PROCEEDINGS OF SCIENCE

Searches for rare and Beyond the Standard Model processes in top quark production and decays with the CMS experiement

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With millions of top quarks produced at the LHC, it is an ideal sector for searching for rare top-quark decays. Besides flavor-changing neutral currents that are highly suppressed in the Standard Model, baryon and lepton number conservation can be probed in top quark events. In this conference proceeding, recent searches by the CMS experiment for rare and beyond the Standard Model top-quark production and decay with significantly increased sensitivity are discussed. Several of the measurements are the first of their kind.

31st International Workshop on Deep Inelastic Scattering (DIS2024)
8–12 April 2024
Grenoble, France

*Speaker

PoS(DIS2024)119

1. Introduction

The LHC is often described as a top quark factory, with hundreds of top quark events produced every minute. The very high top quark mass of 173 GeV/c^2 sets it apart from all other fermions and suggests a special role of the top in electroweak symmetry breaking and makes it a natural sector for searches of new physics. In this conference proceeding the following three searches for new physics in top quark events performed by the CMS experiment [1] are summarized:

- Search for flavor-changing neutral current interactions of the top quark mediated by a Higgs boson in proton-proton collisions at 13 TeV [2]
- Search for baryon number violation in top quark production and decay using proton-proton collisions at $\sqrt{s}$ = 13 TeV collision energy [3]
- Search for charged-lepton flavor violation in the production and decay of top quarks using trilepton final states in proton-proton collisions at $\sqrt{s}$ = 13 TeV [4]

All three analyses are performed using the full Run 2 data-set, collected in 2016-2018, comprising 138 fb^{-1} of integrated luminosity.

2. Search for flavor-changing neutral current interactions of the top quark mediated by a Higgs boson

In the Standard Model (SM), flavor-changing neutral currents (FCNCs) are forbidden at tree level and greatly suppressed at higher order. The SM prediction for the branching ratios Br($t \to Hu$) and Br($t \to Hc$) are of the order 10^{-15} and 10^{-17} respectively. They could be enhanced by many orders of magnitude by new physics processes, such as models with warped extra dimensions or with an extended Higgs sector, making it an interesting mode to probe in search of excesses. The search presented in Ref. [2] considers both FCNC single top production and SM top quark pair production with one top quark decaying via FCNCs, producing a Higgs boson and with either an up or a charm quark in the interaction vertex, as shown in Fig. 1.

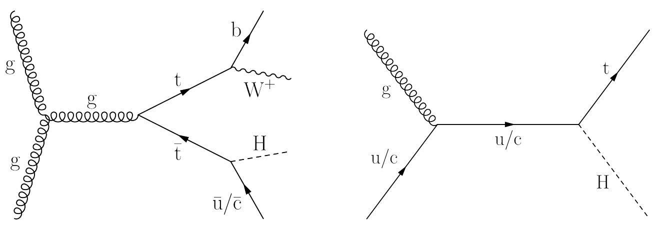

Figure 1: The signal processes considered in the search for FCNCs with the production of a Higgs boson. Both SM top quark pair production with an FCNC decay (left) and FCNC single top production (right) are considered [2].

In the event selection at least one charged same sign lepton pair ($e^{\pm}e^{\pm}$, $\mu^{\pm}\mu^{\pm}$, $e^{\pm}\mu^{\pm}$) is required along with at least one b-tagged jet and at least one additional jet in the dilepton channel. This broad selection targets the decays of the Higgs boson into WW, ZZ and $\tau\tau$.

To enhance the signal, which is expected to be many orders of magnitude lower than the SM background, two different boosted decision trees (BDTs) are trained: one for the tHu and one for the tHc coupling. The BDT output and the event yields are shown in Fig. 2. A large background from non-prompt leptons is evaluated with the tight-to-loose ratio method.

