Rare and Anomalous couplings in top quark production within the SM and beyond

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On behalf of the ATLAS and CMS Collaborations

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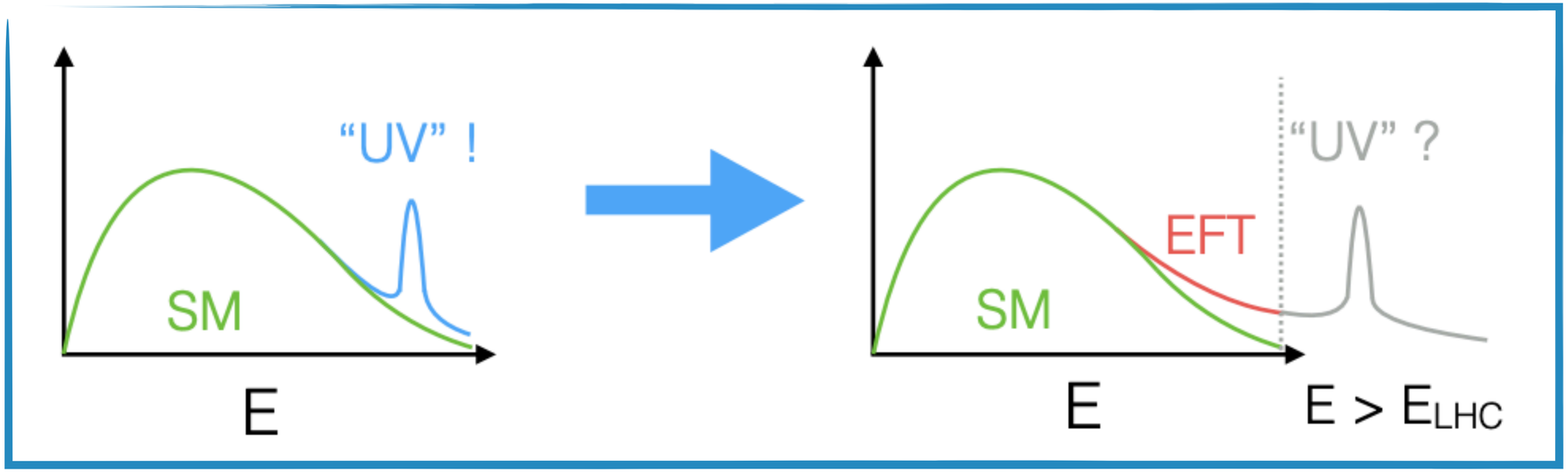
Introduction

- Continue to search beyond the SM:
  - Direct searches:
    - New Physics (NP) scale is within reach of the LHC collision energy
    - Resonant or non-resonant production of new particles
  - Indirect searches:
    - NP energy is beyond the reach of LHC collision energy
    - Rare production and decay of top quark
    - Deviations from SM in measurements of top properties

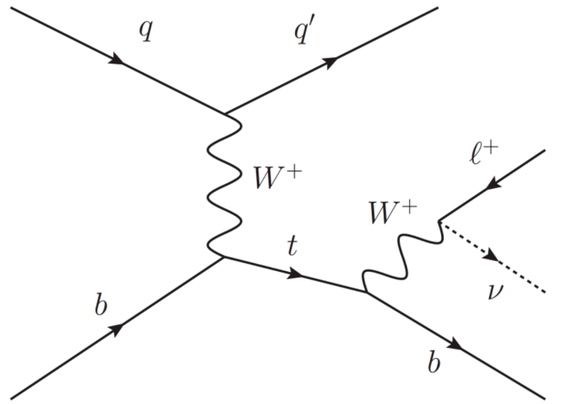


Taken from **slides by K. Mimasu**

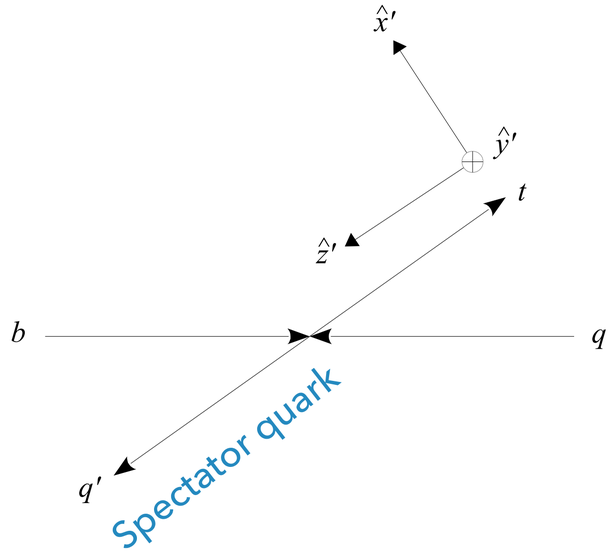
Top Polarisation

Single top polarisation

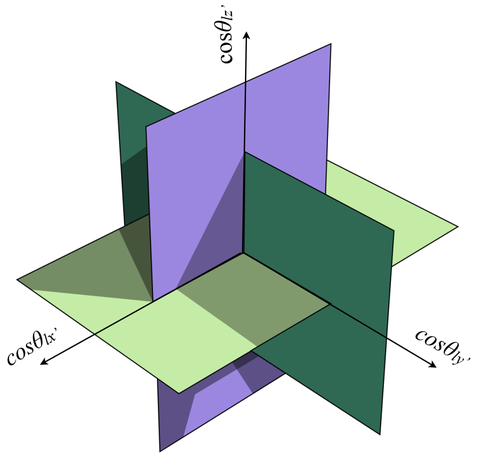
- Top-quark polarisation (P) can only be measured in single top-quark events in p-p collisions at LHC
  - $t\bar{t}$ produces top quarks unpolarised due to parity conservation in QCD
- t-channel dominant process producing **highly polarised top quarks** due to V-A nature
  - spin aligned in direction of down-type quarks
- top decays before hadronisation
  - decay products preserve spin information
  - **accessible via angular distributions** (in top rest frame)
- Measurements of polarisation observables sensitive to new physics phenomena affecting **tWb vertex**
  - Consider O_{tW} EFT operators which would have effects on polarisation
  - Non-zero value for C_{itW} could hint at CP violation
- First measurement of all the top-quark polarisation components @ 13 TeV with Full Run 2 dataset

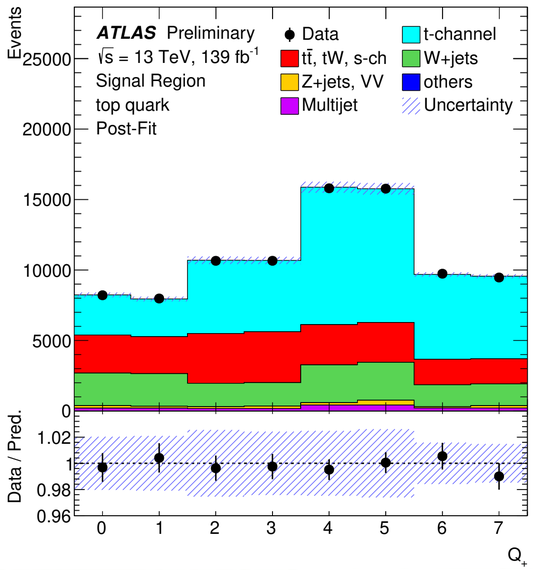


Top-quark rest frame



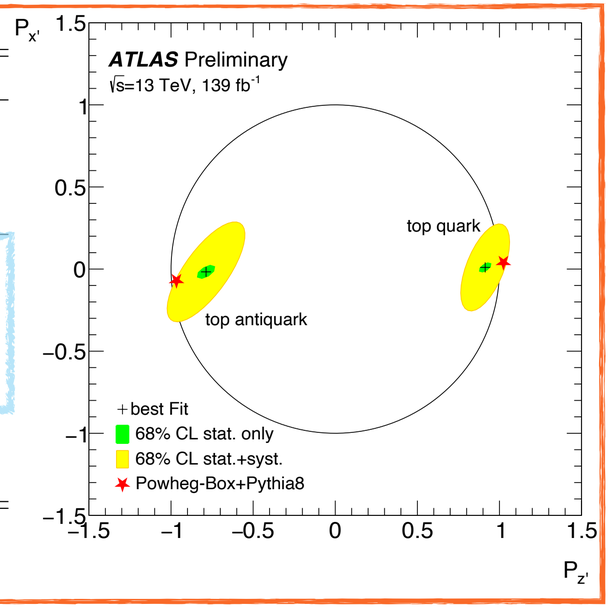
Top Polarisation





Parameter	Extracted value	(stat.)
t-channel norm.	$+1.045 \pm 0.022$	(± 0.006)
W+jets norm.	$+1.148 \pm 0.027$	(± 0.005)
$t\bar{t}$ norm.	$+1.005 \pm 0.016$	(± 0.004)
$P_{x'}^{t}$	$+0.01 \pm 0.18$	(± 0.02)
$P_{x'}^{\bar{t}}$	-0.02 ± 0.20	(± 0.03)
$P_{y'}^{t}$	-0.029 ± 0.027	(± 0.011)
$P_{y'}^{\bar{t}}$	-0.007 ± 0.051	(± 0.017)
$P_{z'}^{t}$	$+0.91 \pm 0.10$	(± 0.02)
$P_{z'}^{\bar{t}}$	-0.79 ± 0.16	(± 0.03)

First measurement ever!



