PROCEEDINGS OF SCIENCE

Searches for BSM in top final states in ATLAS

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The LHC is a top factory and Run 2 has delivered billions of top quarks to the experiments. In this contribution, the results are presented of searches by the ATLAS experiment for Charge Lepton Flavour Violation, and rare flavour-changing neutral current interactions of the top quark. flavour changing neutral currents (FCNC) analyses combine search criterion targeted at top quark decays $t \to qX$ with regions aimed at single top quark production $pp \to tX$, where X is either a gluon, photon, Z-boson or a Higgs boson. The large data set, together with advanced analysis techniques, allow to improve the sensitivity very significantly and competitive bounds on the equivalent branching fraction $\mathcal{B}(t \to qH)$ are presented.

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1. Introduction

Beyond Standard Model (BSM) theories aim to address the limitations of the Standard Model (SM), including the mysteries of dark matter, neutrino masses, and the matter-antimatter asymmetry. The top quark plays a pivotal role in probing these theories due to its large mass, which strongly links it to potential new physics. Its interactions and rare decays, such as those involving flavour-changing neutral currents (FCNCs), can provide insights into BSM scenarios. Precision measurements of top quark properties are crucial for identifying deviations that might signal the presence of new physics.

Recent updates from the ATLAS experiment [1] at the LHC accelerator, include the first-ever probe into charged lepton flavour violation (cLFV) in the $\mu\tau$ channel, extending beyond past analyses that only considered the electron-muon (eμ) final state. This new study provides the first constraints on the $\mu\tau$ channel.

In parallel, the experiment has continued investigating FCNCs, a phenomenon heavily suppressed by the Standard Model. Initial studies revisited the Higgs boson decay to photon pairs using Run 2 data, which offered four times more luminosity, improved flavour-tagging, and an increase in collision energy from 7/8 TeV to 13 TeV. These enhancements led to a roughly 60% increase in the top-quark production rate. The analysis also combined various Higgs boson decay channels, including photon pairs, tau-lepton pairs, and b-quark pairs.

A subsequent FCNC analysis employed a multilepton approach, focusing on top quark decays where a Higgs boson decays into dibosons, with at least one decaying leptonically. This approach was incorporated into the combined dataset, yielding the most recent results from ATLAS.

2. Charged lepton flavour violation

The first analysis [2] explored the interactions of a $\mu\tau qt$ vertex in both the production and decay of a top quark. For production, single top quark production is studied through the $gq \to t\mu^{\pm}\tau^{\mp}$ process, where q is either an up or charm quark. For decay, the analysis instead considers the top quark decay $t \to q\mu^{\pm}\tau^{\mp}$ within top-quark pair ($t\bar{t}$) production. The analysis uses a cut-based approach, where the signal-enriched region is defined by a final state containing two muons with the same electric charge, one hadronically decaying τ-lepton, and exactly one jet identified by a b-tagging algorithm (b-tagged). All other jets in the event were required to be non-b-tagged. The results are interpreted within the effective field theory (EFT), which extends the Standard Model Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_X \frac{c_X}{\Lambda^2} O_X + \ldots \quad (1)$$

where the Wilson coefficients (c_X) weight the EFT operators (O_X) of the effective Lagrangian. This assumes a mass scale of new physics, Λ, much larger than what is achievable at the LHC.

Instead of examining the operators directly in the Lagrangian, the analysis explored the relation

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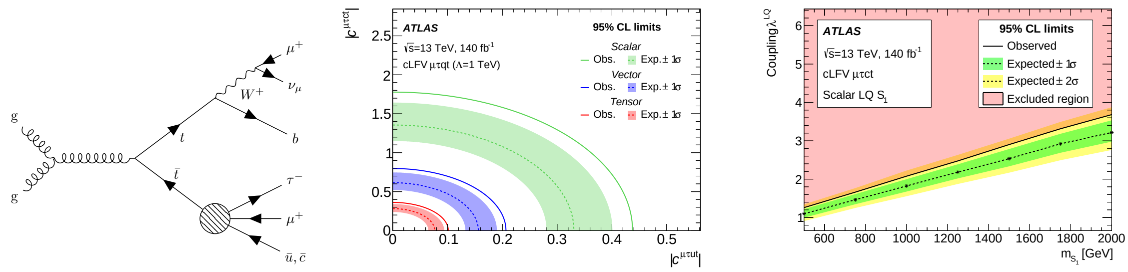
of the Wilson coefficients via the BSM decay width, Γ, of the top quark:

