RESULTS ON RARE AND BSM TOP QUARK INTERACTIONS

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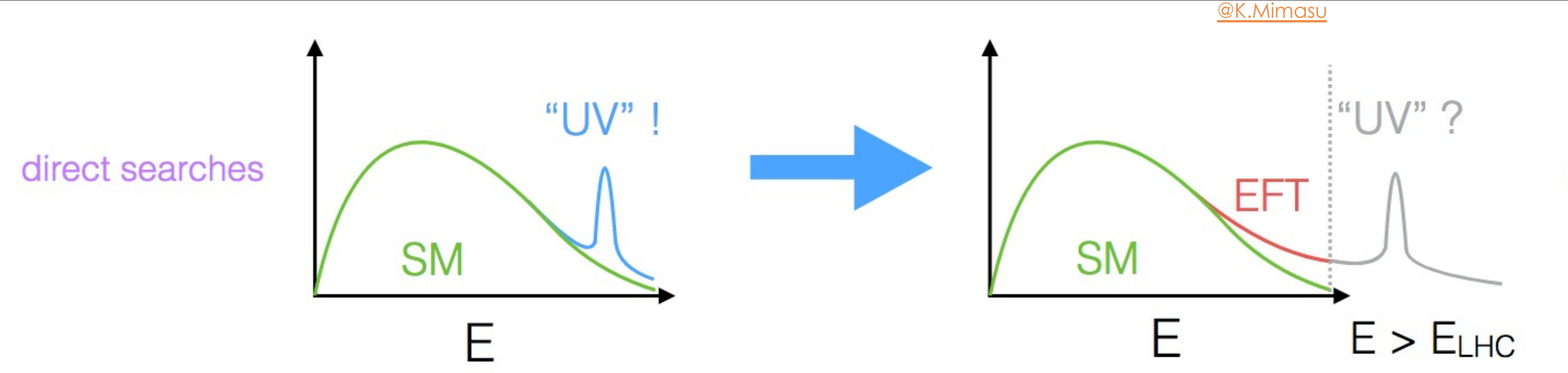
On behalf of the ATLAS and CMS Collaborations

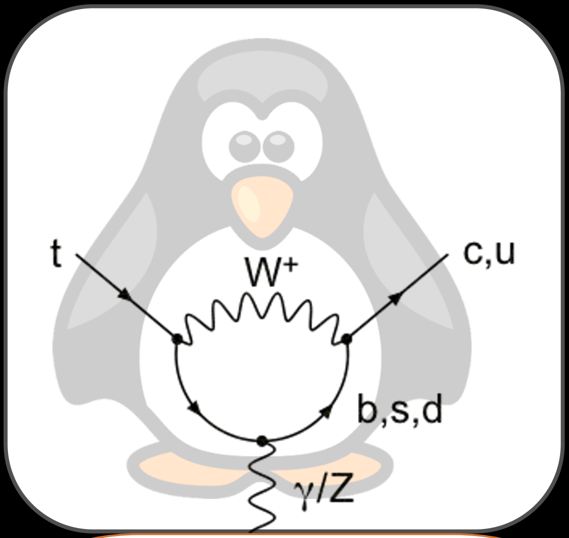
Search for physics BSM

- Standard Model (SM) has been very successful at explaining experimental data
- Some unanswered questions
  - Nature of dark matter, origin of flavor, neutrino mass, matter-antimatter asymmetry,…
  - Experimental hints from SM deviations in flavor sector
- we keep searching beyond the SM
  - **Direct searches** when new physics (NP) scale is with the reach of the LHC's collision energy
    - Resonant or non-resonant production of new particles
  - **Indirect searches** when NP energy is beyond the reach of the LHC's collision energy
    - Rare production and decay of top quark
    - Deviations from SM in measurements of top properties



Search for FCNC in the top sector

- Flavor changing neutral currents (FCNC) allow for transitions between quarks of different flavor but same electric charge
- FCNC processes are highly suppressed in the SM due to the GIM mechanism
  - Small contributions appear at one loop level
- Many extensions of the SM predict the presence of FCNC and give rise to detectable FCNC amplitude



	SM	QS	2HDM	FC 2HDM	MSSM	$R\!\!\!/$ SUSY
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	–	–	2×10^{-6}	3×10^{-5}
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	–	–	2×10^{-6}	1×10^{-6}
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	–	–	8×10^{-5}	2×10^{-4}
$t \to uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	–	10^{-5}	$\sim 10^{-6}$
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$

Branching ratios for top FCN decays in the SM, models with $Q = 2/3$ quark singlets (QS), a general 2HDM, a flavour-conserving (FC) 2HDM, in the MSSM and with R parity violating SUSY.

Aguilar-Saavedra, ACTA Phys. Pol. B 35(2004)

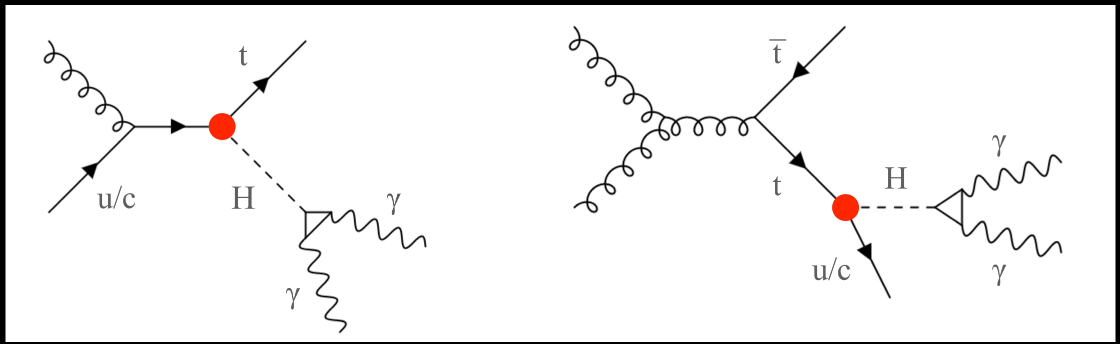
Any evidence of FCNC will indicate the existence of new physics

Search for the FCNC tHq interaction

(CMS-PAS-TOP-20-007)

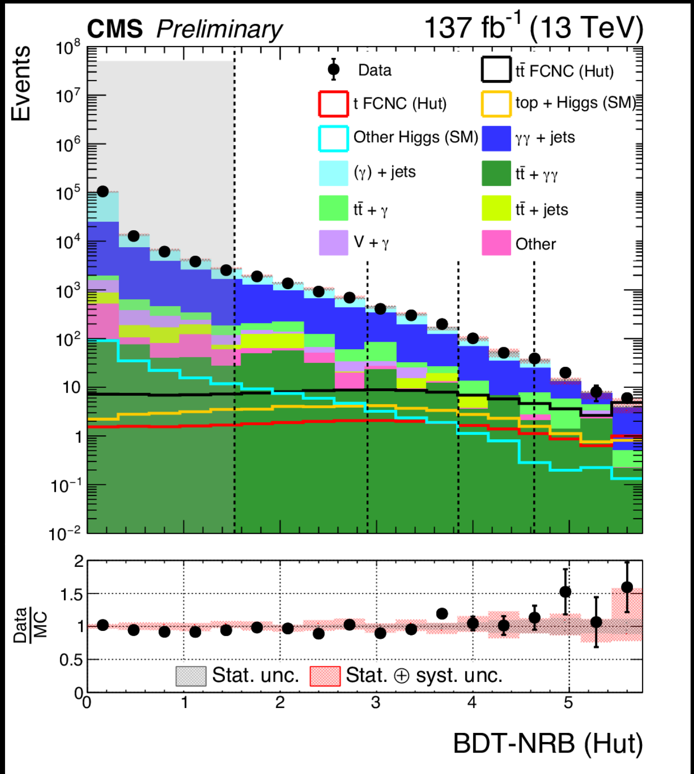
- Search for tHq (q = u,c), **H→γγ** [137 fb^{-1}]
- Production & decay
- Signal regions: 2 photons, 100 < $m_{\gamma\gamma}$< 180 GeV
  - leptonic: ≥1 jet, ≥1ℓ
  - hadronic: ≥3 jet, ≥1 b-jet

Production Decay

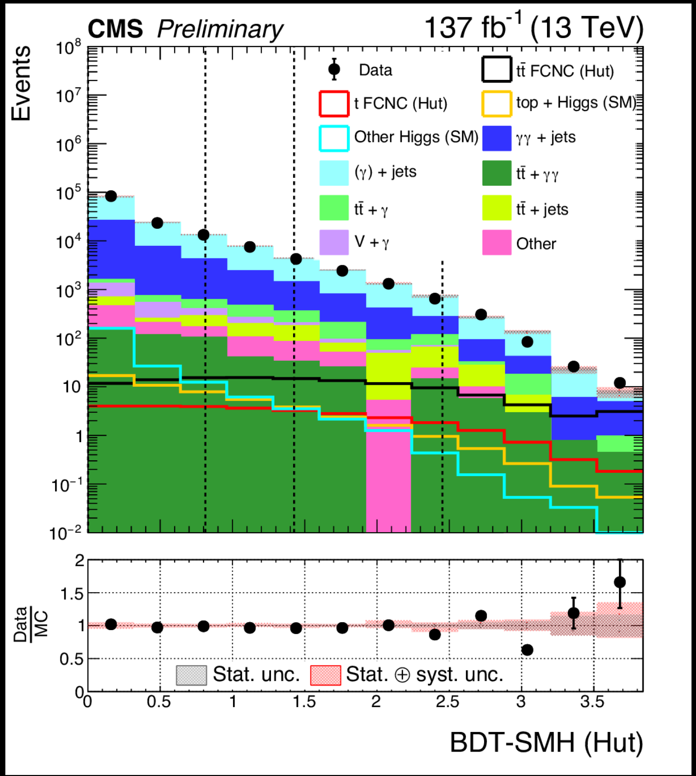


- Backgrounds
  - resonant: ttH, VH, VBF, ggH, bbH, tH
  - non-resonant: γ(γ)+jets, tt+γ(γ), V+γ

