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Searches for flavor-changing neutral currents and charged lepton flavor violation in association with top quarks at ATLAS and CMS

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The latest searches for flavor-changing neutral current (FCNC) and charged lepton flavor violation (CLFV) interactions in top quark events at the CMS and ATLAS experiments are presented. The data collected during the LHC Run 2 data-taking period have been utilized to test various types of beyond the standard model interactions in the top quark sector. With improved data analysis techniques and increased integrated luminosity, the most stringent limits on FCNC and CLFV couplings are set.

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1. FCNC and CLFV interactions in top quark physics

In top quark interactions, it is known that flavor-changing processes are highly suppressed in both tree and loop levels in the Standard Model (SM). The flavor-changing neutral currents (FCNC) are processes where a top quark couples with a neutral particle such as a Higgs boson (H), Z boson (Z), photon (γ), or gluon (g), while the other quark changes its flavor to an up or charm quark. These processes are extremely rare, and their predicted branching fractions ($\mathcal{B}$) are below 10^{-10}, well beyond the reach of the LHC. However, many beyond the SM (BSM) theories enhance the FCNC interactions, leading to branching fractions as high as $10^{-3}-10^{-4}$. This significant difference makes the FCNCs key processes for probing BSM physics through top quark interactions.

The charged lepton flavor violation (CLFV) processes have a very similar character. The flavor structure in the top quark interactions is expected to be conserved with massless neutrinos. However, the flavor mixing of neutrinos has been observed [3, 4], and flavor anomalies in B-physics have been reported [5, 6] in recent years. The parameterization of CLFV interactions in top quark interactions can be achieved by introducing several sets of effective field theory (EFT) operators into the simulation.

In both FCNC and CLFV interactions, the top quark can be either produced (single top production mode) or decayed ($\mathrm{t\bar{t}}$ decay mode). Most of the studies performed by the CMS [1] and ATLAS [2] have utilized both channels to improve sensitivity, with data collected during the LHC Run 2 data-taking period. Detailed explanations of the recent results are presented in the following sections.

2. Recent FCNC results from the CMS and ATLAS experiments

2.1 Search for tqH FCNC in H$\rightarrow \tau\tau$ channel (ATLAS)

A search [7] was performed at the ATLAS experiment looking for the tqH FCNC interactions where the Higgs boson decays into two tau leptons. The events are categorized based on the decay mode (hadronic or leptonic) and electric charge of tau leptons, the number of isolated leptons (electron e or muon μ), and the number of jets, while the number of b-jets is fixed to one. The simulation may not model fake tau and light-lepton events accurately, so these are estimated from the data. In each signal region (SR), a Boosted Decision Tree (BDT) is trained to discriminate FCNC signals from SM events. A simultaneous fit is performed on the BDT output distributions of seven SRs and two validation regions. Then, observed upper limits on branching fractions are set: $\mathcal{B}$(t$\rightarrow$uH) < 0.069% and $\mathcal{B}$(t$\rightarrow$cH) < 0.094%. The limit in tcH interaction shows a slight excess of data, approximately two standard deviations of the uncertainty. The leading SR in this analysis is $t\,\tau_{\mathrm{had}}\tau_{\mathrm{had}}$, and its post-fit distribution in the tcH channel is shown in the Figure 1.

2.2 Search for tqγ FCNC (CMS)

In a search for tqγ FCNC [8] at the CMS experiment, events with one isolated lepton (e or μ) and a photon in the barrel detector region are selected. The events are divided into two SRs; either one b-jet is identified (SR1, production mode), or two or more jets are selected, among which one jet is b-tagged (SR2, decay mode). Due to the presence of a photon and leptons in the events, multiple backgrounds are estimated using data-driven methods. The normalization factors

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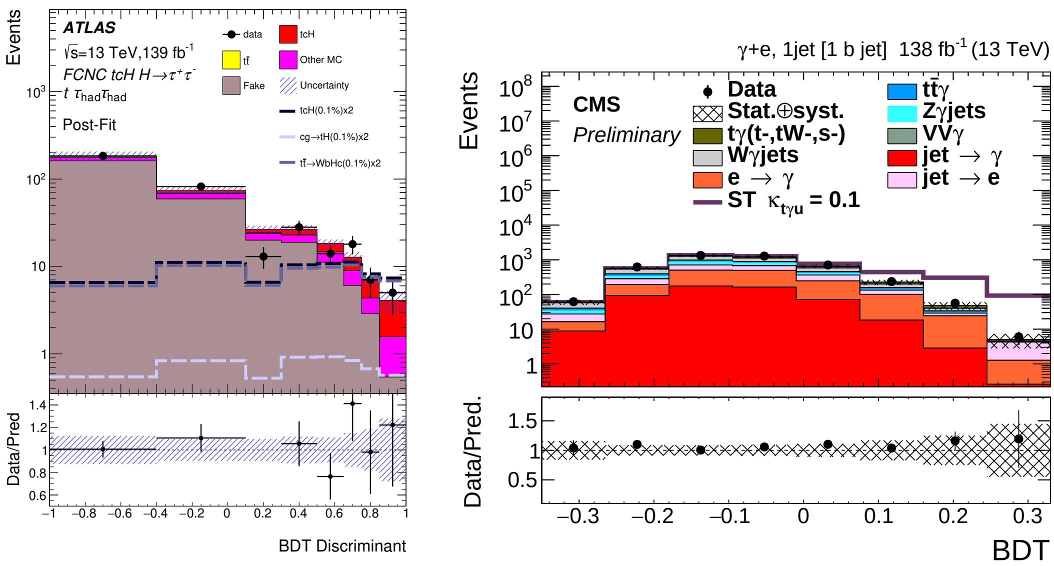