$$\Gamma(t \to \ell_i^+ \ell_j^- q_k) = \frac{m_t}{6144\pi^3}\left(\frac{m_t}{\Lambda}\right)^4 \Big\{4|c_{\rm lq}^{-(ijk3)}|^2 + 4|c_{\rm eq}^{(ijk3)}|^2 + 4|c_{\rm lu}^{(ijk3)}|^2 + 4|c_{\rm eu}^{(ijk3)}|^2 + 2|c_{\rm lequ}^{1(ijk3)}|^2 + 96|c_{\rm lequ}^{3(ijk3)}|^2\Big\}\,, \tag{2}$$

and considered limits on the last two coefficients. Previous ATLAS results [3, 4] set these limits ranging from $|c_{lequ}^{3(2313)}|/\Lambda^2 < 3.4$ TeV^{-2} for the $\mu\tau ut$ interaction to $|c_{lequ}^{1(2313)}|/\Lambda^2 < 29$ TeV^{-2} for the $\mu\tau ct$ interaction. An example Feynman diagram is shown in Figure 1a.

In a second interpretation, a scalar leptoquark (LQ), S_1, is introduced, which can couple to multiple generations of charged leptons and up-type quarks. The coupling strength, $\lambda_{t\tau}$, is the strongest; any change (from 3→2→1 in quark/lepton generations) introduces a factor of 10 times lower coupling. This analysis is optimized for the EFT approach, and the LQ is expected to yield weaker limits.



(a) EFT Feynman diagram **(b)** EFT results **(c)** LQ results

Figure 1: (a) Example of a EFT Feynman diagram used in the analysis. Upper limits for the cLFV analysis: (b) EFT and (c) LQ [2].

In this analysis, two control regions (CR) are considered to estimate the two largest contributions of background in the signal region: fake leptons (both τ-lepton and μ). The distribution of the scalar $p_{\rm T}$ sum of leptons and jets in these regions is included in a binned profile-likelihood fit to extract the signal parameters discussed. This is a statistically dominated analysis, with the leading systematic uncertainties arising from $t\bar{t}X$ and diboson process modeling.

Figure 1b shows the upper limits obtained for the EFT, with an improvement factor of 7.2 for the $\mu\tau ct$ coupling and 41 for the $\mu\tau ut$ coupling compared with previous ATLAS result. Additionally, this analysis sets the first ATLAS limits in the leptoquark interpretation, shown in Figure 1c. The λ_{LQ} scalar coupling upper limits range from 1.3 to 3.7 for masses between 0.5 and 2 TeV.

3. Flavour Changing Neutral Currents

The Standard Model (SM) states that flavour-changing neutral currents (FCNC) are forbidden at tree level and are highly suppressed at the one-loop level and higher orders. FCNCs involving the top quark are extremely rare in the SM [5], with a branching fraction ($\mathcal{B}$):

$$\mathcal{B}(t \to cH) = 4.2 \times 10^{-15} \qquad \mathcal{B}(t \to uH) = 3.7 \times 10^{-17} \tag{3}$$

Therefore, the observation of such a process would provide clear evidence of Beyond Standard Model (BSM) physics.

The EFT Lagrangian ($\mathcal{L}_{\text{EFT}}$) for the tqH process can be written as:

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{q=u,c} \left[\frac{C^{qt}_{u\phi}}{\Lambda^2} O^{qt}_{u\phi} + \frac{C^{tq}_{u\phi}}{\Lambda^2} O^{tq}_{u\phi} \right] \tag{4}$$

with four FCNC operators contributing at tree level, each associated with four Wilson coefficients.

Since top quarks are produced unpolarized in $t\bar{t}$, and the Higgs boson is a scalar particle, no kinematic differences are expected between $O^{tq}_{u\phi}$ and $O^{qt}_{u\phi}$. In the phase space considered for single-top production, simulation results also showed negligible differences. For this reason, only the average of the two (per quark) Wilson coefficients was considered: $O^{tu}_{u\phi}$ and $O^{tc}_{u\phi}$.

