Rare and BSM top-quark production and decays

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Olga Bessidskaia Bylund
on behalf of the CMS collaboration

University of Rochester

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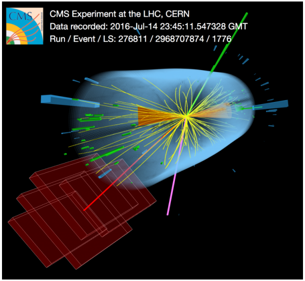
Overview

The LHC is a top quark factory, producing hundreds of top events/minute.

The very high top mass points to a special role in electroweak symmetry breaking.



Do top quark processes harbor signs of new physics?

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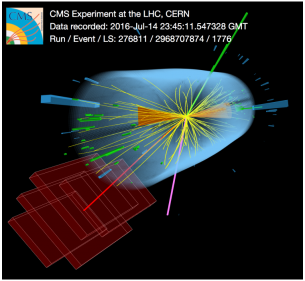


Do top quark processes harbor signs of new physics?

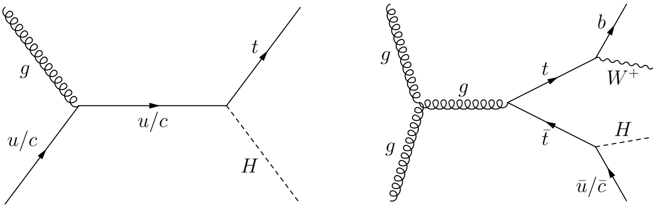
The following searches are covered here:

- FCNC tHq production with SS dileptons CMS-PAS-TOP-22-002
- BNV in top quark events 2402.18461 *submitted to PRL*
- LFV in top production and decay in 3L channel 2312.03199 *submitted to PRD*

All performed at $\sqrt{s} = 13$ TeV, with 138 fb^{-1} of data collected 2016-2018.

FCNC tHq objectives

- Flavour changing neutral currents (FCNCs) are forbidden at tree level in the Standard Model (SM).
- Probing $t \to Hu$, $t \to Hc$ branching ratios. SM prediction: 10^{-15}, 10^{-17}, could be greatly enchanced by new physics.
- Signal contains FCNC in single top production (followed by SM top decay) and SM top pair production followed by one FCNC decay.

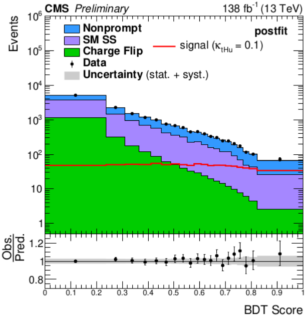


- Requiring at least one same sign lepton pair (e, μ), at least one b-jet, at least 1 (2) jets in total for dilepton (multilepton) events.
  - Targeting WW, ZZ, and $\tau\tau$ final states.

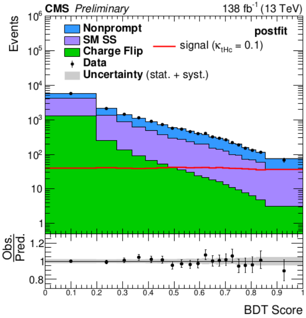
FCNCs tHq extraction

- Two BDTs using XGBOOST are trained to identify each signal.
  - Input features: particle multiplicities, kinematics, *b*- & *c*-tagging scores.
- The nonprompt lepton background is evaluated with the "tight-to-loose" ratio method (loose: relaxed isolation etc.)

$t \rightarrow Hu$

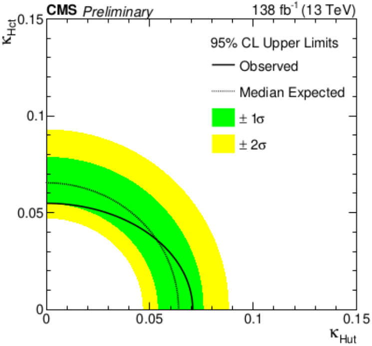


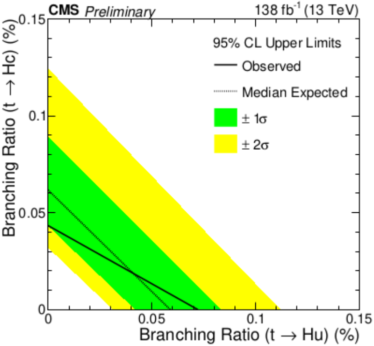
$t \rightarrow Hc$



- A binned likelihood fit is performed, with theoretical and experimental uncertainties entering as nuisance parameters.
  - Main uncertainties on the signal predictions: *b*- and *c*-tagging.