Figure 1: Post-fit BDT output distributions: $t\,\tau_{\rm had}\tau_{\rm had}$ in ATLAS tqH FCNC in H$\rightarrow\tau\tau$ search [7] (left) and tuγ $\gamma+e$ channel in CMS tqγ FCNC analysis [8].

of t$\bar{\rm t}\gamma$ and Z/Wγ processes are determined through the fit of background predictions to the data. Jet faking photon and lepton events are corrected using the control regions defined by orthogonal object selections. Finally, electron-to-photon fake is estimated by applying correction factors calculated in the Z-enriched region. BDTs are trained for each lepton flavor, quark (up and charm) channel, and SR. The observed upper limits on branching fraction are set as follows; $\mathcal{B}(\rm t\rightarrow u\gamma) < 0.95\times10^{-5}$ and $\mathcal{B}(\rm t\rightarrow c\gamma) < 1.51\times10^{-5}$. The tu$\gamma$ channel benefits from the SR1 due to the higher production mode cross section and well-discriminated lepton charge, as shown in the right plot of Figure 1. However, the combined limit is better in the tcγ channel, marking the best limit achieved so far.

2.3 Search for tqZ FCNC (ATLAS)

A search for the FCNC interactions in tqZ coupling [9] was conducted by the ATLAS Collaboration. Events with three leptons, which include an opposite-sign, same-flavor (OSSF) lepton pair close to the Z boson mass, are selected. The events are further categorized into two SRs based on the jet multiplicity: at least two jets (SR1, decay mode) and one or two jets(SR2, production mode), one of which is b-tagged in both SRs. The top quark and W boson are reconstructed by minimizing χ^2 of mass, and the reconstructed masses are required within twice the resolution. The mass of FCNC top quark (OSSF lepton pair and a jet) is also used to ensure the orthogonality between SR1 and SR2, considering that there is no FCNC top quark in SR2. While background prediction relies on the simulated events, their normalization is determined by fitting additionally defined CRs to the data. The signal events are distinguished using BDT classifiers. One BDT for t$\bar{\rm t}$ signal against all backgrounds is trained for SR1 since there is not much difference between the tuZ and tcZ decay processes. In contrast, considering a higher contribution from the production signal in tuZ coupling, two BDTs are trained separately for tuZ and tcZ channels in SR2. Further cuts are applied to the BDT distributions to ensure fit stability. The simultaneous fit of BDT distributions

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on SRs yields observed upper limits on branching fractions: $\mathcal{B}(t\to uZ) < 6.2 \times 10^{-5}$ and $\mathcal{B}(t\to cZ) < 13 \times 10^{-5}$ for the left-handed couplings. The post-fit BDT output distribution of SR1 of the tcZ coupling is shown in the Figure 2

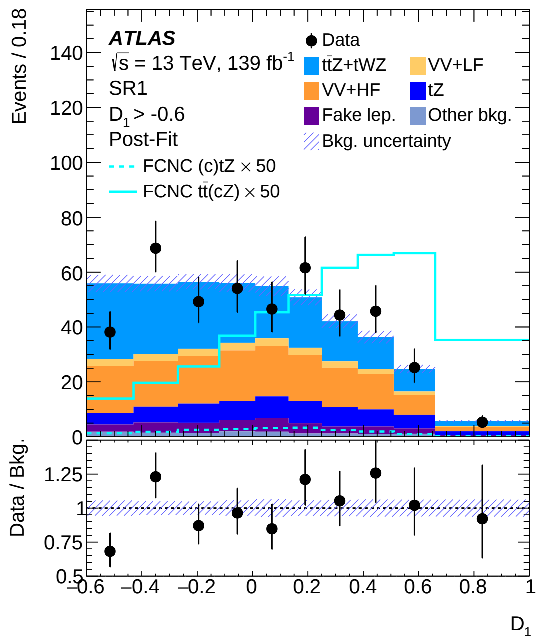

Figure 2: Post-fit BDT output distributions: tcZ decay mode in ATLAS tqZ FCNC search [9].