- Strategy
  - 8 BDTs: (u, c) × (lep, had) × (res, non-res bkg)
  - 7 categories defined by BDT score
  - 14 $m_{\gamma\gamma}$ distributions to fit



Non-resonant BG

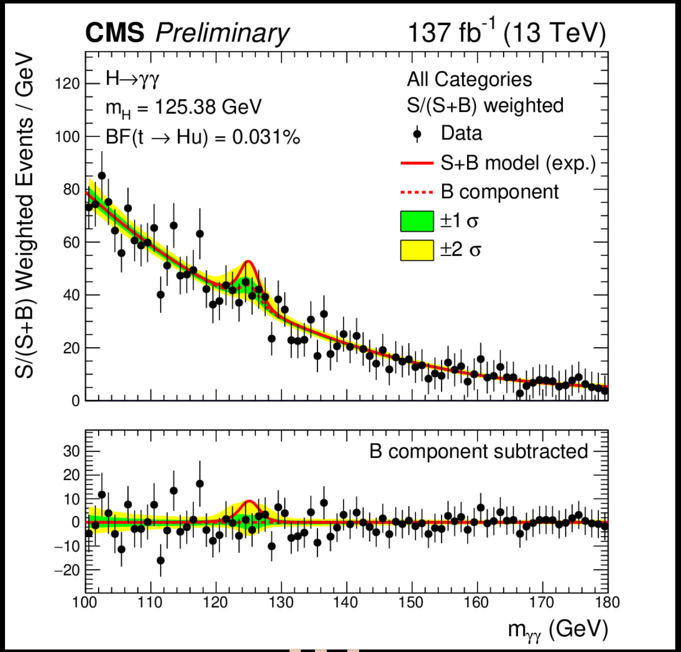


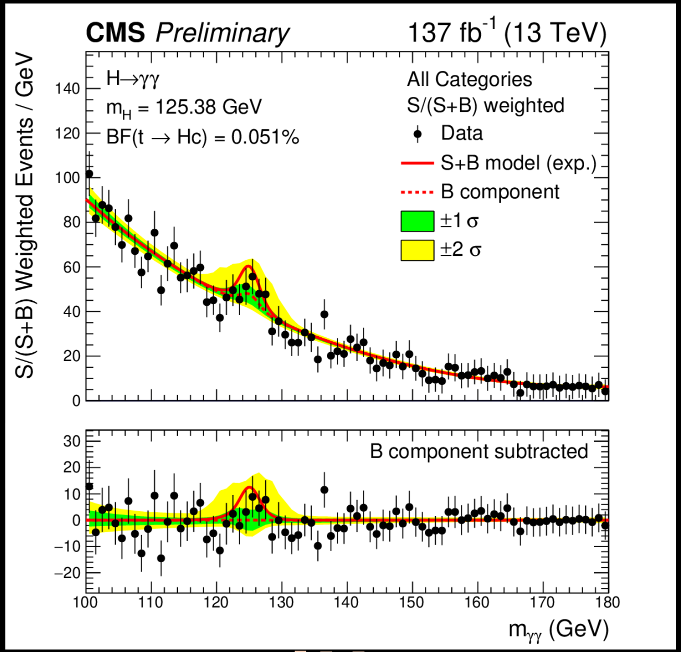
Resonant BG

- Signal modeling: effective Lagrangian

$$\mathcal{L} = \sum_{q=u,c} \frac{g}{\sqrt{2}} \bar{t} \kappa_{Hqt} \left(F^{L}_{Hq} P_L + F^{R}_{Hq} P_R \right) qH + h.c.,$$

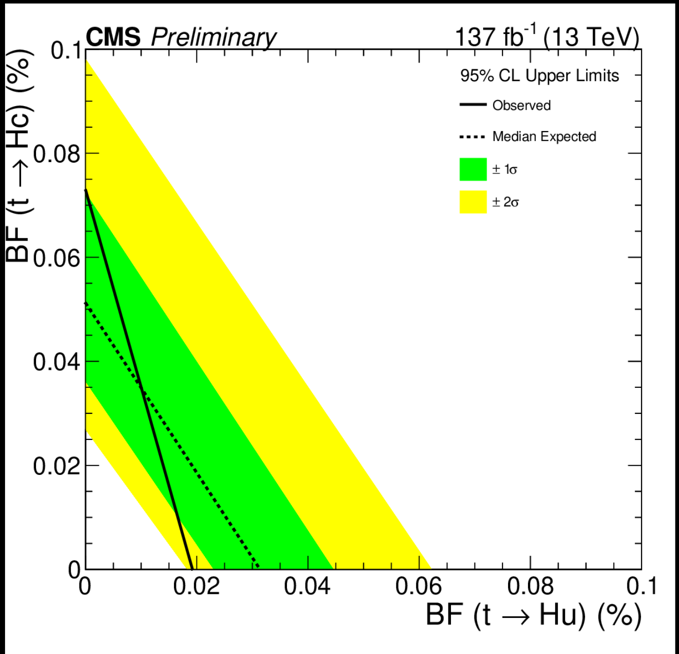
- Dominant uncertainties: b-tagging and γ identification
- Data compatible with absence of signal
- Upper limits on the signal cross sections are translated to the strength of the tqH anomalous couplings and related branching fractions
- 95% CL upper limits:
  - $B(t \to Hu) < 1.9\times10^{-4}$ (exp. 3.1×10^{-4})
  - $B(t \to Hc) < 7.3\times10^{-4}$ (exp. 5.1×10^{-4})