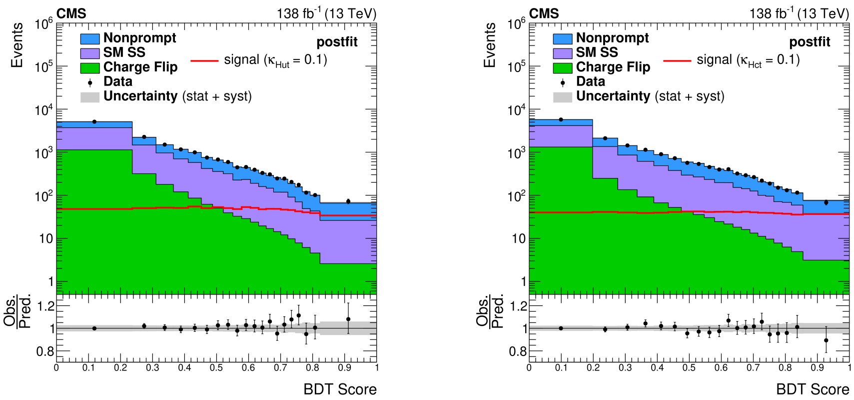

Figure 2: The BDT output and the post-fit yields for the FCNC search in for the tHu (left) and tHc (right) channels [2].

The signal strength is extracted with a binned likelihood fit, where the theoretical and experimental uncertainties enter as nuisance parameters. The main uncertainties on the signal predictions originate from the tagging of bottom and charm jets. No excess above the SM prediction is observed and 95% CL limits on branching ratios are set using the CL$_s$ method to Br($t \to Hu$) < 0.072% and Br($t \to Hc$) < 0.043%. A combination with the CMS FCNC analyses that target the Higgs boson decay modes $H \to b\bar{b}$ [5] and $H \to \gamma\gamma$ [6] is performed, as summarized in Table 1. The search presented here drives the limits on the $t \to Hc$ channel and the combination provides the best limits on Br($t \to Hu$) to date.

Analysis	$\mathcal{B}$(t → Hu) observed (expected)	$\mathcal{B}$(t → Hc) observed (expected)
H → b$\bar{\text{b}}$ [24]	0.079 (0.11)%	0.094 (0.086)%
H → $\gamma\gamma$ [25]	0.019 (0.031)%	0.073 (0.051)%
Leptonic (this analysis)	0.072 (0.059)%	0.043 (0.062)%
Combination	0.019 (0.027)%	0.037 (0.035)%

Table 1: The combination of the search for FCNCs for different decay modes of the Higgs boson [2].

3. Search for baryon number violation

Baryon number is a conserved quantity without any underlying symmetry in the SM. Meanwhile, baryon number violation (BNV) is needed to explain the excess of matter over anti-matter in the Universe. In grand unified theories and in supersymmetric models BNV occurs naturally and the LHC provides the best sensitivity to BNV in the top quark sector. The search described in Ref. [3]

uses for the first time single top quark production in addition to top quark pair production to probe BNV, as illustrated in Fig. 3, with the analysis being optimized for single top BNV production.

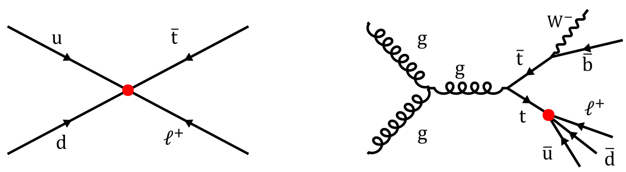

Figure 3: Feynman diagrams illustrating the signal processes for the BNV search, namely single top BNV production (left) and top quark pair production followed by a BNV decay (right) [3].

The BNV interactions can be parameterized with effective field theory, with separate couplings for exchange in the s- and t-channel for the heavy mediator. In total, 12 different four-fermion operators contribute for each of the channels (for different lepton and quark flavors).

A final state with exactly one opposite sign dilepton pair (e^+e^-, $\mu^+\mu^-$ or $e^\pm\mu^\mp$) is required along with exactly one b-tagged jet. A cut on the invariant mass of the dilepton pair is applied to suppress the Drell-Yan+jets background. A BDT is trained to distinguish any BNV events from SM backgrounds, merging signal events with different quark and lepton flavors using equal weights. Ten input variables are used for the BDT training, exploiting the momentum, distances and invariant masses of the two leptons and the top quarks (and of combinations of these objects). The main backgrounds are constituted by SM top quark pair and single top production and Drell-Yan. The BDT output and the post-fit event yields are shown in Fig. 4.