FCNC tHq results





Upper limits on branching ratios

95% CL limits set using the CL_s criterion.

- Observed: $Br(t \to uH) < 0.072\%$, $Br(t \to cH) < 0.043\%$.
- Expected: $Br(t \to uH) < 0.059\%$, $Br(t \to cH) < 0.062\%$.

CMS-PAS-TOP-22-002

FCNC tHq combination

Combination performed with CMS analyses targeting $H \to b\bar{b}$ and $H \to \gamma\gamma$ decay modes.

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

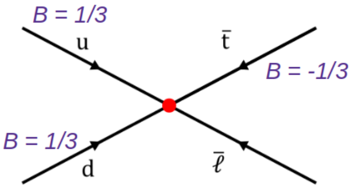
This analysis drives the limits on $\text{Br}(t \to Hc)$.
The combination provides the best limits on the $t \to Hu$ branching ratio to date.

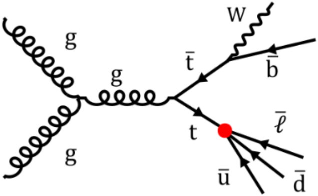
Improvement in limits by an order of magnitude from 8 TeV CMS results.

CMS-PAS-TOP-22-002

Search for BNV in top quark production and decays

- In the SM baryon number is conserved without an underlying symmetry. Baryon number violation (BNV) is needed to explain the abundance of matter over anti-matter.
- BNV occurs naturally in grand unified theories and supersymmetry.
- The LHC provides the best sensitivity to BNV in top quark processes.

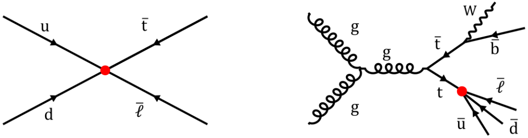




The analysis is optimised for BNV in single top production. This is the first search for BNV in single top production at 13 TeV.

- Opposite sign dilepton final states are used.
- Exactly 1 *b*-tagged jet is required.

Baryon number violation with effective field theory



An effective lagrangian introduces the new interactions.

Separate couplings for *s*- and *t*-channel exchanges of a heavy mediator.

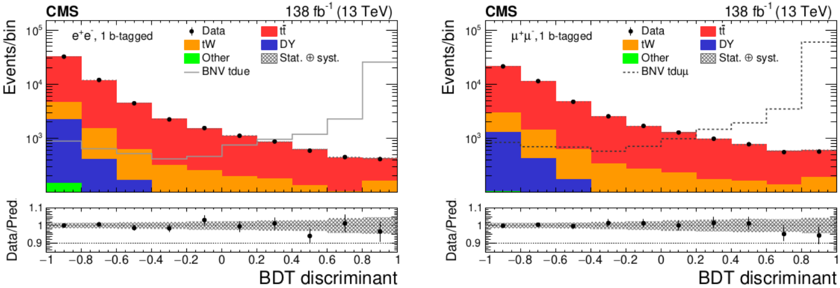
$$\mathcal{L}_{\text{eff}} = \frac{C_s}{\Lambda^2}\epsilon^{\alpha\beta\gamma}[\overline{\mathrm{t}^c_\alpha}\mathrm{d}_\gamma][\overline{\mathrm{u}^c_\beta}\ell] + \frac{C_t}{\Lambda^2}\epsilon^{\alpha\beta\gamma}[\overline{\mathrm{t}^c_\alpha}\ell][\overline{\mathrm{u}^c_\beta}\mathrm{d}_\gamma] + \text{h.c.}$$

12 four-fermion operators contribute (ℓ: e, μ, q_u: u, c, q_d: d, s, b)

Search for BNV in top quark production and decays

A BDT is trained to distinguish events with BNV in single top production.

- 10 input variables: p_T, distances, invariant mass and momentum differences of (combinations of) the two leptons and the top quark.
- Signal events with different BNV flavours are merged with equal weights. The backgrounds are weighted by their cross sections.



Drell-Yan+jets is suppressed by cutting on the dilepton invariant mass. This background process is normalised using a control region.