Event Selection

- 1 tight charged lepton (e,μ) pT > 30 GeV
- 2 jets, 1 b-tagged
- E_T^{miss}> 35 GeV; $m_T(W)$ > 60 GeV
- Additional multijet rejection cut

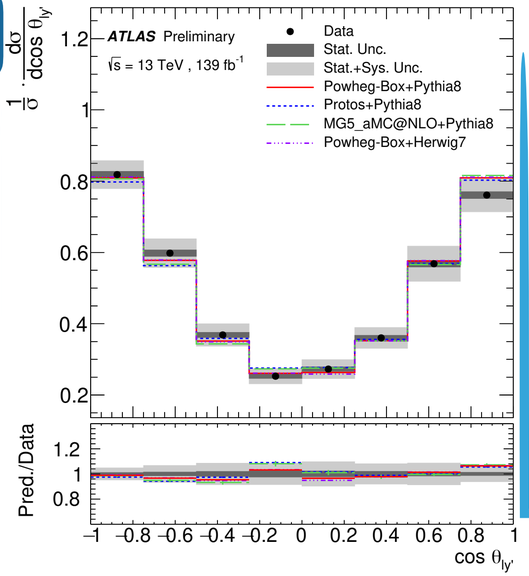
Measurement of polarisation vectors

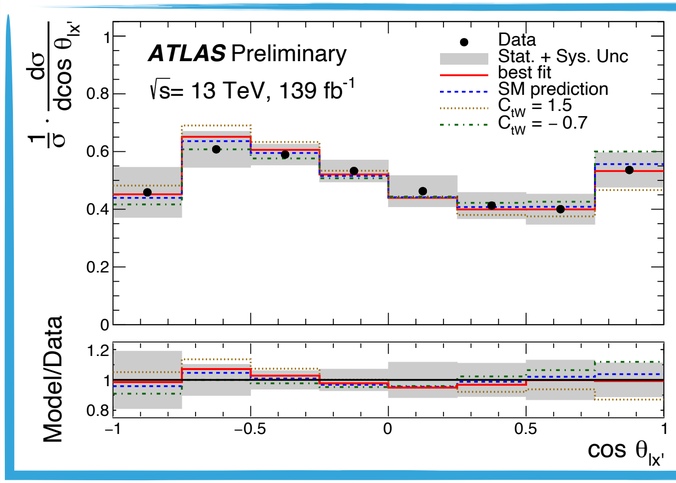
- Profile likelihood fit in 4 regions
  - 2 SRs (top & antitop): Octant variable Q: Phase space sliced depending on the sign of cos θ_j
  - 2 CRs ($t\bar{t}$ and W+jets): 2-bin splitting based on lepton charge
- 6 simulated Protos+Pythia8 templates with fully polarised states are used in the fit ($P_{x',y',z'} = \pm 1$)
- 6 POI ($P_{x'}^{t}$, $P_{y'}^{t}$, $P_{z'}^{t}$, $P_{x'}^{\bar{t}}$, $P_{y'}^{\bar{t}}$, $P_{z'}^{\bar{t}}$) + 3 normalisations ($t\bar{t}$, W+jets & t-channel signal)
- Systematics: Mainly dominated by **jet-energy resolution**
- Measurements in agreement with SM MC predictions (stat.):
  - $P_{x'}^{t} = 0.040 \pm 0.012$, $P_{x'}^{\bar{t}} = -0.070 \pm 0.016$,
  - $P_{z'}^{t} = 1.024 \pm 0.015$, $P_{z'}^{\bar{t}} = -0.967 \pm 0.020$,
  - $P_{y'}$ is expected to be 0 from CP symmetry

Top Polarisation

Normalised differential cross-section measurements

- **Three angular distributions** (cos $\theta_{lx'}$, cos $\theta_{ly'}$, cos $\theta_{lz'}$) sensitive to new physics effects in the tWb vertex
- Normalisations of W+jets and top-quark backgrounds and t-channel signal constrained with maximum likelihood fit to data in SRs and CRs
- After background subtraction distributions are unfolded with Iterative Bayesian Unfolding to particle-level in fiducial region
- Systematics: Mainly dominated by jet-energy resolution, jet-energy scale and t-channel modelling.



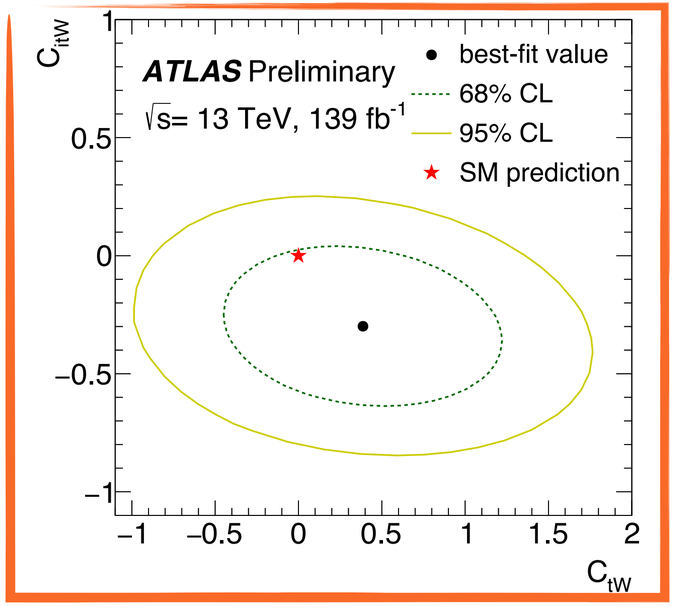


EFT interpretation

- Results interpreted in EFT context to set limits on Wilson coefficients
- Profile likelihood fit is performed including morphing templates to simulate BSM effects

	C_{tW}		C_{itW}	
	68% CL	95% CL	68% CL	95% CL
All terms	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^4$	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^2$	[-0.2, 1.0]	[-0.7, 1.7]	[-0.5, -0.1]	[-0.8, 0.2]

Best limits for C_{itw} so far!



CP Violation in Top Quark

Search for CP violation in top quark events

Dipole top-gluon couplings

$$\mathscr{L} = \frac{g_s}{2}\bar{t}T^a\sigma^{\mu\nu}(a_t^g + i\gamma_5 d_t^g)tG_{\mu\nu}^a$$

CP-odd CEDM

Asymmetry for observable

$$A_{CP}(O_i) = \frac{N(O_i > 0) - N(O_i < 0)}{N(O_i > 0) + N(O_i < 0)}$$

- CP symmetry is violated in SM, though not enough to explain matter-antimatter asymmetry in universe
- Search for new sources of CP violation on-going in many areas
  - top quark sector is relatively unexplored
- Potential source of large CP violation in BSM via chromo-electric dipole moment (CEDM) in production and decay of top quark pairs
- Analysis considers 4 T-odd physics observables, chosen based on well measured final-state objects

$$O_3 = Q_\ell \epsilon(p_b, p_{\bar{b}}, p_\ell, p_{j_1}) \propto Q_\ell \vec{p'}_b \cdot (\vec{p'}_\ell \times \vec{p'}_{j_1})$$

$$O_6 = Q_\ell \epsilon(P, p_b - p_{\bar{b}}, p_\ell, p_{j_1}) \propto Q_\ell (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1})$$

$$O_{12} = q \cdot (p_b - p_{\bar{b}}) \epsilon(P, q, p_b, p_{\bar{b}}) \propto (\vec{p}_b - \vec{p}_{\bar{b}})_z \cdot (\vec{p}_b \times \vec{p}_{\bar{b}})_z$$

$$O_{14} = \epsilon(P, p_b + p_{\bar{b}}, p_\ell, p_{j_1}) \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1})$$

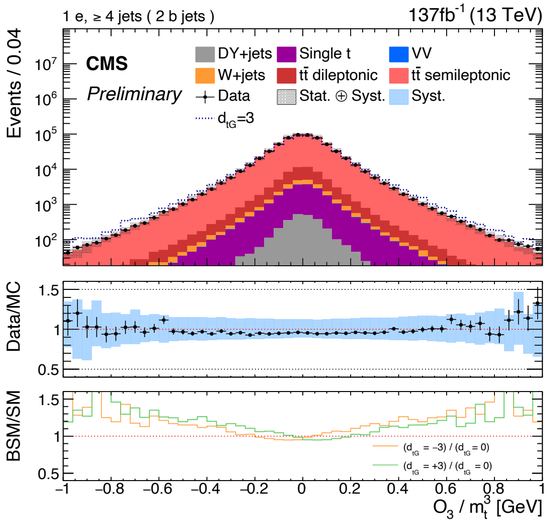
- A_{CP} zero in SM, predictions of anomalous CEDM contributions could lead to A_{CP} of around 8% (0.4%) for O_3 (O_{12}) [1]

