FCNC and EFT interpretations at LHC

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on behalf of the ATLAS and CMS collaborations

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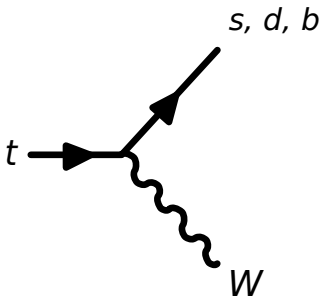
CERN/FIS-PAR/0008/2017

top quark decays



Dominant decay mode $t \to bW$

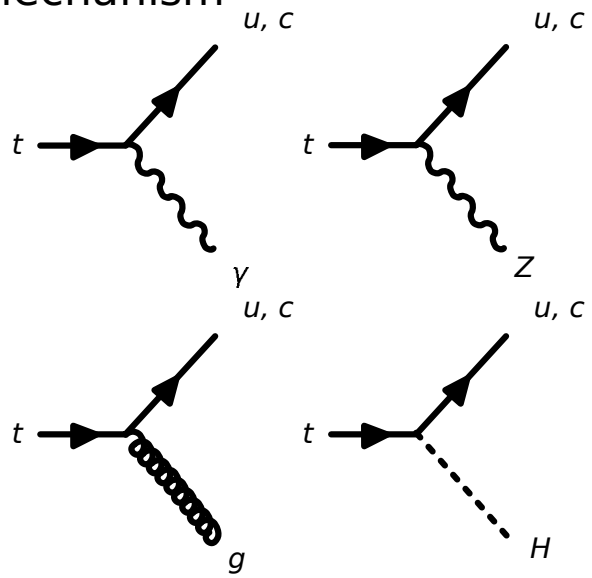
$BR(t \to bW)_{SM} = 9.98 \times 10^{-1}$

$BR(t \to sW)_{SM} = 1.64 \times 10^{-3}$

$BR(t \to dW)_{SM} = 7.85 \times 10^{-5}$

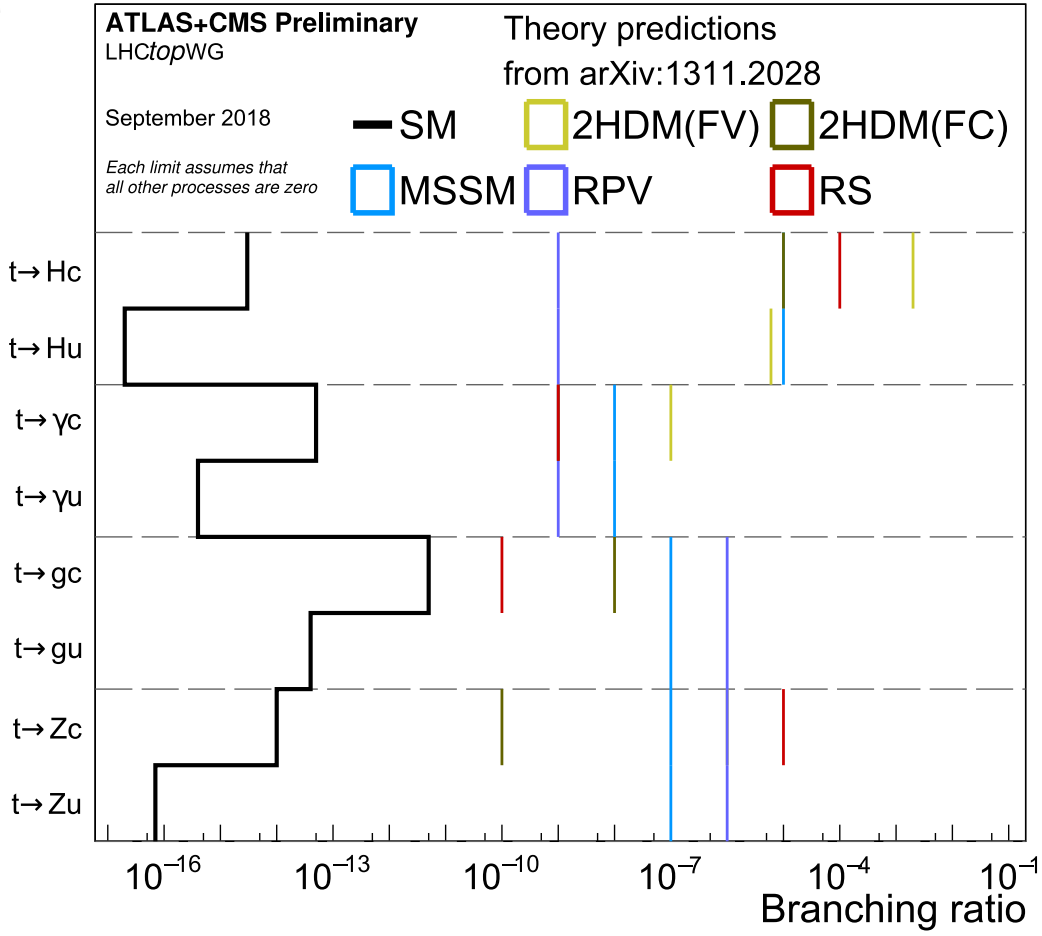
Flavour-changing neutral currents (FCNC) decays are forbidden at tree level

Occur at one-loop level but are strongly suppressed by the GIM mechanism



FCNC vertices can be probed in both production and decay modes

~ maximum BR in several models:



effective field theory

model independent approach for physics beyond the SM using an effective Lagrangian:

$$\mathscr{L} = \mathscr{L}_{SM} + \frac{1}{\Lambda^2} \sum_i c_i \mathcal{O}_i + \ldots$$

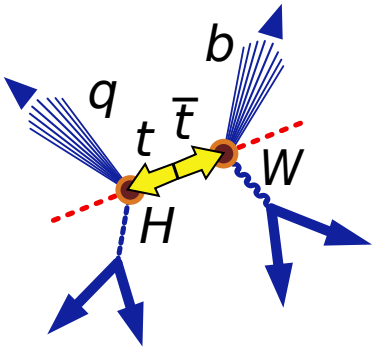
- Λ new physics energy scale (usually set to 1 TeV)
- $\mathcal{O}_i$ dimension 6 operators
  (59 total with lepton and baryon conservation;
  just 15 are relevant for top quark physics)
- c_i Wilson coefficients (WC)
  (intensity of new physics operators)
- top quark anomalous couplings can be expressed in terms of WC (or WC combinations)
- agreement in top quark community for common standards for EFT interpretation (1802.07237)

TOPQ-2017-07
13 TeV, 36.1 fb^{-1}

PRD 98 (2018) 032002
13 TeV, 36.1 fb^{-1}

JHEP 10 (2017) 129
13 TeV, 36.1 fb^{-1}

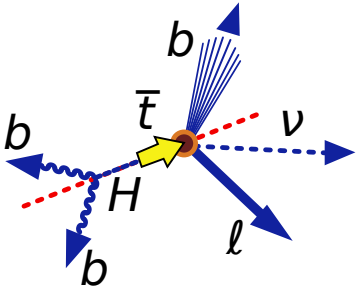
- $t\bar{t}$ production with FCNC decay and 4 H decay topologies:
  - $H \to bb$
  - $H \to \tau\tau$
  - $H \to$ multileptons$(WW, \tau\tau, ZZ)$
  - $H \to \gamma\gamma$

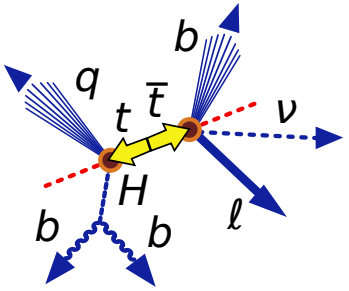


- dominant systematic (multi leptons chan.):
  non-prompt lepton background estimation (8%)
- combined result from simultaneous fit to distributions of the 4 analyses