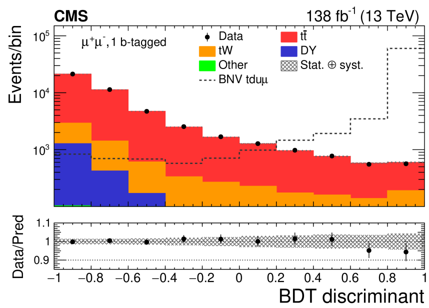

Figure 4: The BDT output and the post-fit event yields for the BNV search in the $\mu^+\mu^-$ channel [3].

A binned maximum-likelihood fit is performed, with exclusion limits on the effective couplings extracted with the CL_s method. The limits on the effective operators are translated into limits on branching fractions of the top quark, as shown in Fig. 5, improving previous limits by CMS from the $\sqrt{s} = 8$ TeV data-set [7] by several orders of magnitude. The differences in limits on the different decay modes of the top are mainly explained by differences in parton distribution functions for different quark flavors for single top production. The limiting uncertainties are the normalization of the SM tW production cross section, the muon energy scale and the modeling of the transverse momentum for top quark pair production, which is used to reweight the next-to-leading-order SM prediction to next-to-next-to-leading order.

Vertex	C_x	C_x/Λ^2 [TeV^{-2}] Exp.	C_x/Λ^2 [TeV^{-2}] Obs.	$\mathcal{B}_x$ [10^{-6}] Exp.	$\mathcal{B}_x$ [10^{-6}] Obs.
teud	s	0.055	0.048	0.015	0.011
	t	0.031	0.027	0.005	0.003
tμud	s	0.046	0.036	0.010	0.006
	t	0.025	0.020	0.003	0.002
tecd	s	0.207	0.184	0.208	0.164
	t	0.114	0.102	0.063	0.050
tμcd	s	0.178	0.141	0.153	0.095
	t	0.100	0.080	0.048	0.030
teus	s	0.115	0.101	0.063	0.050
	t	0.064	0.056	0.019	0.015
tμus	s	0.102	0.079	0.050	0.030
	t	0.056	0.043	0.015	0.009
tecs	s	0.448	0.403	0.973	0.786
	t	0.243	0.218	0.286	0.229
tμcs	s	0.394	0.311	0.752	0.468
	t	0.217	0.169	0.228	0.138
teub	s	0.199	0.178	0.191	0.154
	t	0.109	0.097	0.057	0.045
tμub	s	0.168	0.134	0.136	0.087
	t	0.095	0.076	0.044	0.028
tecb	s	0.718	0.657	2.503	2.090
	t	0.405	0.367	0.795	0.652
tμcb	s	0.703	0.564	2.393	1.521
	t	0.386	0.307	0.722	0.455

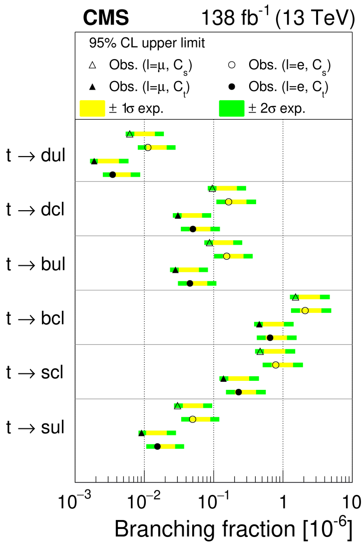

Figure 5: The limits on the BNV couplings in effective field theory (left) and the corresponding limits on branching fractions of the top quark via BNV processes (right) [3].

4. Search for charge lepton flavor violation in the production and decay of top quarks

In the Standard Model, lepton number is conserved as an accidental symmetry. However, neutrino oscillations confirm the mixing of massive neutrinos and indicate the presence of charged lepton flavor violation (CLFV). The LHC provides the best sensitivity to CLFV in the production and in two- and three-body decays of heavy elementary particles.