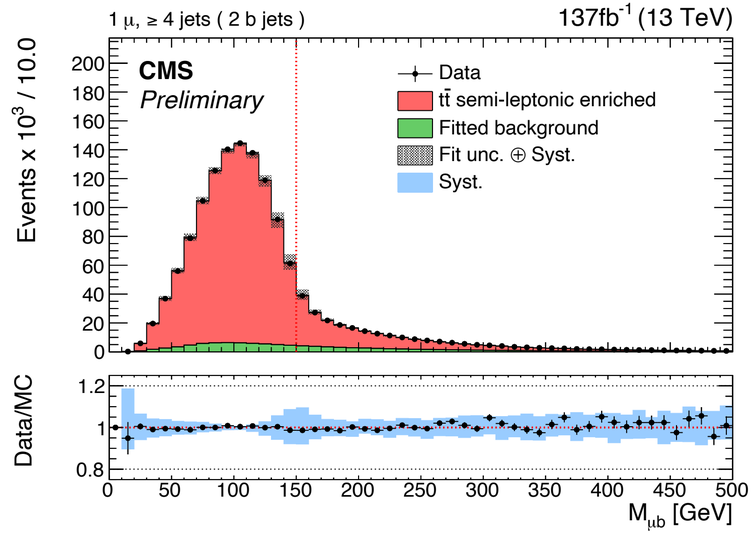
[1] Phys. Rev. D 93 (2016) 014020

CP Violation in Top Quark

Search for CP violation in top quark events

- Analysis with Full Run 2 dataset 137 fb^{-1}
- Selection: lepton+jets $t\bar{t}$ final state
- Top quark and antiquark candidates are reconstructed using a χ^2 sorting algorithm
- Background contribution estimated from fit to the M_{lb} mass distribution in W+jets control region
- Measured effective asymmetries A_{CP}' are affected by dilution effects from experimental factors
  - E.g. due to mis-assignment of the quark/ antiquark
  - Parametrised with a dilution factor comparing generator level to reconstruction level observable
  - Also Observable-dependent



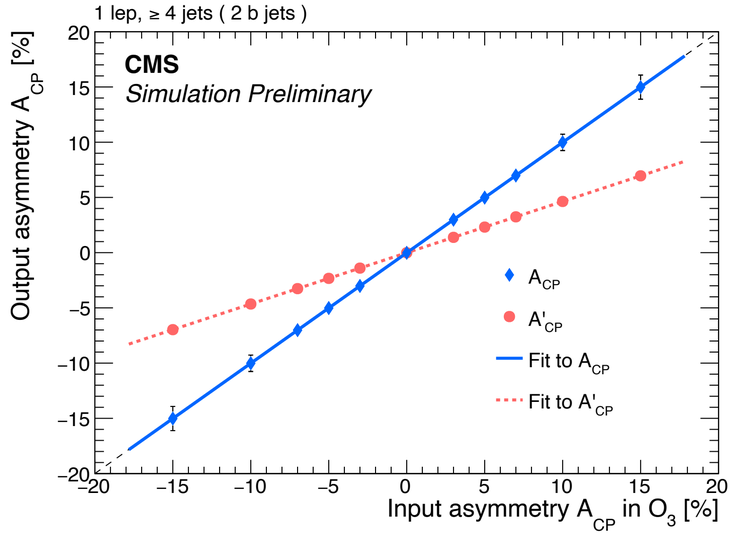


Dilution factor

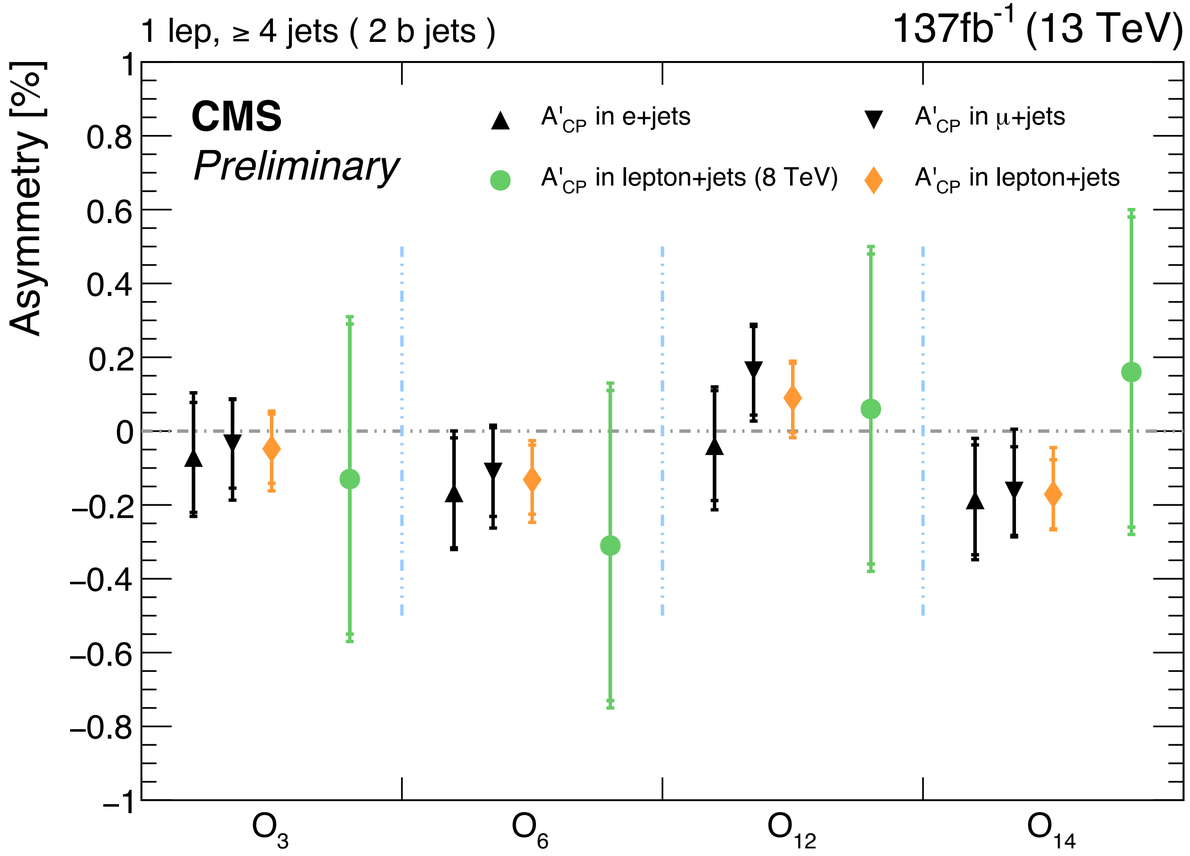
$$D = \epsilon_c - \epsilon_w$$

Correct sign fraction

Wrong sign fraction



CP Violation in Top Quark



Results

- Effective asymmetries A_{CP}' obtained after fitting procedure
- Shown separately for e+jets and μ+jets, as well as combined channel
- No significant evidence of CPV in both channels for each observable, in agreement with SM
- Uncertainties reduced by a factor ~3 compared with 8 TeV results

	$A'_{CP}(\%)$		
	$e+jets$	$\mu+jets$	$Combined$
O_3	$-0.071 \pm 0.149(\text{stat.})^{+0.092}_{-0.058}(\text{syst.})$	$-0.035 \pm 0.120(\text{stat.})^{+0.022}_{-0.094}(\text{syst.})$	$-0.048 \pm 0.094(\text{stat.})^{+0.041}_{-0.065}(\text{syst.})$
O_6	$-0.167 \pm 0.149(\text{stat.})^{+0.077}_{-0.038}(\text{syst.})$	$-0.111 \pm 0.120(\text{stat.})^{+0.042}_{-0.093}(\text{syst.})$	$-0.131 \pm 0.094(\text{stat.})^{+0.049}_{-0.068}(\text{syst.})$
O_{12}	$-0.039 \pm 0.149(\text{stat.})^{+0.056}_{-0.090}(\text{syst.})$	$+0.163 \pm 0.120(\text{stat.})^{+0.038}_{-0.065}(\text{syst.})$	$+0.090 \pm 0.094(\text{stat.})^{+0.034}_{-0.053}(\text{syst.})$
O_{14}	$-0.186 \pm 0.149(\text{stat.})^{+0.075}_{-0.065}(\text{syst.})$	$-0.162 \pm 0.120(\text{stat.})^{+0.117}_{-0.032}(\text{syst.})$	$-0.171 \pm 0.094(\text{stat.})^{+0.085}_{-0.023}(\text{syst.})$

FCNC in Top Quark

UNIVERSITY OF SUSSEX

Flavour Changing Neutral Current in top

- Top quark couples to an **up-type quark** (u or c) and a **neutral boson** (γ,Z,H,g)
- **Forbidden at tree-level in SM** and heavily suppressed at higher orders via GIM suppression
  - not observable with current dataset, BRs $<10^{-12}$
- BSM can **enhance FCNC up to ~10^{-4}**
  - Many potential models e.g. warped extra dimensions, 2HDM, RPV SUSY etc.
  - Any observation of FCNC can indicate new physics
- FCNC probe can be done in both top quark production, and decay

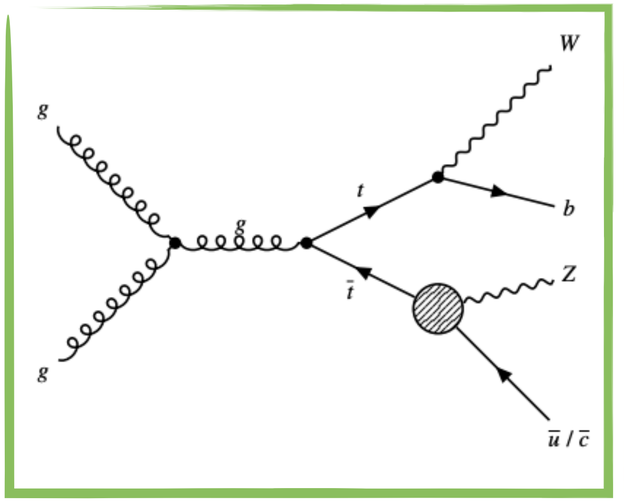
Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