JHEP 06 (2018) 102
13 TeV, 35.9 fb^{-1}

- both production and decay FCNC channels with $H \to bb$
- 5 categories based on the no. jets and no. b-tagged jets
- full kinematic reconstruction for signal and background hypotheses
- BDTs to optimise signal and background discrimination
- dominant systematic: b-tagging (8–30%)





tqH

TOPQ-2017-07
13 TeV, 36.1 fb^{-1}

PRD 98 (2018) 032002
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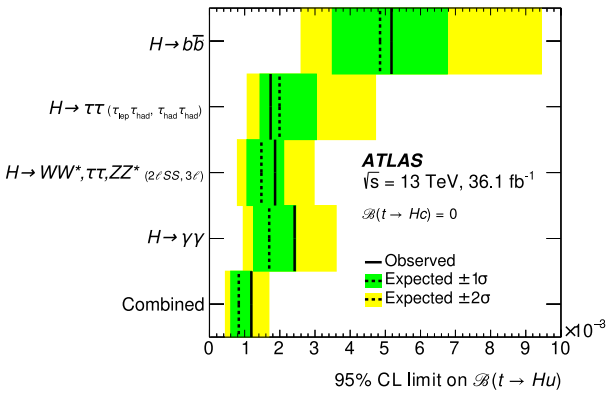
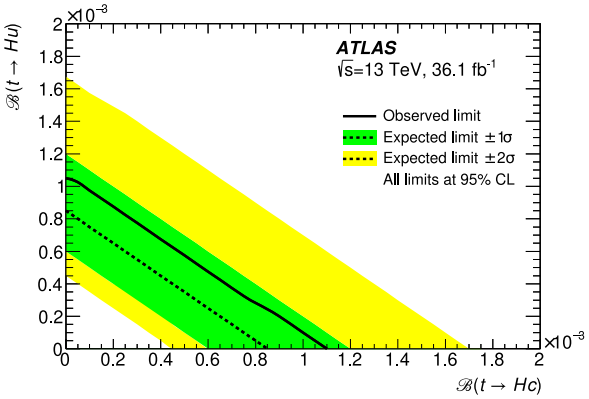
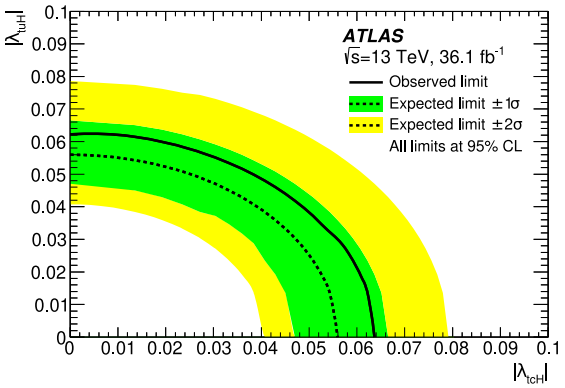
JHEP 10 (2017) 129
13 TeV, 36.1 fb^{-1}





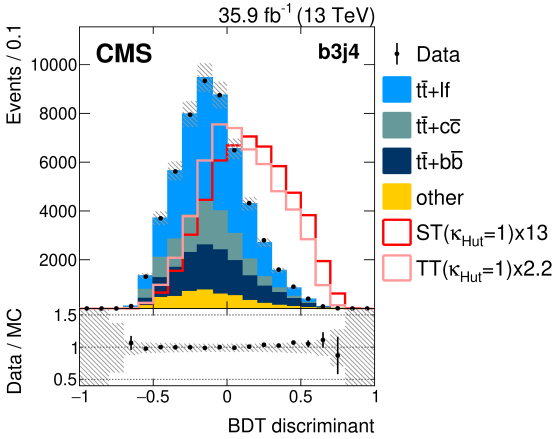


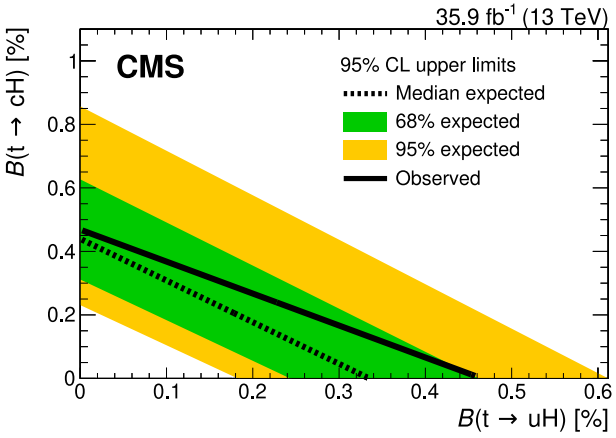
observed (expected) limits:

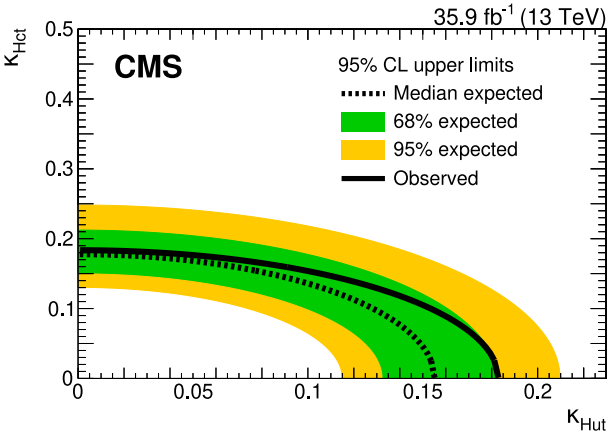
$|\lambda_{tuH}| < 0.066\ (0.055)$ $\quad$ $|\lambda_{tcH}| < 0.064\ (0.055)$

$\mathrm{BR}(t \to uH) < 1.2 \times 10^{-3}\ (8.3 \times 10^{-4})$ $\quad$ $\mathrm{BR}(t \to cH) < 1.1 \times 10^{-3}\ (8.3 \times 10^{-4})$

JHEP 06 (2018) 102
13 TeV, 35.9 fb^{-1}







observed (expected) limits:

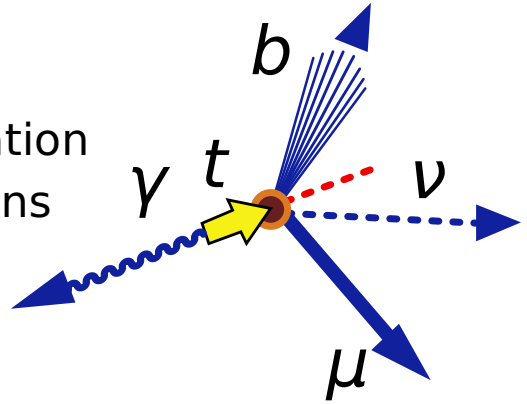
$\kappa_{Hut} < 0.18\ (0.16)$ $\quad$ $\kappa_{Hct} < 0.18\ (0.18)$

