FCNC, EFT, anomalous couplings in CMS

R. Schöfbeck (HEPHY Vienna)

a common language

- top quark probes SM in wildly different settings
  - systematically limited high precision differential x-sec meas.
  - rare-event type searches (4t, …)
  - everything in between (T/TT+Z/W/H/γ, FCNC, …)
  - → uncertainties evolve differently with time
- different energies 7/8/13 TeV, growing PU, evolving detector
  - Want to confront all that with plethora (and evolving) BSM predictions
    AND include Tevatron/LEP/EWPT results
    AND enjoy the results for some time – demand longevity.
- First approach: anomalous coupling to Lagrangian
  - defined in the broken phase, simple, facilitates physics intuition
  - can break symmetries, difficult beyond LO, no global hierarchy of effects
  - this could all be solved, but relevance of results will decline with time

effective field theory

Grzadkowski et.al.
JHEP 1010 (2010) 085
https://arxiv.org/pdf/1008.4884.pdf

- generic extension of the Standard Model

$$\mathcal{L}_{eff} = \mathcal{L}_{SM}^{(4)} + \sum \frac{C_x}{\Lambda^2} O_{6,x} + h.c.$$

$O_{6,x}$ 59 dim-6 gauge-invariant ops.
C_x Wilson coefficients (complex)
Λ scale of dim-6 interactions

- defined in unbroken phase of SM → complex pattern after EWSB
- based on limited & well defined approximations
  - global way to look for NP in SM measurements
  - parameterizes deviations from higher-order SM predictions due to interference of NP with SM; even if new particles are too massive for LHC energies
- EFT provides guidance to exp. searches

$$\sigma = \sigma_{\rm SM} + \sum_i \frac{1\,{\rm TeV}^2}{\Lambda^2} C_i \sigma_i + \sum_{i \le j} \frac{1\,{\rm TeV}^4}{\Lambda^4} C_i C_j \sigma_{ij}.$$

  - e.g. on combination strategy in TT+X
  - e.g. to include 4-f ops in 2l FCNC states
  - etcetc.

new challenges for analysis design:

- understand operator hierarchy, understand EFT validity
- longevity/unfolding → sensibly balance exp. uncertainties and longevity. MVA ?

FCNC

- FCNC suppressed to $10^{-12} - 10^{-15}$ in SM by GIM mechanism
- sensitive probe BSM models: 2HDM, SUSY, etc. arXiv:1311.2028
- anomalous coupling Lagrangian:

$$
\begin{aligned}
\mathcal{L}_{FCNC} = \sum_{q=u,c} \Bigg[& \frac{\sqrt{2}}{2} g_s \frac{\kappa_{\mathrm{tgq}}}{\Lambda} \left(\bar{q}\sigma^{\mu\nu}T^a (f^L_{gq} P_L + f^R_{gq} P_R) t\right) G^a_{\mu\nu} \\
& + \frac{eQ_t}{\sqrt{2}} \frac{\kappa_{\mathrm{tq}\gamma}}{\Lambda} \left(\bar{q}\sigma^{\mu\nu} (f^L_{\gamma q} P_L + f^R_{\gamma q} P_R) t\right) F_{\mu\nu} \\
& + \frac{g}{\sqrt{2}} \kappa_{\mathrm{tqH}} \left(\bar{q} (f^L_{Hq} P_L + f^R_{Hq} P_R) t\right) H \\
& + \frac{\sqrt{2}g}{4c_W} \frac{\kappa_{\mathrm{tqZ}}}{\Lambda} \left(\bar{q}\sigma^{\mu\nu} (\hat{f}^L_{Zq} P_L + \hat{f}^R_{Zq} P_R) t\right) Z_{\mu\nu} \\
& + \frac{g}{4c_W} \zeta_{\mathrm{tqZ}} \left(\bar{q}\gamma^{\mu} (\bar{f}^L_{Zq} P_L + \bar{f}^R_{Zq} P_R) t\right) Z_{\mu} \Bigg] + \mathrm{h.c.}
\end{aligned}
$$

latest results:

- tgq: *7 & 8 TeV**
- tqγ: *8 TeV**
- tqH: *8 & 13 TeV*
- tqZ: *8 & 13 TeV*

nevermind prefactors - different conventions in use. Compare BR.

- often simplify chiral structure, e.g. $f^R = 1$.
- q = u,c with more sensitivity to u (higher x-sec)

** see backup*

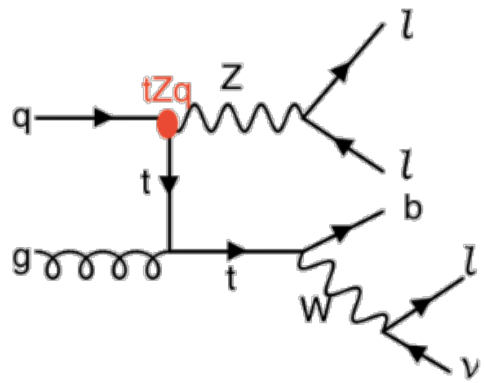
FCNC t/tt qZ

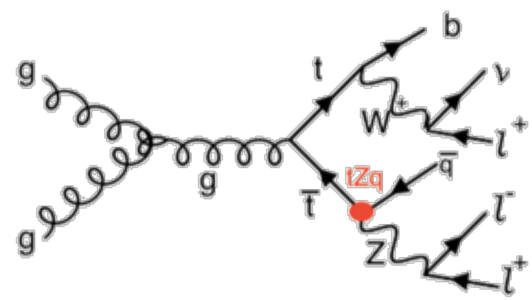
- combine t & tt FCNC channels

8 TeV TOP-12-039
JHEP 07 (2017) 003
https://arxiv.org/abs/1702.01404

13 TeV TOP-17-017
http://cds.cern.ch/record/2292045

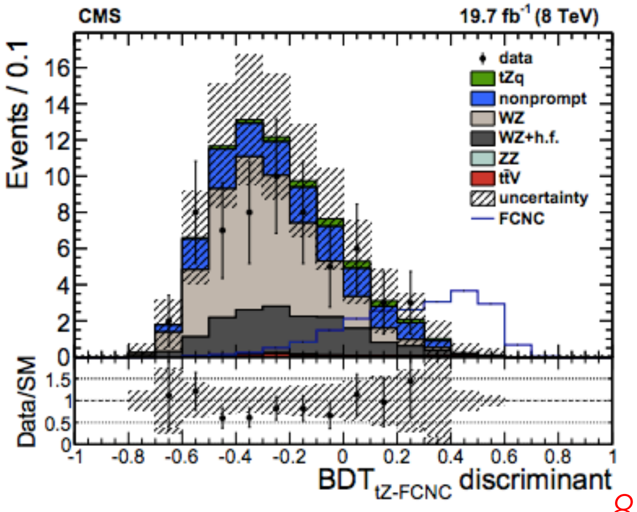
FCNC signal single-top-quark	FCNC signal $t\bar{t}$
1 jet, $\lvert\eta\rvert<2.4$ 1 b tag	$\geqslant 2$ jets, $\lvert\eta\rvert<2.4$ $\geqslant 1$ b tag
$m_T^W > 10$ GeV $p_T^{miss} > 40$ GeV	$m_T^W > 10$ GeV $p_T^{miss} > 40$ GeV

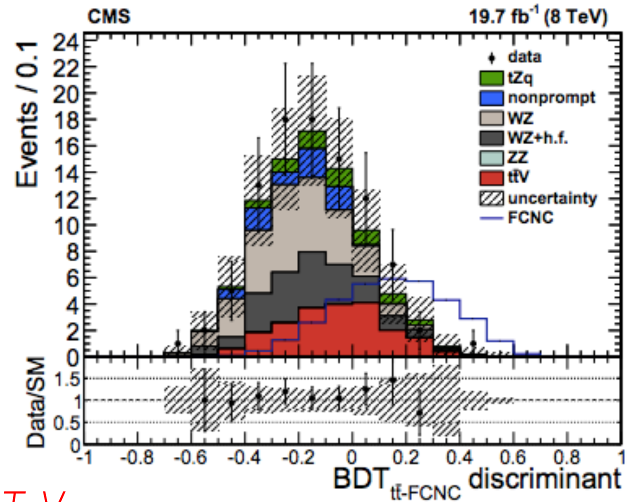




- consider all flavor combinations eee/μee/μμe/μμμ
  require same-flavor opposite-sign Z candidate
- consider only tensor coupling κ_{tqZ}
- three low njet/nbjet SB for (1) non-prompt leptons and W+Jets (separated by m_T(W) and per flavor) and for NPL + (2) t and (3) tt
- train BDTs to separate t and tt-FCNC signal,
  fit output discriminator in CR and SR simultaneous in t/tt

FCNC t/tt qZ





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JHEP 07 (2017) 003
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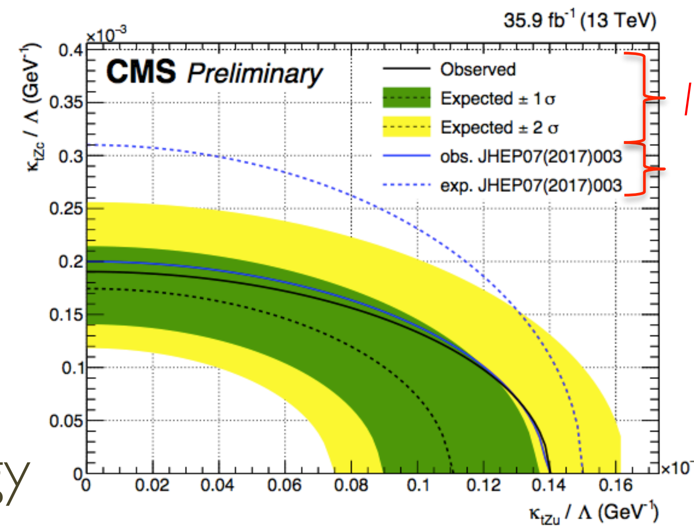
- BDT output for t- and tt FCNC

8 TeV

Branching fraction	Expected	68% CL range	Observed
$\mathcal{B}(t \to Zu)$ (%)	0.027	0.018 – 0.042	0.022
$\mathcal{B}(t \to Zc)$ (%)	0.118	0.071 – 0.222	0.049