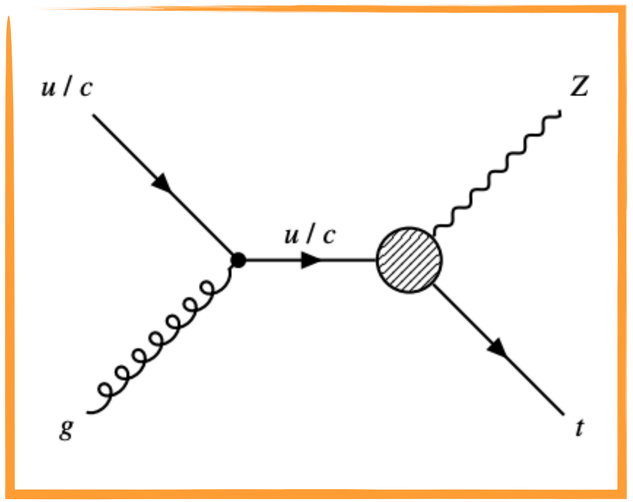
[K. Agashe et al., arXiv:1311.2028]

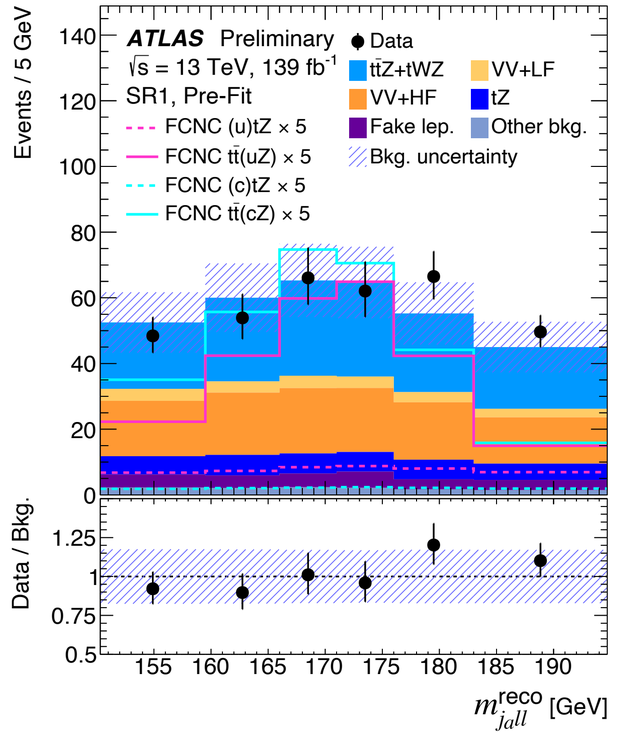
FCNC in Top Quark

Search for tZq couplings

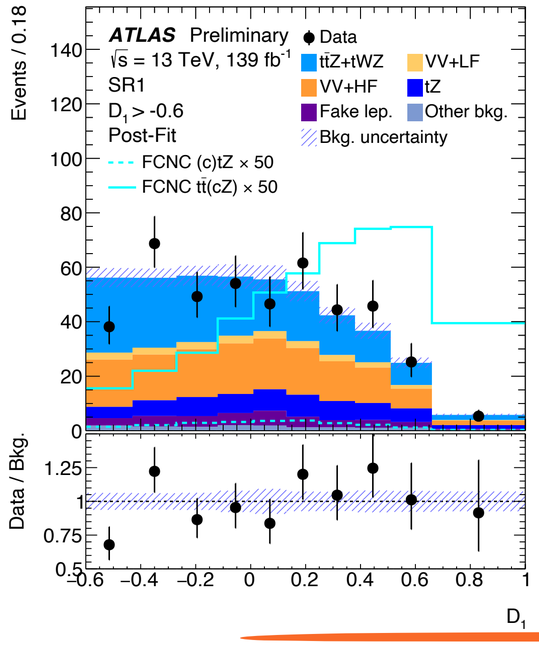
- Analysis using Full Run 2 dataset 139 fb^{-1}
- Event selection:
  - 3 leptons (e, μ), ≥2 jets, (one b-tagged) and E_T^{miss}
  - Only Z boson decays into charged leptons and leptonic W boson decays are considered as signal
- 2 SRs considered targeting FCNC in production and decay:
  - SR1 ($t\bar{t}$ decay): ≥2 jets, 1 b-tag
  - SR2 (tZ production): 1&2 jets,1 b-tag
- Events reconstructed via minimisation of kinematic properties of the final state objects under the FCNC top hypothesis
  - Mass veto to ensure orthogonality in 2j events
- Diboson, $t\bar{t}Z$ and tZ largest background contributions

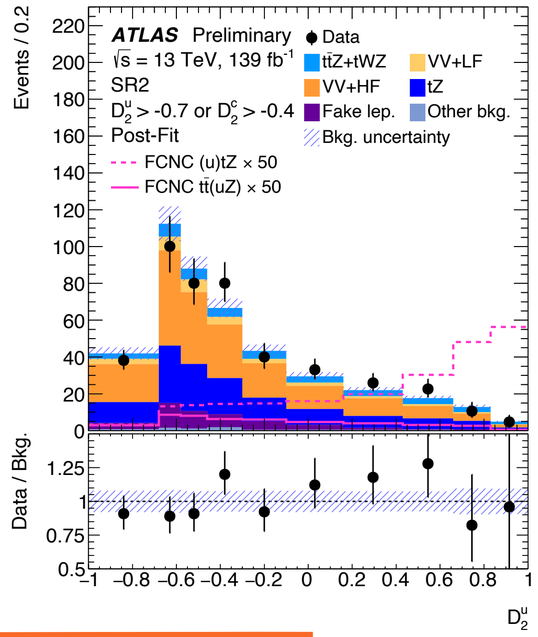






FCNC in Top Quark





Observable	Vertex	Coupling	Observed	Expected
		SR1+CRs		
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	LH	9.7	$8.6^{+3.6}_{-2.4}$
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	RH	9.5	$8.2^{+3.4}_{-2.3}$
		SR2+CRs		
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	LH	7.8	$6.1^{+2.7}_{-1.7}$
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	RH	9.0	$6.6^{+2.9}_{-1.8}$
		SRs+CRs		
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	LH	6.2	$4.9^{+2.1}_{-1.4}$
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	RH	6.6	$5.1^{+2.1}_{-1.4}$
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZc	LH	13	11^{+5}_{-3}
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZc	RH	12	10^{+4}_{-3}
$\lvert C_{uW}^{(13)*}\rvert$ and $\lvert C_{uB}^{(13)*}\rvert$	tZu	LH	0.15	$0.13^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(31)}\rvert$ and $\lvert C_{uB}^{(31)}\rvert$	tZu	RH	0.16	$0.14^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(23)*}\rvert$ and $\lvert C_{uB}^{(23)*}\rvert$	tZc	LH	0.22	$0.20^{+0.04}_{-0.03}$
$\lvert C_{uW}^{(32)}\rvert$ and $\lvert C_{uB}^{(32)}\rvert$	tZc	RH	0.21	$0.19^{+0.04}_{-0.03}$

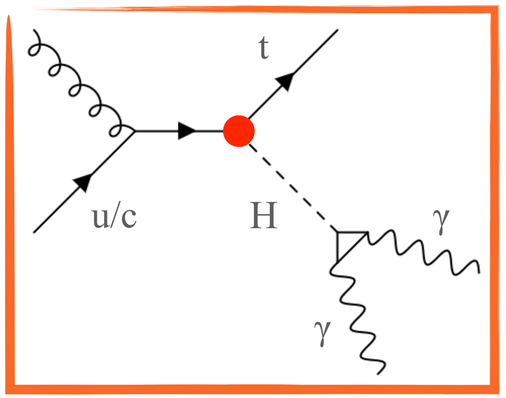
Search for tZq couplings

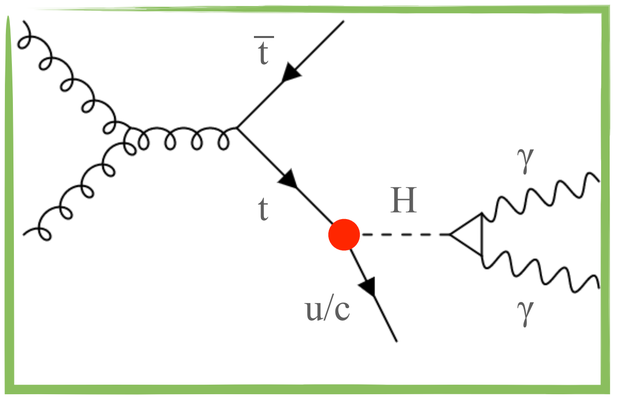
- Gradient BDT used to better separate signal from backgrounds
- Four separate fits performed to extract LH and RH results for the FCNC tZu and tZc couplings:
  - SRs defined by cuts on GBDT discriminant
  - CRs: SR1/2 mass side-bands, $t\bar{t}$ CR and $t\bar{t}Z$ CR
- Good agreement between MC predictions and data
- 95% CL upper limits set on branching ratios
  - Improve by a factor of 2-3 on previous limits
- Limits on relevant EFT Wilson coefficients for vertices also set