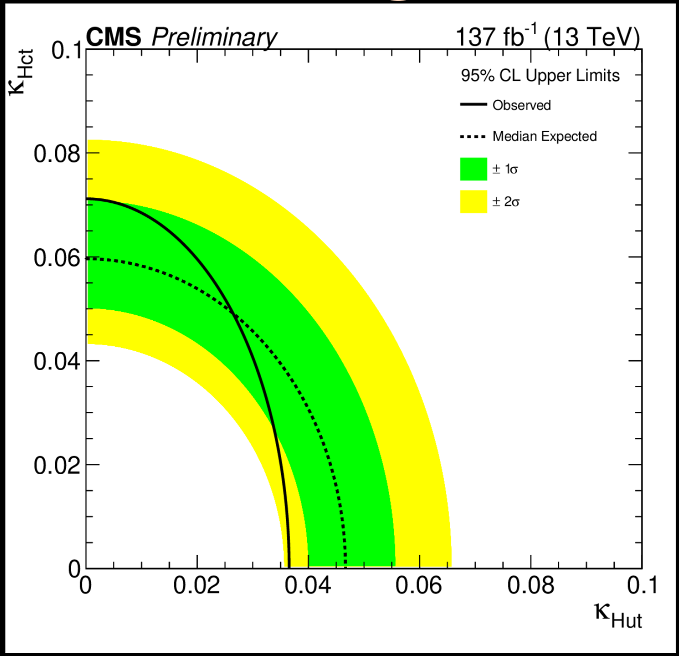




tHu

tHc



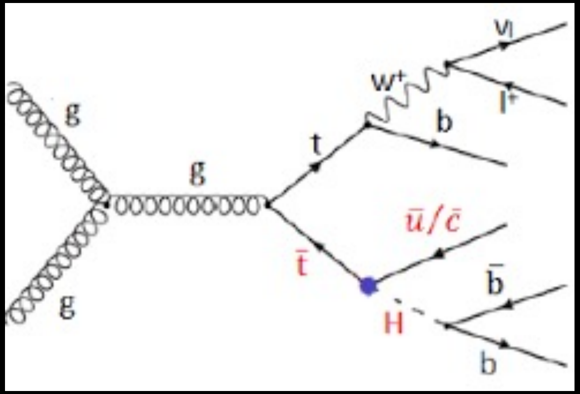


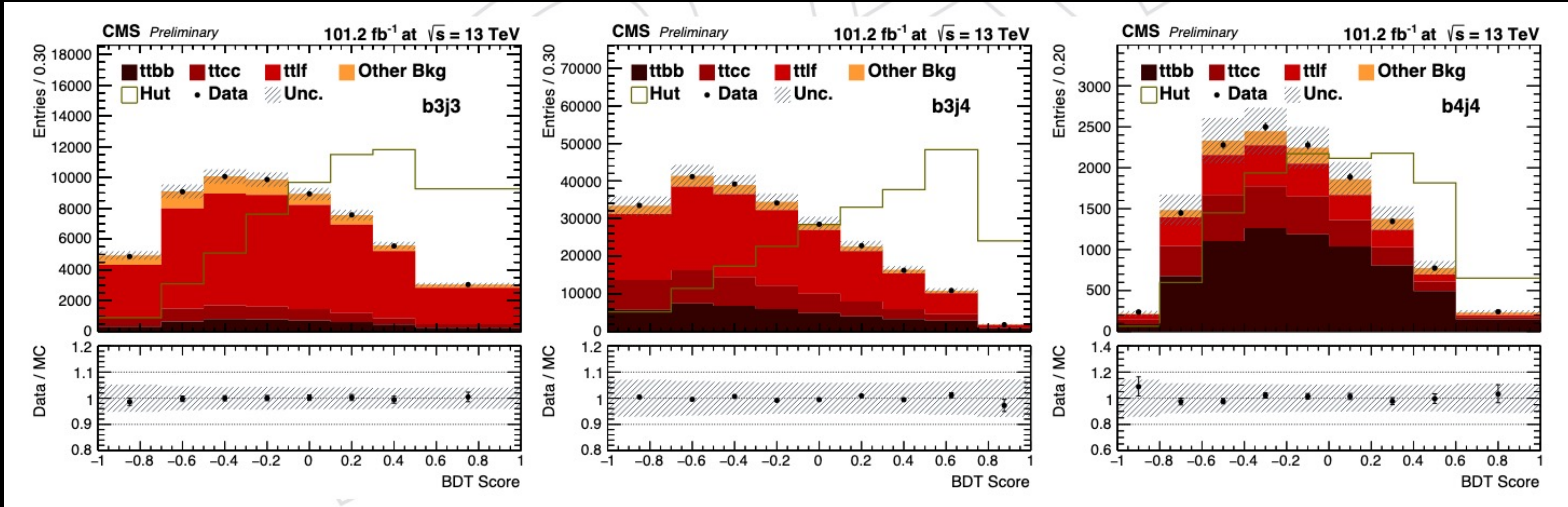
Search for the FCNC tHq interaction

(CMS-PAS-TOP-19-002)

new

- Searches for tHq (q = u,c), **H→bb** [137 fb^{-1}]
- Production & decay
- Signal region: 1ℓ , ≥3 jet, ≥2 b-jet
- A deep neural network is used to associate the reconstructed objects to the matrix-element partonic final state
- BDTs are used to distinguish the signal from the background events

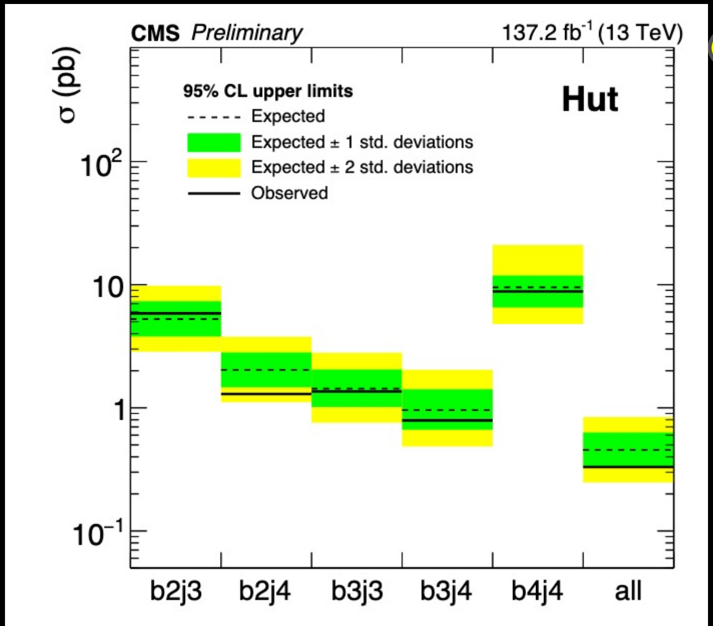




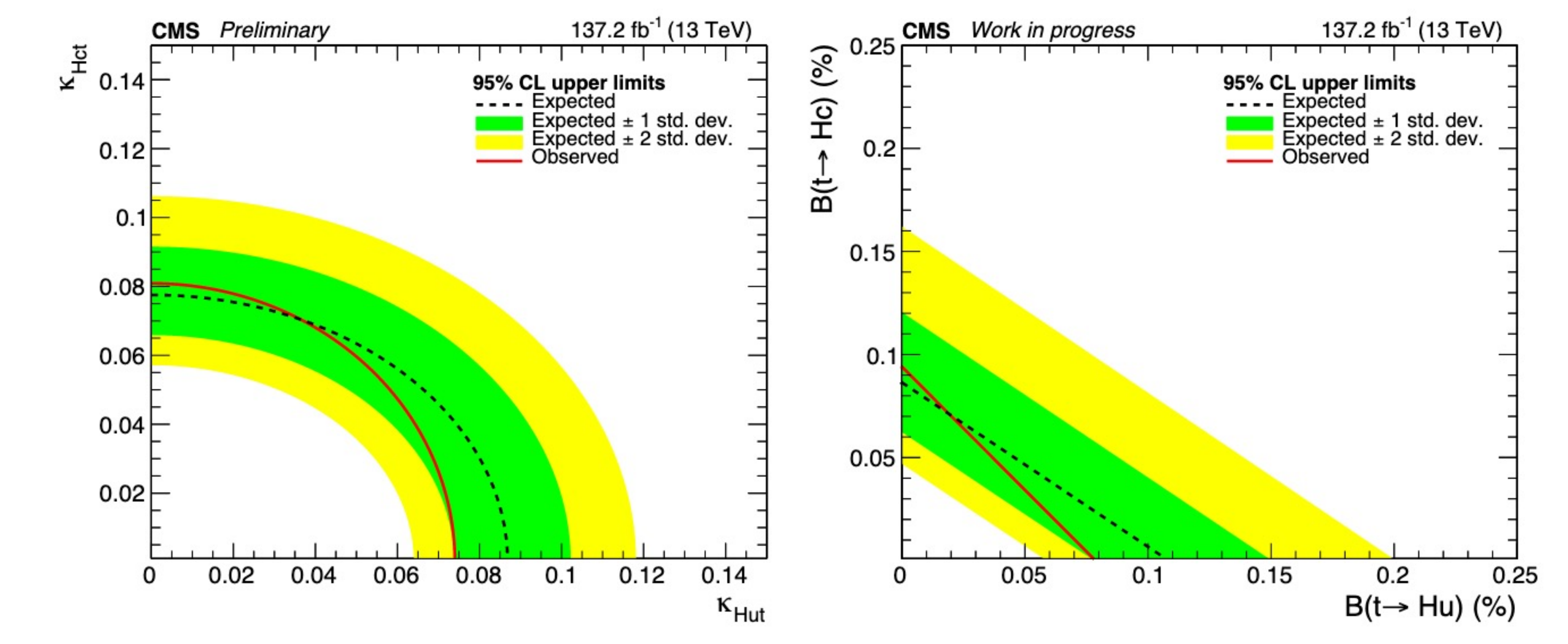
(c) b3j3 (d) b3j4 (e) b4j4

new

- No significant excess with respect to the SM background expectations
  - 95% CL limits are set on the xs, couplings and BRs
- All bjet-jet categories are combined
  - The b3j4 category has the highest sensitivity
- Significant improve with respect to the early run-2 search
  - JHEP 06 (2018) 102

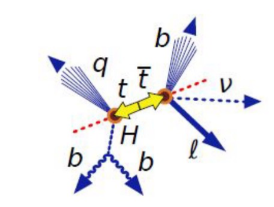


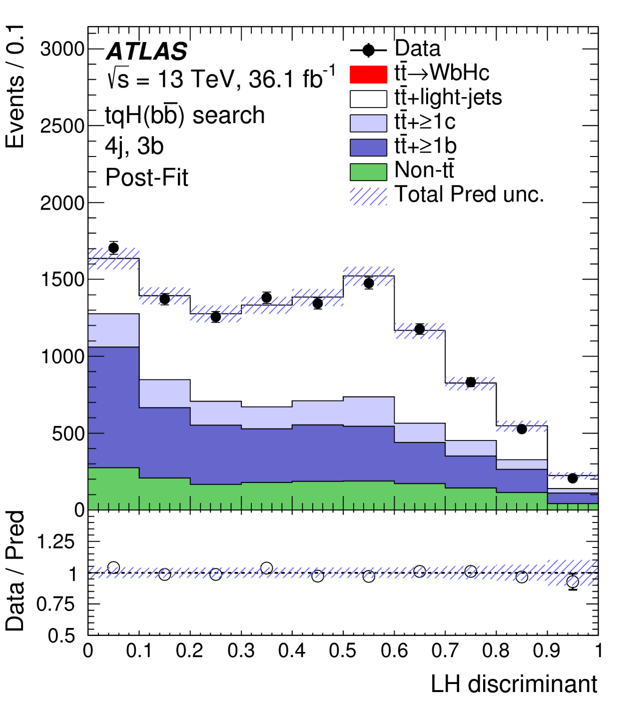
- Upper limits:
  - $B(t \to Hu) <$
    - obs: 8×10^{-4}
    - exp: 11×10^{-4}
  - $B(t \to Hc) <$
    - obs: 9×10^{-4}
    - Exp: 9×10^{-4}