Branching fraction	Expected	Observed
$\mathcal{B}(t \to Zu)$ (%)	0.015	0.024
$\mathcal{B}(t \to Zc)$ (%)	0.037	0.045

13 TeV



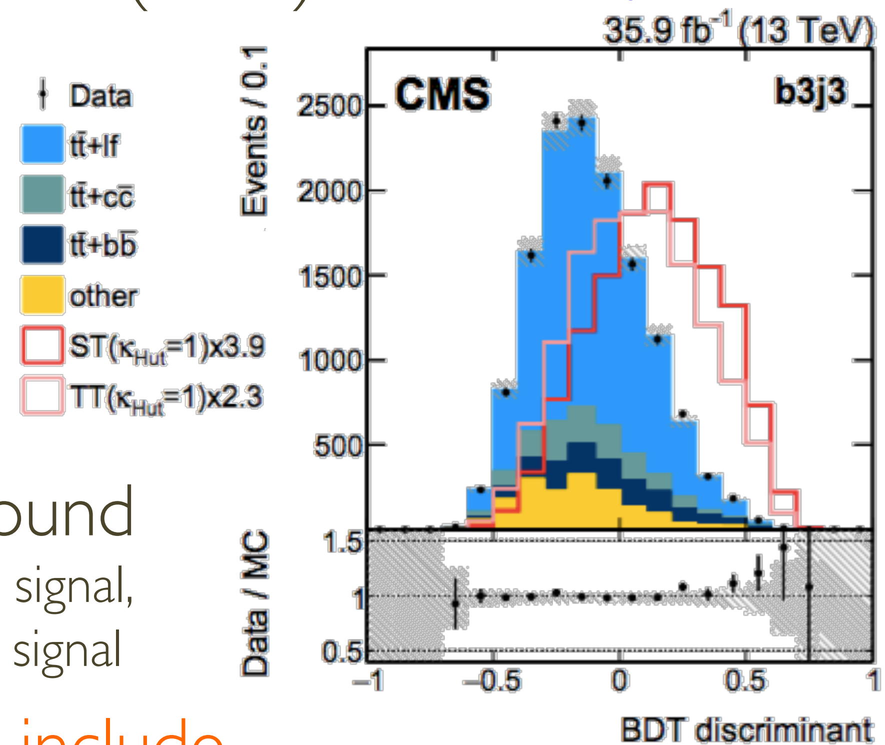
13 TeV
8 TeV

- statistics dominated; profit from energy and lumi; excluded BR ~ O(10^{-4})

FCNC tqH

13 TeV TOP-17-003
https://arxiv.org/abs/1712.02399
8 TeV TOP-13-017
JHEP 02 (2017) 079
https://arxiv.org/abs/1610.04857

- Combine 8 TeV results from top quark pair production in H→bb/γγ/WW+ττ(+ZZ)
- H→γγ most sensitive
  bkg estimation from $m_{\gamma\gamma}$ SB fit
- For H→WW+ττ(+ZZ)
  combine SS and multi-lepton channels
- H→bb has largest branching
  but large combinatorial background
  BDT to select correct assignment in FCNC signal,
  ANN (8 TeV) or BDT (13 TeV) to selecting signal
- At 13 TeV, focus on H→bb but include tH production (+20% sensitivity from PDF enhancement when q=u)



UL[%]	8 TeV	13 TeV (bb)
BR(t→Hu)	0.55(0.40)	0.47(0.34)
BR(t→Hc)	0.40(0.43)	0.47(0.44)

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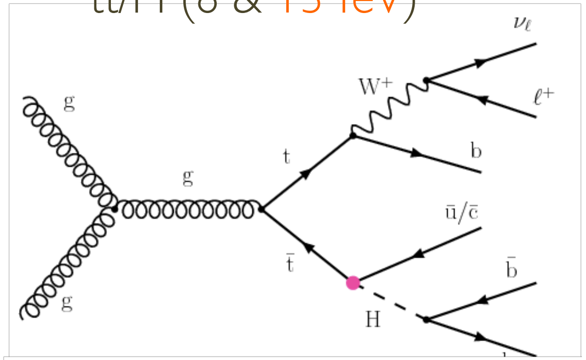
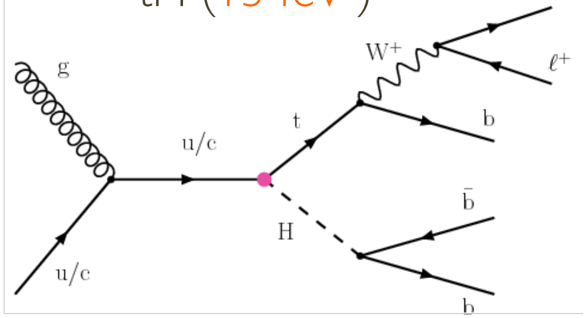
tt/H (8 & 13 TeV)



tH (13 TeV)



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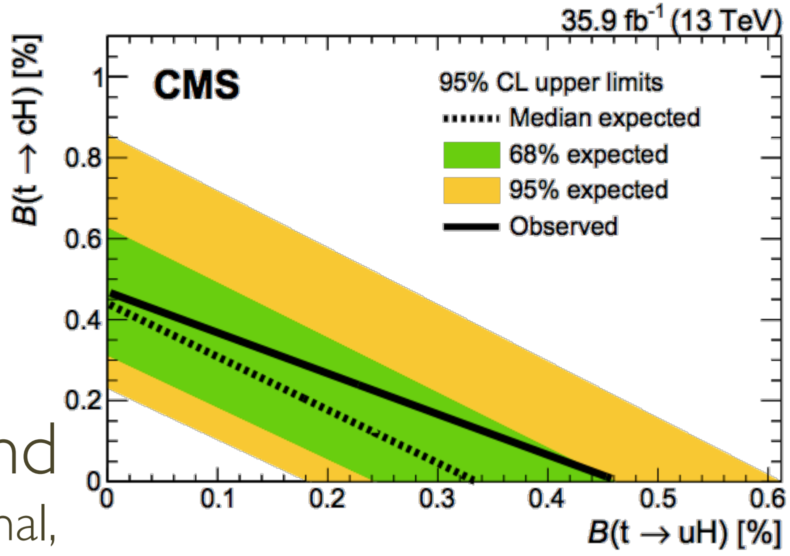

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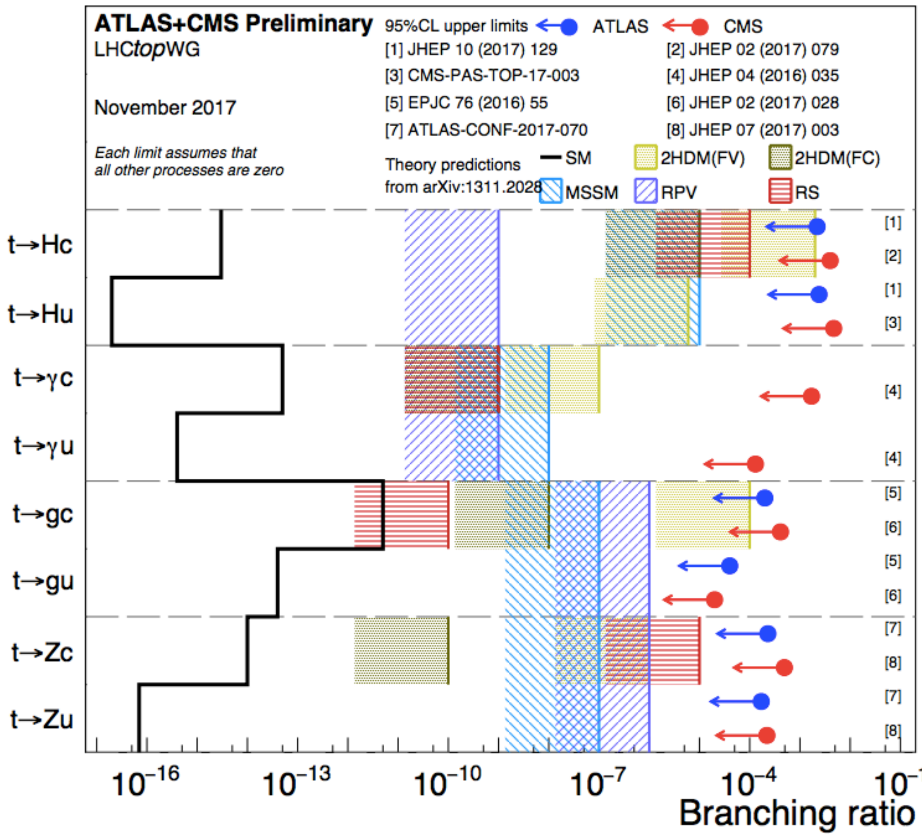
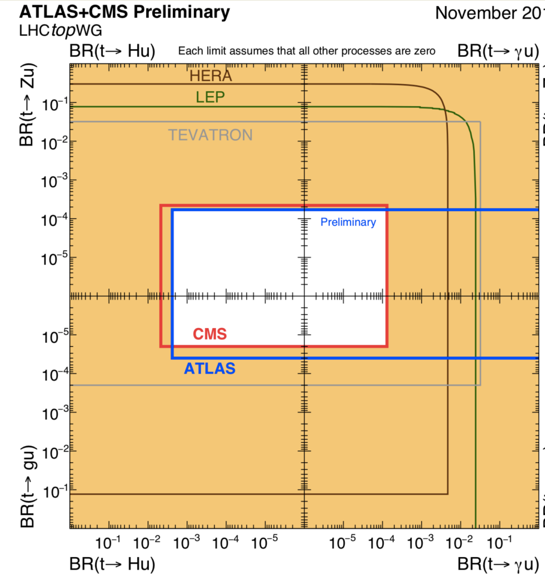
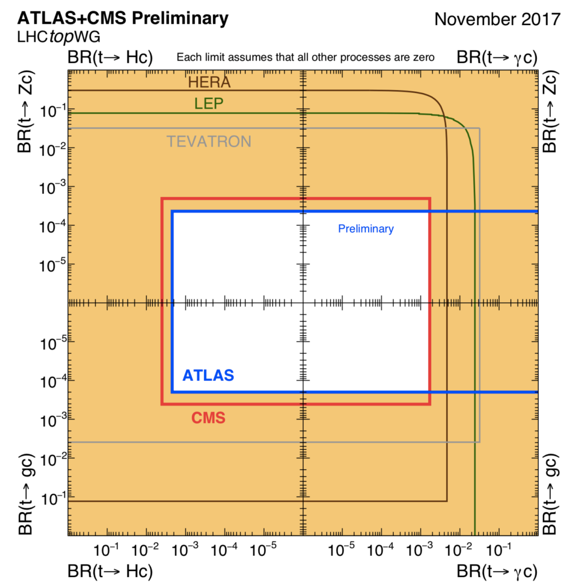
FCNC summary – ATLAS & CMS