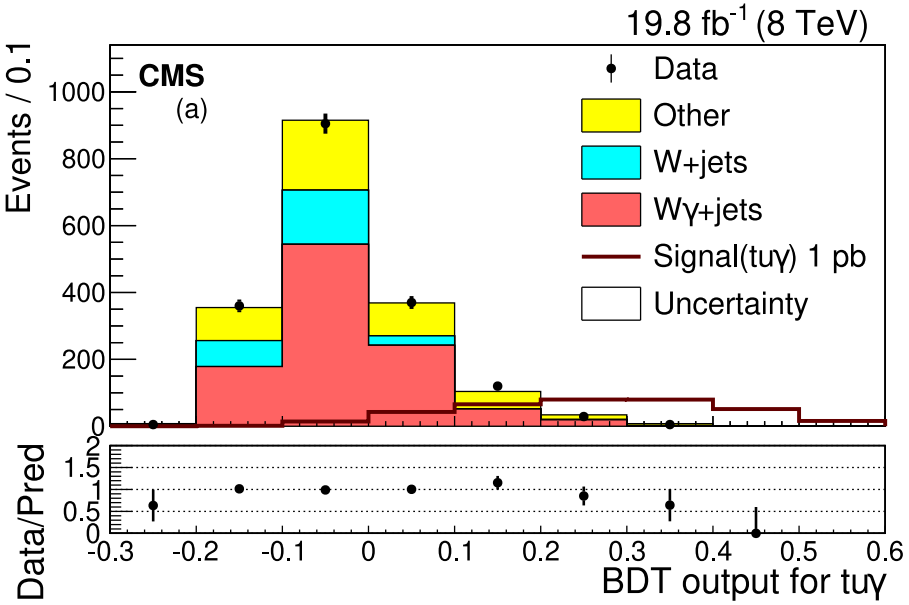
$\mathrm{BR}(t \to uH) < 4.7 \times 10^{-3}\ (3.4 \times 10^{-3})$ $\quad$ $\mathrm{BR}(t \to cH) < 4.7 \times 10^{-3}\ (4.4 \times 10^{-3})$

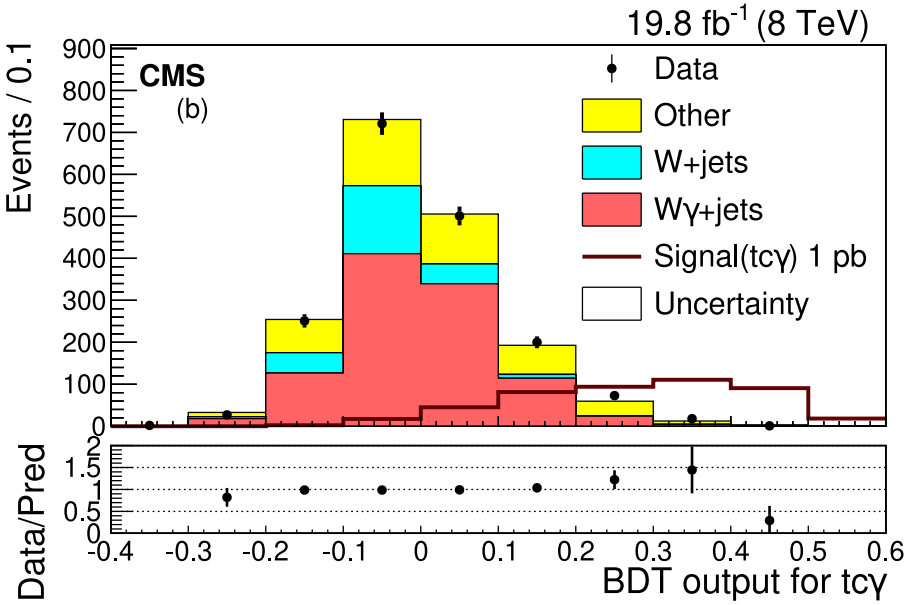
$tq\gamma$

JHEP 04 (2016) 035
8 TeV, 19.8 fb^{-1}

- search for single top production via FCNC (QED)
- BDT with 8 variables used to improve $W+\gamma$ discrimination
- dominant systematics: $W+\gamma$ and W+jets normalisations







observed (expected) limits:

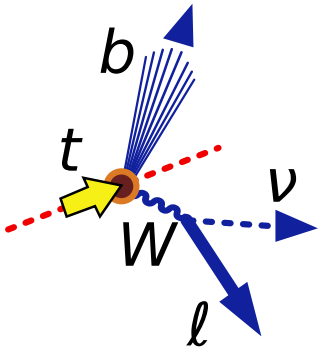
$\kappa_{tu\gamma} < 0.025\ (0.031)$ $\quad$ $\kappa_{tc\gamma} < 0.091\ (0.098)$

$\mathrm{BR}(t \to u\gamma) < 1.3 \times 10^{-4}\ (1.9 \times 10^{-4})$ $\quad$ $\mathrm{BR}(t \to c\gamma) < 1.7 \times 10^{-3}\ (2.0 \times 10^{-3})$

tqg

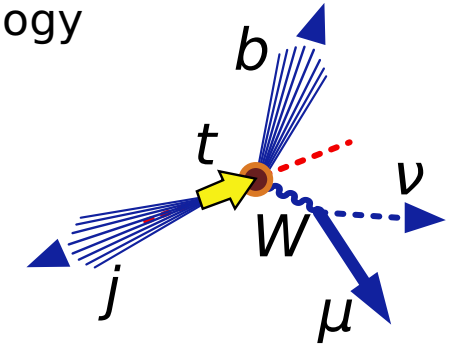
EPJ C76 (2016) 55
8 TeV, 20.3 fb^{-1}

- $t\bar{t}$ production with $t \to qg$ decay difficult to distinguish from multijet production
- search for single top production via FCNC (strong sector)
- neural-network with 13 variables
- dominant systematics: b-tag, $E_{\mathrm{T}}^{\mathrm{miss}}$, background modelling



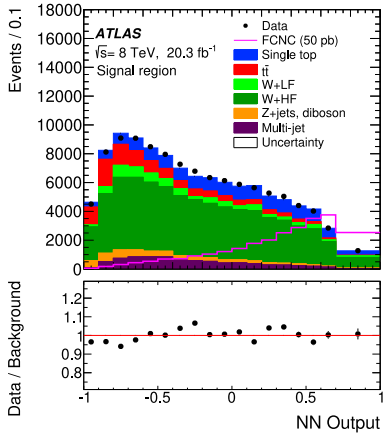
JHEP 02 (2017) 028
7+8 TeV, 5.0+19.7 fb^{-1}

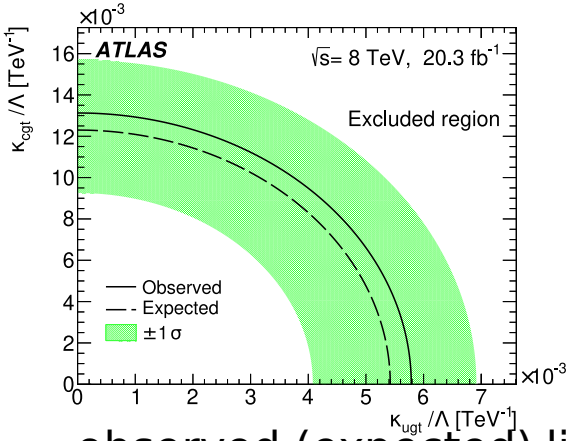
- search for single top production via FCNC in t-channel topology
- different b-tagged jets and light jets CRs
- neural-network with 4 variables used to reduce QCD
- neural-network with 9 (10) variables used to define tug (tcg) region
- dominant systematics: PDF (5%), signal generator (5%)