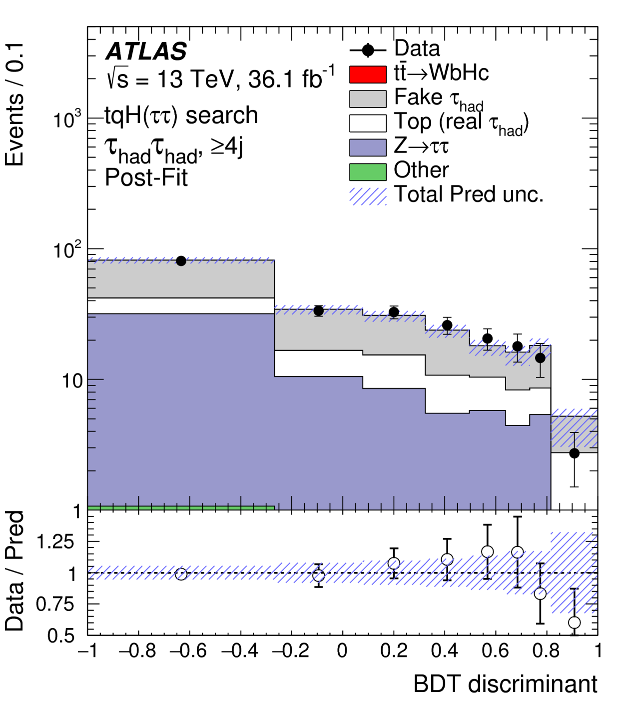
Search for the FCNC tHq interaction [JHEP 05 (2019) 123]

- Searches for tHq (q = u,c) FCNC decays in tt events [36 fb^{-1}]
- H→bb
  - Single lepton, ≥ 4 jets (2 b-tagged)
  - Backgrounds: ttbar+HF/LF
  - Data-driven estimate for non prompt leptons
  - Event classification on the jet (4, 5, ≥ 6) and b-tagged jet (2, 3, ≥ 4)
  - Likelihood-based discriminant

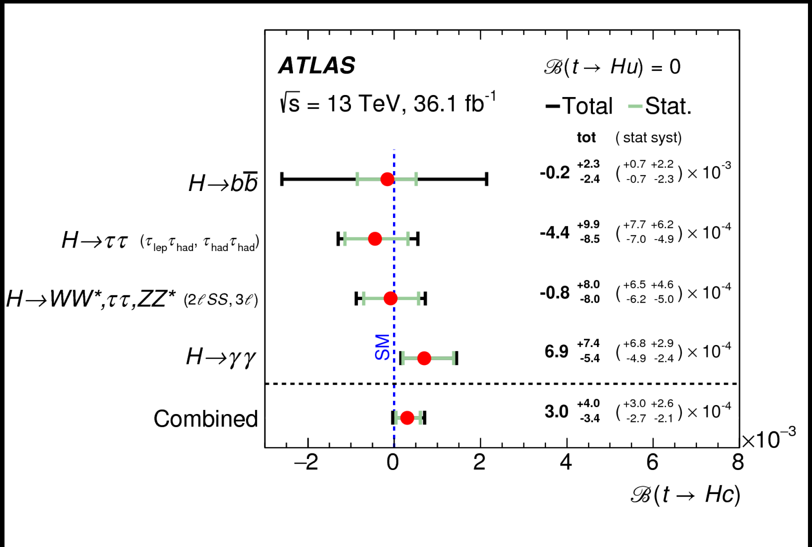


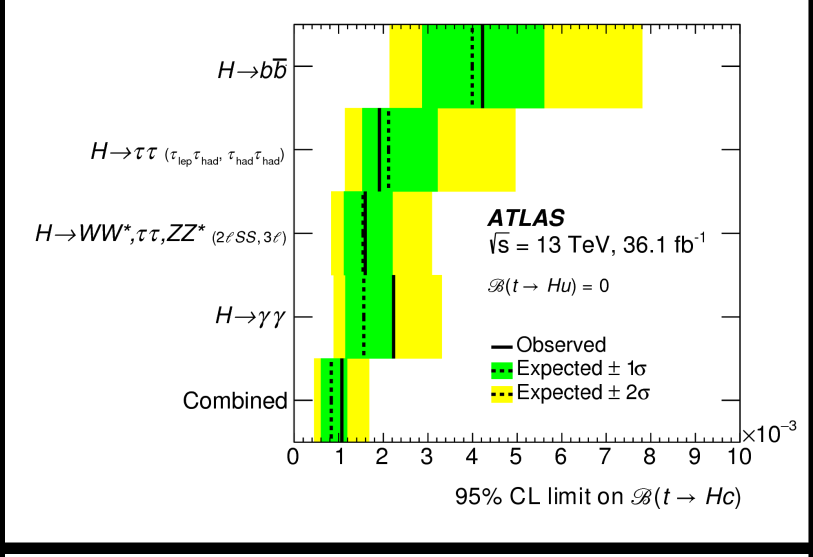


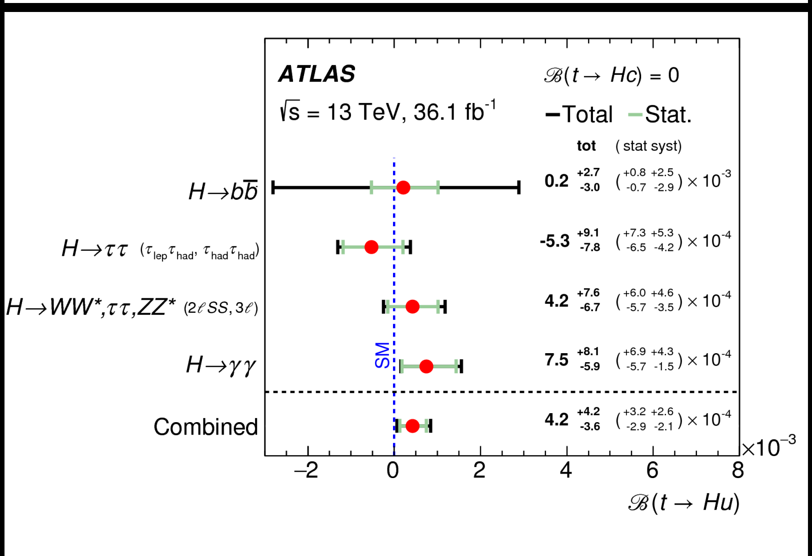
- H→ $\tau\tau$
  - Single lepton ($\tau_{lep}\tau_{had}$), di-tau ($\tau_{had}\tau_{had}$), ≥ 3 jets (1 b-tagged)
  - Backgrounds: fakes (ttbar), Z→$\tau\tau$
  - Data-driven estimate for fake τ_{had}
  - Event classification on the jet multiplicity (3j, ≥ 4j)
  - BDT discriminant

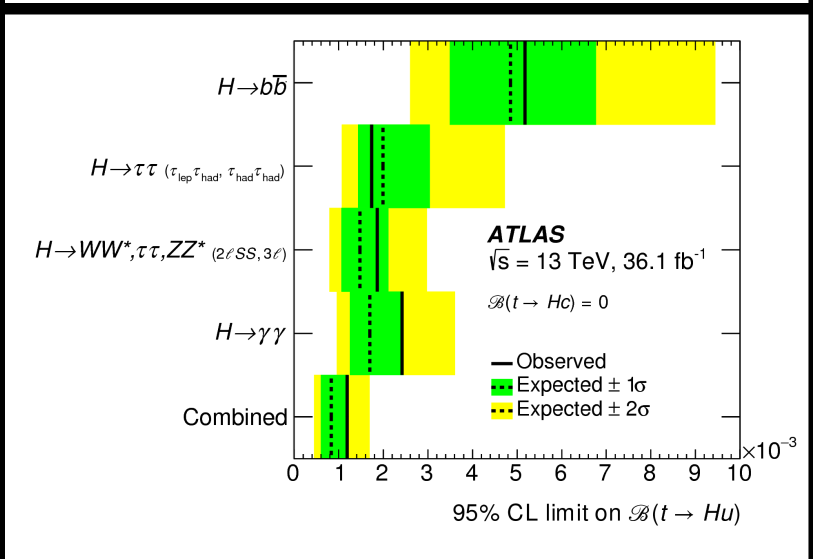


- No significant excess of events above the background expectation is found
  - 95% CL upper limits on the t→Hq
- Results are combined with
  - H→γγ [JHEP10 (2017) 129]
  - H→WW*, ττ, ZZ* (2ℓvSS,3ℓ) [Phys. Rev. D 98, 032002]