- common language pragmatic choice: BR
- EFT approach in: *G. Durieux, F. Maltoni, C. Zhang Phys. Rev. D 91, 074017 (2015)* https://arxiv.org/pdf/1412.7166.pdf
  - points out few missed contributions

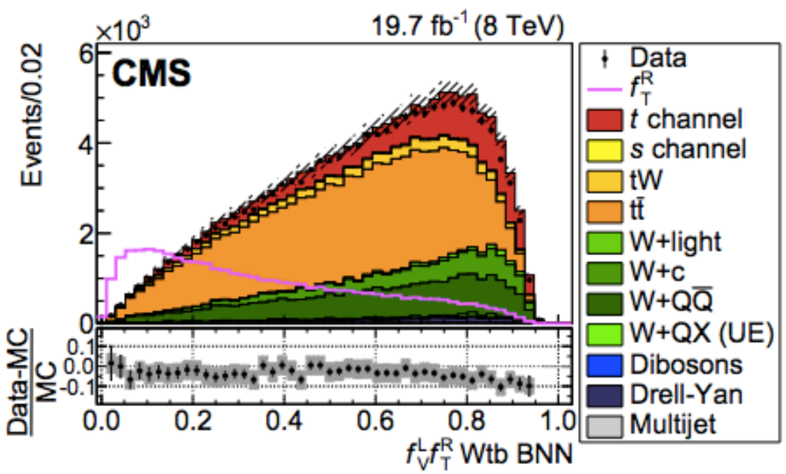
anomalous charged current

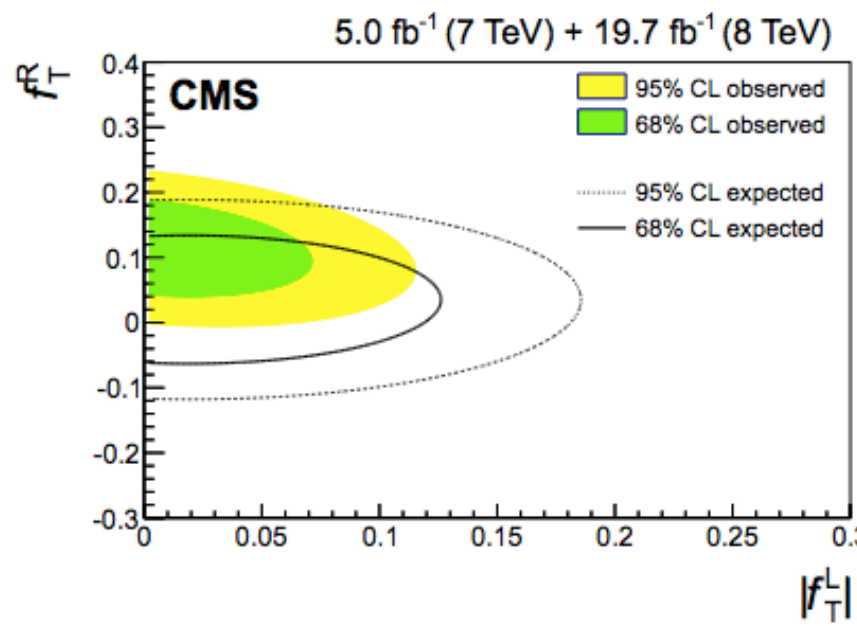
8 TeV TOP-14-007
JHEP 02 (2017) 028
https://arxiv.org/pdf/1610.03545.pdf

- charged current anomalous interactions

$$\mathfrak{L} = \frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(f_{V}^{L}P_{L} + f_{V}^{R}P_{R}\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{\sigma^{\mu\nu}\partial_{\nu}W_{\mu}^{-}}{M_{W}}\left(f_{T}^{L}P_{L} + f_{T}^{R}P_{R}\right)t + \text{h.c.}$$

- constrained in single-top t-channel (1 μ) at 7 & 8 TeV
  - 3 BNNs to separate V_L contributions from V_R, g_L, g_R
  - 3D analysis in right handed vector- and the L&R tensor couplings





95%CL @ 8 TeV
$\lvert V_R\rvert < 0.16$
$\lvert g_L\rvert < 0.057$, $-0.049 < g_R < 0.048$

helicity fractions

8 TeV TOP-13-008
Phys.Lett. B762 (2016) 512-534
https://arxiv.org/abs/1605.09047

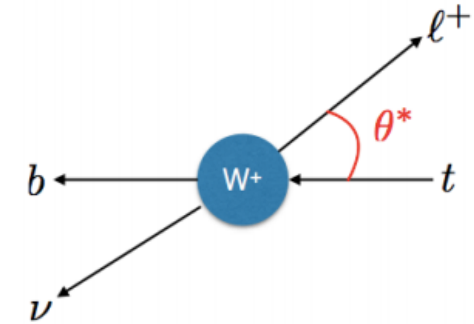
- charged current anomalous interactions

$$\mathcal{L} = \frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(f_V^L P_L + f_V^R P_R\right) t W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{\sigma^{\mu\nu}\partial_{\nu}W_{\mu}^{-}}{M_W}\left(f_T^L P_L + f_T^R P_R\right) t + \text{h.c.}$$

  - also modifies helicity fractions and diff. decay w.

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\ell}^{*}} = \frac{3}{8}(1+\cos\theta_{\ell}^{*})^2 F_R + \frac{3}{8}(1-\cos\theta_{\ell}^{*})^2 F_L + \frac{3}{4}\sin^2\theta_{\ell}^{*} F_0$$

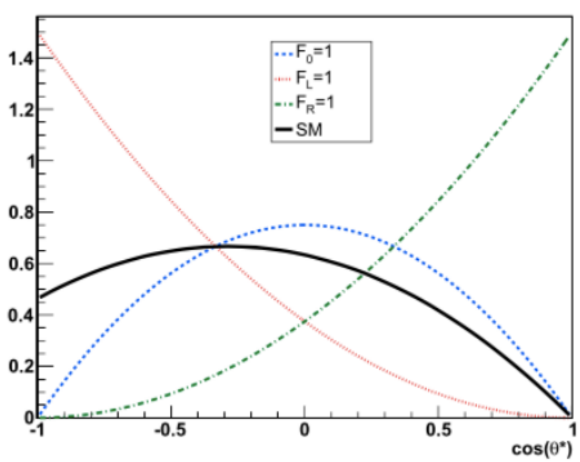
  - semi-lep tt+jets with full kinematic reco

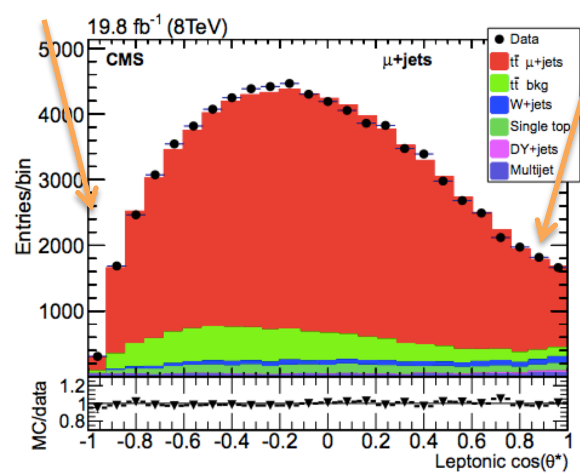


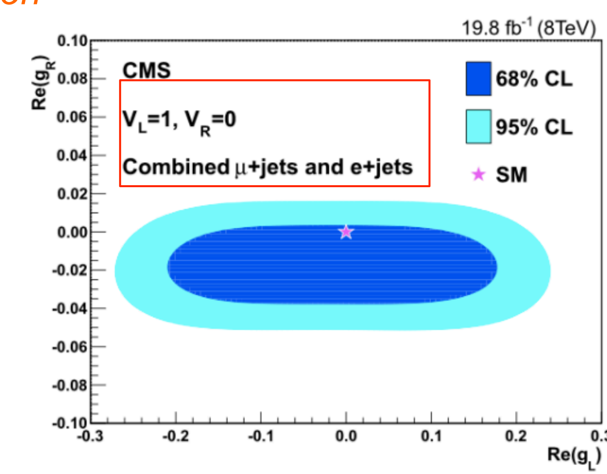
F_0 = 0.681 ± 0.012 (stat.) ± 0.023 (syst.)
F_L = 0.323 ± 0.008 (stat.) ± 0.014 (syst.)
F_R = 0.004 ± 0.005 (stat.) ± 0.014 (syst.)

angular l/j separation

resolution







spin correlation

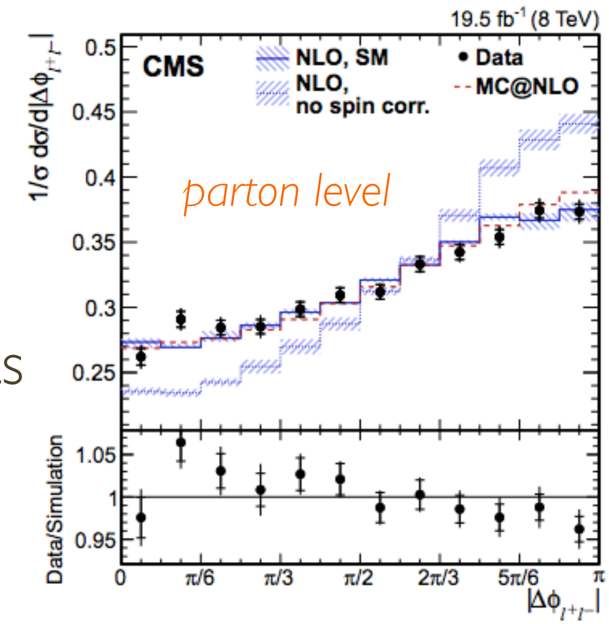
8 TeV TOP-14-023
PRD 93 (2016) 052007
https://arxiv.org/pdf/1601.01107.pdf

