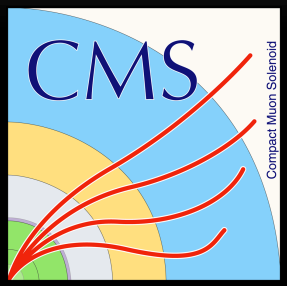
FCNC, Anomalous Couplings, EFT



Geoffrey Smith (U. Notre Dame, U.S.)

on behalf of the CMS + ATLAS collaborations

11th International Workshop on Top Quark Physics

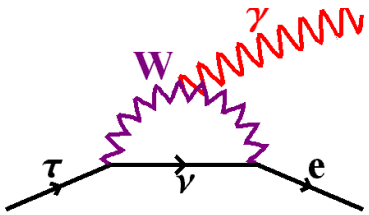
19 September 2018

Top quarks as New Physics probes

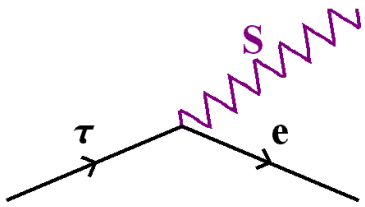
- Top sector is an attractive place to look for NP (New Physics)
  - Just starting to collect enough ttX/tX data to study Top couplings in detail → deviations from SM couplings may hint at possible NP
  - Clean/unique decay signature of top quark → relatively easy to ID decay products, events containing tops
- FCNC, anomalous couplings and EFT can all be used as tools to search for NP in Top sector