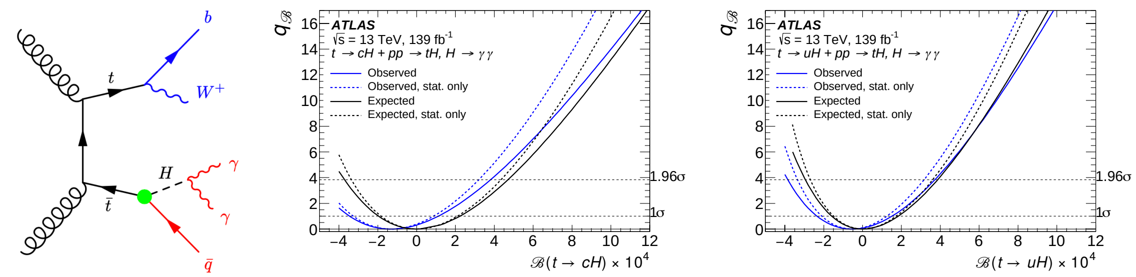
ATLAS upper limits at 95% confidence level are presented in terms of branching ratio, and the state-of-the-art before the update from the analyses considered is summarized in Table 1.

H decay	$H \to \tau^+\tau^-$ [6]	$H \to b\bar{b}$ [7]	$H \to \gamma\gamma$ [8]
$\mathcal{B}(t \to cH)$	$< 9.4 \times 10^{-4}$	$< 12.0 \times 10^{-4}$	$< 7.8 \times 10^{-3}$
$\mathcal{B}(t \to uH)$	$< 6.9 \times 10^{-4}$	$< 7.7 \times 10^{-4}$	$< 7.8 \times 10^{-3}$

Table 1: Upper limits for the branching ratio for FCNC from ATLAS before the analysis presented.

In the FCNC analyses, the Higgs boson is produced either as a decay of the top quark, as shown in Figure 2a, or in association with single-top quark production (Figure 3a). Both FCNC analyses are statistically dominated, and only the leading systematic uncertainties are highlighted here.

3.1 $\mathcal{B}(t \to qH)$ with Higgs boson decaying: $H \to \gamma\gamma$



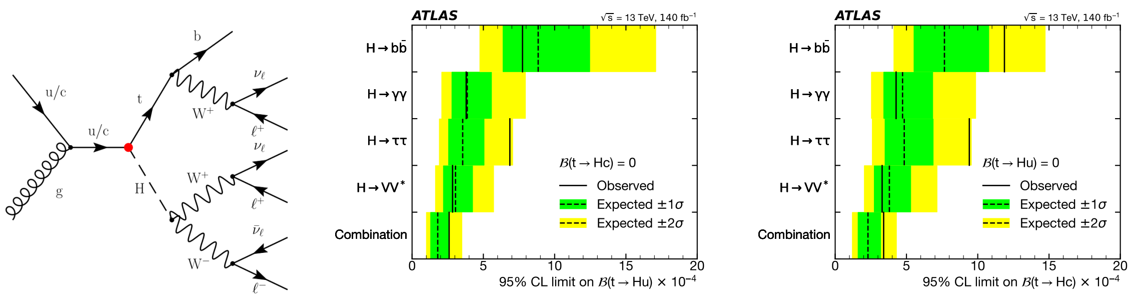
(a) EFT Feynman diagram **(b)** $\mathcal{B}(t \to cH)$ **(c)** $\mathcal{B}(t \to uH)$

Figure 2: (a) Example of a EFT Feynman diagram used in the analysis with top quark decaying to $qH(\to \gamma\gamma)$. Upper limits for the FCNC analysis for the qtH vertex, with $q \equiv c(b)$ and $q \equiv u(c)$ [9].

This analysis considers the Higgs boson decaying into a pair of photons via a t, W loop. For simplicity, in Figure 2a, this loop was omitted. The reconstructed mass of the FCNC top ($m_{\gamma\gamma j}$) is constrained between 152 and 190 GeV. Additional selection criteria help distinguish between the semi-leptonic and hadronic decays of the top quark, whether the jet from the FCNC top decay is c-tagged, and whether the production comes from top decay ($t\bar{t}$) or single-top production with a bremsstrahlung Higgs boson. To improve sensitivity, several distributions from these categories are fed into a boosted decision tree (BDT). A profile-likelihood fit is used to extract the branching ratio, assuming a single coupling: either tcH or tuH. The main systematics arise from the non-resonant background from the Higgs boson $m_{\gamma\gamma}$ side-band. The results are shown in Figures 2b and 2c, respectively. This analysis sets new limits for this Higgs boson decay, improving previous limits by about a factor of 20, to $< 3.8(4.0) \times 10^{-4}$ for $t \to Hc$ ($t \to Hu$), and producing the first combination with the $H \to \tau\tau$ and $H \to b\bar{b}$ channels, resulting in $< 5.8 \times 10^{-4}$ and $< 4.0 \times 10^{-4}$ for the branching ratios of $t \to Hc$ and $t \to Hu$, respectively.