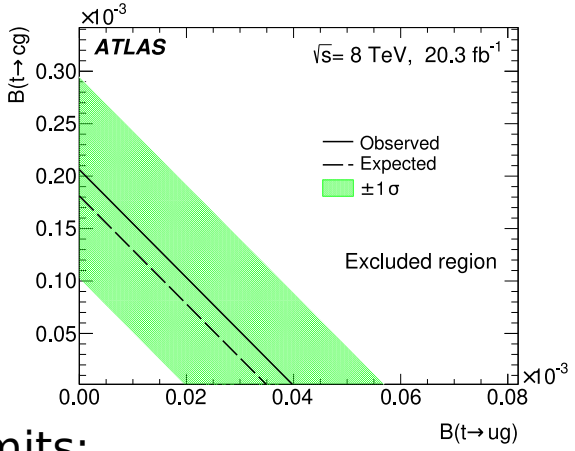


tqg

EPJ C76 (2016) 55
8 TeV, 20.3 fb^{-1}





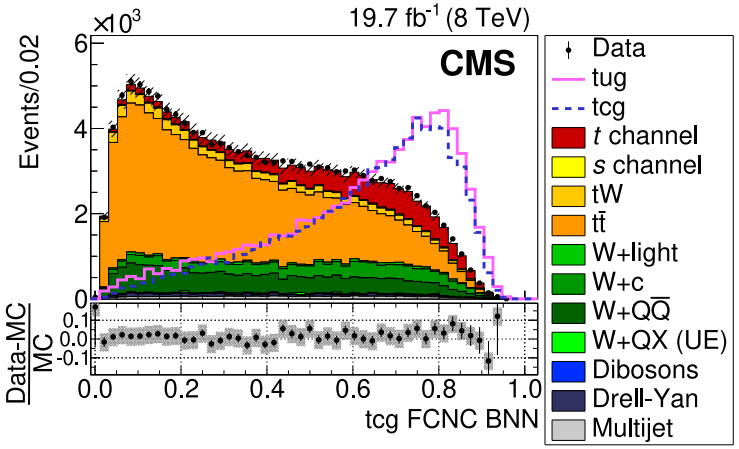


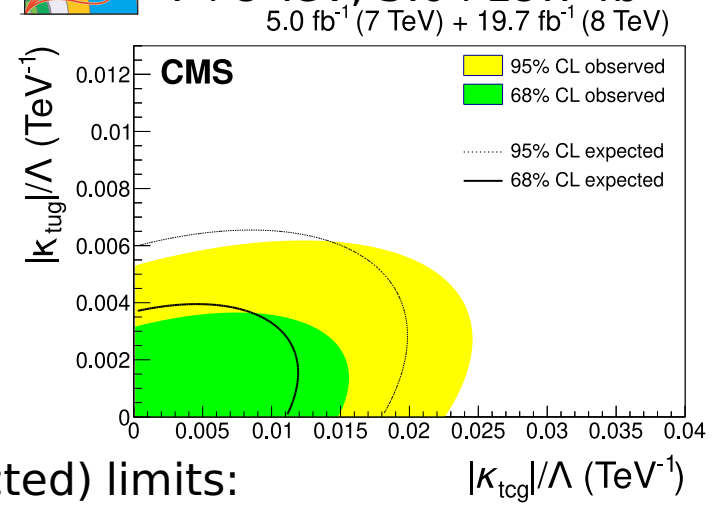
observed (expected) limits:

$\kappa_{tug}/\Lambda < 5.8 \times 10^{-3}$ TeV^{-1} $\quad$ $\kappa_{tcg}/\Lambda < 1.3 \times 10^{-2}$ TeV^{-1}

$\mathrm{BR}(t \to ug) < 4.0 \times 10^{-5}$ $\quad$ $\mathrm{BR}(t \to cg) < 2.0 \times 10^{-4}$

JHEP 02 (2017) 028
7+8 TeV, 5.0+19.7 fb^{-1}





observed (expected) limits:

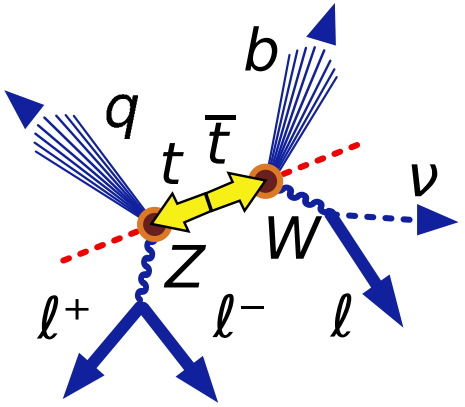
$|\kappa_{tug}|/\Lambda < 4.1 \times 10^{-3}$ (4.8×10^{-3}) $\quad$ $|\kappa_{tcg}|/\Lambda < 1.8 \times 10^{-2}$ (1.5×10^{-2})

$\mathrm{BR}(t \to ug) < 2.0 \times 10^{-5}$ (2.8×10^{-5}) $\quad$ $\mathrm{BR}(t \to cg) < 4.1 \times 10^{-4}$ (2.8×10^{-4})

tqZ

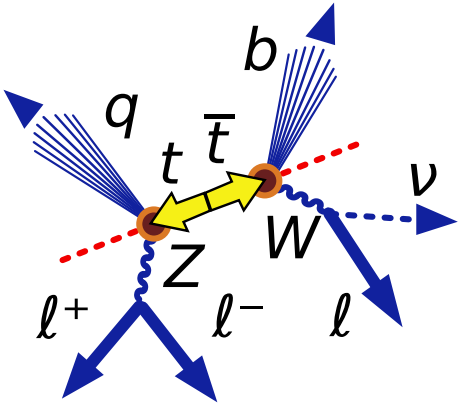
JHEP 07 (2018) 176
13 TeV, 36 fb^{-1}

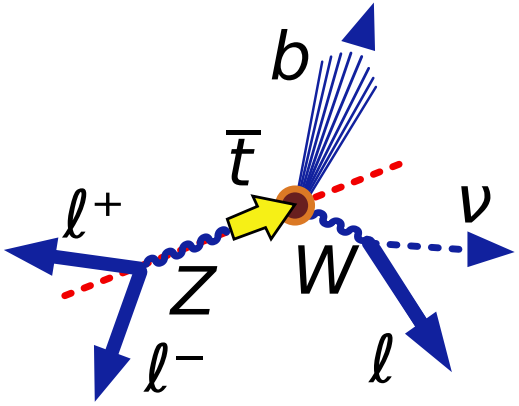
- 3 leptons (e, μ), 2 jets (1 b-tag), $E_{\mathrm{T}}^{\mathrm{miss}}$
- event reconstruction through χ^2 minimisation
- simultaneous fit to 6 distributions in SR and CR
- dominant systematics: event modelling, jets



CMS-PAS-TOP-17-017
13 TeV, 35.9 fb^{-1}

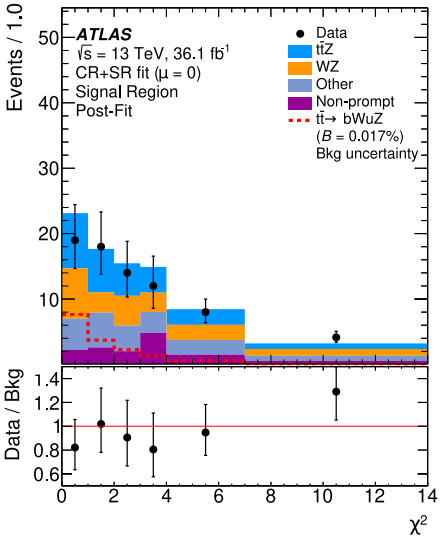
- search for tqZ vertex in production and decay
- BDTs improve signal/background separation
- simultaneous fit to five SRs/CRs
- dominant systematics: non-prompt leptons