Flavor Changing Neutral Currents

Standard Model FCNC suppressed by GIM (Glashow–Iliopoulos–Maiani) mechanism

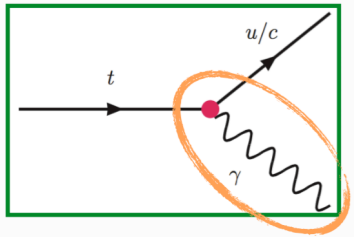


Beyond–the–SM FCNC

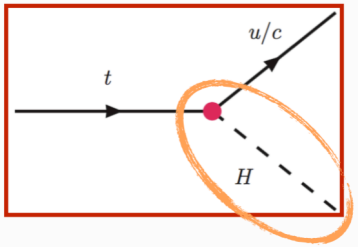


BSM FCNC With Tops

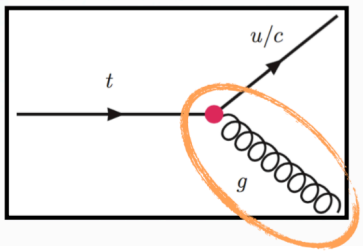
Top+gamma



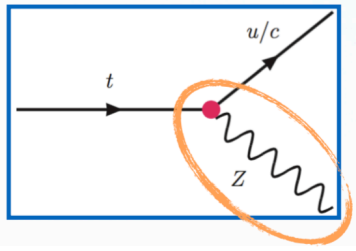
Top+Higgs



Top+gluon



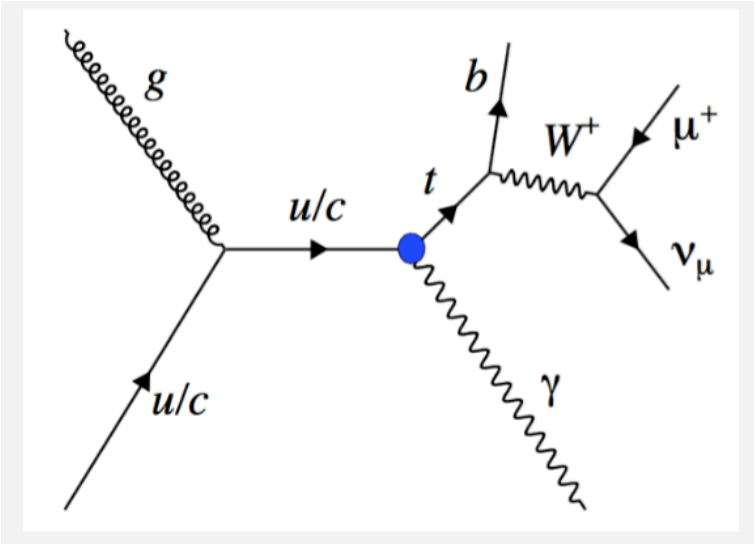
Top+Z



Model:	SM	QS	2HDM	FC 2HDM	MSSM	RPV SUSY	RS	EMF
$\mathcal{B}(t \to qZ)$:	10^{-14}	10^{-4}	10^{-6}	10^{-10}	10^{-7}	10^{-6}	10^{-5}	10^{-6}

Many NP models affected by Top FCNC
(Ref[1-10] in JHEP 07 (2018) 176)

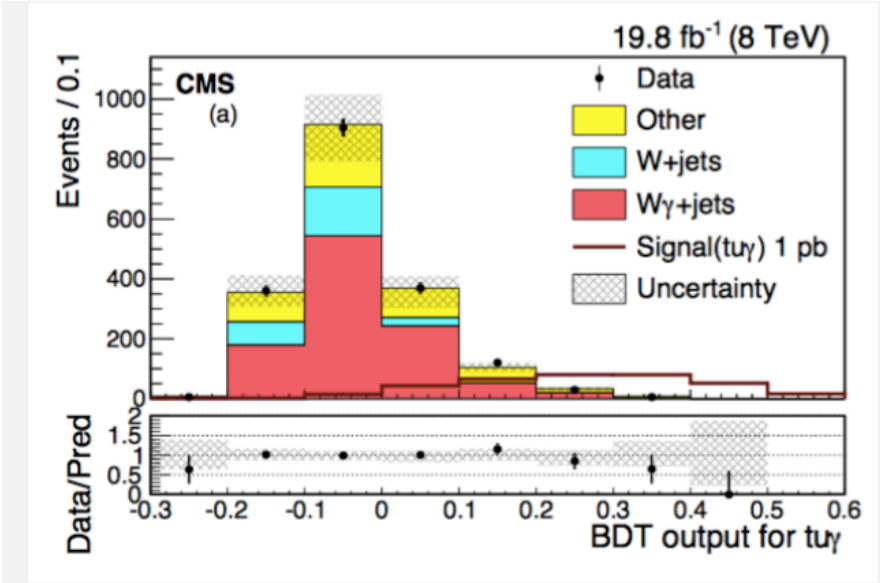
Top-γ FCNC



- Search for tqγ FCNC in single top + γ events
- Topology: isolated muon+photon, large missing transverse energy, 0 and 1 b jet
- BDT to separate signal from W+γ
- Constraints on tqγ couplings translated to limits on B(t→γq)

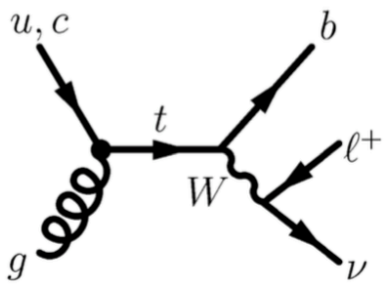
JHEP 04 (2016) 035

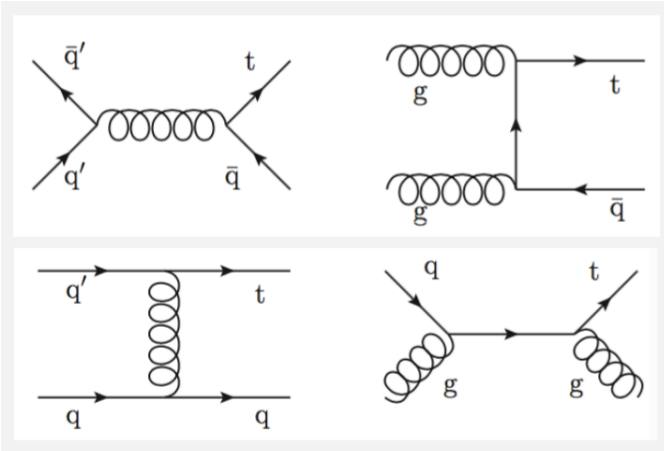
20 fb^{-1} @ 8 TeV



B(t→γu) < 0.013 % (obs)
0.019 % (exp)
B(t→γc) < 0.200 % (obs)
0.170 % (exp)

