SEARCH FOR RARE TOP-QUARK DECAYS AT THE LHC

FILIPE VELOSO on behalf of the ATLAS and CMS Collaborations
LIP e Departamento de Física da Universidade de Coimbra, 3004-516 Coimbra, Portugal

Flavour-changing neutral-current (FCNC) top quark decays are suppressed by the GIM mechanism, but are enhanced by BSM models. Any evidence for top-quark FCNC decays could be an evidence for new physics. Searches for the FCNC decays \( t \to qX \) where \( X = Z, \gamma, H, g \) and \( q = u, c \) performed by the ATLAS and CMS Collaborations are presented. Data collected during 2011 and 2012 from proton-proton (\( pp \)) collisions at the LHC at a centre-of-mass energy of \( \sqrt{s} = 7 \) and 8 TeV, corresponding to integrated luminosities ranging from 2.1 fb\(^{-1} \) to 25 fb\(^{-1} \), are analysed. Top-quark pair-production events with one top quark decaying through the \( t \to qZ, q\gamma, qH \) channels and the other through the dominant Standard Model mode \( t \to bW \) are considered as signal, as well as direct top production for the \( t \to qg \) channel. No evidence for FCNC signals are found and upper limits on the \( t \to qX \) branching ratios are set at 95\% confidence level.

1 Introduction

The top quark is the heaviest elementary particle known and has such a short lifetime that it decays without hadronisation. It decays dominantly to a down-type quark (\( b, s \) or \( d \) quarks) and a \( W \) boson. The corresponding branching ratios (BR) are \( \text{BR}(t \to bW) = 9.98 \times 10^{-1} \), \( \text{BR}(t \to sW) = 1.64 \times 10^{-3} \) and \( \text{BR}(t \to dW) = 7.85 \times 10^{-5} \). Due to the GIM mechanism, top-quark decays involving flavour changing neutral currents (FCNC) \( t \to qX \) (where \( X = Z, \gamma, H, g \) and \( q = u, c \)) are suppressed in the Standard Model (SM) and their BR are always lower than \( 10^{-12} \), as can be seen in Table 1. Several SM extensions, such as the quark-singlet model (QS), the two-Higgs-doublet model with (FC 2HDM) or without (2HDM) flavour conservation, the minimal supersymmetric model (MSSM), supersymmetry with R-parity violation (\( \tilde{R} \) SUSY) or models with warped extra dimensions (RS), predict higher FCNC BR values, which are also shown in Table 1. For details and references see\(^1,2,3\). The measurements of these rare top-quark decays are a good test of the SM. If a signal was found, this would be a clear proof of existence of physics behind the SM.

Both Large Hadron Collider (LHC) general collaborations, ATLAS\(^4\) and CMS\(^5\), have searched for these top-quark rare decays. The analyses with best sensitivity for each decay channel from each collaboration are covered below.

| \( t \to cZ \)   | \( 10^{-14} \) | \( 10^{-4} \) | \( 10^{-6} \) | \( 10^{-10} \) | \( 10^{-7} \) | \( 10^{-6} \) | \( 10^{-9} \) | \( 10^{-5} \) |
| \( t \to cg \)  | \( 10^{-12} \) | \( 10^{-7} \) | \( 10^{-4} \) | \( 10^{-8} \) | \( 10^{-7} \) | \( 10^{-6} \) | \( 10^{-10} \) |
| \( t \to c\gamma \) | \( 10^{-14} \) | \( 10^{-9} \) | \( 10^{-7} \) | \( 10^{-9} \) | \( 10^{-8} \) | \( 10^{-9} \) | \( 10^{-9} \) |
| \( t \to cH \)  | \( 10^{-15} \) | \( 10^{-5} \) | \( 10^{-3} \) | \( 10^{-5} \) | \( 10^{-5} \) | \( 10^{-9} \) | \( 10^{-4} \) |
2 Search for $t \rightarrow qZ$

ATLAS searched for the $t \rightarrow qZ$ decay\(^6\) in an integrated luminosity $\mathcal{L} = 2.1$ fb\(^{-1}\) of $\sqrt{s} = 7$ TeV data using two orthogonal channels: one with three leptons reconstructed using the standard identification definitions (ID) and another requiring 2 ID leptons and an additional high quality inner detector track (TL). The events were required to have two leptons with same flavour and opposite charges, with a reconstructed mass within 15 GeV of the $Z$ boson mass, at least two jets (with transverse momentum $p_T > 25$ GeV and pseudorapidity $|\eta| < 2.5$), missing transverse momentum $E_T^{\text{miss}} > 20$ GeV, reconstructed top quark masses between 132.5 GeV and 212.5 GeV, and reconstructed $W$ boson mass between 50.4 GeV and 110.4 GeV. The 2ID+TL channel required additionally one $b$-tagged jet in the event. After the selection criteria, 8 data events are found in each channel, which agree with the SM expectation of $11.8 \pm 4.4$ ($8.9 \pm 2.3$) for the 3ID (2ID+TL) channel. The main background for the 3ID channel comes from $ZZ$ and $WZ$ production, while for the 2ID+TL one the main background is mainly from jets faking TL. No evidence for signal was found in both analysis and an observed (expected) combined limit of $\text{BR}(t \rightarrow qZ) < 0.73\%$ ($\text{BR}(t \rightarrow qZ) < 0.93\%$) was derived at $95\%$ CL using the CL\(_s\) method. The main sources for systematic uncertainties of the 3ID analysis are the $ZZ$ and $WZ$ simulation modelling, while for the 2ID+TL analysis it is the fake-TL estimation.