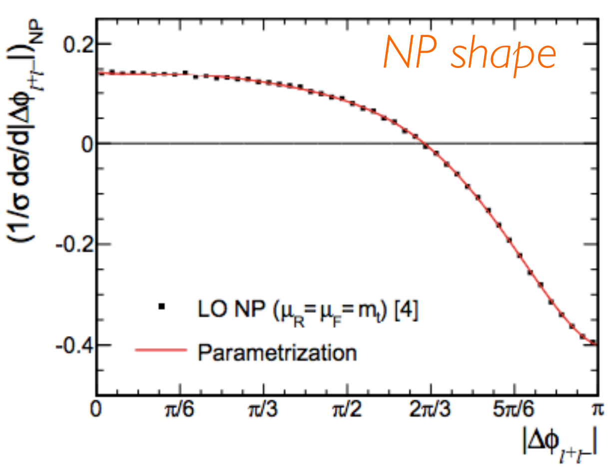
- top decay products are a probe of the ttbar spin correlation

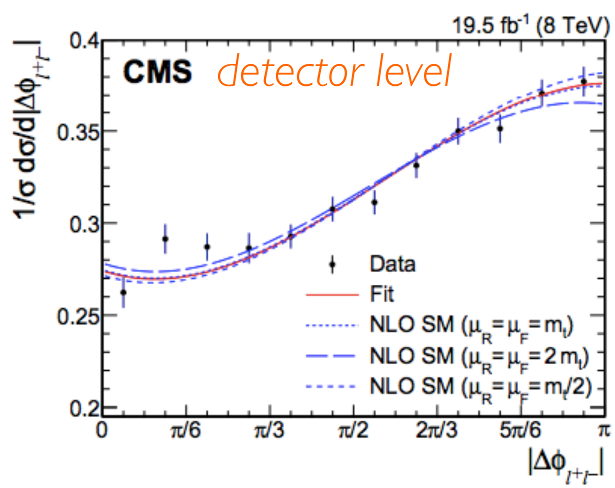
$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production}\\ 10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime}\\ 10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization}\\ 10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip}\\ 10^{-21}\ \text{s}}}$$

- $|\Delta\Phi(ll)|$ in 2l-ttbar unfolded to parton-level
- sensitive to chromo magn. & el. dipole moments

$$\mathcal{L}_{\text{eff}} = -\frac{\tilde{\mu}_t}{2}\bar{t}\sigma^{\mu\nu}T^a t G^a_{\mu\nu} - \frac{\tilde{d}_t}{2}\bar{t}i\sigma^{\mu\nu}\gamma_5 T^a t G^a_{\mu\nu}$$







$|\Delta\Phi(ll)|$ & other asymmetries:

$$-0.053 < \text{Re}(\hat{\mu}_t) < 0.026$$
$$-0.068 < \text{Im}(\hat{d}_t) < 0.067$$

spin correlation

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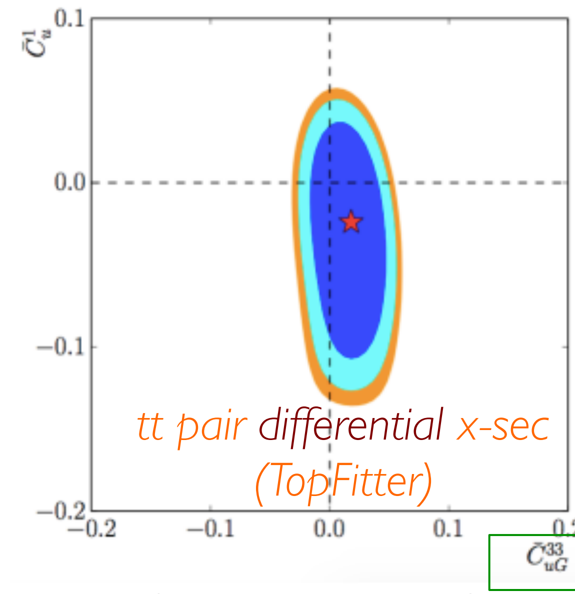
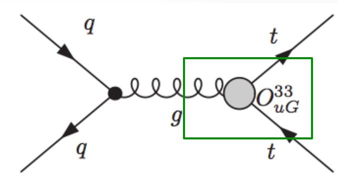
TOP Fitter
JHEP 1604 (2016) 015
https://arxiv.org/abs/1512.03360





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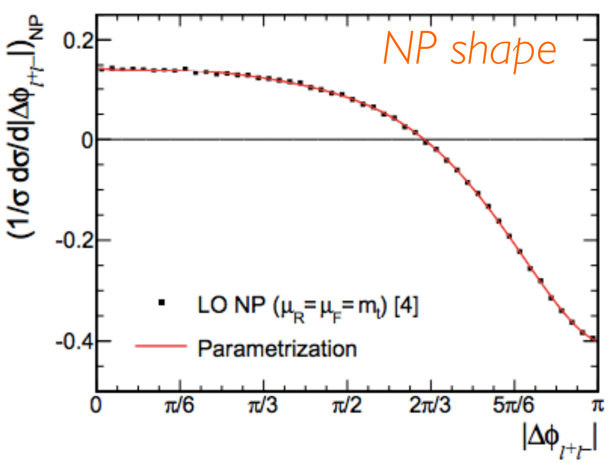

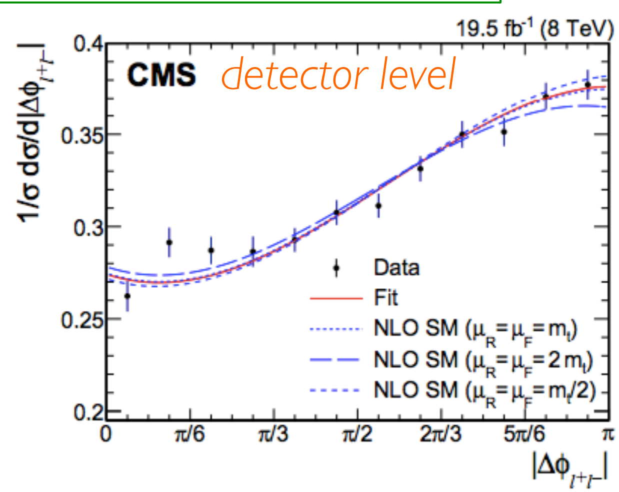

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JHEP 1604 (2016) 015
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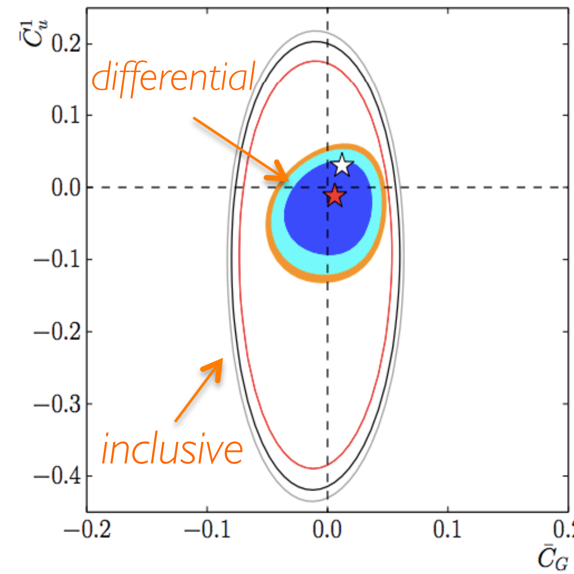

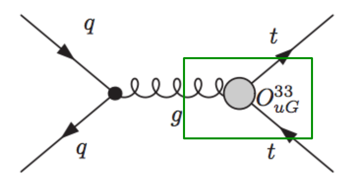

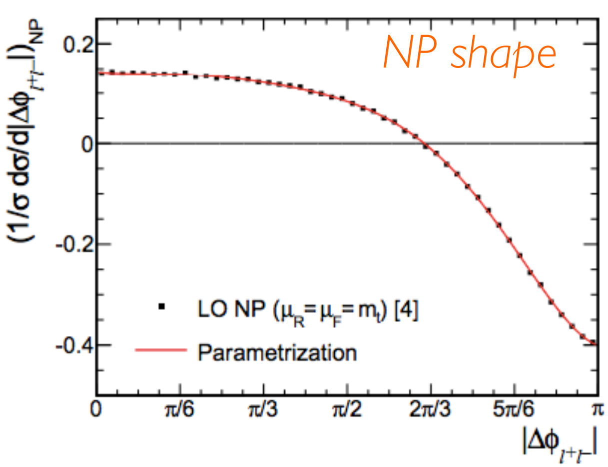

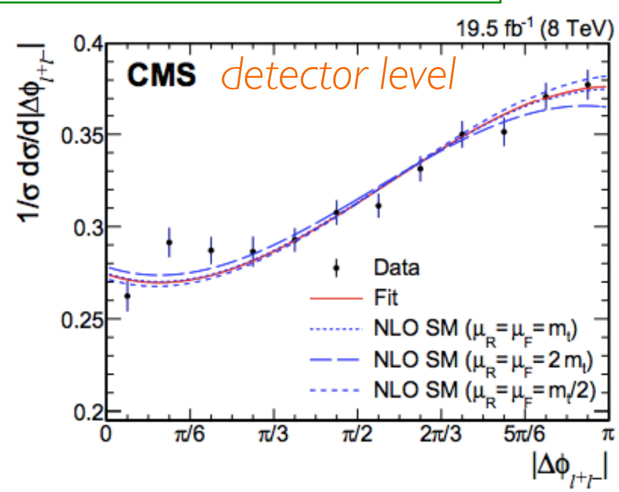

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associate production

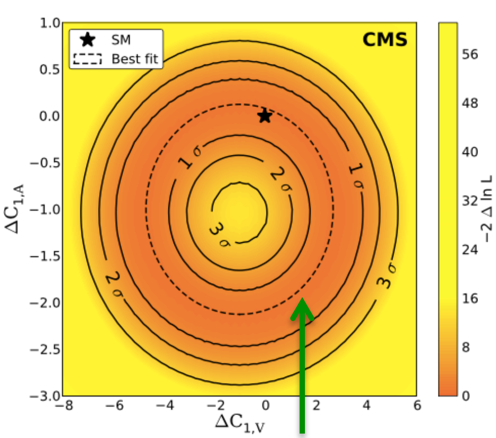
13 TeV TOP-17-005
submitted to JHEP
https://arxiv.org/abs/1711.02547
8 TeV TOP-14-021
JHEP 01 (2016) 096
https://arxiv.org/abs/1510.01131
A. Alloul, B. Fuks, V. Sanz
JHEP 1404 (2014) 110
https://arxiv.org/abs/1310.5150