Top-gluon FCNC





EPJ C (2016) 76:55

20.3 fb^{-1} @ 8 TeV

ATLAS EXPERIMENT

B(t→**g**u) < 0.0040 % (obs)
0.0035 % (exp)
B(t→**g**c) < 0.020 % (obs)
0.018 % (exp)

- Search for tqg FCNC in single top events (specifically W→lν)
- Topology: isolated lepton, large missing transverse energy, ==1 b jet and (in case of CMS analysis) ==1 non-b jet
- NNs to separate signal from background (tt̄ or W+jets)
- Constraints on tqg couplings translated to limits on B(t→gq)

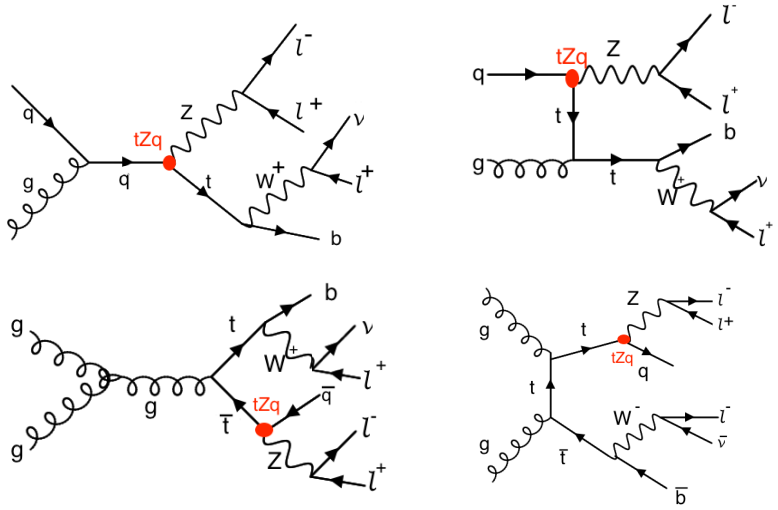
JHEP 02 (2017) 028

5+20 fb^{-1} @ 7+8 TeV

CMS

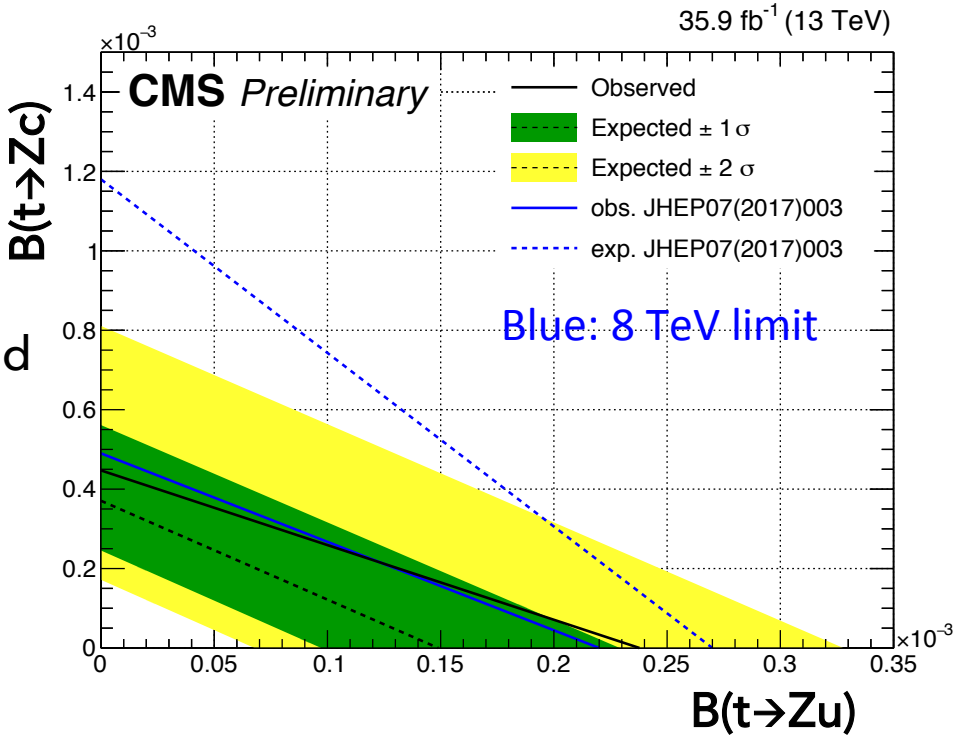
B(t→**g**u) < 0.0020 % (obs)
0.0028 % (exp)
B(t→**g**c) < 0.041 % (obs)
0.028 % (exp)