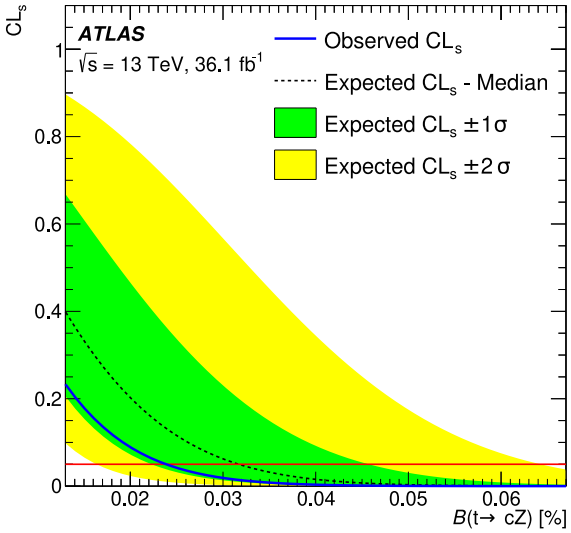




tqZ

JHEP 07 (2018) 176
13 TeV, 36 fb^{-1}

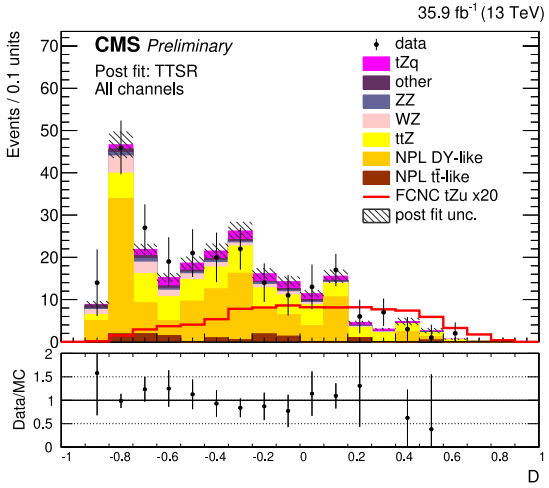


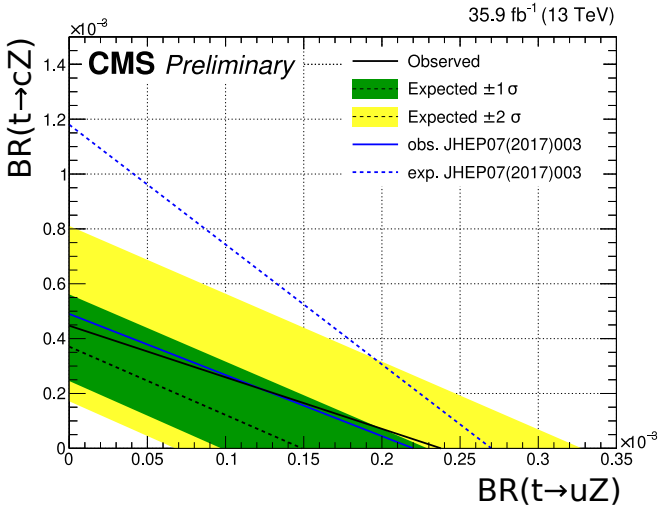


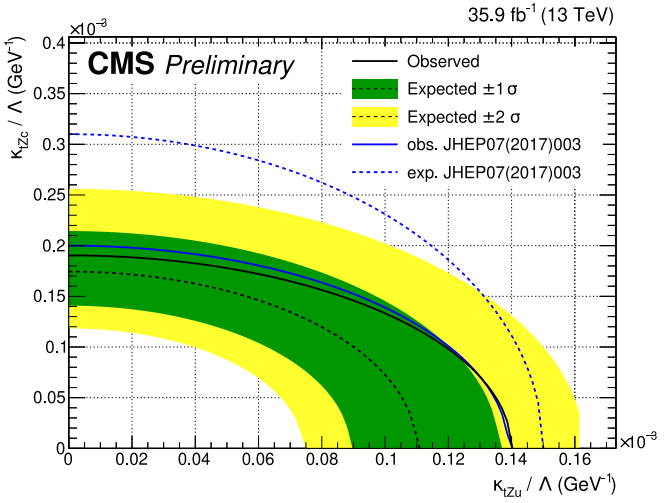
	$\mathcal{B}(t \to uZ)$	$\mathcal{B}(t \to cZ)$
Observed	1.7×10^{-4}	2.4×10^{-4}
Expected -1σ	1.7×10^{-4}	2.2×10^{-4}
Expected	2.4×10^{-4}	3.2×10^{-4}
Expected $+1\sigma$	3.4×10^{-4}	4.6×10^{-4}

Operator	Observed	Expected
$\lvert C_{uB}^{(31)} \rvert$	0.25	0.30
$\lvert C_{uW}^{(31)} \rvert$	0.25	0.30
$\lvert C_{uB}^{(32)} \rvert$	0.30	0.34
$\lvert C_{uW}^{(32)} \rvert$	0.30	0.34