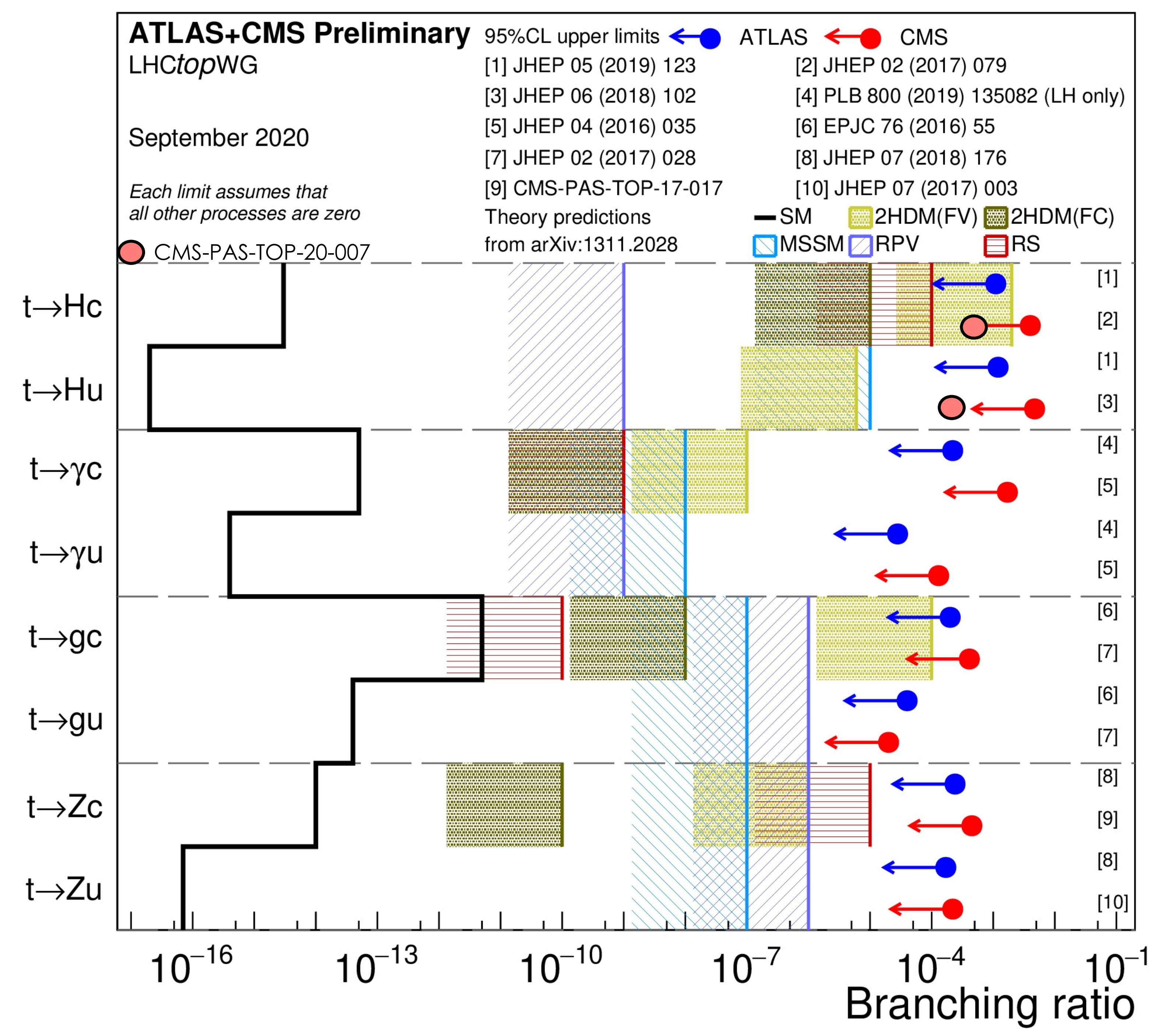




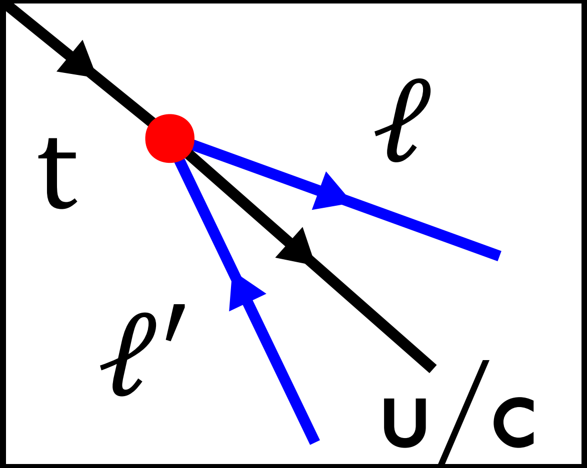


FCNC summary

- Search for FCNC are performed in various channels
- start probing models predicting highest branching ratios



Search for LFV in the top sector



- In the SM, lepton flavor is conserved in all interactions
  - The neutrino mass terms predict charged Lepton flavor violation (CLFV) at loop level (highly suppressed due to the tiny values of neutrino masses)
- Many new physics models predict sizable CLFV (neutrino mass models, multi-Higgs doublet models,…)
- If the new physics responsible for the CLFV is at scales beyond what the LHC can directly probe, the SM Lagrangian can be extended by dimension-6 operators

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_x \frac{C_x}{\Lambda^2} O_x + \dots ,$$

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

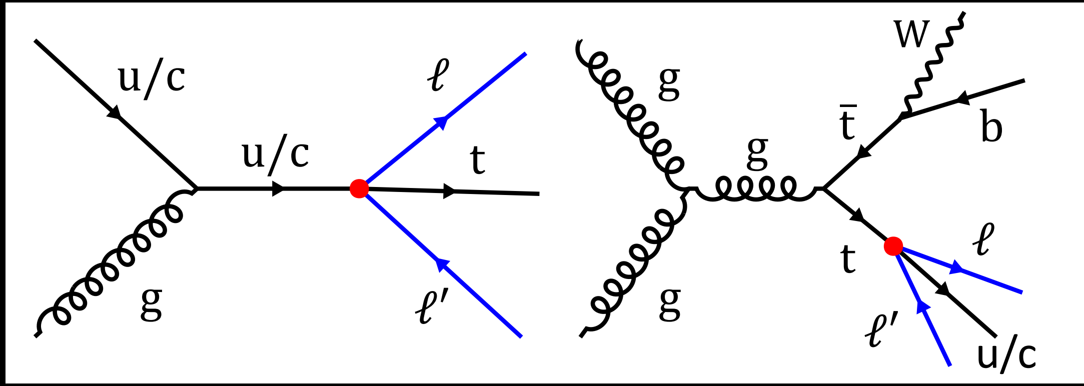
- CLFV interaction types
  - **Vector**: $O_{lq}^{1(ijkl)}, O_{lq}^{3(ijkl)}, O_{lu}^{(ijkl)}, O_{eq}^{(ijkl)}, O_{eu}^{(ijkl)}$
  - **Scalar**: $O_{lequ}^{1(ijkl)}$
  - **Tensor**: $O_{lequ}^{3(ijkl)}$