3.2 $\mathcal{B}(t \to qH)$ with Higgs boson multi-lepton channel decay

This search also investigates the multilepton final state of the tqH FCNC. For example, Figure 3a illustrates the case in which the Higgs boson decays into two W bosons, and all three W bosons in the event decay leptonically, producing a 3-charged-lepton event. This is one of the final states of the analysis, where the sum of charges is ± 1. The other channel consists of only two same-sign charged leptons. Again, the analysis separates events from decay or production based on the number of jets. Seven control regions are used to constrain fake leptons (originating from semileptonic decays of heavy-flavour jets) and $t\bar{t}+V$ events. In this analysis, a neural network is used to separate signal from background. The modeling of the heavy-flavour background dominates the systematic uncertainty. This analysis sets limits of $< 3.3(2.8) \times 10^{-4}$ for $\mathcal{B}(t \to cH)$ ($\mathcal{B}(t \to uH)$). Additionally, the analysis combines all current ATLAS results, as shown in Figures 3b and 3c. The combined results are $\mathcal{B}(t \to cH) < 2.6 \times 10^{-4}$ and $\mathcal{B}(t \to uH) < 3.4 \times 10^{-4}$, respectively.



(a) EFT Feynman diagram **(b)** $\mathcal{B}(t \to cH)$ **(c)** $\mathcal{B}(t \to uH)$

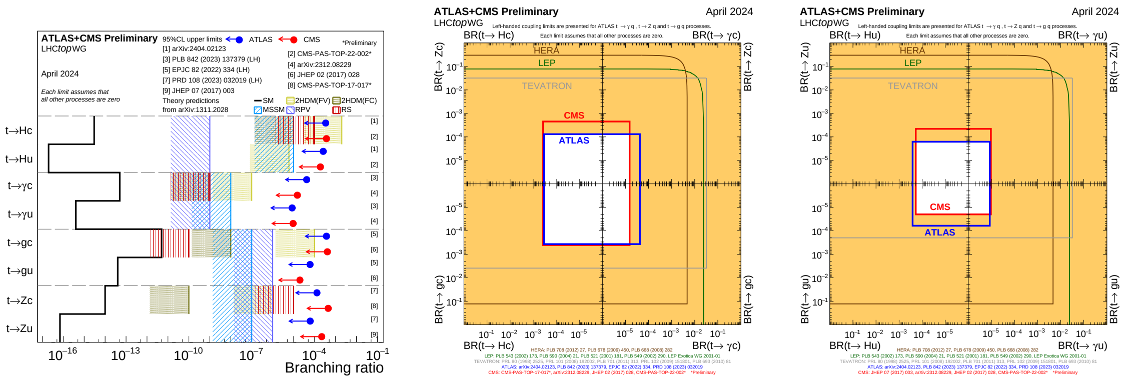
Figure 3: (a) Example of a EFT Feynman diagram used in the analysis with Higgs boson decaying to a pair or photon. (b-c) Upper limits for the FCNC analysis with top quark decaying to $H(\to \gamma\gamma)$ [10].

3.3 FCNC summary plots for top quark decay

Recently, the LHC top working group (ATLAS+CMS) published a summary of their FCNC results for top decays into a boson and a quark [11]. Figure 4 shows the results compared with several models (a), and compares them with previous accelerators for $\mathcal{B}(t \to Xc)$ (b) and $\mathcal{B}(t \to Xu)$ (c), where $X \equiv H, \gamma, g, Z$.

4. Summary

The top quark continues to deliver precise measurements that validate the Standard Model (SM). Furthermore, collisions involving top quarks, as recorded by the ATLAS detector, are utilized to



(a) Comparison with models **(b)** $\mathcal{B}(t \to Xc)$ **(c)** $\mathcal{B}(t \to Xu)$

Figure 4: Comparison of ATLAS and CMS FCNC results with (a) different models and (b-c) different accelerators [11].

investigate physics beyond the Standard Model. Three analyses are presented here, although no BSM physics has yet been observed. An exciting time awaits, as we anticipate what Run 3 of the LHC data collection might reveal about the top-quark sector.

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