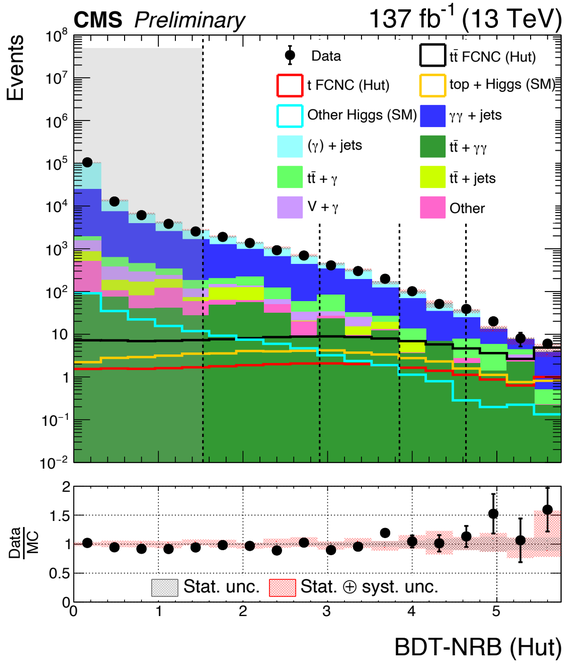
FCNC in Top Quark

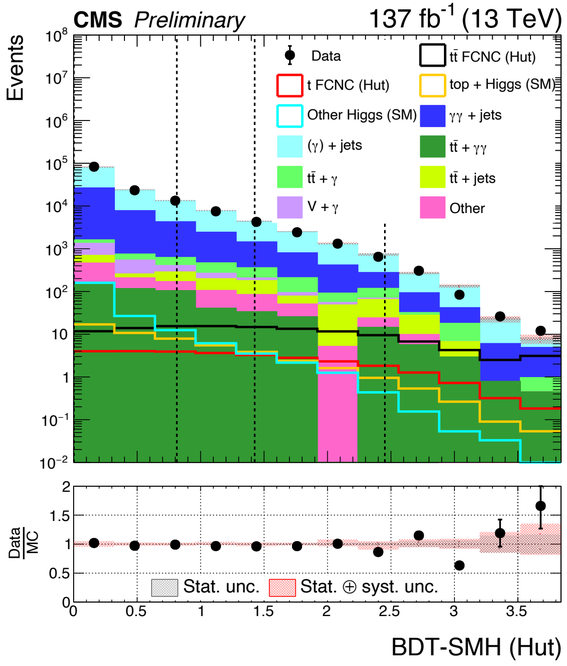
Search for tqH(→γγ) couplings

- Two channels considered:
  - Single top quark FCNC production (pp→tH)
  - Top quark pair production with FCNC decay (t→qH)
- Analysis using Full Run 2 dataset: 137fb^{-1}
- Selection:
  - 2 photon candidates used to build Higgs candidates
    - $100 < m_{\gamma\gamma} < 180$ GeV
  - 2 channels:
    - Leptonic: ≥1 jets, ≥1 leptons
    - Hadronic: ≥3 jets, ≥1 b-tagged jets
- Backgrounds
  - Non-resonant: γ(γ)+jets, tt+γ(γ), V+γ
  - Resonant: $t\bar{t}H$, VH, VBF, ggH, bbH, tH
- Strategy:
  - Total of **8 BDTs** for classification trained using XGBOOST:
    - 2 couplings x 2 channels x 2 bkg. categories
  - 7 categories defined by BDT scores
    - 14 $m_{\gamma\gamma}$ distributions to fit

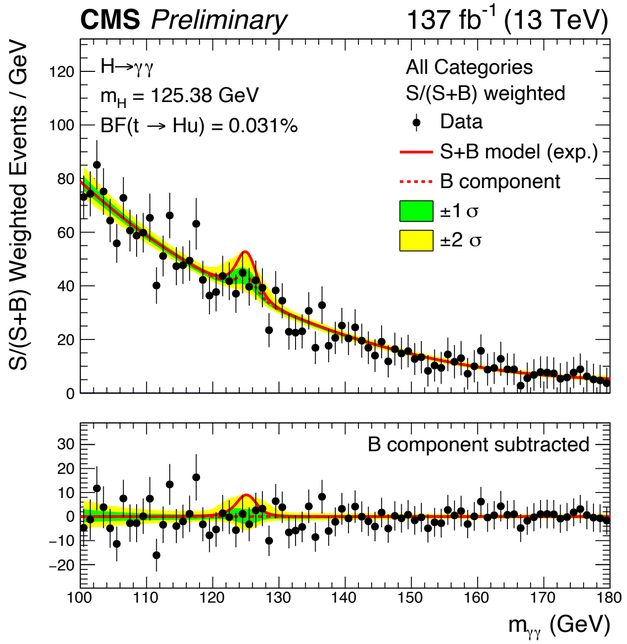


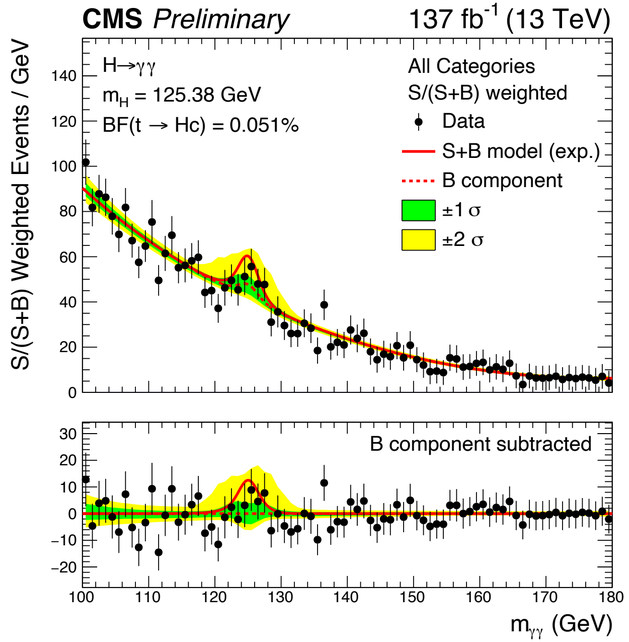


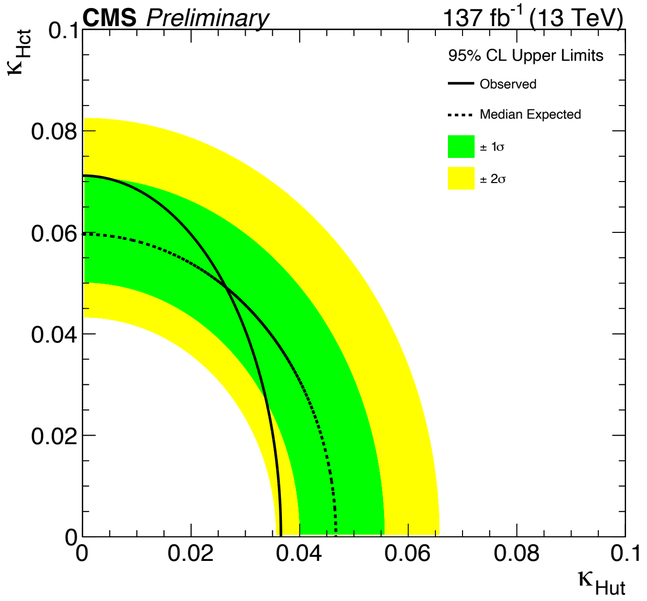


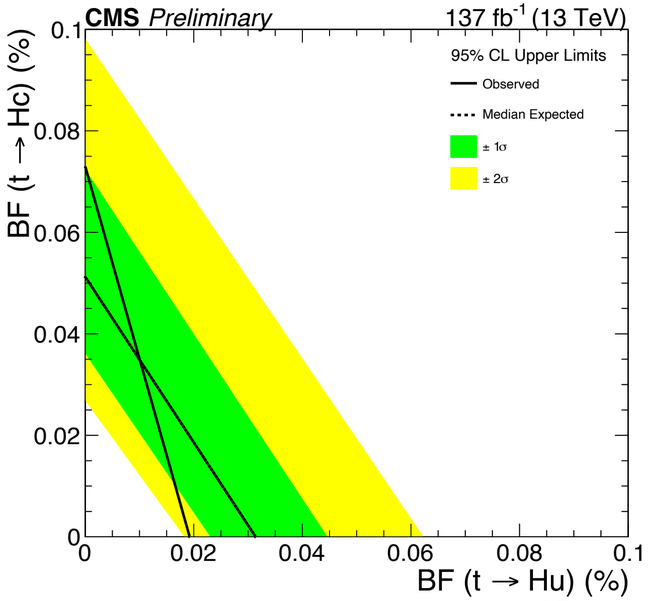


FCNC in Top Quark









Search for tqH(→γγ) couplings

- Simultaneous binned fits of $m_{\gamma\gamma}$ distributions performed for each coupling
- Dominant uncertainties from b-tagging and γ identification
- Data compatible with absence of signal
- Extract 95% CL upper limits of B(t→Hu) and B(t→Hc) as well as anomalous couplings
  - Assumes one non-zero coupling at a time
- Coupling and branching fraction related by:

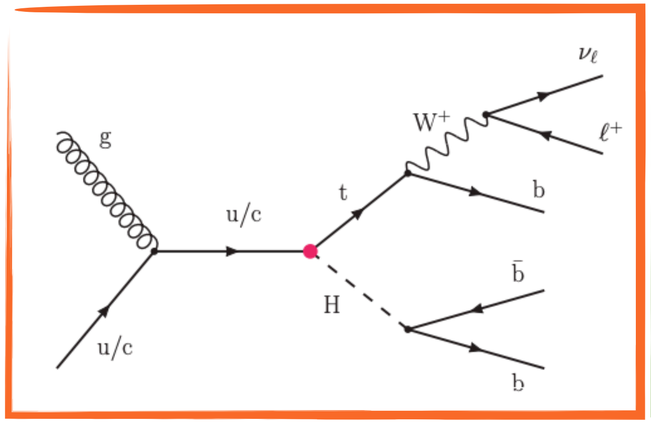
$$\kappa^2_{Hqt} = \mathrm{BF}(t \to Hq)\frac{\Gamma_t}{\Gamma_{Hqt}}$$