Top-Z FCNC NEW!



CMS PAS TOP-17-017

35.9 fb^{-1} @ 13 TeV



- Search for top-Z FCNC in single top and $t\bar{t}$ production
- tZq vertex in production or decay
- Event selection:
  - 3 isolated, charged leptons (2 SFOS)
  - 1-3 jets (1 or more b jets)
  - 4 channels based on lepton flavor
- Main background: non-prompt leptons
- BDT used as final discriminating variable
  - trained on event-level kinematic + b-tagging observables

B(t→Zu) < 0.024% (obs)
0.015% (exp)
B(t→Zc) < 0.045% (obs)
0.037% (exp)

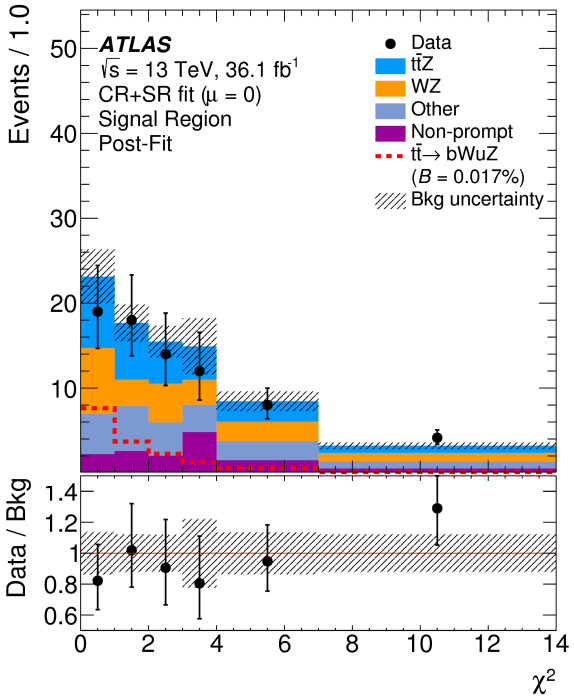
Top-Z FCNC NEW!

- Search for top-Z FCNC in top pair production
- Event topology:
  - 3 isolated charged leptons
  - At least 2 jets (1 b jet)
  - Missing transverse energy

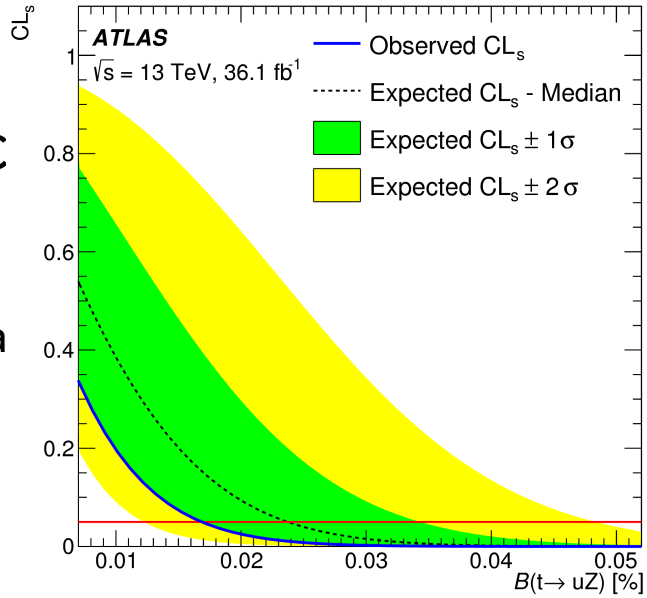
See poster by Ana Peixoto!

