15 \times 10^{-4} \] [21]. The \( tHq \) projections for LHeC yield 
\[ \mathcal{B}(t \to H u) < 7.3 \times 10^{-4} \] [22]. Future Circular Collider for electron-positron (FCC-ee) and proton-proton (FCC-hh) collisions is a planned set of research activities targeted at the timescale beyond the operation time of the HL-LHC. Preliminary projections suggest the following expected limits: 
\[ \mathcal{B}(t \to Z q) < 5.6 \times 10^{-6} \quad \text{(FCC-ee)} \] [24], 
\[ \mathcal{B}(t \to Z q) < \mathcal{O}(10^{-7}) \quad \text{(FCC-hh)} \] [23], 
\[ \mathcal{B}(t \to \gamma q) < 3.6 \times 10^{-6} \quad \text{(FCC-ee)} \] [24], and 
\[ \mathcal{B}(t \to \gamma q) < \mathcal{O}(10^{-7}) \quad \text{(FCC-hh)} \] [23]. Future linear electron-positron colliders (ILC/CLIC) can also provide a competitive sensitivity to top FCNC studies with the expected limits of 
\[ \mathcal{B}(t \to Z q) < \mathcal{O}(10^{-5}) \] [25], 
\[ \mathcal{B}(t \to \gamma q) < \mathcal{O}(10^{-5}) \] [25], and 
\[ \mathcal{B}(t \to H q) < \mathcal{O}(10^{-5}) \] [26].

3 Conclusion

The most stringent limits on top quark FCNC branching fractions obtained at the LHC are compared to theoretical predictions in the SM, as well as to various new physics models. A summary of these results is presented in Figure 1, and several projections of the upper limits for future experiments are summarized in Figure 2. A large number of experimental results on top quark FCNC interactions is available from the LHC. The latest results obtained at 13 TeV significantly improve the upper limits set with the 8 TeV data. The preliminary results of future projections represent good prospects for pushing top FCNC boundaries to even higher constraints.

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Figure 1: Summary of branching fraction limits for top quark FCNC decays, compared to the SM and new physics models predictions. Experimental results are shown from [9, 10](tgq), [11, 12](tZq), [13](tγq), and [14, 15, 16](tHq).

Figure 2: Summary of branching fraction limits for top quark FCNC decays, compared to the SM predictions, as well as to various projections for future experiments. Experimental results are shown from [9, 10](tgq), [11, 12](tZq), [13](tγq), and [14, 15, 16](tHq). Projections are taken from [18, 19, 20](HL-LHC), [21, 22](LHeC), [23, 24](FCC), and [25](ILC).
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