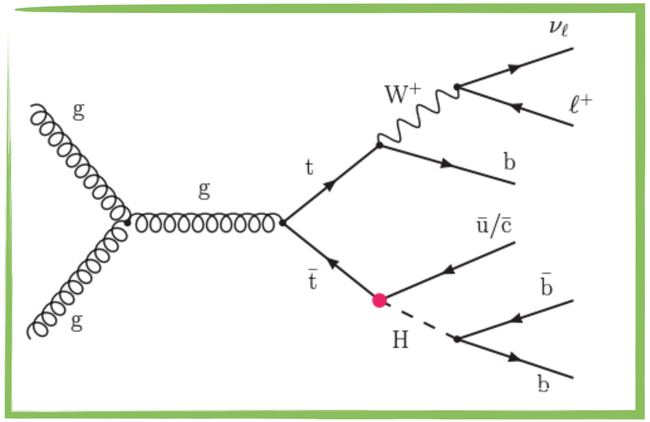
- 95% CL upper limits:
  - BF(t→Hu) <
    - Obs: 1.9×10^{-4}, Exp: 3.1×10^{-4}
  - BF(t→Hc) <
    - Obs: 7.3×10^{-4}, Exp: 5.1×10^{-4}

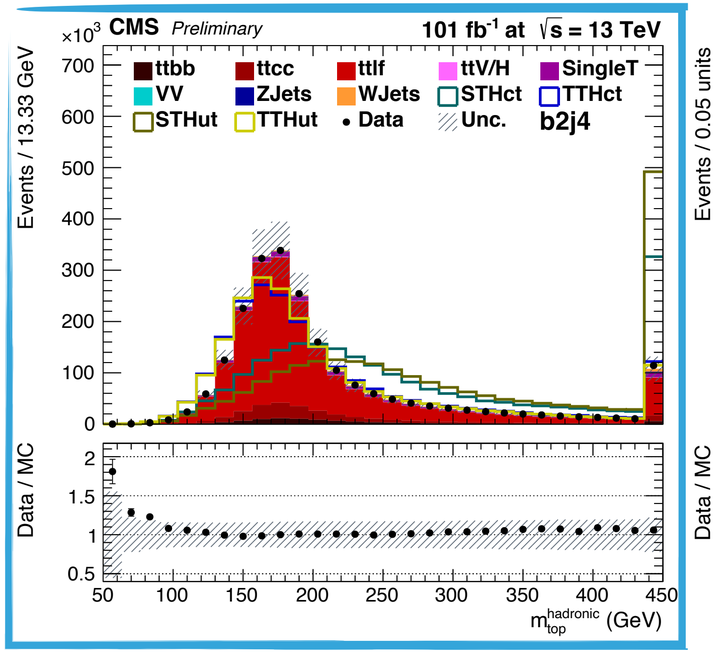
FCNC in Top Quark

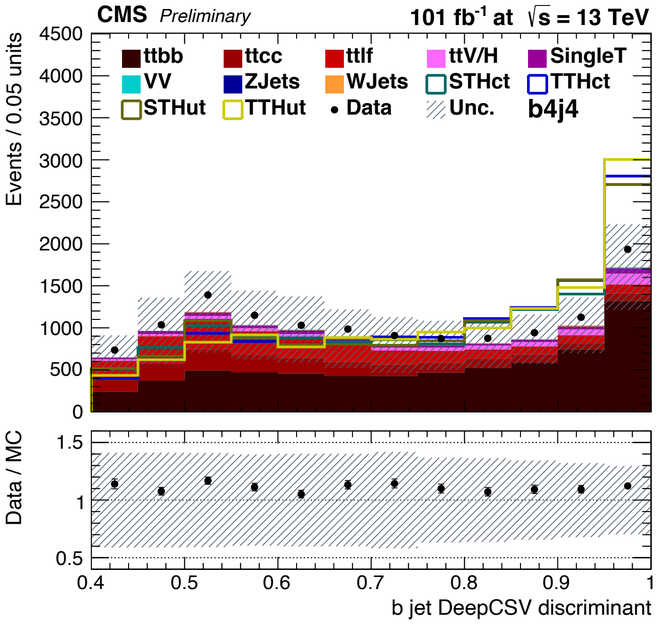
Search for tqH(→bb) couplings

- Analysis with Full Run 2 dataset 137fb^{-1}
- FCNC considered in both production and decay channels
- Looks for events with:
  - One isolated lepton (e,μ) and at least 3 jets, at least 2 b-tagged
  - Reconstructed with DNNs targeting the different processes
    - Associate combination of objects to the matrix-element partonic final state
- Dominant background is SM $t\bar{t}$ production
- Dedicated BDT discriminants for 5 signal regions to distinguish signal from backgrounds