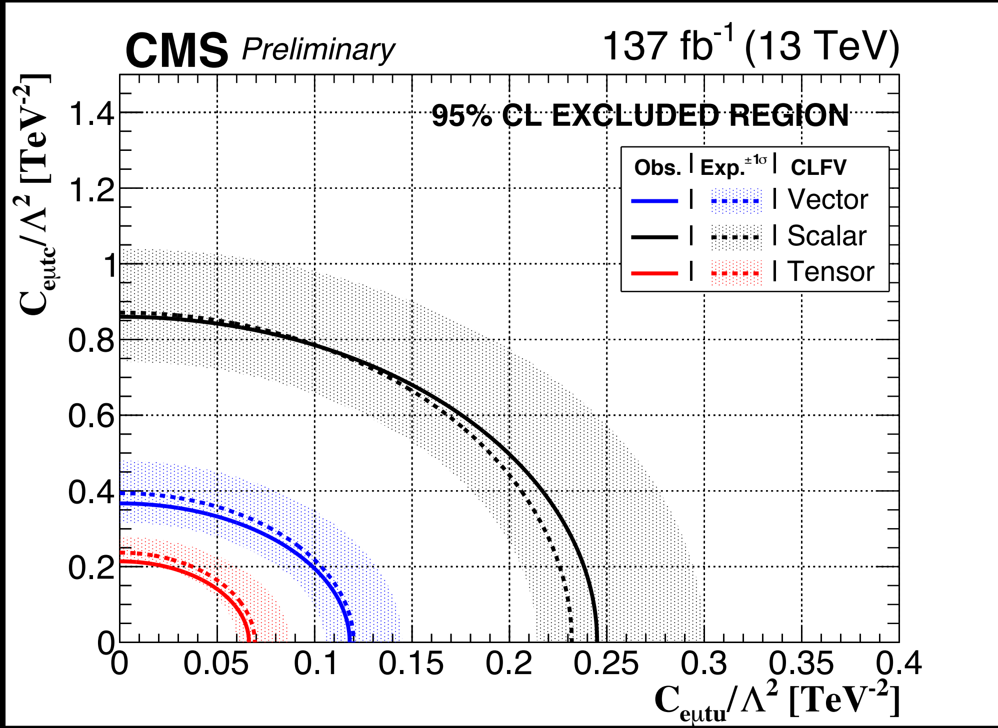
Search for the eμ LFV interactions

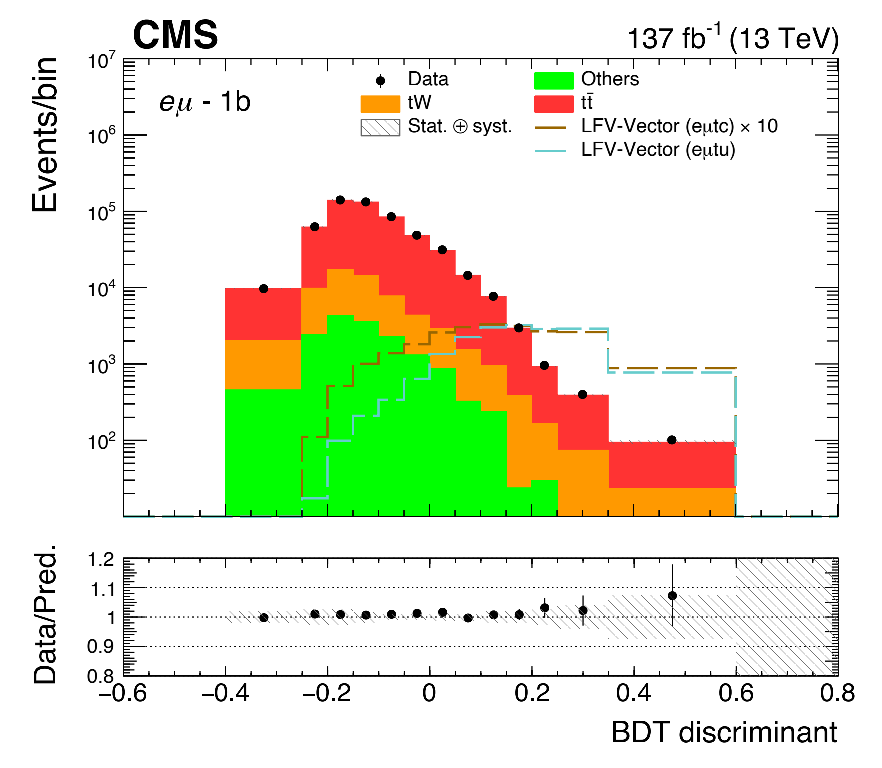
(CMS-PAS-TOP-19-006)

- Search for CLFV in eμ final state [137 fb^{-1}]
- Production & decay
- Signal: CLFV vector, scalar and tensor
- BDT is used to discriminate signal from BG events
- Data consistent with SM expectation
  - Upper limits are set at 95% CL

Production Decay





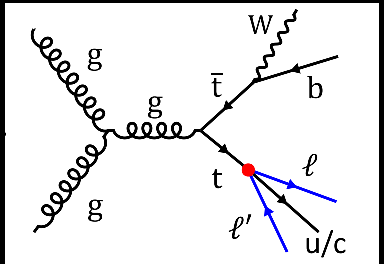


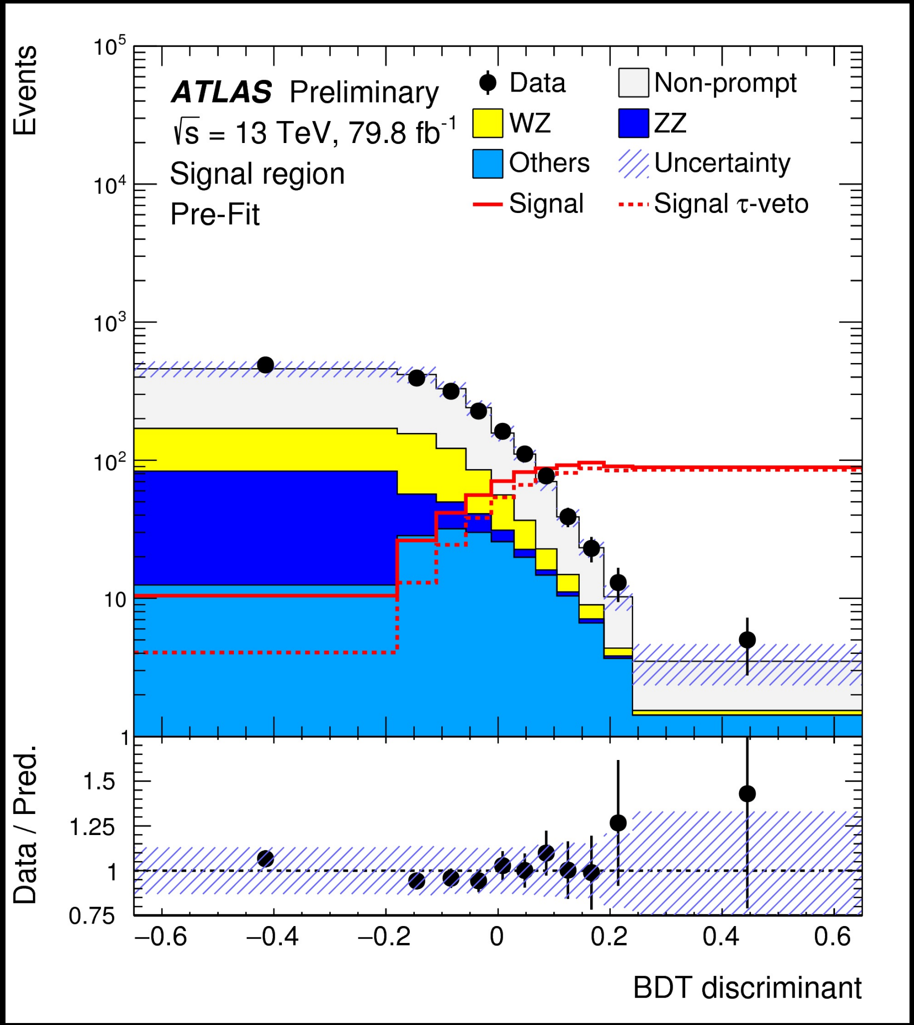
Search for the eμ LFV interactions

(ATLAS-CONF-2018-044)

- Search for CLFV in final states with three isolated charged leptons [80 fb^{-1}]
- Decay only
- CLFV top reconstructed from two opposite sign different-flavour leptons and a jet
- Non-prompt background: ttbar, Z+jets, estimated with matrix method in data (dominant uncertainty)
- Prompt background: WZ, ZZ
- BDT is used to discriminate signal from BG events
- Data consistent with SM expectation
  - Upper limits are set at 95% CL

$B(t \to \ell\ell' q) < 1.86(1.36)\times10^{-5}$ obs (exp)
$B(t \to e\mu q) < 6.6(4.8)\times10^{-6}$ obs (exp)



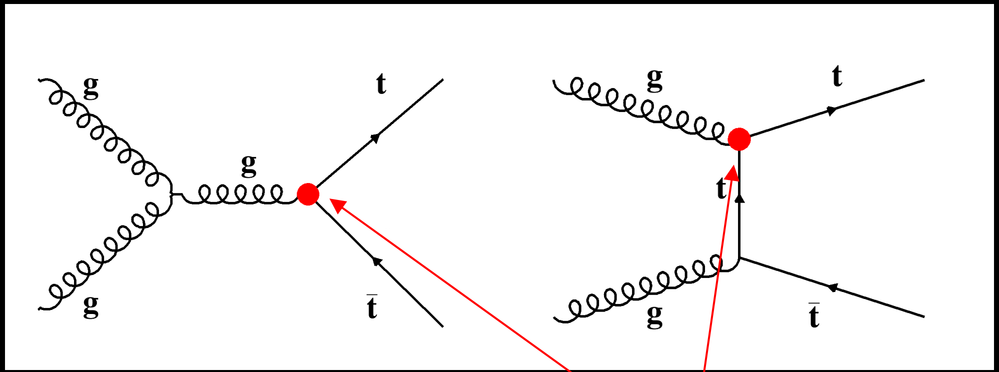


Search for CPV in the top sector

- CP violation in SM is not large enough to describe the matter-antimatter asymmetry of the universe
- In the SM, CPV in the production and decay of top quark pairs is predicted to be very small
- Top-quark pair production and decay provide a unique opportunity to study CPV
- Simple CP odd observables
  - triple-product observables of the form v1. (v2x v3) where vi are spin/four momentum of top decay products, Oi, are odd under CP transformation

$$A_i = \frac{N(\mathcal{O}_i > 0) - N(\mathcal{O}_i < 0)}{N(\mathcal{O}_i > 0) + N(\mathcal{O}_i < 0)}.$$

- chromo-electric dipole moment (CEDM) of top quark in top pair production induces CPV



$$\mathcal{L} = \frac{g_S}{2}\bar{t}T^a\sigma^{\mu\nu}(a_t^g + i\gamma_5 d_t^g)tG^{\mu\nu},$$

Search for the CPV interactions

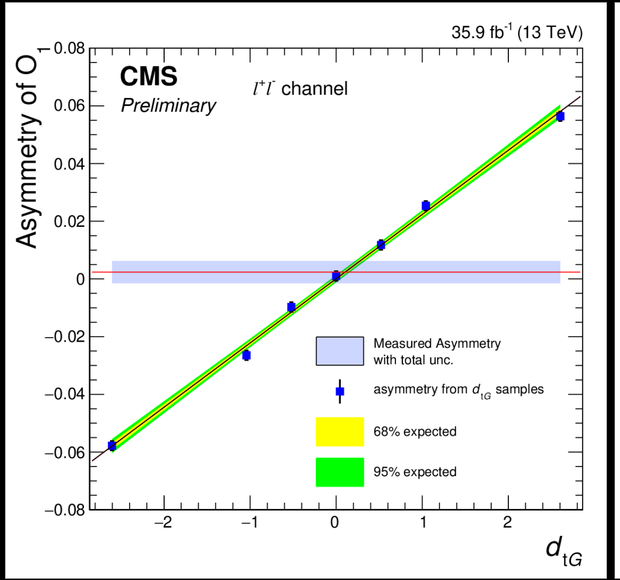
(CMS-PAS-TOP-18-007)