3. Recent CLFV results from the CMS and ATLAS experiments

The searches for CLFV in top quark interactions have been commonly using several combinations of dim-6 EFT operators. The EFT operators are grouped by their Lorentz structure: scalar, vector, and tensor. Similar to FCNC processes, the predicted cross section of production mode depends on the flavor of the incoming quark (up or charm) and is higher in the case of the up quark channel. In addition, there are several highly energetic leptons associated with the EFT vertex in production modes, which give distinctive kinematic signatures.

3.1 Search for CLFV in $e\mu$tq interactions (CMS)

A search for CLFV in tri-lepton final state [10] was carried out by the CMS Collaboration. Events with three leptons, where the transverse momentum of the leading lepton is greater than 38 GeV, are selected. The events are required to have an opposite sign $e\mu$ pair, one or more jets, and one or zero b-jet. Non-prompt background events are estimated by a data-driven method and validated using CRs. Two SRs are defined with respect to the mass of $e\mu$ pair ($m_{e\mu}$) to target decay ($m_{e\mu}$ < 150 GeV) and production ($m_{e\mu}$ > 150 GeV) modes separately. BDTs are trained for the two different SRs, and the post-fit BDT output distribution of the production SR is presented in Figure 3. The upper limits on the branching fraction and EFT coupling are calculated from the fit of the BDT distribution. The tensor structure provides the best constraints on the EFT operators due to higher predicted cross sections. The observed top quark branching fractions are on the order of 10^{-9} to 10^{-8} in $e\mu$tu coupling, while they are around 10^{-7} in the $e\mu$tc channel.

3.2 Search for CLFV in $\mu\tau$tq interactions (ATLAS)

A search for CLFV in $\mu\tau$tq channel [11] was performed by the ATLAS Collaboration. The analysis focuses on events containing same-sign muons, a hadronically decaying tau lepton, and one or more jets, one of which is b-tagged. Due to the similar kinematics, the up and charm quark channels are not distinguished. Background events containing fake tau lepton are corrected using scale factors measured in the CR while non-prompt muon contributions are estimated by the fitting to the data in another control region. Depending on the number of jets, two SRs are defined (exactly one jet or more). The predicted number of events in SRs and a CR for non-prompt muon estimation are fitted together to set the limits. Upper limits on branching fraction are extracted for each of EFT couplings, and the combined observed result is calculated, yielding $\mathcal{B}(\mathrm{t} \to \mu\tau\mathrm{q}) < 11 \times 10^{-7}$. The pre-fit distribution of the fitted template is shown in Figure 3 to give an idea on the expected signal contributions in each SRs, assuming a Wilson coefficient of 0.3 and new physics scale (Λ) of 1 TeV.

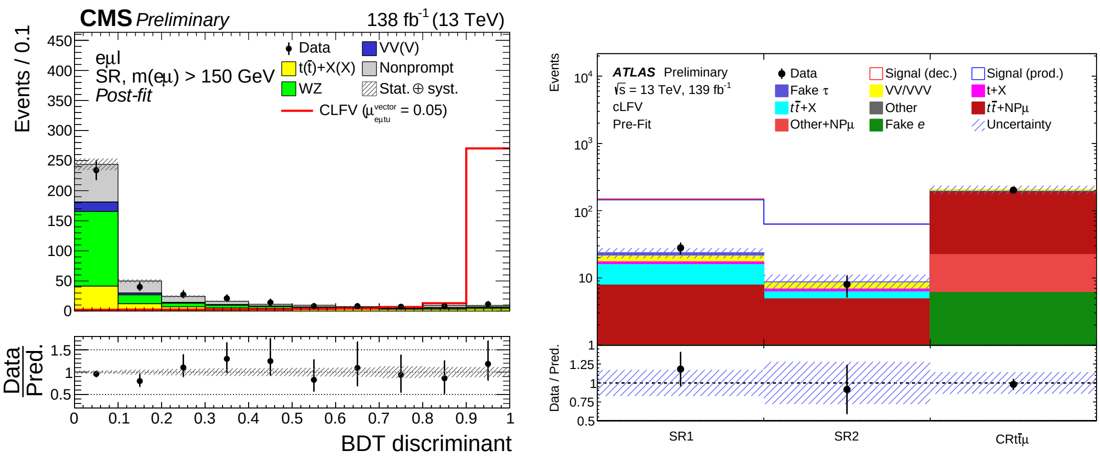

Figure 3: Post-fit BDT output distribution of single top quark production mode in CMS $e\mu\ell$ CLFV search [10] (left) and pre-fit yield distribution of in ATLAS $\mu\tau$tq CLFV search [11] (right)

4. Summary and outlook

The ATLAS and CMS Collaborations have performed a variety of studies with the LHC Run 2 data. The flavor-changing neutral interactions and lepton flavor violation processes have been extensively tested because they can be highly enhanced in many beyond the Standard Model (SM) scenarios. So far, there is no significant excess in data over the SM predictions. Many analyses are still in progress using Run 2 data, or even the latest Run 3 data. With the upcoming results, the full picture of top quark physics will be unveiled with unprecedented precision.

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