CMS searched for $t \rightarrow qZ$ decay\(^7\) by analysing 19.7 fb\(^{-1}\) of 8 TeV data. Events were required to have three leptons (with $p_T > 20$ GeV), of which two had to have the same flavour, opposite charges and reconstructed mass between 78 GeV and 102 GeV. The events were also required to have $E_T^{\text{miss}} > 30$ GeV, at least two jets (with $p_T > 30$ GeV and $|\eta| < 2.4$), of which at least one should be $b$-tagged. The reconstructed top quark with the FCNC (SM) decay should have a mass within 25 GeV (35 GeV) of 172.5 GeV. One data event was selected, in agreement with the SM expectation of $11.8 \pm 4.4$ ($8.9 \pm 2.3$) for the 3ID (2ID+TL) channel. The main background for the 3ID channel comes from $ZZ$ and $WZ$ production, while for the 2ID+TL one the main background is mainly from jets faking TL. No evidence for signal was found and an observed (expected) combined limit of $\text{BR}(t \rightarrow qZ) < 0.05\%$ ($< 0.09\%$) was derived by combining these results with those from the previous analysis of 5 fb\(^{-1}\) of 7 TeV data. The main signal systematic uncertainties arose from the renormalisation and factorisation scales, parton density functions (PDF), and SM $t\bar{t}$ cross-section.

3 Search for $gg \rightarrow t$

ATLAS searched for single top-quark production\(^8\) through the FCNC $tqg$ vertex in a $\sqrt{s} = 8$ TeV data set with $\mathcal{L} = 14.2$ fb\(^{-1}\). The events were required to have one lepton (with $p_T > 25$ GeV), $E_T^{\text{miss}} > 30$ GeV, one jet (with $p_T > 30$ GeV and that should also be $b$-tagged) and a reconstructed $W$ boson transverse mass greater than 50 GeV. A neural-network with 13 variables was applied to the events in order to improve the analysis. No evidence for signal was found and observed limits on the $t \rightarrow ug$ and $t \rightarrow cg$ BR were derived as $3.1 \times 10^{-5}$ and $1.6 \times 10^{-4}$, respectively. The dominant systematic uncertainty sources were related to $b$-tagging, $E_T^{\text{miss}}$ and background modelling.

CMS also searched\(^9\) $\mathcal{L} = 5$ fb\(^{-1}\) of $\sqrt{s} = 7$ TeV data for single top-quark production via FCNC in the $t$-channel topology. Events were required to have one muon (with $p_T > 15$ GeV) and two or three jets (all with $p_T > 30$ GeV and $|\eta| < 4.7$), of which at least one should be $b$-tagged another should be light). A Bayesian neural-network with 15 (20) variables was used to further discriminate between the $tug$ ($tcg$) signal- and background-like events. No evidence for signal was found and observed (expected) limits on the $t \rightarrow gg$ BR were computed as $\text{BR}(t \rightarrow ug) < 3.55 \times 10^{-4}$ ($1.58 \times 10^{-4}$), and $\text{BR}(t \rightarrow cg) < 3.44 \times 10^{-3}$ ($1.05 \times 10^{-3}$). The dominant sources of systematic uncertainties are the PDF (9%) and the signal generator (5%).
4 Search for $t \rightarrow q\gamma$

CMS searched for the $tq\gamma$ interaction in single top production via FCNC with $\mathcal{L} = 19.1$ fb$^{-1}$ of $\sqrt{s} = 8$ TeV data. Events with one muon ($p_T > 26$ GeV and $|\eta| < 2.1$), one photon (with $p_T > 50$ GeV, $|\eta| < 2.5$ and angular separation $\Delta R(\mu, \gamma) > 0.7$), at most one $b$-tagged jet (with $p_T > 30$ GeV, $|\eta| < 2.5$ and $\Delta R(b, \gamma) > 0.7$), $E_T^{\text{miss}} > 30$ GeV and a reconstructed top-quark with mass between 130 GeV and 220 GeV were selected. A boosted decision tree with eight variables was then applied in order to improve the analysis. No evidence for signal was found and BR($t \rightarrow \mu\gamma < 1.6 \times 10^{-4}$) BR($t \rightarrow c\gamma < 1.8 \times 10^{-5}$) observed (expected) limits were derived at 95% CL. An improvement of about 28% is expected if next-to-leading order corrections are considered in the production cross-section. The dominant contributions to the systematic uncertainties come from $W + \gamma$ and $W + \text{jets}$ backgrounds normalisations.