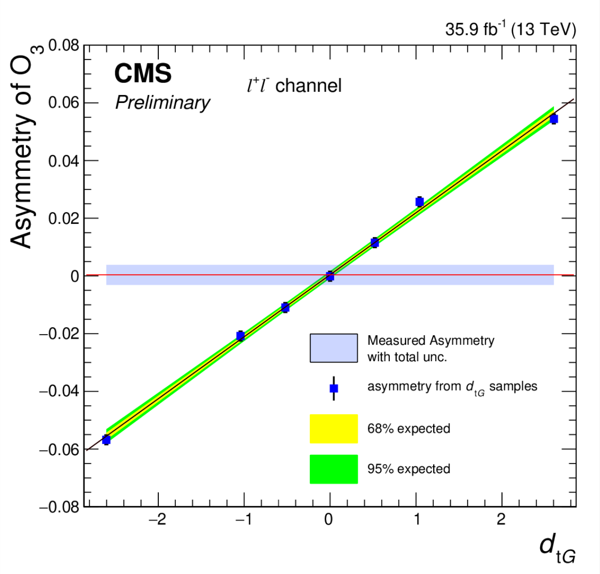
- Extraction the asymmetry and CEDM in top pair events in the dilepton final states [36 fb^{-1}]
- Observables; O_1 and O_3 (Phys. Rev. D 93, 014020 (2016))
- The measured asymmetries are consistent with the Standard Model prediction
- Asymmetry and CEDM have linear correlation
- CEDM is extracted by exploiting its correlation with the asymmetry

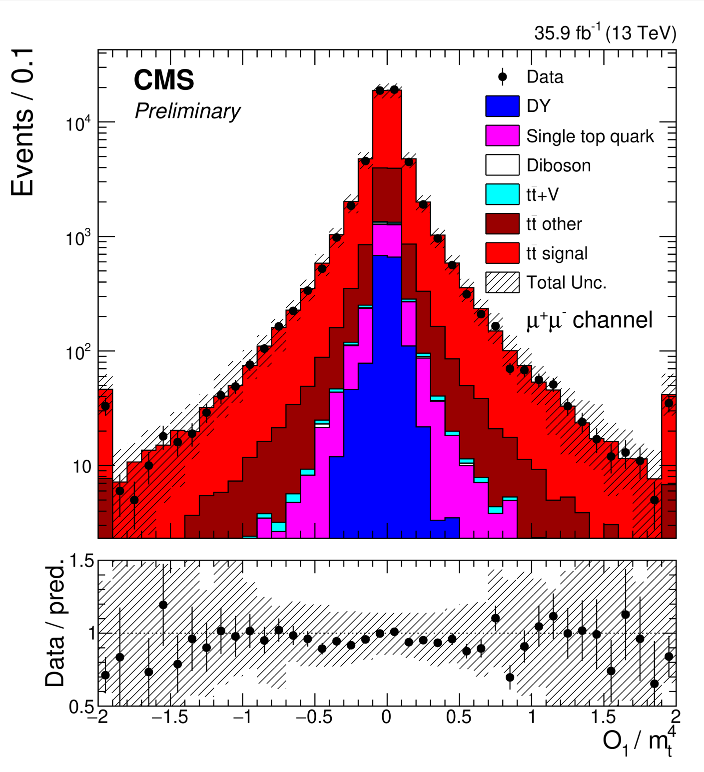
$$\mathcal{O}_1 = \epsilon(p_{\mathrm{t}}, p_{\bar{\mathrm{t}}}, p_{\ell^+}, p_{\ell^-}) = \begin{vmatrix} E_{\mathrm{t}} & p_{\mathrm{t}_x} & p_{\mathrm{t}_y} & p_{\mathrm{t}_z} \\ E_{\bar{\mathrm{t}}} & p_{\bar{\mathrm{t}}_x} & p_{\bar{\mathrm{t}}_y} & p_{\bar{\mathrm{t}}_z} \\ E_{\ell^+} & p_{\ell_x^+} & p_{\ell_y^+} & p_{\ell_z^+} \\ E_{\ell^-} & p_{\ell_x^-} & p_{\ell_y^-} & p_{\ell_z^-} \end{vmatrix}$$

$$\mathcal{O}_3 = \epsilon(p_{\mathrm{b}}, p_{\bar{\mathrm{b}}}, p_{\ell^+}, p_{\ell^-}) = \begin{vmatrix} E_{\mathrm{b}} & p_{\mathrm{b}_x} & p_{\mathrm{b}_y} & p_{\mathrm{b}_z} \\ E_{\bar{\mathrm{b}}} & p_{\bar{\mathrm{b}}_x} & p_{\bar{\mathrm{b}}_y} & p_{\bar{\mathrm{b}}_z} \\ E_{\ell^+} & p_{\ell_x^+} & p_{\ell_y^+} & p_{\ell_z^+} \\ E_{\ell^-} & p_{\ell_x^-} & p_{\ell_y^-} & p_{\ell_z^-} \end{vmatrix}$$

Physics observable	d_{tG}	CEDM (10^{-18} $g_s \cdot$ cm)
$\mathcal{O}_1$	$0.10 \pm 0.12(\mathrm{stat}) \pm 0.12(\mathrm{syst})$	$0.58 \pm 0.69(\mathrm{stat}) \pm 0.70(\mathrm{syst})$
$\mathcal{O}_3$	$0.00 \pm 0.13(\mathrm{stat}) \pm 0.10(\mathrm{syst})$	$-0.01 \pm 0.72(\mathrm{stat}) \pm 0.58(\mathrm{syst})$







Search for the CPV interactions

(CMS-PAS-TOP-20-005)

new

- Lepton + jets final states [137 fb^{-1}]
- Observables; O_3, O_6, O_{12} and O_{14} (Phys. Rev. D 93, 014020 (2016))

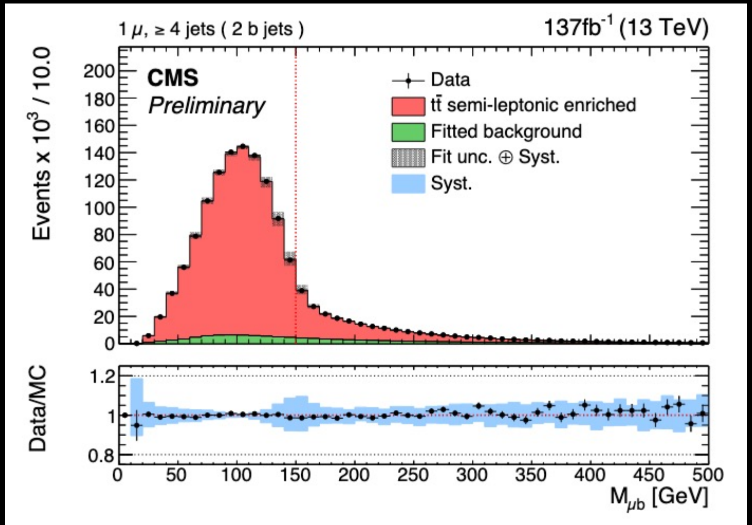
$$O_3 = Q_\ell \epsilon(p_b, p_{\bar{b}}, p_\ell, p_{j_1}) \propto Q_\ell \vec{p'}_b \cdot (\vec{p'}_\ell \times \vec{p'}_{j_1})$$