Search for BNV in top quark production and decays

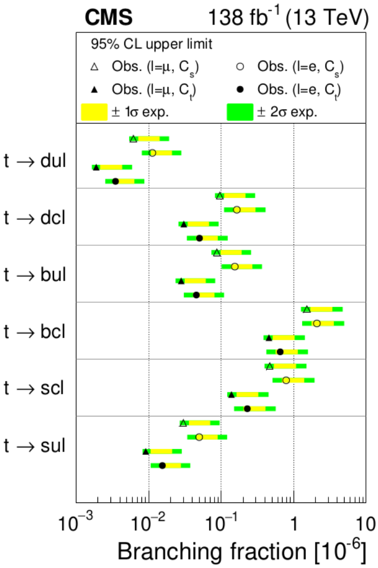
Limiting uncertainties

- SM tW normalisation
- muon energy scale
- $t\bar{t}$ p_T modelling (NNLO reweighting).

- Fitting one at a time, the effective couplings are consistent with 0.
- Recast as branching ratios - difference in expected limits stem from differences in pdfs.

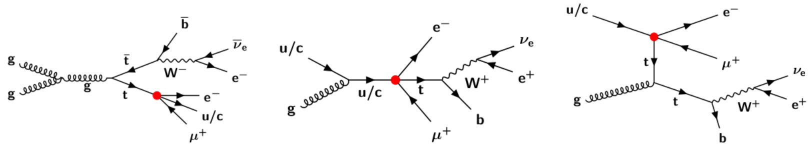
2402.18461 *submitted to PRL*

Improvement of previous limits (8 TeV) by 3-6 orders of magnitude.



LFV in top production in the 3L channel

- Lepton number is conserved in the SM via accidental symmetry.
- Neutrino oscillations confirm the mixing of massive neutrinos and indicate the presence of charged lepton flavour violation (CLFV).
- LHC provides the best sensitivity to CLFV in both production and 2- and 3-body decays of heavy particles.
- Observed flavour anomalies in B-decays by LHCb have renewed interest in CLFV searches.



Three charged leptons (e, μ) with a net charge of ±1 are required together with at least 1 jet of which at most 1 is b-tagged.

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{(4)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} O_a^{(6)} + O(\frac{1}{\Lambda^4})$$

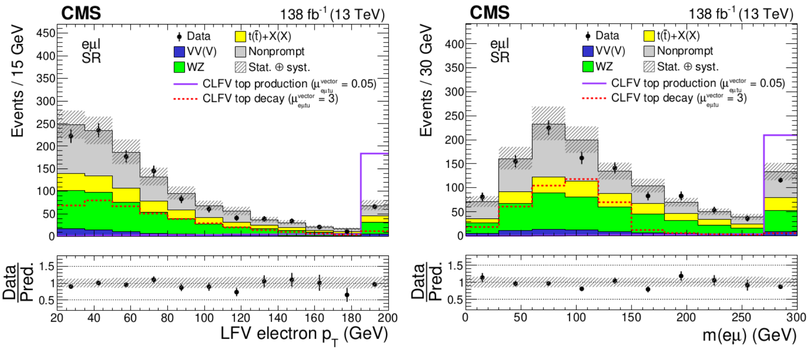
Six relevant dimension-6 operators:

Lorentz structure	Operator		
Vector	$O_{\rm lq}^{(1)ijkl}$	=	$(\bar{\rm l}_i\gamma^\mu {\rm l}_j)(\bar{\rm q}_k\gamma_\mu {\rm q}_l)$
	$O_{\rm lu}^{ijkl}$	=	$(\bar{\rm l}_i\gamma^\mu {\rm l}_j)(\bar{\rm u}_k\gamma_\mu {\rm u}_l)$
	$O_{\rm eq}^{ijkl}$	=	$(\bar{\rm e}_i\gamma^\mu {\rm e}_j)(\bar{\rm q}_k\gamma_\mu {\rm q}_l)$
	$O_{\rm eu}^{ijkl}$	=	$(\bar{\rm e}_i\gamma^\mu {\rm e}_j)(\bar{\rm u}_k\gamma_\mu {\rm u}_l)$
Scalar	$O_{\rm lequ}^{(1)ijkl}$	=	$(\bar{\rm l}_i{\rm e}_j)\ \varepsilon\ (\bar{\rm q}_k u_l)$
Tensor	$O_{\rm lequ}^{(3)ijkl}$	=	$(\bar{\rm l}_i\sigma^{\mu\nu}{\rm e}_j)\ \varepsilon\ (\bar{\rm q}_k\sigma_{\mu\nu}{\rm u}_l)$

$i \neq j$; k, l: one is 3, the other 1 or 2

LFV in top production in the 3L channel

- The nonprompt lepton background is parameterised with the data-driven Matrix Method in dedicated measurement regions.