JHEP 07 (2018) 176

36.1 fb^{-1} @ 13 TeV

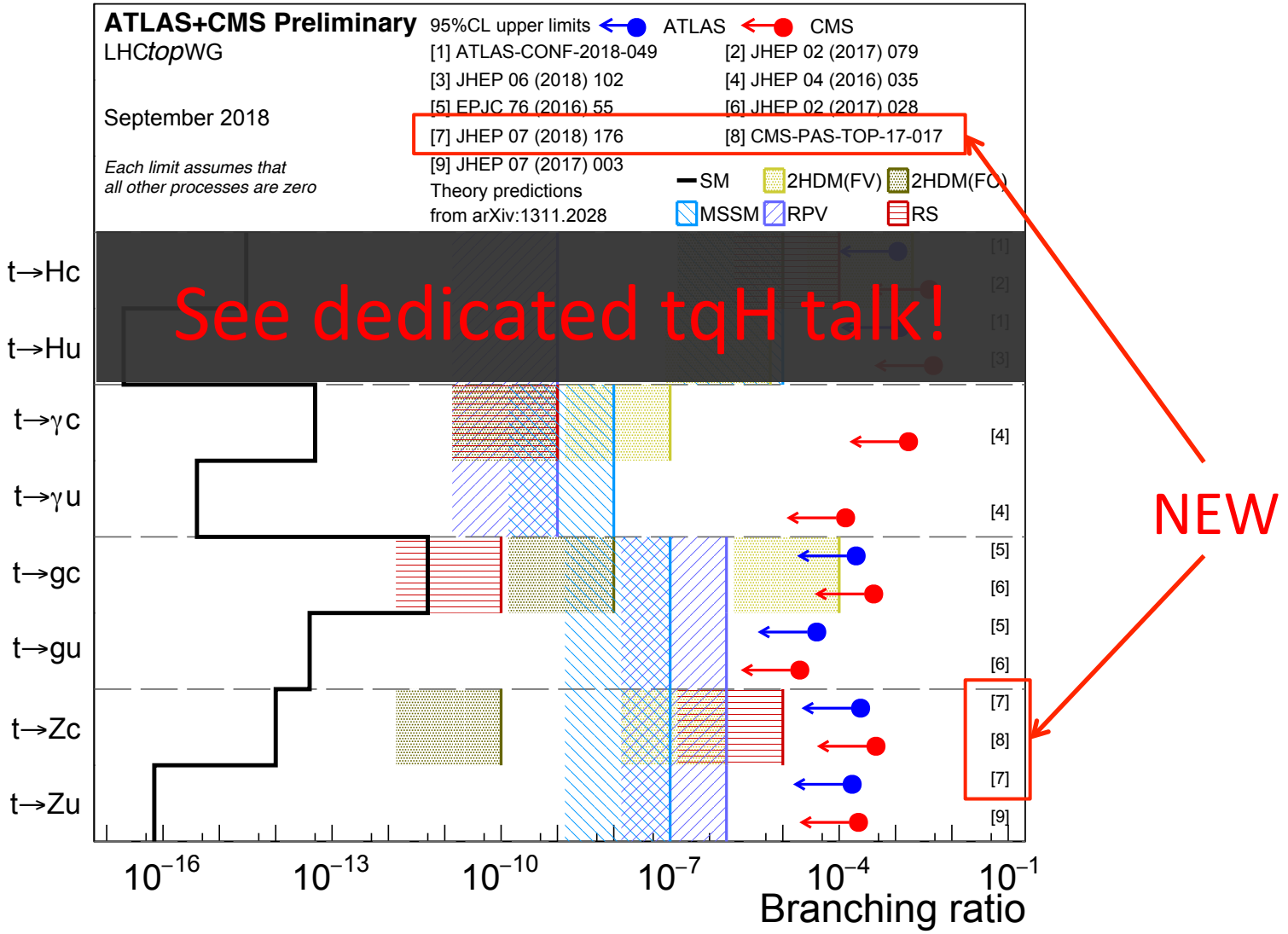


- χ^2 minimization to invariant masses of W, SM top and FCNC top to reconstruct event
- Result extracted via a simultaneous fit to χ^2 value in signal regions, and to kinematic