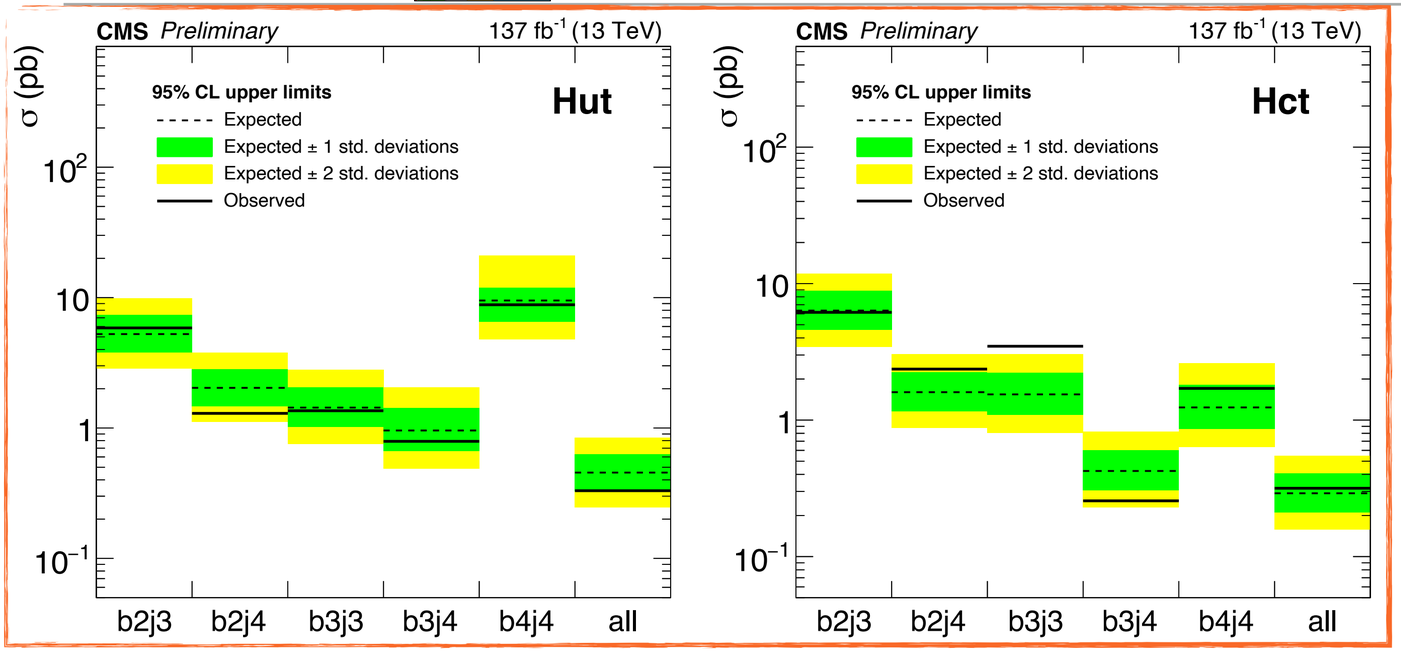


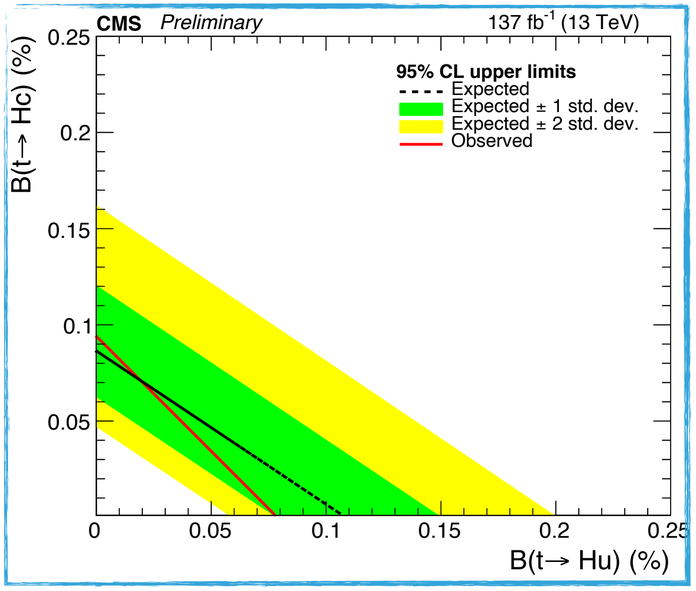


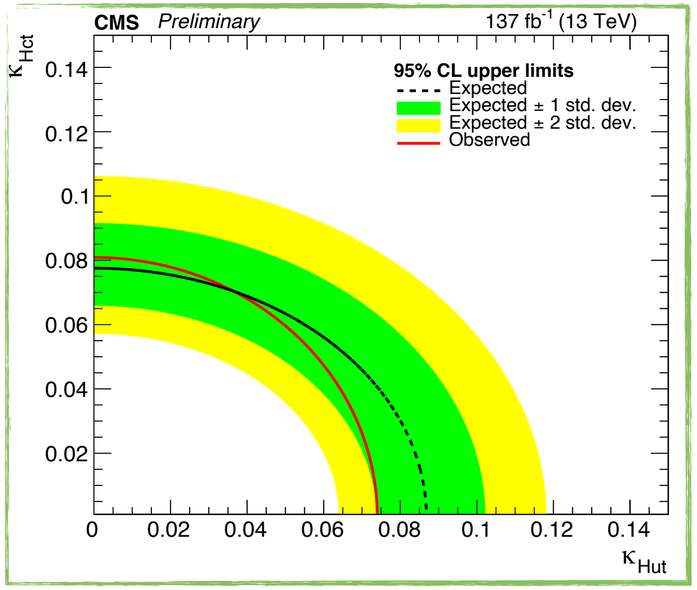




FCNC in Top Quark





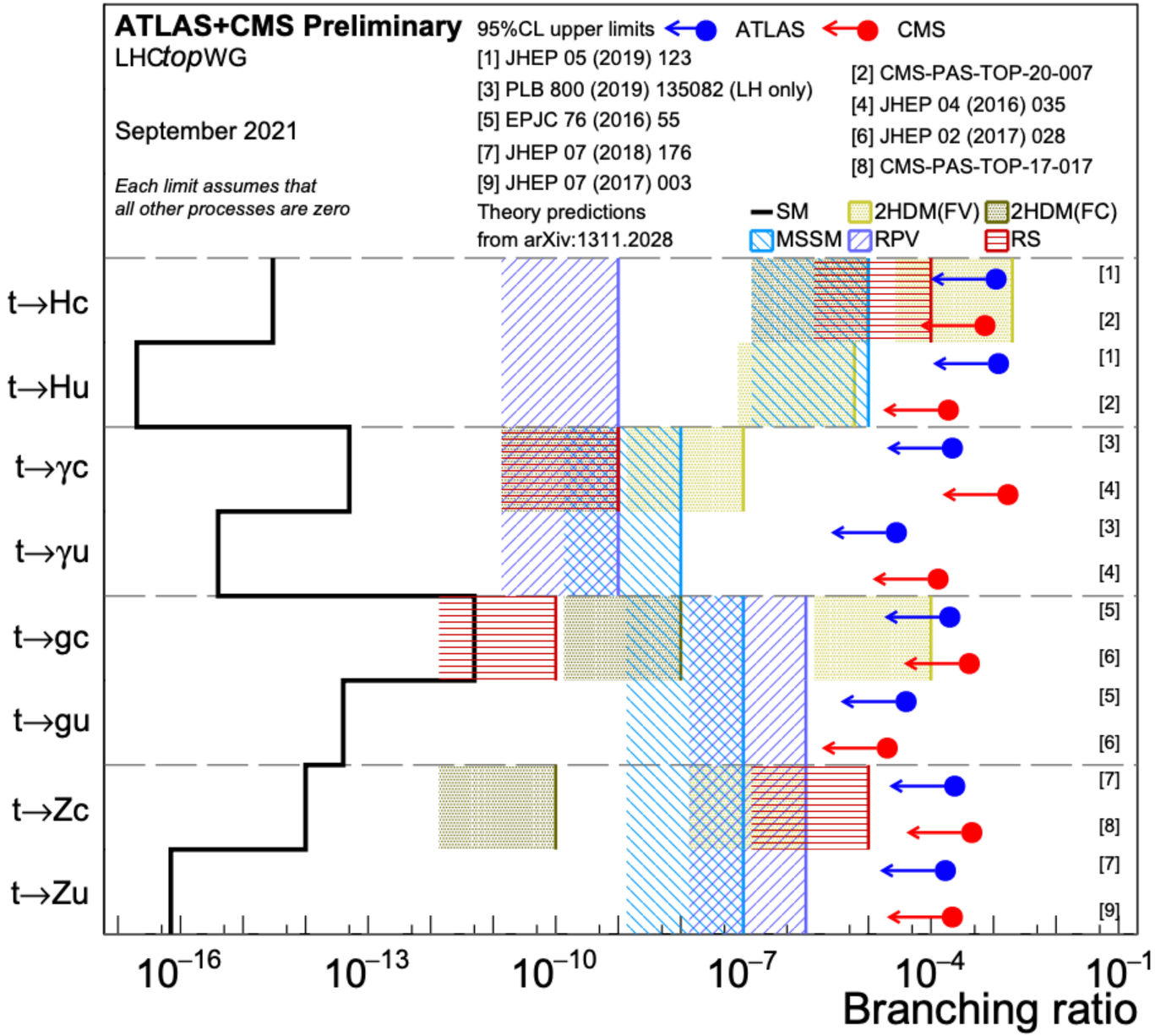


Search for tqH(→bb) couplings

- No significant excess with respect to the SM backgrounds expectations
- Set 95% CL limits on the cross-sections, couplings and branching ratios of t→qH process
- All b-jet and jet categories combined for fit
  - b3j4 category has highest sensitivity
- Dominant uncertainty comes from b-tagging (mis-)identification rate
- Upper limits:
  - $B(t \to Hu) <$
    - Obs: 7.9×10^{-4}, Exp: 1.1×10^{-3}
  - $B(t \to Hc) <$
    - Obs: 9.4×10^{-4}, Exp: 8.6×10^{-4}
- Significant improvement (factor 3-6) compared to early Run 2 search JHEP 06(2018) 102

FCNC in Top Quark

New!



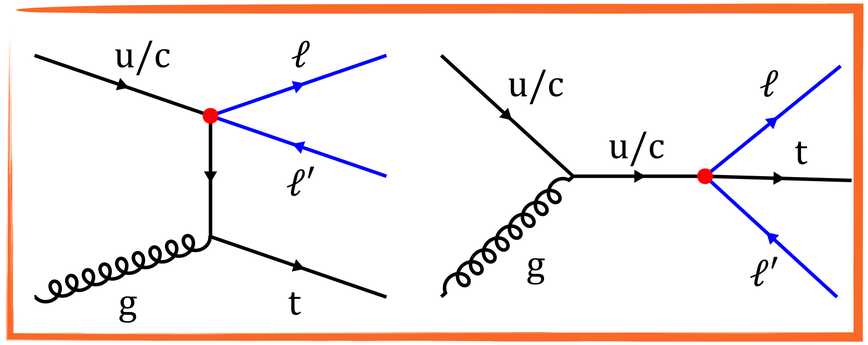
Note: new tZq results not included

LFV in top quarks

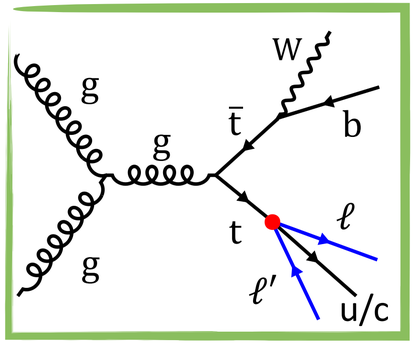
Search for eμ LFV interactions

- Lepton flavour conserved in all SM interactions:
  - Neutrino mass terms predict charged Lepton flavour violation (CLFV) at loop level
  - Highly suppressed due to the tiny neutrino masses
  - Any experimental evidence would serve as clear signature of new physics
- Many new physics models predict sizeable CLFV:
  - leptoquarks, multi-Higgs doublets, MSSM, inverse seesaw, …
- If new physics responsible for CLFV, at scales beyond available at LHC, SM Lagrangian can be extended by dimension-6 operators
  - Grouped by operator type

Production



Decay



Dim-6 operators involved in CLFV

$$
\begin{aligned}
O_{\mathrm{lq}}^{(3)ijkl} &= (\bar{\mathrm{l}}_i\gamma^\mu\tau^I\mathrm{l}_j)(\bar{\mathrm{q}}_k\gamma^\mu\tau^I\mathrm{q}_l),\\
O_{\mathrm{lq}}^{(1)ijkl} &= (\bar{\mathrm{l}}_i\gamma^\mu\mathrm{l}_j)(\bar{\mathrm{q}}_k\gamma^\mu\mathrm{q}_l),\\
O_{\mathrm{lu}}^{ijkl} &= (\bar{\mathrm{l}}_i\gamma^\mu\mathrm{l}_j)(\bar{\mathrm{u}}_k\gamma^\mu\mathrm{u}_l),\\
O_{\mathrm{eq}}^{ijkl} &= (\bar{\mathrm{e}}_i\gamma^\mu\mathrm{e}_j)(\bar{\mathrm{q}}_k\gamma^\mu\mathrm{q}_l),\\
O_{\mathrm{eu}}^{ijkl} &= (\bar{\mathrm{e}}_i\gamma^\mu\mathrm{e}_j)(\bar{\mathrm{u}}_k\gamma^\mu\mathrm{u}_l),\\
O_{\mathrm{lequ}}^{(1)ijkl} &= (\bar{\mathrm{l}}_i\mathrm{e}_j)\,\varepsilon\,(\bar{\mathrm{q}}_k\mathrm{u}_l),\\
O_{\mathrm{lequ}}^{(3)ijkl} &= (\bar{\mathrm{l}}_i\sigma^{\mu\nu}\mathrm{e}_j)\,\varepsilon\,(\bar{\mathrm{q}}_k\sigma_{\mu\nu}\mathrm{u}_l),
\end{aligned}
$$