- measured inclusive tt+Z/W/γ x-sec at 8 & 13 TeV

$$\mathcal{L}_{SM+BSM} = e\bar{u}(p_t)\left(\gamma^\mu \underbrace{(C_{1,V}+\gamma^5 C_{1,A})}_{\text{vector}} + \frac{i\sigma^{\mu\nu}q_\nu}{m_Z}\underbrace{(C^Z_{2,V}+i\gamma^5 C^Z_{2,A})}_{\text{tensor} \rightarrow \text{EWK dipole moments}}\right) v(p_{\bar{t}}) Z_\mu$$

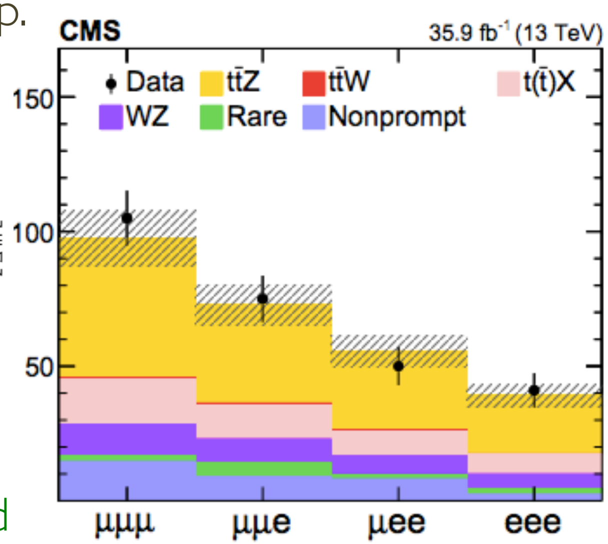
- 8 TeV: limit on current couplings $C_{1V,A}$
  - also used tt+Z inclusive x-sec to constrain "HEL" & anomalous couplings
- 13 TeV: Combine tt+W/Z inclusive x-sec to constrain 7 W.C.

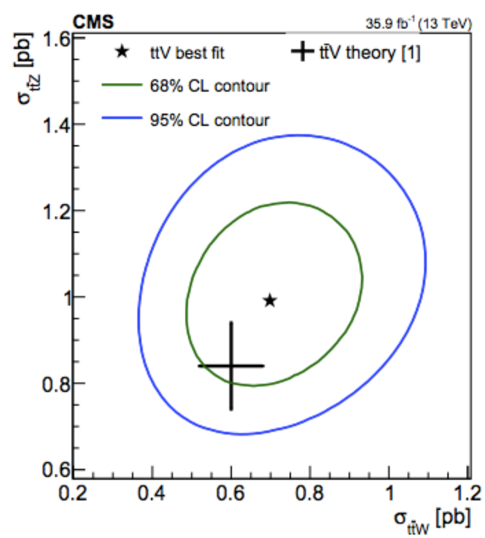
8 TeV x-sec anom coup.

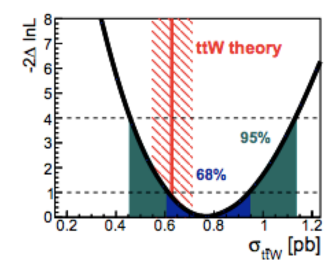


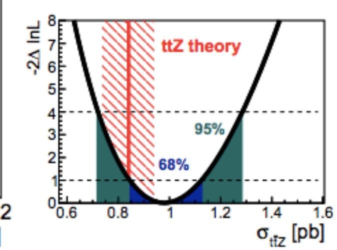
full circle equally allowed

13 TeV inclusive





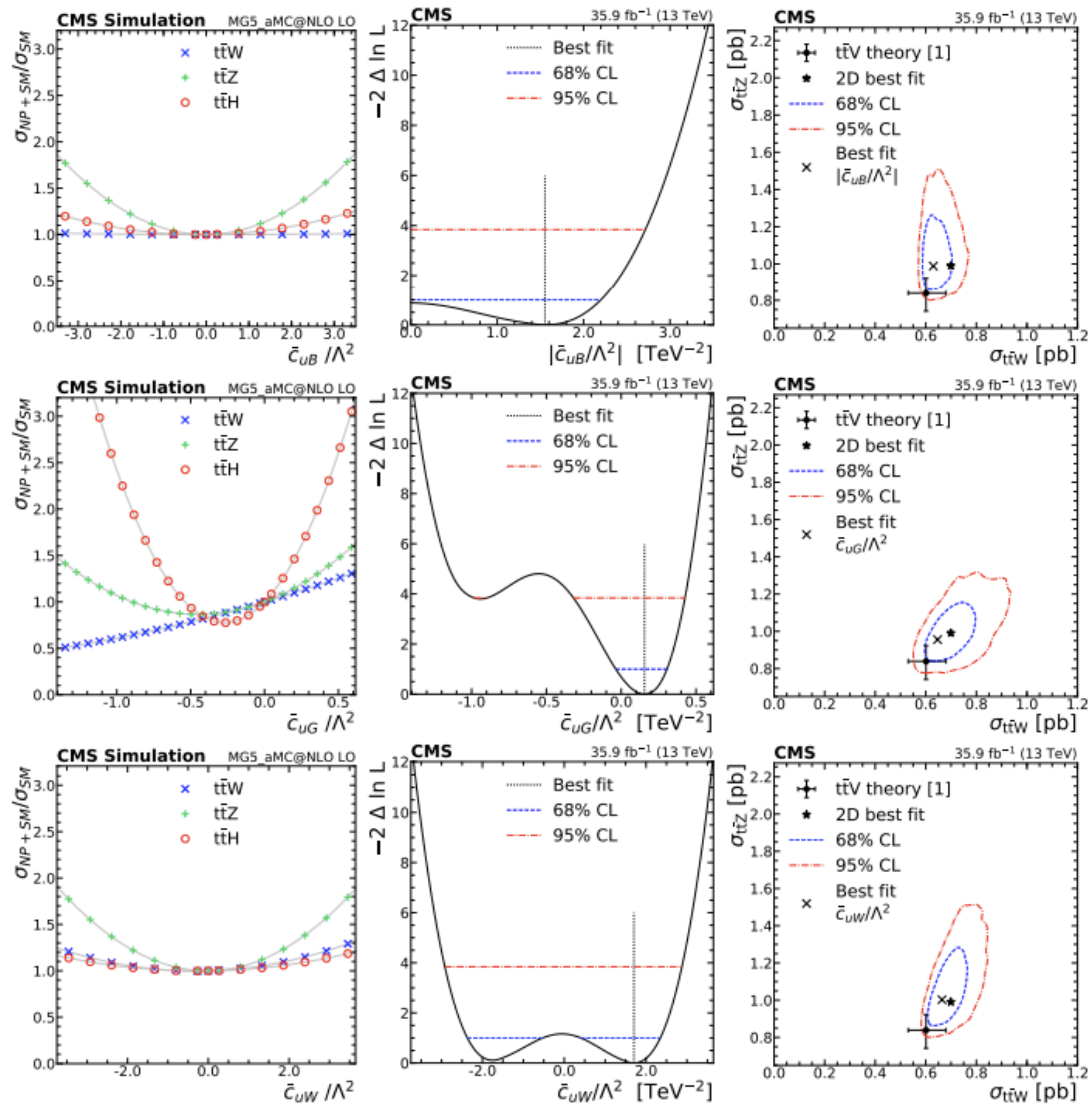




constraints from tt+Z/W

	Wilson coefficient	68% CL [TeV^{-2}]	95% CL [TeV^{-2}]
$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{\varphi} W^I_{\mu\nu}$	$\bar{c}_{\mathrm{uW}} / \Lambda^2$	$[-1.6, 1.5]$	$[-2.2, 2.2]$
$\partial^\mu [\Phi^\dagger \Phi] \partial_\mu [\Phi^\dagger \Phi]$	$\lvert \bar{c}_{\mathrm{H}} / \Lambda^2 - 16.8\,\mathrm{TeV}^{-2} \rvert$	$[3.7, 23.4]$	$[0, 28.7]$
$f^{abc} G^{a\,\nu}_{\mu} G^{b\,\rho}_{\nu} \widetilde{G}^{c\,\mu}_{\rho}$	$\widetilde{c}_{3\mathrm{G}} / \Lambda^2$	$[-0.5, 0.5]$	$[-0.7, 0.7]$
$f^{abc} G^{a\,\nu}_{\mu} G^{b\,\rho}_{\nu} G^{c\,\mu}_{\rho}$	$\bar{c}_{3\mathrm{G}} / \Lambda^2$	$[-0.3, 0.7]$	$[-0.5, 0.9]$
$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{\varphi} G^A_{\mu\nu}$	$\bar{c}_{\mathrm{uG}} / \Lambda^2$	$[-0.9, -0.8]$ and $[-0.3, 0.2]$	$[-1.1, 0.3]$
$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{\varphi} B_{\mu\nu}$	$\lvert \bar{c}_{\mathrm{uB}} / \Lambda^2 \rvert$	$[0, 1.5]$	$[0, 2.1]$
$(\bar{u}_R \gamma^\mu u_R)\,(H^\dagger \overleftrightarrow{D}_\mu H)$	$\bar{c}_{\mathrm{Hu}} / \Lambda^2$	$[-9.2, -6.5]$ and $[-1.6, 1.1]$	$[-10.1, 2.0]$
$(D^\mu G_{\mu\nu})^a\,(D_\rho G^{\rho\nu})^a$	$\bar{c}_{2\mathrm{G}} / \Lambda^2$	$[-0.7, 0.4]$	$[-0.9, 0.6]$