CMS-PAS-TOP-17-017
13 TeV, 35.9 fb^{-1}

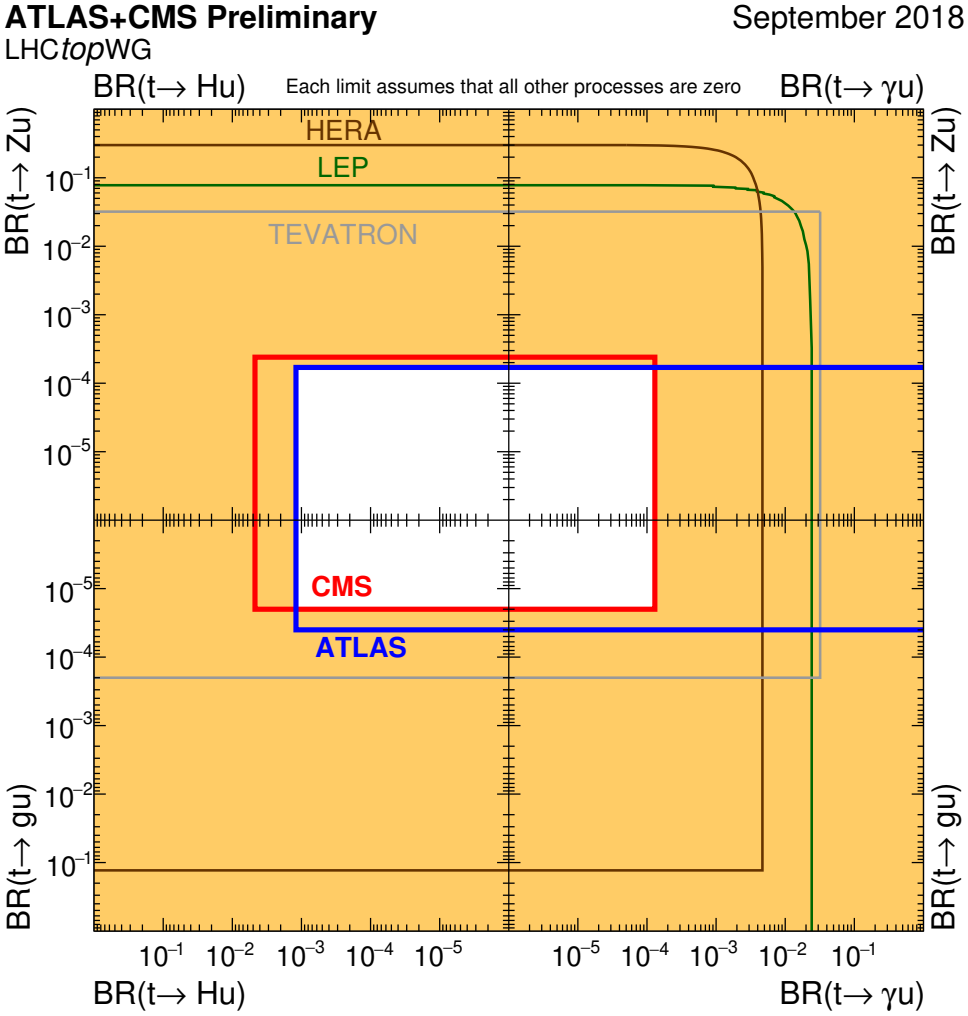


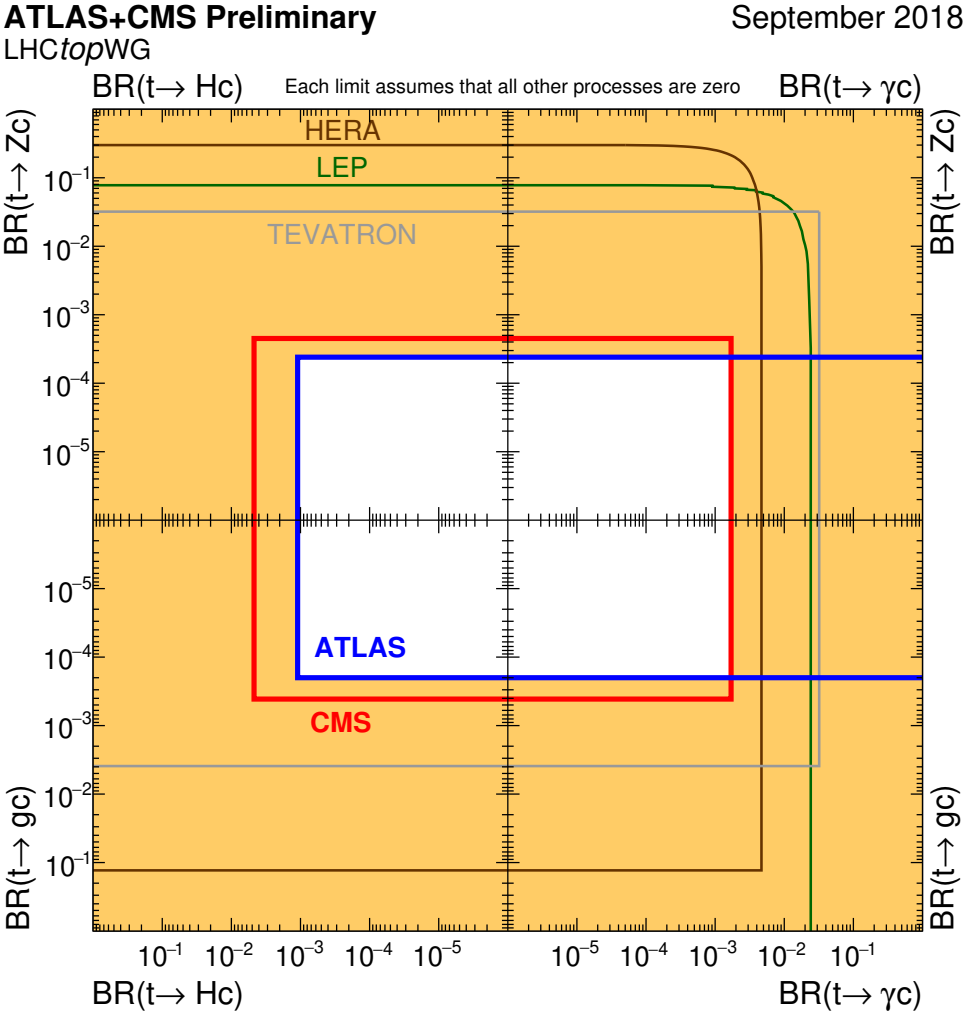




$\mathrm{BR}(t \to uZ) < 2.4 \times 10^{-4}$ (1.5×10^{-4}) $\mathrm{BR}(t \to cZ) < 4.5 \times 10^{-4}$ (3.7×10^{-4})

summary


ATLAS+CMS Preliminary
September 2018
LHCtopWG
BR(t→ Hu)
Each limit assumes that all other processes are zero
BR(t→ γu)
HERA
LEP
TEVATRON
CMS
ATLAS
BR(t→ Zu)
BR(t→ gu)
BR(t→ Hu)
BR(t→ γu)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BR(t→ Hc)
BR(t→ γc)

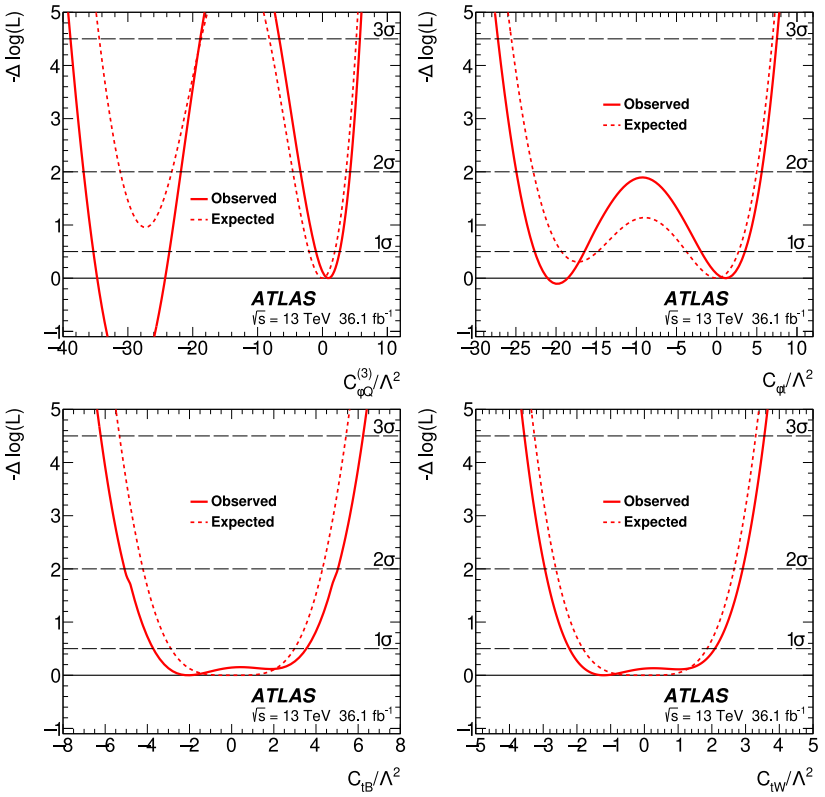
ttV

see details in Rick's talk

PRD 99 (2019) 072009
13 TeV, 36.5 fb^{-1}

- $\sigma(t\bar{t}Z)$ and $\sigma(t\bar{t}W)$ simultaneously measured
- 2 (SS, OS), 3 and 4 lepton final states
- measured $\sigma(t\bar{t}Z)$ used to constrain four operators ($C_{\phi Q}^{(1)}$ set to zero):

Operator	Expression
$O_{\phi Q}^{(3)}$	$(\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi)(\bar{Q}\gamma^\mu \tau^I Q)$
$O_{\phi Q}^{(1)}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{Q}\gamma^\mu Q)$
$O_{\phi t}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{t}\gamma^\mu t)$
O_{tW}	$(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W^I_{\mu\nu}$
O_{tB}	$(\bar{Q}\sigma^{\mu\nu} t)\tilde{\phi} B_{\mu\nu}$