The search for CLFV in the top sector, presented in Ref. [4], targets vertices with one top quark, one light quark and two leptons of different flavor (electron or muon), as illustrated in Fig. 6. Both CLFV in single top quark production and SM top quark pair production followed by a CLFV decay of one top are considered. The selection contains three charged leptons (electrons or muons), with a net charge of ±1 and at least one jet of which at most one is b-tagged. An interpretation in the framework of effective field theory, with the vector, scalar and tensor Lorentz structure, is made.

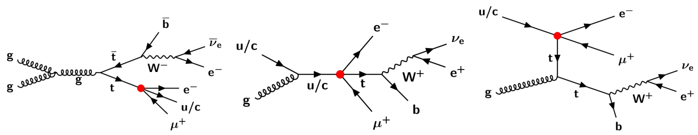

Figure 6: Feynman diagrams for the search for CLFV in the top quark sector [4].

The main backgrounds are constituted of non-prompt leptons, dibosons and top quarks produced with one or two vector bosons. Two signal regions are defined: one with low and and one with high dilepton invariant mass. The former targets CLFV in top decays and the latter in top quark production. Two boosted decision trees are trained to enhance the signal, exploiting that events with CLFV in single top production tend to have a lepton with a high transverse momentum. The BDT outputs and the post-fit yields are shown in Fig. 7. Signal events with different Lorentz structure and flavor are combined in the training.

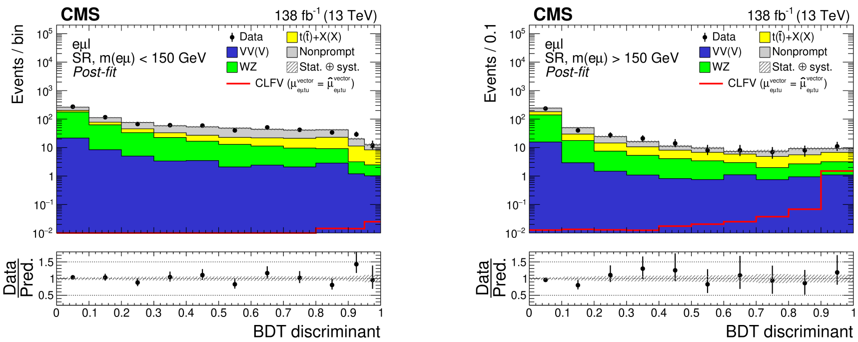

Figure 7: The BDT output and the post-fit event yields for the charged lepton flavor violation search in the low-mass (left) and high-mass (right) signal regions [4].

A binned maximum likelihood fit is performed using the BDT output, using the CL$_s$ criterion to set 95% CL limits on the couplings. These limits are recast as limits on branching ratios, as shown in Table 2, which constitute the world's best limits to date in the $e\mu$ channel.

CLFV coupling	Lorentz structure	$C_{e\mu tq}/\Lambda^2$ (TeV^{-2}) Exp. (68% CL range)	Obs.	$\mathcal{B}(t \to e\mu q) \times 10^{-6}$ Exp. (68% CL range)	Obs.
eμtu	Tensor	0.022 (0.018–0.026)	**0.024**	0.027 (0.018–0.040)	**0.032**
	Vector	0.044 (0.036–0.054)	**0.048**	0.019 (0.013–0.028)	**0.022**
	Scalar	0.093 (0.077–0.114)	**0.101**	0.010 (0.007–0.016)	**0.012**
eμtc	Tensor	0.084 (0.069–0.102)	**0.094**	0.396 (0.272–0.585)	**0.498**
	Vector	0.175 (0.145–0.214)	**0.196**	0.296 (0.203–0.440)	**0.369**
	Scalar	0.385 (0.318–0.471)	**0.424**	0.178 (0.122–0.266)	**0.216**

Table 2: The limits on CLFV couplings and on the corresponding top quark branching ratios [4]

5. Summary and conclusions

In summary, the CMS experiment has performed several challenging searches for top quark processes that are either absent or extremely rare in the SM, using the Run 2 data-set at 13 TeV collision energy. The world's best limits to date are provided on the branching ratio Br($t \to Hu$), on baryon number violation in the top quark sector and on charged lepton flavor violation in top quark processes with an electron and a muon in the final state. New searches are currently ongoing at 13.6 TeV collision energy, with data available at yet higher luminosity, thus further stress testing the Standard Model.

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