constraints from tt+Z/W

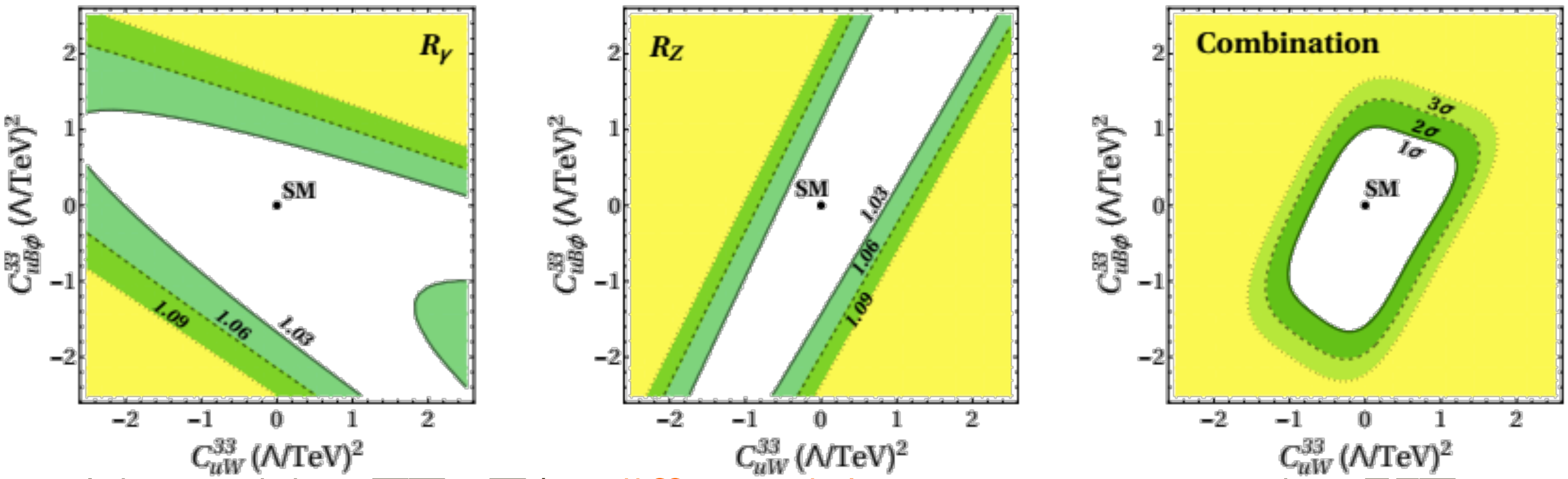


lessons on TT+V from EFT

$$\mathcal{L}_{SM+BSM} = e\bar{u}(p_t)\left(\gamma^\mu\left(C_{1,V}+\gamma^5 C_{1,A}\right)+\frac{i\sigma^{\mu\nu}q_\nu}{m_Z}\left(C^Z_{2,V}+i\gamma^5 C^Z_{2,A}\right)\right)v(p_{\bar{t}})Z_\mu + e\bar{u}(p_t)\left(\gamma^\mu+\frac{i\sigma^{\mu\nu}q_\nu}{m_Z}\left(C^\gamma_{2,V}+i\gamma^5 C^\gamma_{2,A}\right)\right)v(p_{\bar{t}})A_\mu$$

M. Schulze, Y. Soreg
Eur.Phys.J. C76 (2016) no.8, 466
https://arxiv.org/abs/1603.08911

- gauge symmetry relate EWK dipole moments
- manifest in EFT → Same W.C. enter $C_2^{Z/\gamma}$, but in different lin. comb.



- should combine TT+Z/γ differential x-sec to constraint EFT
- gauge symmetries relate $C_2^{Z/\gamma}$ also with the Wtb vertex
  - new "dim6_top" EFT from TopLHCWG disentangles tt+V from Wtb

new model from TopLHCWG

- global strategy provides conservative, well-defined & enduring results
- "dim6 top EFT" from TopLHCWG http://desy.de/~durieux/topbasis/eft_note-submitted-to-readers.pdf

"**6 A simple analysis strategy**

The simplest strategy to constrain the standard-model effective field theory with measurements in the top sector could rely on fiducial observables defined at, and unfolded to, the particle level. It is meant to be simultaneously practical and useful on a long-term basis, being for instance able to"

unfolding	advantages	disadvantages
None (detector level)	high precision, MVAs feasible	hard to integrate in global effort difficult to profit from e.g. theory & MC developments
particle level unfolding (fiducial)	scalable, can use cutting edge theory, active role for theorists	less precise data, limits on e.g. MVA
parton level unfolding (full phase space)	scalable, can use cutting edge theory	least precise, frozen unc. e.g. from acceptance, correlation pattern, strong limits on MVA usage

EFT is not a simple BSM model

C. Zhang, 2017
https://arxiv.org/pdf/1708.05928.pdf
TOP-17-009
https://arxiv.org/pdf/1710.10614.pdf

- recent tttt x-sec constraints C_{tu}

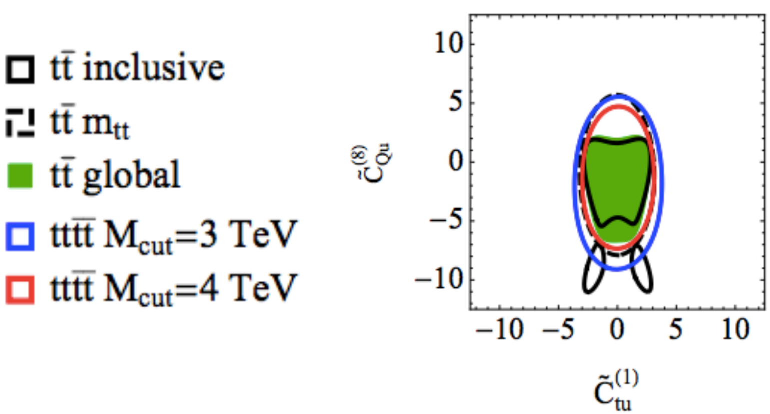
$$\mathcal{O}_{tu}^{(8)} = (\bar{t}_R\gamma_\mu T^a t_R)(\bar{u}_R\gamma^\mu T^a u_R)$$

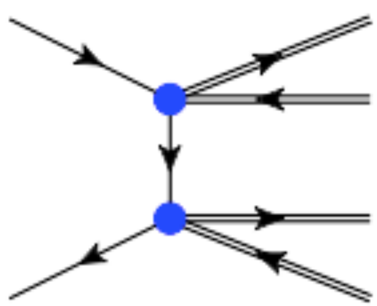
$$\sigma_{LO}(4t) = 6.1+0.10\tilde{C}_{tu}^{(8)}+0.081\tilde{C}_{tu}^{(8)2}+0.016\tilde{C}_{tu}^{(8)3}+0.0048\tilde{C}_{tu}^{(8)4}$$

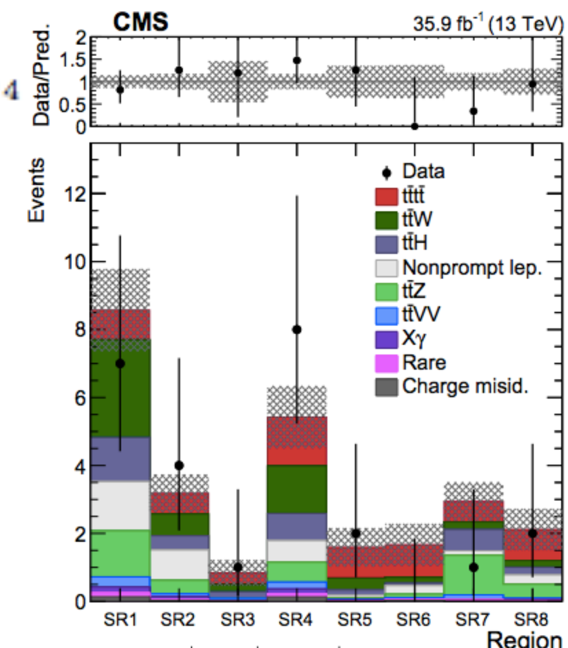
- 4th power in W.C., two dim-6 insertions
  can neglect dim-8 for wide class of BSM

4t xsec: $-8.8<\tilde{C}_{tu}^{(8)}<7.1$

inclusive tt x-sec: $-11.8<\tilde{C}_{tu}^{(8)}<4.6$







N_ℓ	N_b	N_{jets}	Region
2	2	≤5	CRW
		6	SR1
		7	SR2
		≥8	SR3
	3	5, 6	SR4
		≥7	SR5
	≥4	≥5	SR6
≥3	2	≥5	SR7
	≥3	≥4	SR8
Inverted Z veto			CRZ

final remarks

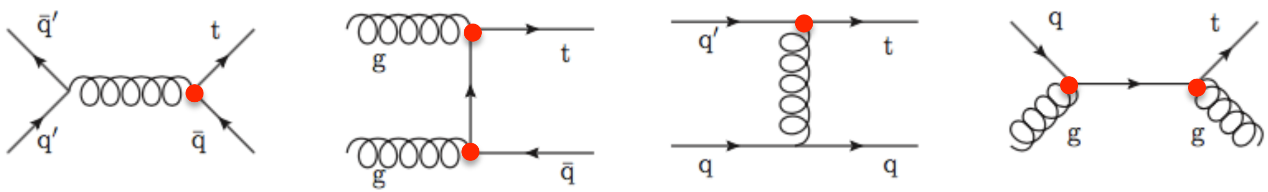
- we'll always have anomalous coupling interpretations
  - comprehensible, quickly doable, a selling point
- Run-II endgame: we should have (carefully planned) EFT interpretations using (multi-) differential distributions
  - TT+W/Z/γ/H: profit from independent linear combinations
  - ttbar x-sec + spin corr constrain tt pair production & chromo moments
  - Wtb/single-t + helicity constraint the Wtb vertex
  - FCNC
- similar to e.g. SUSY-pMSSM efforts
  - EFT is not a simple BSM model
- particle-level unfolding is a good compromise & defines a suitable interface to theorists

FCNC tgq (q=u/c)

8 TeV TOP-14-007
JHEP 02 (2017) 028
https://arxiv.org/pdf/1610.03545.pdf

- single top t-channel events (1 μ final state)