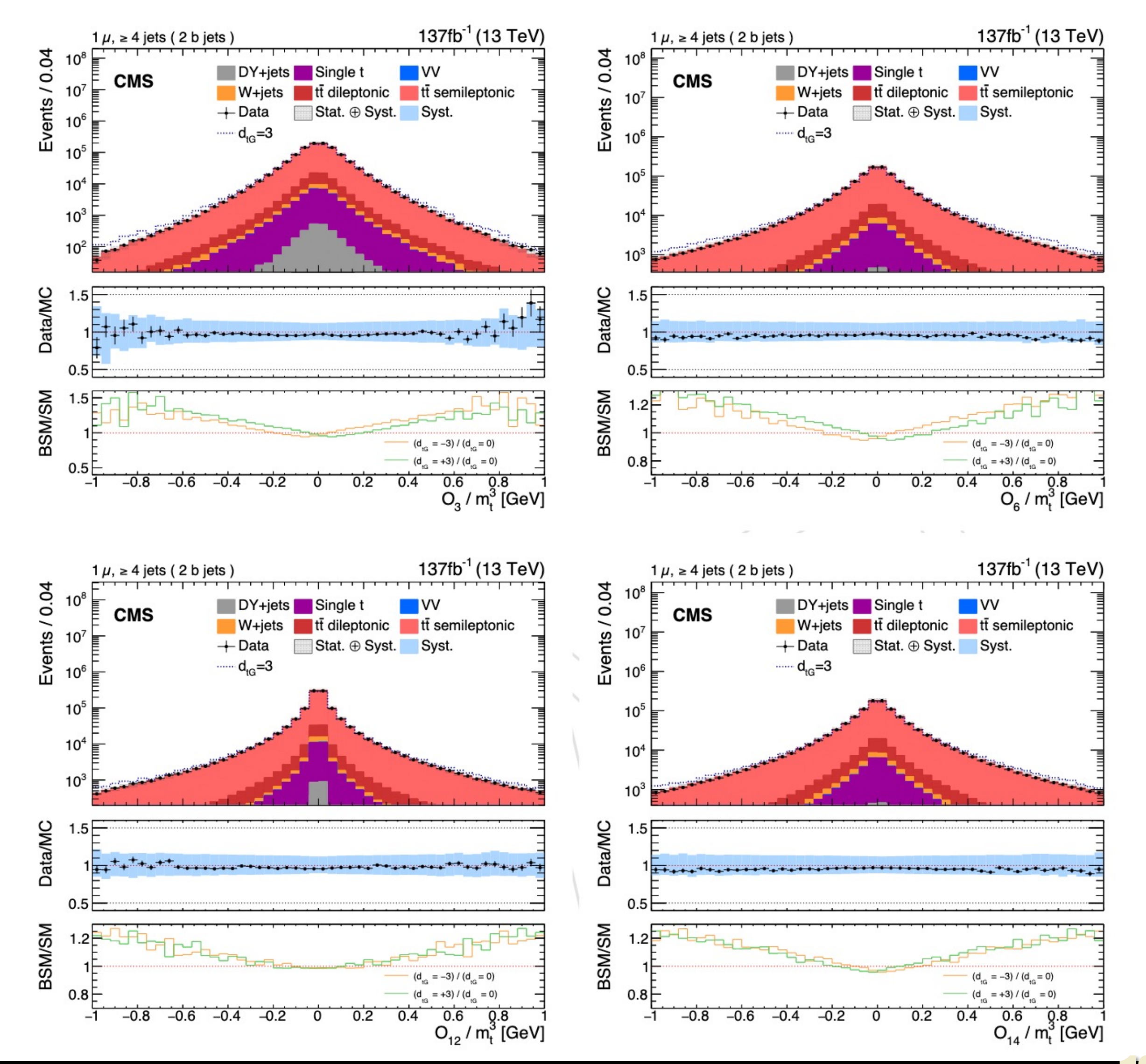
$$O_6 = Q_\ell \epsilon(P, p_b - p_{\bar{b}}, p_\ell, p_{j_1}) \propto Q_\ell (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1})$$

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

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

- Top quark and antiquark candidates are reconstructed using a χ^2 sorting algorithm
- The background contribution in the signal region is estimated from a fit to the mass distribution M_{lb}





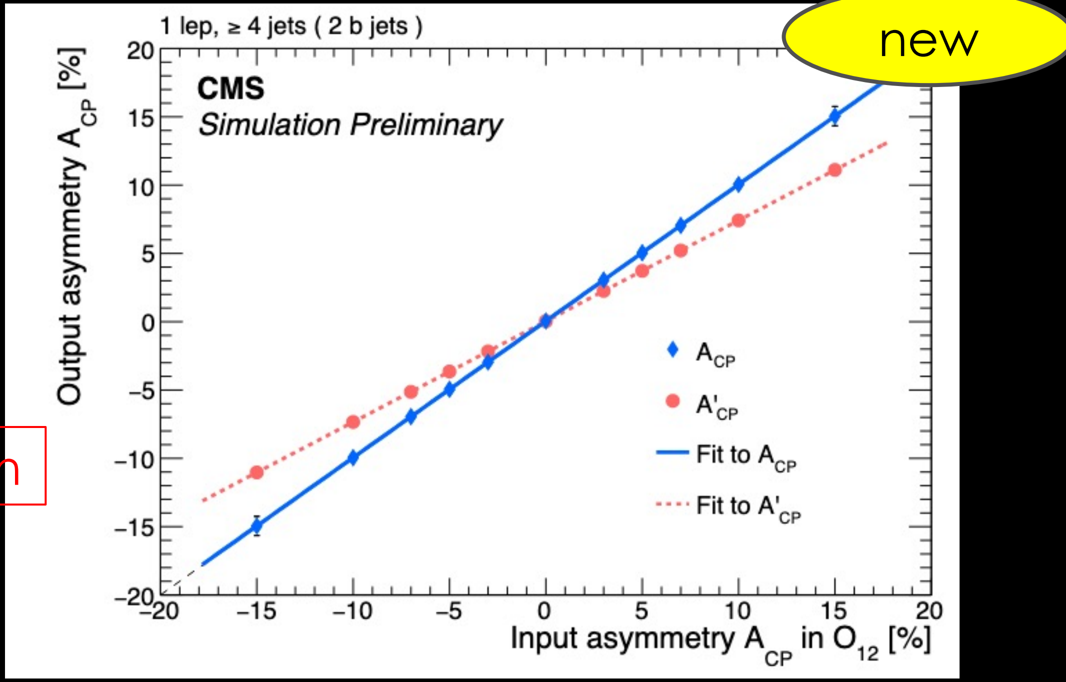
- Experimental factors that affect the measurements are parametrised with a dilution factor
  - Comparing GEN level to RECO level observable
  - Observable-dependent

$$D = \epsilon_c - \epsilon_w.$$

Correct sign fraction (ϵ_c)

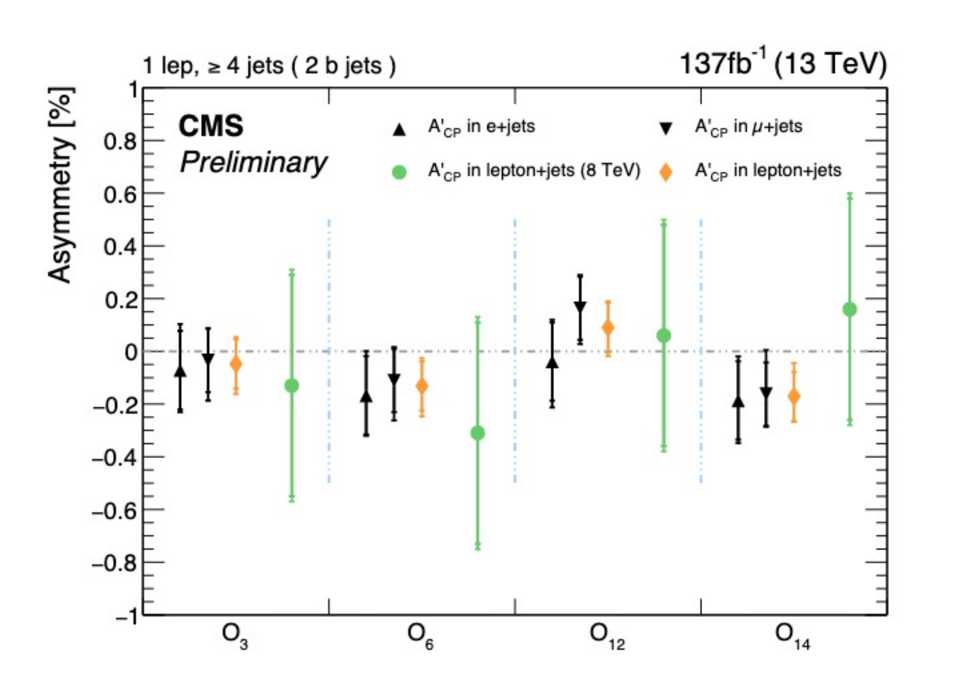
Wrong sign fraction (ϵ_w)

Observable	Dilution factor D
O_3	$0.4642^{+0.0007}_{-0.0007}(\text{stat.})\ ^{+0.0135}_{-0.0167}(\text{syst.})$
O_6	$0.4368^{+0.0007}_{-0.0007}(\text{stat.})\ ^{+0.0124}_{-0.0152}(\text{syst.})$
O_{12}	$0.7381^{+0.0006}_{-0.0006}(\text{stat.})\ ^{+0.0129}_{-0.0171}(\text{syst.})$
O_{14}	$0.5989^{+0.0007}_{-0.0007}(\text{stat.})\ ^{+0.0112}_{-0.0143}(\text{syst.})$



- There is no significant evidence of CPV in each observable
  - Consistent with the SM prediction

	$A'_{CP}(\%)$		
	$e+jets$	$\mu+jets$	*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}	$-0.186 \pm 0.149(\text{stat.})^{+0.075}_{-0.065}(\text{syst.})$	$-0.162 \pm 0.120(\text{stat.})^{+0.117}_{-0.032}(\text{syst.})$	$-0.171 \pm 0.094(\text{stat.})^{+0.085}_{-0.023}(\text{syst.})$



Summary

- LHC is efficient top quark factory, allow ATLAS and CMS for rare top quark interactions
  - FCNC
  - CLFV
  - CPV
  - tZq (see David Walter talk)
  - Four-top-quarks (see Paolo Sabatini talk)
  - …
- Contribution of the new physics can be parameterized using effective field theory
- Results are well in agreement with the SM prediction and no significance deviation is observed
- More searches are performed with full run-2 data and will be published soon, stay tuned!

Thanks for your attention