5 Search for $t \rightarrow qH$

ATLAS searched for the $t \rightarrow qH$ decay, looking for $t\bar{t} \rightarrow bWqH$ events, with $H \rightarrow \gamma\gamma$, in $\mathcal{L} = 4.7$ fb$^{-1}$ of $\sqrt{s} = 7$ TeV and $\mathcal{L} = 20.3$ fb$^{-1}$ of $\sqrt{s} = 8$ TeV data. Events were required to have at least two photons, the leading one with $p_T > 40$ GeV and the sub-leading one with $p_T > 30$ GeV. Two topologies, depending on the $W$ boson decay, were then searched for: a hadronic one, corresponding to the $W \rightarrow qq'$ decay, where events with four jets (one of them being $b$-tagged), reconstructed $\gamma\gamma j_1 (jj_1)$ masses between 156 GeV and 191 GeV (130 GeV and 210 GeV) and without leptons were selected; and a leptonic topology, for the $W \rightarrow l\nu$ decay, where events were required to have one lepton, a $W$ boson transverse mass greater than 30 GeV, at least two jets (one of them being $b$-tagged) and reconstructed $\gamma\gamma j_1 (l\nu j_2)$ masses between 156 GeV and 191 GeV (135 GeV and 205 GeV). After the event selection, 50 hadronic and one leptonic events were found. No evidence for signal was found and a maximum likelihood fit was performed to derive the 0.79% (0.51%) observed (expected) exclusion limit at 95% CL on BR($t \rightarrow cH$). The dominant systematics were $\gamma$ identification, jet energy scale, initial and final state radiation and $b$-tagging.

CMS also searched for the $t \rightarrow qH$ decay in $\sqrt{s} = 7$ TeV (with $\mathcal{L} = 5$ fb$^{-1}$) and $\sqrt{s} = 8$ TeV (with $\mathcal{L} = 19.5$ fb$^{-1}$) data. Events with at least three leptons ($e, \mu$ or $\tau_{\text{had}}$) or with one lepton and two photons (the leading one with $p_T > 40$ GeV and the sub-leading with $p_T > 30$ GeV) were selected. Multilepton events were then classified in different channels according to the number of leptons, flavour and charge combinations, $Z$ boson reconstruction ($75 < m_{Z} < 105$ GeV) and $E_T^{\text{miss}}$ bins. Dilepton events ($120 < m_{\gamma\gamma} < 130$ GeV) were classified in channels according to the lepton flavour, the presence or not of a $b$-tagged jet and $E_T^{\text{miss}}$ bins. No evidence for signal was found in all channels and limits on the $t \rightarrow qH$ decay BR were derived. Combining all multilepton and diphoton channels gave a 0.56% (0.65%) observed (expected) BR limit. The dominant sources of systematic uncertainties are diphoton background estimation as well as $t\bar{t}$ and $\tau_{\text{had}}$ misidentification.

6 HL-LHC sensitivities

Search for top-quark FCNC decays can be one of goals of the high luminosity (HL) LHC phase. ATLAS and CMS sensitivities for top-quark FCNC decays at $\sqrt{s} = 14$ TeV with 3 ab$^{-1}$ were estimated using either extrapolations from 7 TeV or 8 TeV results or dedicated simulation samples. It is expected that the exclusion limits improve by one order of magnitude. For the $t \rightarrow qZ$, $t \rightarrow q\gamma$ and $t \rightarrow qH$ channels, ATLAS predicts limits of $4.1 \times 10^{-5}$, $1.3 \times 10^{-5}$, and $1.5 \times 10^{-4}$, respectively, while CMS predicts a limit of $7 \times 10^{-5}$ for the $t \rightarrow qZ$ BR value. Figure 1 compares the expected $t \rightarrow qZ$ and $t \rightarrow q\gamma$ BR ATLAS sensitivities with the current observed limits.
7 Conclusions

ATLAS and CMS searches for top-quark FCNC decays at $\sqrt{s} = 7$ TeV and 8 TeV were reviewed, covering the $qZ$, $q\gamma$, $qH$ and $qq$ (with $q = u, c$) channels. No evidence for signal was found and 95% CL limits were derived. ATLAS and CMS sensitivities at $\sqrt{s} = 14$ TeV with 3 ab$^{-1}$ are expected to improve by one order of magnitude. Figure 1 shows the observed $t \rightarrow qZ$ and $t \rightarrow q\gamma$ BR limits, as well as the expected ATLAS sensitivities for the $\sqrt{s} = 14$ TeV data of the HL-LHC phase.

![Figure 1 – Current observed $t \rightarrow qZ$ and $t \rightarrow q\gamma$ BR limits are shown, as well as the expected ATLAS sensitivities at $\sqrt{s} = 14$ TeV. Adapted from reference 13.](image)

Acknowledgments

F. Veloso has been supported by FCT and FEDER/COMPETE-QREN (grant SFRH/BPD/47928/2008 and project CERN/FIS-NUC/0005/2015).

References