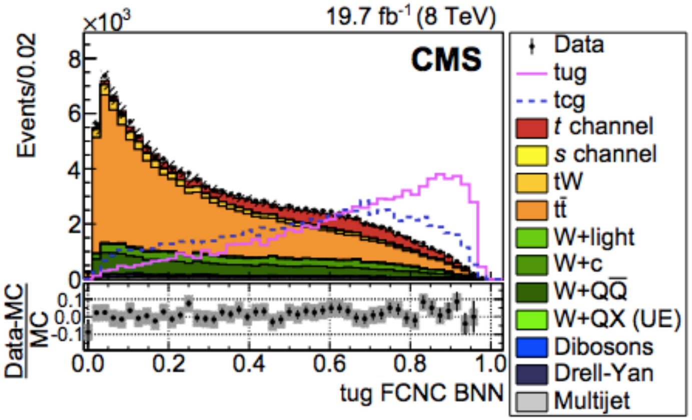
FCNC

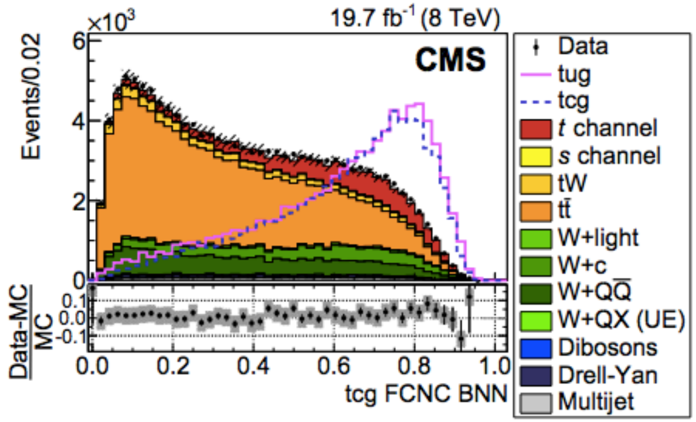


- require 1 bjet, 1 light forward jet as predicted in t-channel
- BNN to reject multijet BG (fit to normalize)
- In FCNC, light forward jet is softer + more subtle effects
- top reconstruction (W mass → neutrino z momentum)
- BNN to distinguish FCNC from SM
  - combine kinematic and angular observables (FCNC top softer)
  - lepton charge & PDF effect in u & c → different BNN

FCNC tgq (q=u/c)

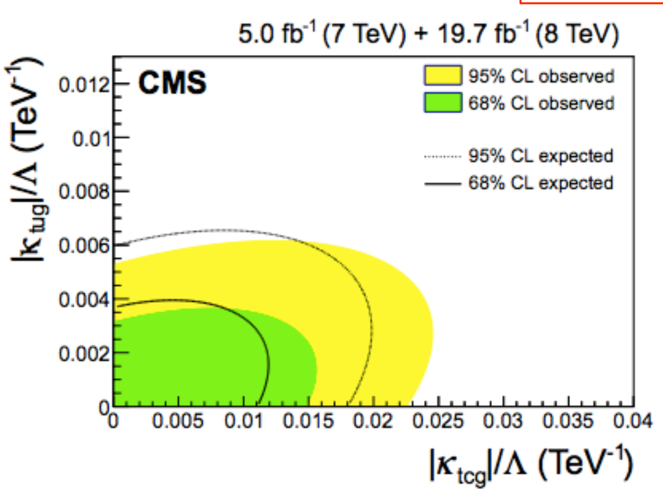
8 TeV TOP-14-007
JHEP 02 (2017) 028
https://arxiv.org/pdf/1610.03545.pdf





MVA output
↓
fit
↓
Observed (expected) limits

$\sqrt{s}$	$\lvert\kappa_{tug}\rvert/\Lambda$ (TeV^{-1})	$\mathcal{B}(t \to ug)$	$\lvert\kappa_{tcg}\rvert/\Lambda$ (TeV^{-1})	$\mathcal{B}(t \to cg)$
7 TeV	14 (13) $\times 10^{-3}$	24 (21)$\times 10^{-5}$	2.9 (2.4) $\times 10^{-2}$	10.1 (6.9)$\times 10^{-4}$
8 TeV	5.1 (5.9) $\times 10^{-3}$	3.1 (4.2)$\times 10^{-5}$	2.2 (2.0) $\times 10^{-2}$	5.6 (4.8)$\times 10^{-4}$
7 and 8 TeV	4.1 (4.8) $\times 10^{-3}$	2.0 (2.8)$\times 10^{-5}$	1.8 (1.5) $\times 10^{-2}$	4.1 (2.8)$\times 10^{-4}$

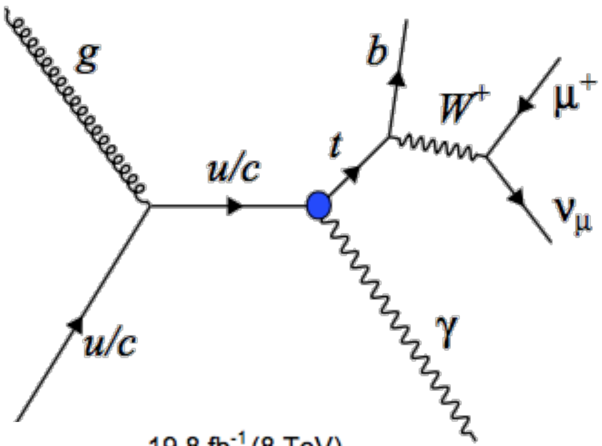


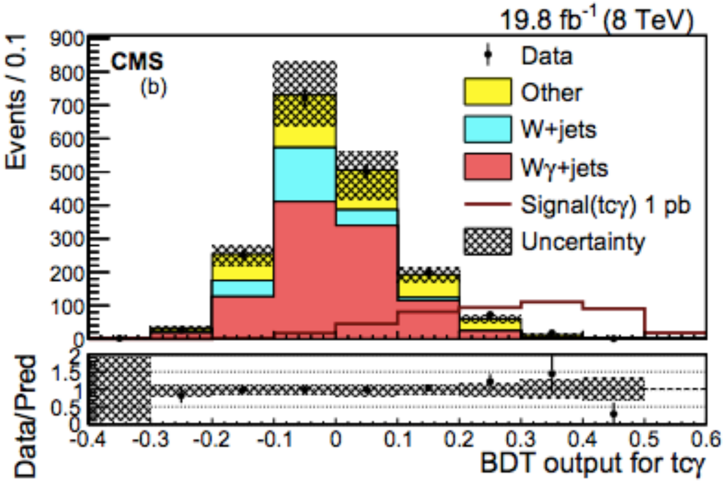
- fit procedure to extract individual limits on κ_{tgq} and BR for q=u/c
- BR(t→ug) < 2.0 10^{-5}
  BR(t→cg) < 4.1 10^{-4}

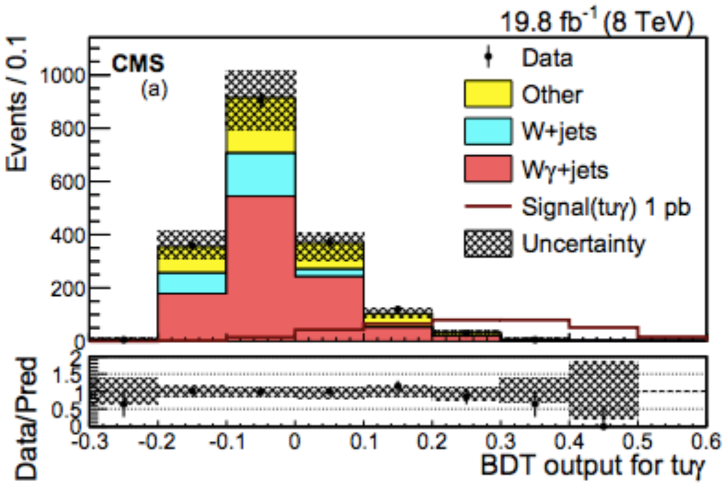
FCNC tqγ

8 TeV TOP-14-003
JHEP 04 (2016) 035
https://arxiv.org/abs/1511.03951

- single top t-channel (→ single μ final state)
- $p_T(\gamma)$>50 GeV, ≤1 b jet
- top reconstruction ($p_T(\nu)$ from m_W)
- main bkg W+jets with real or fake γ
  - extract normalisation from NN shape fit in data: ±17% (Wγ) and ±23% (W+jets)







FCNC tqγ

8 TeV TOP-14-003
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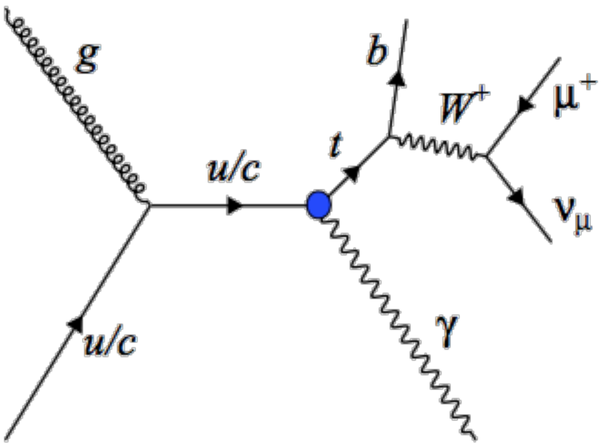


	Exp. limit (LO)	±1σ (exp. limit)	±2σ (exp. limit)	Obs. limit (LO)
$\sigma_{tu\gamma}\,\mathcal{B}$ (fb)	40	30–56	23–78	25
$\sigma_{tc\gamma}\,\mathcal{B}$ (fb)	39	30–55	24–76	34
$\kappa_{tu\gamma}$	0.036	0.032–0.043	0.028–0.051	0.029
$\kappa_{tc\gamma}$	0.111	0.098–0.132	0.087–0.16	0.10
$\mathcal{B}(t \to u\gamma)$	2.7×10^{-4}	$(2.0 - 3.8) \times 10^{-4}$	$(1.6 - 5.4) \times 10^{-4}$	1.7×10^{-4}
$\mathcal{B}(t \to c\gamma)$	2.5×10^{-3}	$(1.9 - 3.6) \times 10^{-3}$	$(1.5 - 4.9) \times 10^{-3}$	2.2×10^{-3}