quantities (such as leading lepton p_T) in background regions



B(t→Zu) < 0.017% (obs)
0.024% (exp)
B(t→Zc) < 0.024% (obs)
0.032% (exp)

Summary of current FCNC limits



Top quark Anomalous Couplings

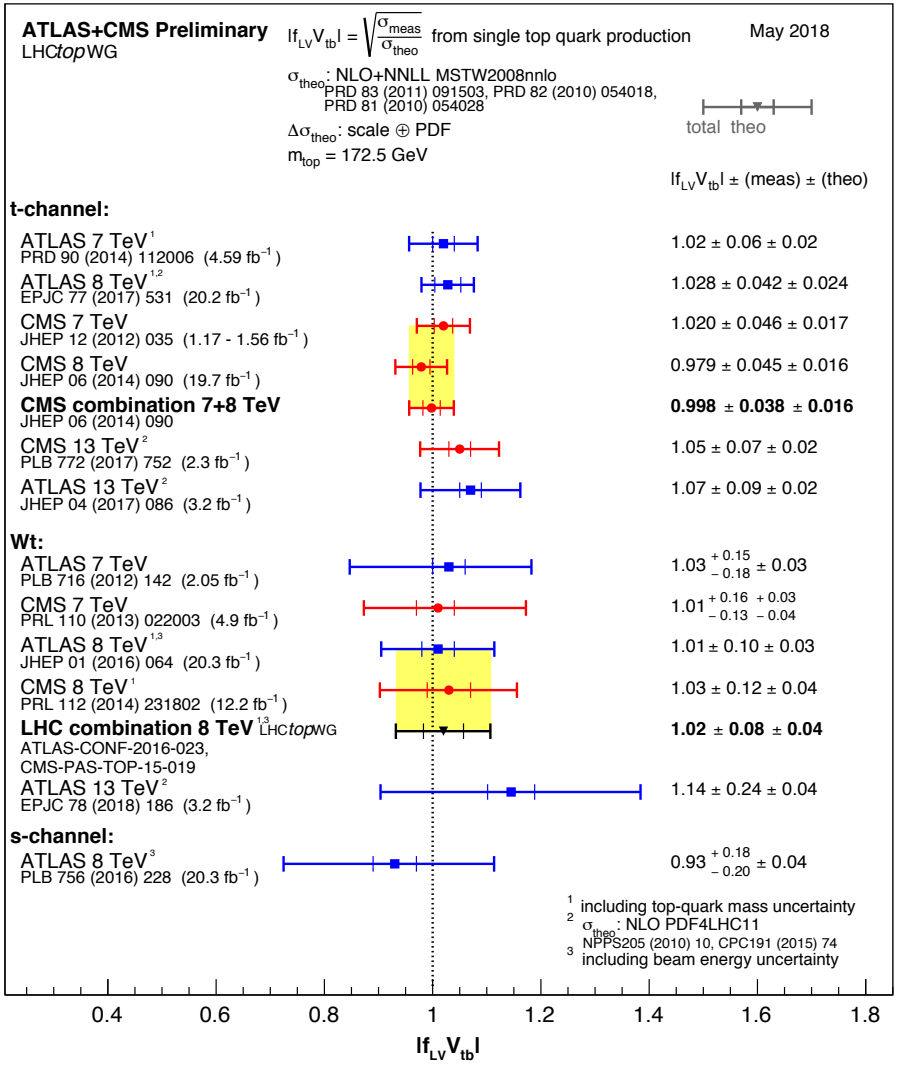
Probes of *Wtb* vertex:

- W polarization (and related observables) in $t\bar{t}$ + single top events
- Generalized single top observables (e.g. angular distributions)
- Indirect limits

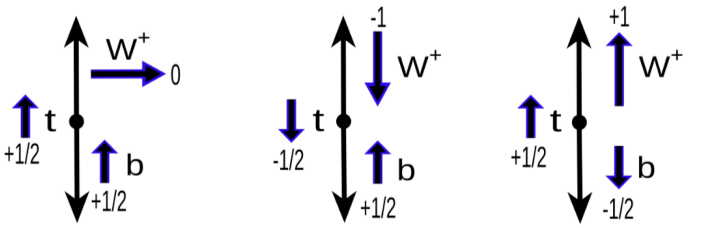
$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)\, t\, W_{\mu}^{-}$$
$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_L P_L + g_R P_R)\, t\, W_{\mu}^{-} + \text{h.c.}$$

$V_L = V_{tb} \approx 1$ (within SM)
V_R, g_R, g_L → anomalous couplings

[EPJC50 (2007) 519, NPB804 (2008) 160, NPB812 (2009) 181]



W helicity and top quark ACs



longitudinal W
SM (L0): $F_0 = 0.6966$
[PRD81 (2010) 111503]

left-handed W
$F_L = 0.3030$

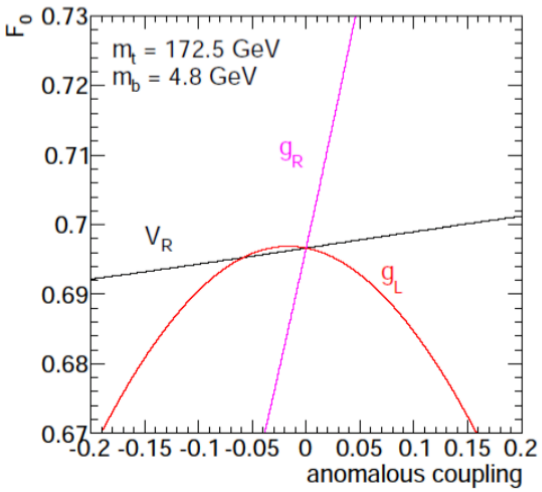
right-handed W
$F_R = 0.0004$

$$\frac{1}{N}\frac{dN}{d\cos\theta^*} = \frac{3}{2}\left[F_0\left(\frac{\sin\theta^*}{\sqrt{2}}\right)^2 + F_L\left(\frac{1-\cos\theta^*}{2}\right)^2 + F_R\left(\frac{1+\cos\theta^*}{2}\right)^2\right]$$

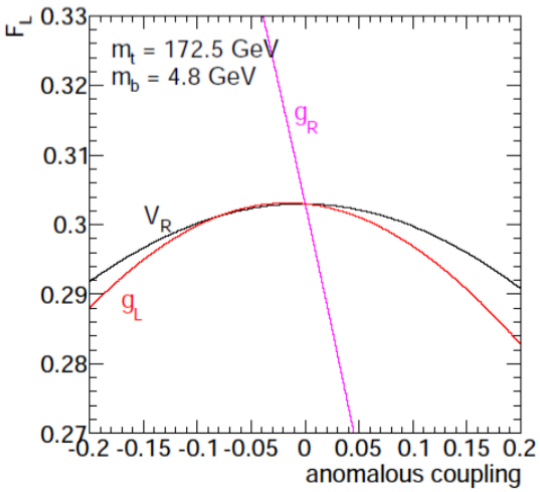
- Information on W helicity obtained by looking at top decay products (single top or $t\bar{t}$)
- Anomalous couplings → deviations on helicity fractions (F_0, F_L and F_R observables)