Coefficients	$C_{\phi Q}^{(3)}/\Lambda^2$	$C_{\phi t}/\Lambda^2$	C_{tB}/Λ^2	C_{tW}/Λ^2
Previous indirect constraints at 68% CL	[–4.7, 0.7]	[–0.1, 3.7]	[–0.5, 10]	[–1.6, 0.8]
Previous direct constraints at 95% CL	[–1.3, 1.3]	[–9.7, 8.3]	[–4.0, 3.5]	[–0.2, 0.7]
Expected limit at 68% CL	[–2.1, 1.9]	[–3.8, 2.7]	[–2.9, 3.0]	[–1.8, 1.9]
Expected limit at 95% CL	[–4.5, 3.6]	[–23, 4.9]	[–4.2, 4.3]	[–2.6, 2.6]
Observed limit at 68% CL	[–1.0, 2.7]	[–2.0, 3.5]	[–3.7, 3.5]	[–2.2, 2.1]
Observed limit at 95% CL	[–3.3, 4.2]	[–25, 5.5]	[–5.0, 5.0]	[–2.9, 2.9]

ttZ

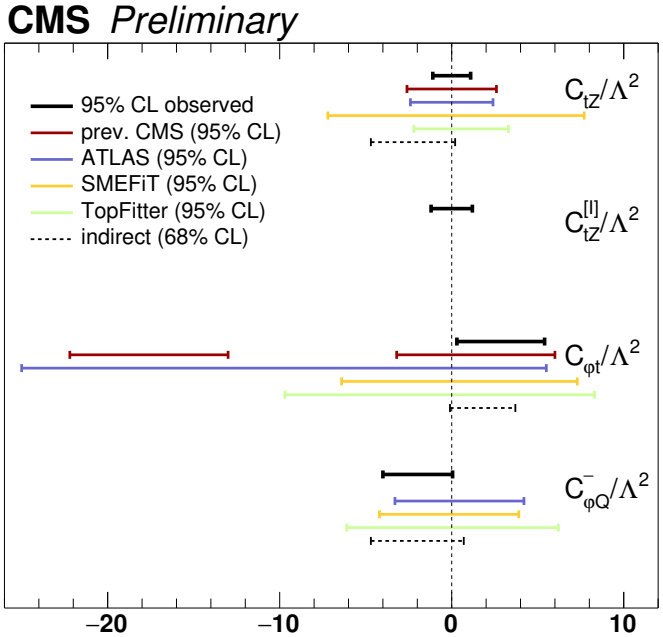
see details in Rick's talk

CMS-PAS-TOP-18-009
13 TeV, 77.5 fb^{-1}

- $\sigma(t\bar{t}Z)$ measurement in 3 and 4 lepton final states
- differential cross sections (dp_T^Z and $d\cos\theta_Z^*$) are also measured
- constraints on anomalous ttZ couplings and on four operators:

$$
\begin{aligned}
c_{tZ} &= \mathrm{Re}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right) \\
c_{tZ}^{[I]} &= \mathrm{Im}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right) \\
c_{\phi t} &= C_{\phi t} = C_{\phi u}^{(33)} \\
c_{\phi Q}^{-} &= C_{\phi Q} = C_{\phi q}^{1(33)} - C_{\phi q}^{3(33)}
\end{aligned}
$$

- limits from reweighting procedure based on MC implementation of EFT at LO:

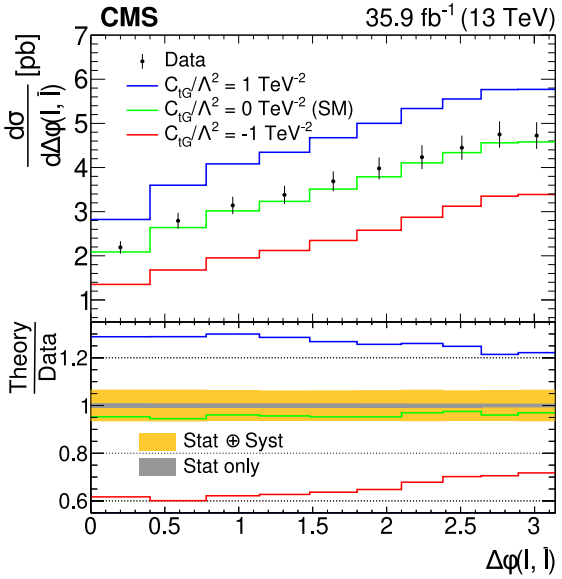


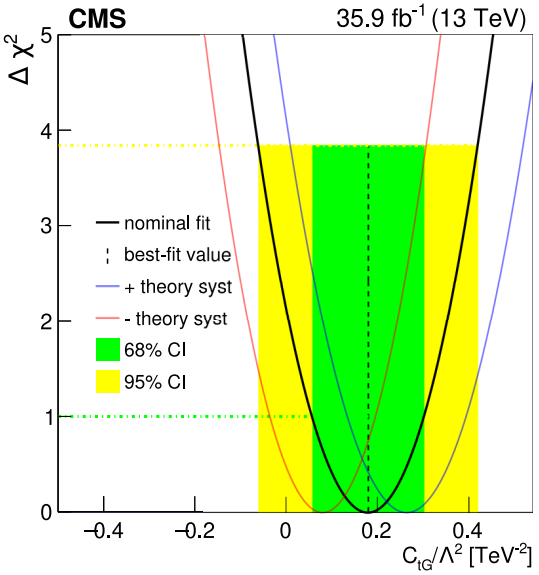
$d\sigma_{t\bar{t}}$

see details in Jose's talk

JHEP 02 (2019) 149
13 TeV, 35.9 fb^{-1}

- differential $\sigma(t\bar{t})$ measured as function of 14 observables (at parton and particle level) and 19 observables (at particle level only)
- anomalous top quark chromomagnetic dipole moment (CMDM) constrained from the absolute differential tt cross section as a function of $\Delta\phi(\ell^+, \ell^-)$ at particle level





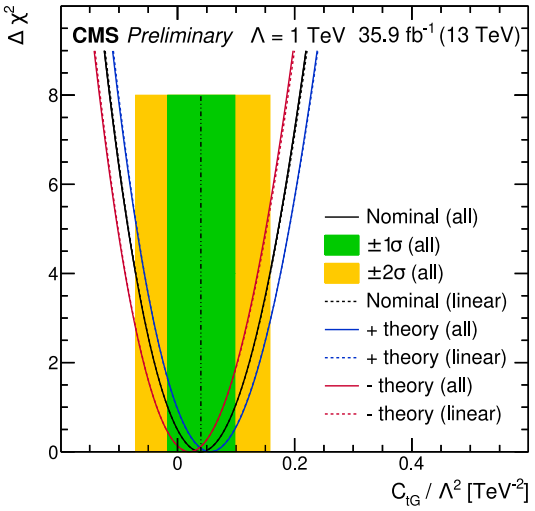
spin correlations

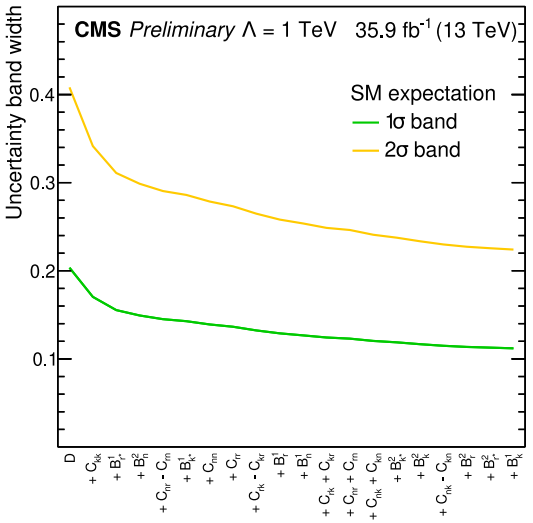
see details in Brent's talk

CMS-TOP-18-006
13 TeV, 35.9 fb^{-1}

- CMDM can also be studied from the measurement of the $t\bar{t}$ production spin density matrix
- χ^2 fit to 20 distributions unfolded to parton level
- systematics from theoretical sources are estimated separately