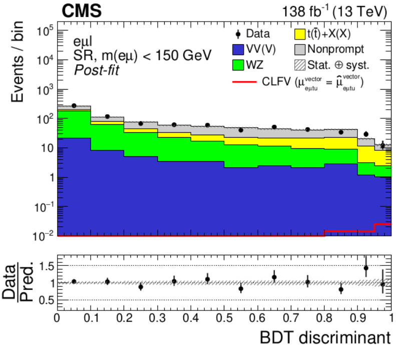


- BDTs are trained to separate the LFV signal from the backgrounds.
  - Events with CLFV in top production have a lepton with high p_T.
  - Signal events with different Lorentz structure and flavour are combined.

LFV in top production in the 3L channel

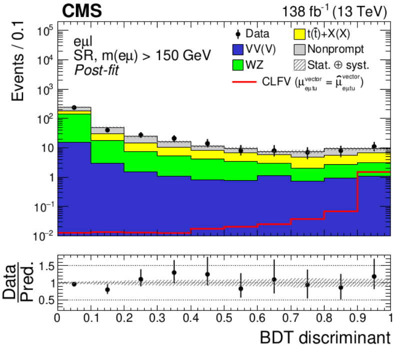
Two signal regions are defined, with separate BDTs trained in each SR.
A binned likelihood fit using the BDT output is performed.

Low m($e\mu$) - LFV in top decays



BDT inputs: $m^{SF}_{\ell^+\ell^-}$, n_b, m^{LFV}_t
Main uncertainty: initial and final state radiation

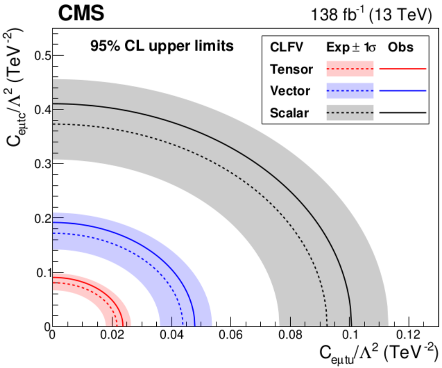
High m($e\mu$) - LFV in production

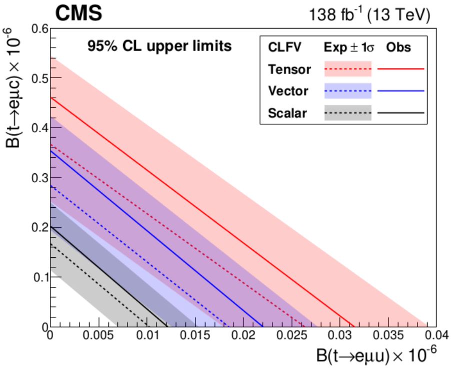


BDT inputs: $m^{LFV}_{e\mu}$, $p^{LFV}_T(\ell_{i=1,2})$
Main uncertainty: modelling of high p_T lepton

LFV in top production in the 3L channel

No excess is observed. 95% CL limits are placed.





World's best $e\mu$ limits on CLFV in top, improvement by an order of magnitude.

2312.03199 *submitted to PRD*

	$\mathrm{Br}(t \to e\mu u)$	$\mathrm{Br}(t \to e\mu c)$
tensor	$0.032 \cdot 10^{-6}$	$0.498 \cdot 10^{-6}$
vector	$0.022 \cdot 10^{-6}$	$0.369 \cdot 10^{-6}$
scalar	$0.012 \cdot 10^{-6}$	$0.216 \cdot 10^{-6}$

Summary and conclusions

- CMS has performed impressive searches for processes that do not occur or are extremely rare in the SM, using the Run 2 dataset.
- The best limits to date are provided for $\mathrm{Br}(t \rightarrow Hu)$, baryon number violation in the top sector and charged lepton flavour violation with $e\mu$ in top quark processes.
- New searches are ongoing at 13.6 TeV collision energy, expecting to reach a higher luminosity in Run 3.

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Thank you for your attention!