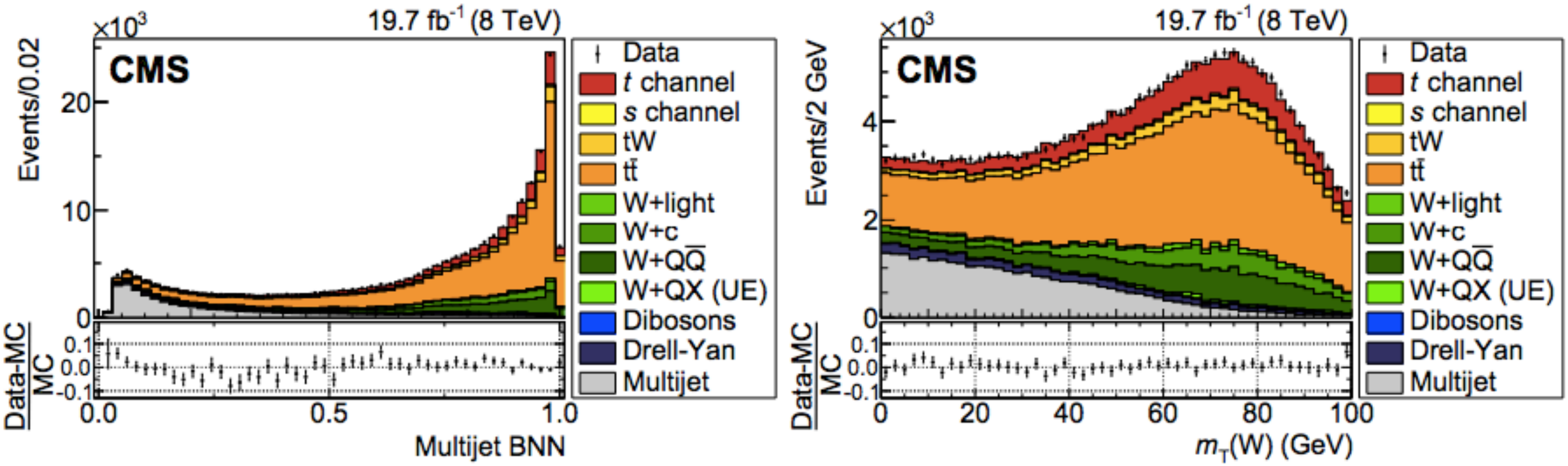
the 59 SM EFT operators

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star (\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde W B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$				

FCNC tgq

- multijet BNN discriminator



FCNC tHq, H→bb

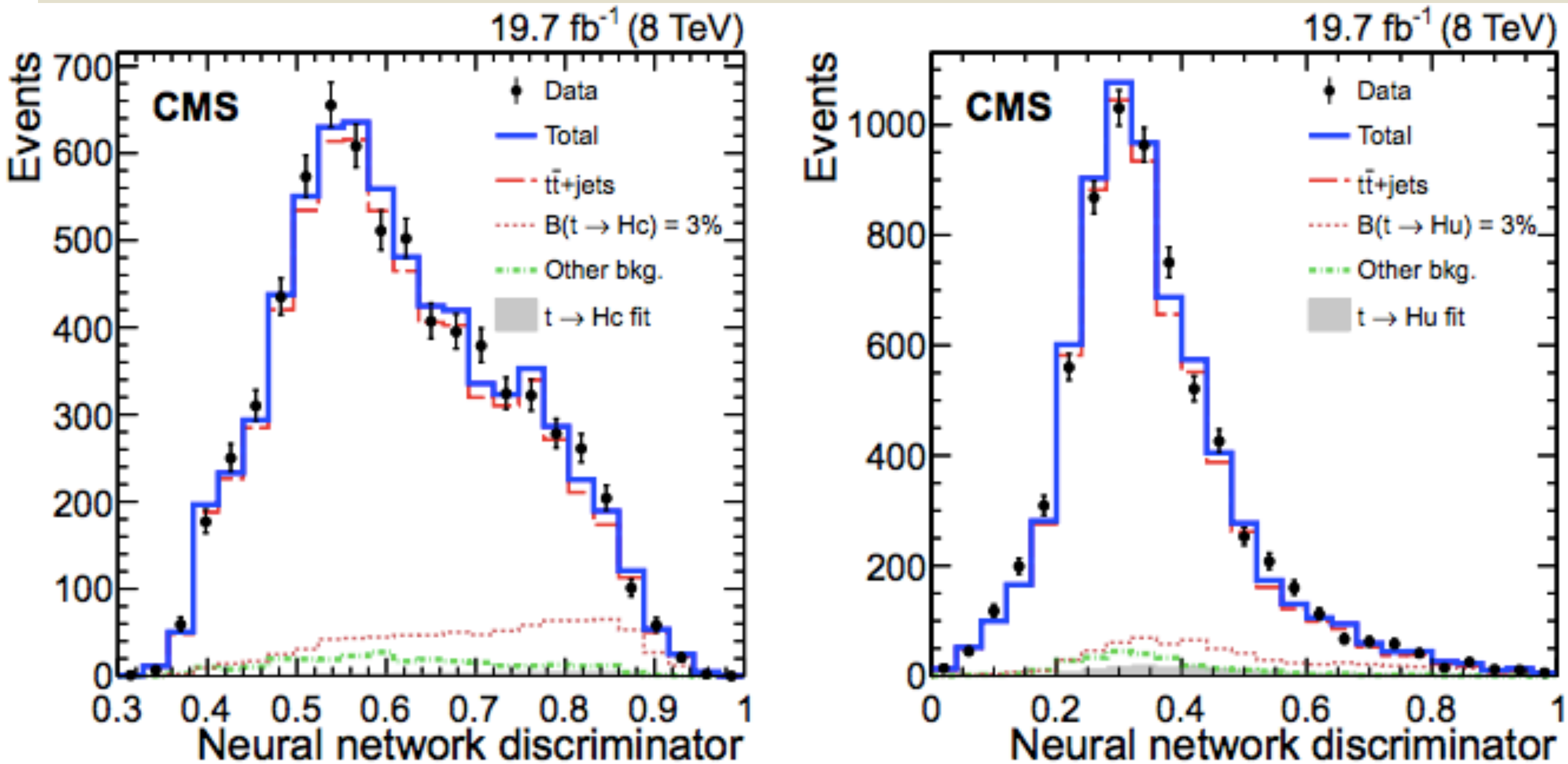


Figure 6: The output distributions from the ANN discriminator for data (points) and simulated background (lines) where the ANN was trained to discriminate the backgrounds from either $t \rightarrow Hc$ (left) or $t \rightarrow Hu$ (right) decays. The solid line shows the result of the fit of the signal and background templates to data. The dotted line gives the predicted signal distribution from simulation for $\mathcal{B}(t \rightarrow Hc) = 3\%$ and the filled histogram shows the proportion of signal estimated from the fit.

tZq individual limits

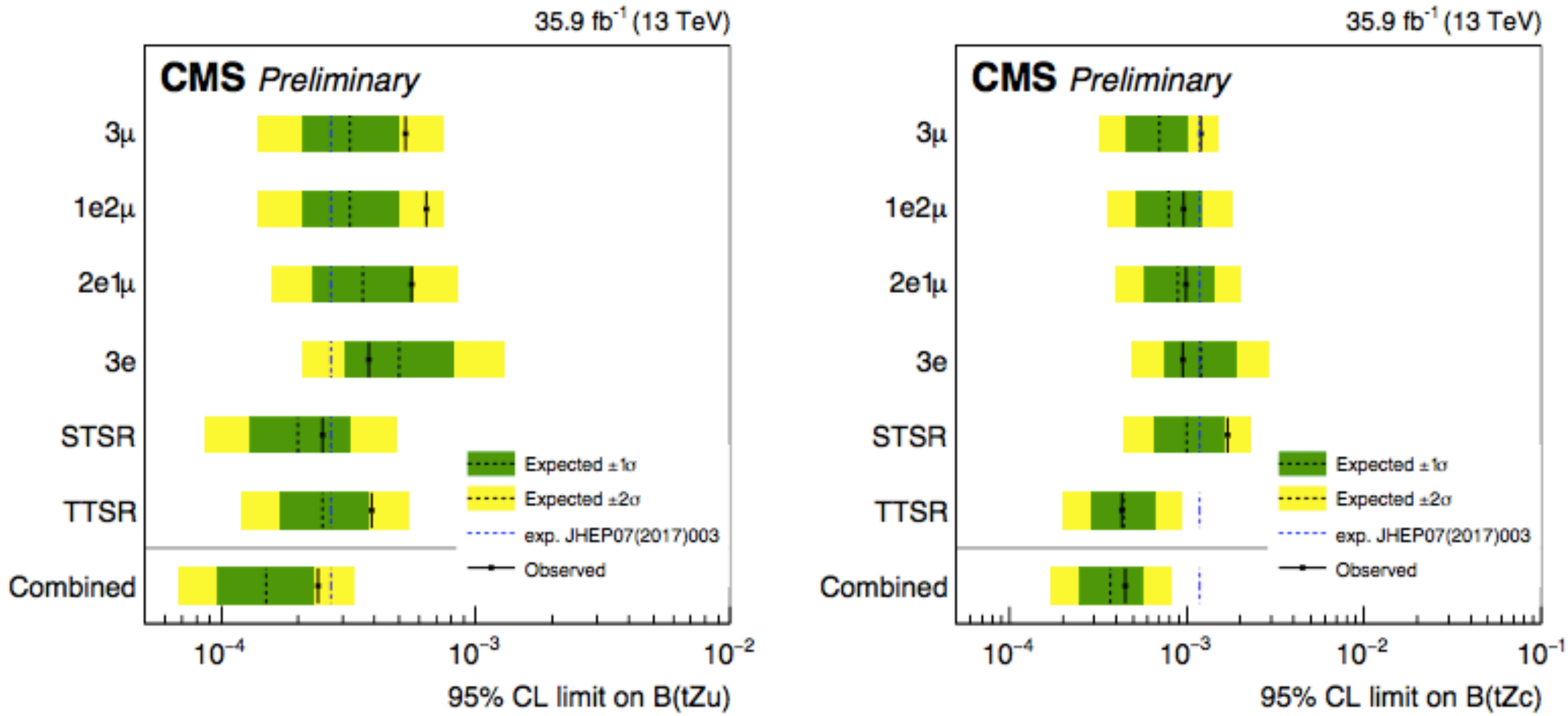


Figure 6: Exclusion limits at 95% CL for each leptonic channel and signal region on the FCNC tZu (left) and tZc (right) branching fractions considering one non-vanishing coupling at a time. The CMS 8 TeV [7] observed (expected) limit of is given with a blue dashed line).