$$-0.07 < C_{tG}/\Lambda^2 < 0.16 \text{ TeV}^{-2}$$

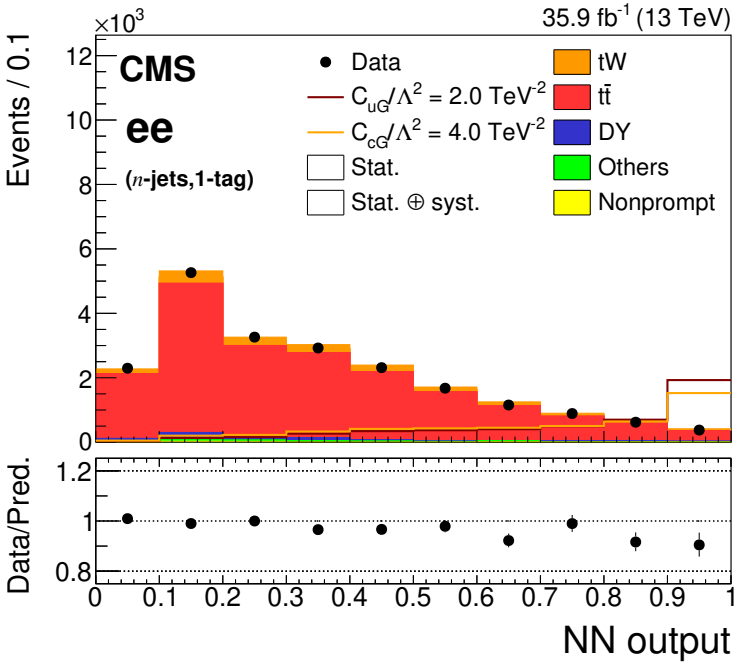


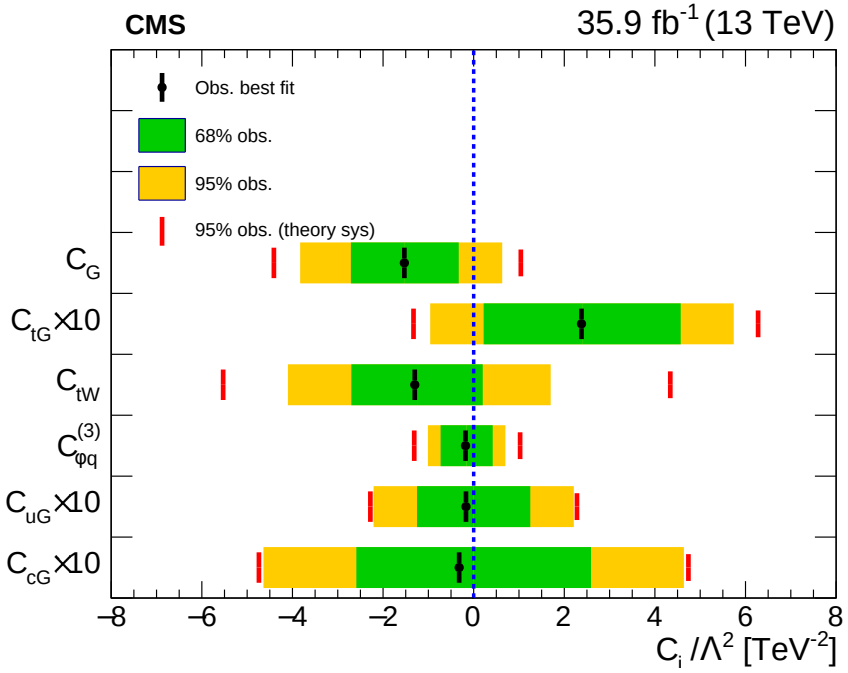


tt, Wt

CMS-TOP-17-020
13 TeV, 35.9 fb^{-1}

- search for new physics in dilepton final states of $t\bar{t}$ and Wt events
- first time constraining EFT in an experimental analysis directly
- first search for new physics that uses the Wt process
- neural networks used to discriminate between signals and background
- constraints on 6 operators (one at a time)
- 2 operators also allow to derive limits of FCNC BRs





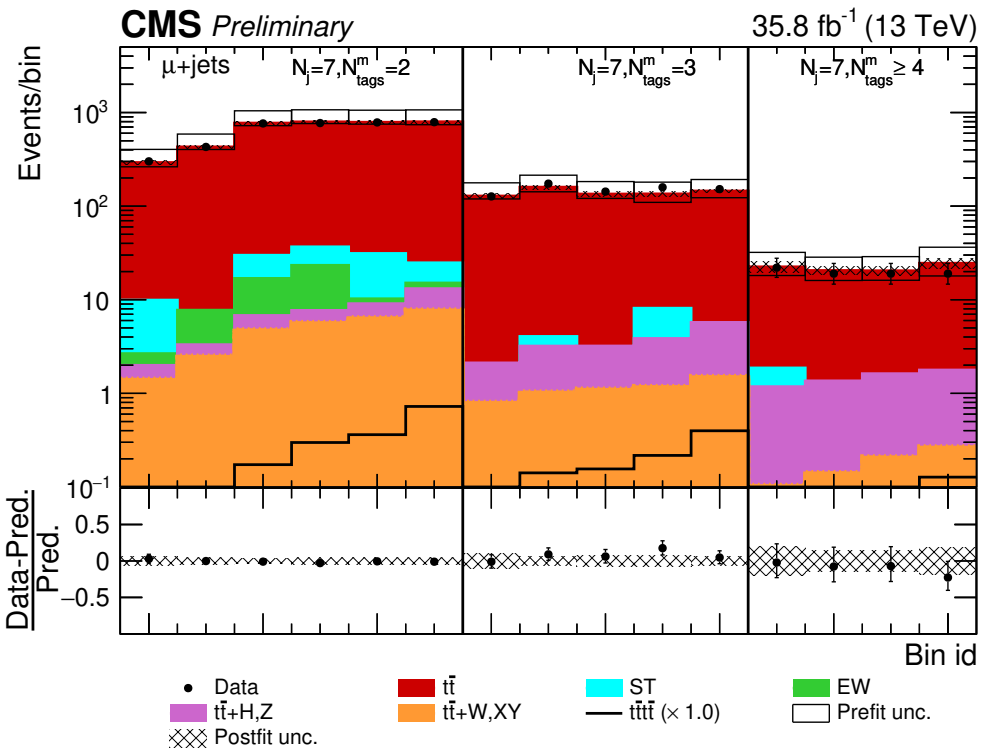
BR($t \to ug$) < 1.2×10^{-3} (2.2×10^{-3}) BR($t \to cg$) < 5.3×10^{-3} (1.05×10^{-2})

$tttt$

see details in Rick's talk

CMS-TOP-17-019
13 TeV, 35.9 fb^{-1}

- search for the SM production of four top quarks ($pp \to t\bar{t}t\bar{t}$)
- single-lepton and OS dilepton channels
- BDT to discriminate signal events from $t\bar{t}$ background



Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{tt}$	$[-1.5, 1.3]$	$[-2.1, 2.0]$
$\mathcal{O}^1_{QQ}$	$[-1.5, 1.3]$	$[-2.2, 2.0]$
$\mathcal{O}^1_{Qt}$	$[-2.4, 2.4]$	$[-3.5, 3.5]$
$\mathcal{O}^8_{Qt}$	$[-5.6, 4.3]$	$[-7.9, 6.6]$

summary

- ATLAS and CMS searches for rare / anomalous top quark couplings
- FCNC with H, γ, g and Z bosons covered
- no evidence for new physics found
- 95% CL limits on BR / couplings / WC derived
- EFT interpretations are becoming more frequent
- different approaches are being explored
- stay tuned for more!