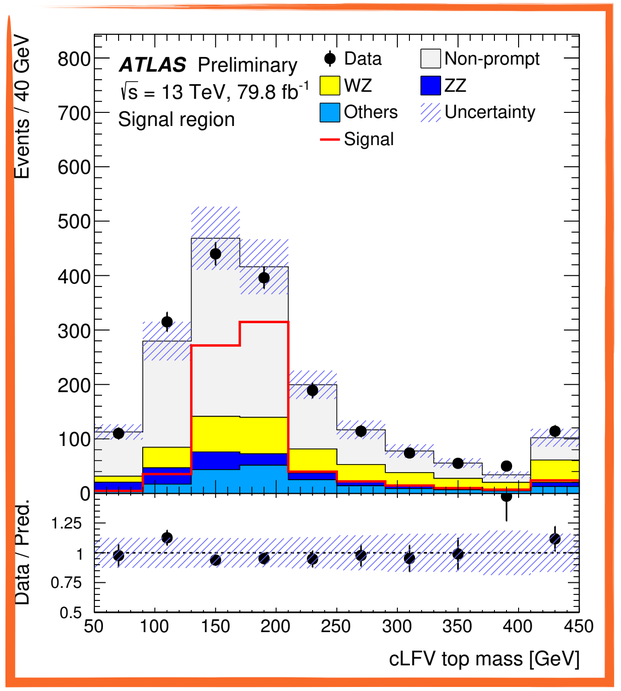
CLFV interaction types

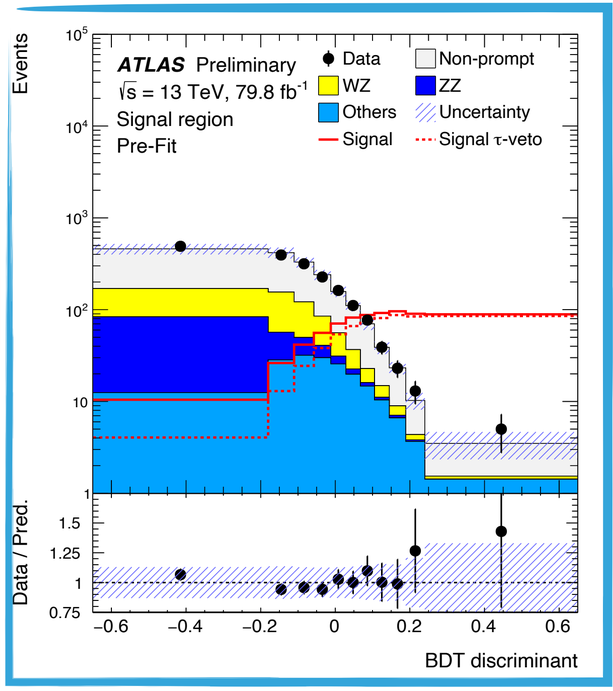
$$
\begin{aligned}
O_{\mathrm{vector}} &= O_{\mathrm{lq}} + O_{\mathrm{lu}} + O_{\mathrm{eq}} + O_{\mathrm{eu}},\\
O_{\mathrm{scalar}} &= O_{\mathrm{lequ}}^{(1)},\\
O_{\mathrm{tensor}} &= O_{\mathrm{lequ}}^{(3)}
\end{aligned}
$$

LFV in top quarks

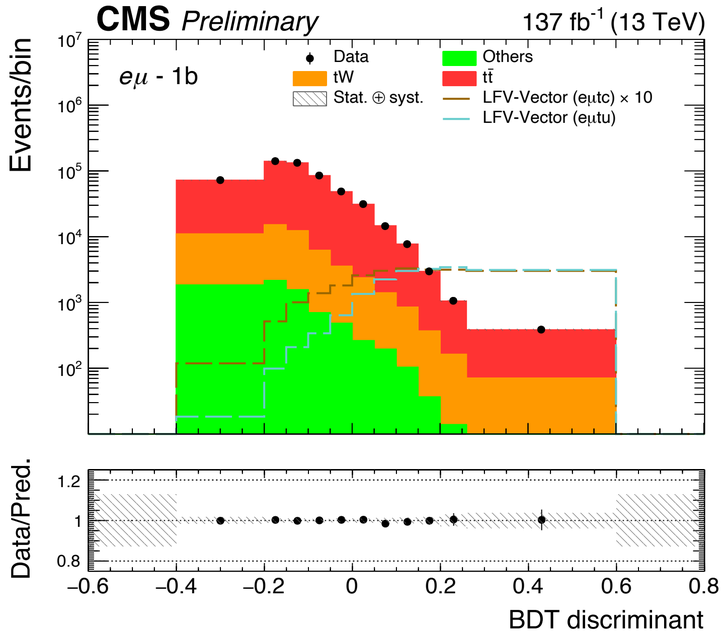
Search for eμ LFV interactions

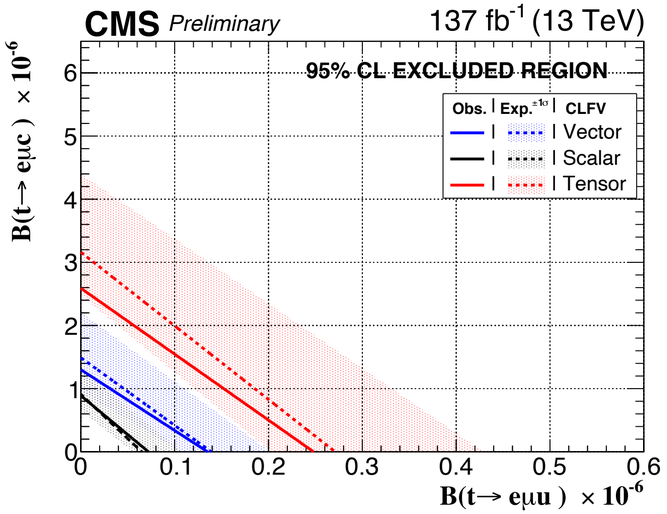
- Search for CLFV in final states with three isolated charged leptons using 80 fb^{-1}
  - Decay only considered
- CLFV top reconstructed from two opposite sign different-flavour leptons and a jet
- Backgrounds:
  - Non-prompt: $t\bar{t}$ & Z+jets
    - estimated with matrix method in data (dominant uncertainty)
  - Prompt: WZ, ZZ
- BDT is used to discriminate signal from background events
- Data consistent with SM expectation
- Upper limits are set at 95% CL
  - B(t→ll'q) <
    - Obs: 1.86 ×10^{-5}, Exp: 1.36 ×10^{-5}
  - B(t→eμq) <
    - Obs: 6.6 ×10^{-6}, Exp: 4.8 ×10^{-6}

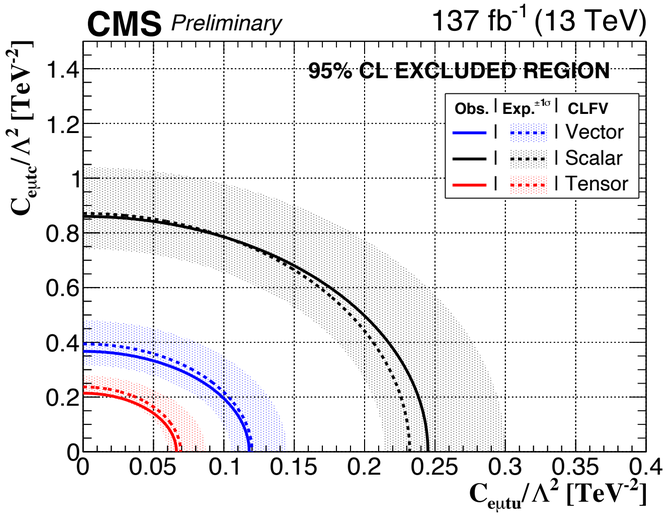




LFV in top quarks







Search for eμ LFV interactions

- Search for both production & decay CLFV in eμ final state @13 TeV with 137 fb^{-1}
- Selection:
  - oppositely charged eμ pair, $m_{e\mu} > 20$ GeV
  - ≥1 jets, with at least 1 b-tag (SR ≡1b-tag)
- $t\bar{t}$ is dominant background
  - Estimated in CR with ≥2 b-tags
- BDT is used to discriminate signal from background events
- Data consistent with SM expectation
- Upper limits are set on CFLV Wilson coefficients and branching fractions at 95% CL:
  - B_{scalar} (t→eμu(c)) < 0.07 × 10^{-6} (0.89 × 10^{-6})
  - B_{vector} (t→eμu(c)) < 0.135 × 10^{-6} (1.3 × 10^{-6})
  - B_{tensor} (t→eμu(c)) < 0.25 × 10^{-6} (2.59 × 10^{-6})

Summary

- Lots of on-going searches for BSM effects in the top sector:
  - Deviations from SM in angular distributions
  - CPV in top quarks
  - FCNC production and decays of top quarks
  - Lepton Flavour Violation
- Contributions of new physics can be parameterised using EFTs
- Results so far in agreement with the SM and no significant deviations observed

Thanks for listening!