g_R
g_L
V_R

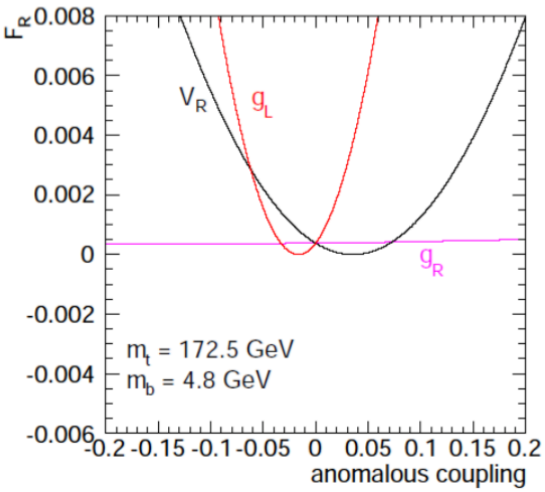
F_0



F_L

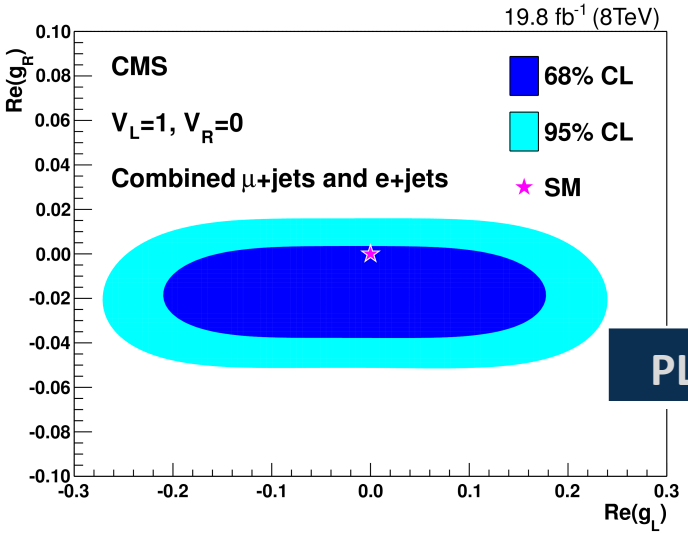


F_R



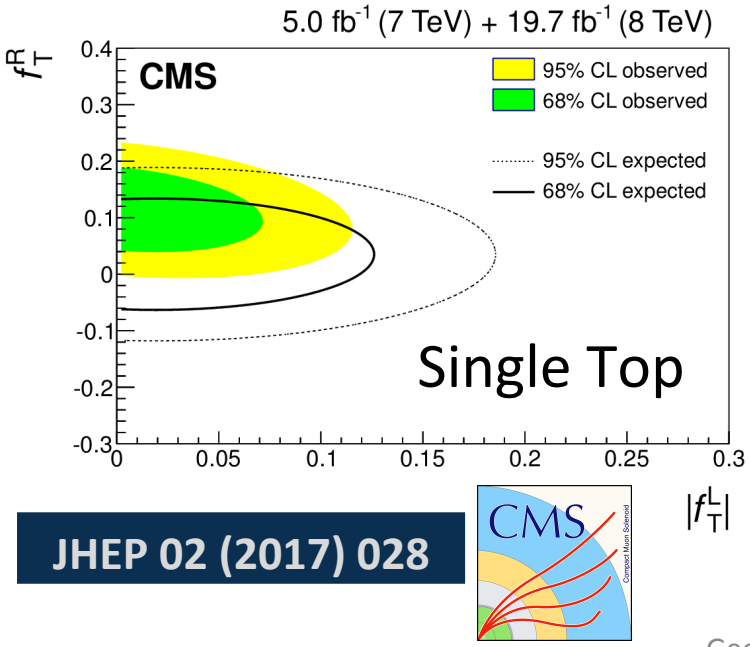
W helicity AC results

- Several W helicity analyses that set AC limits
- Various combinations of couplings considered, as well as independent measurements of helicity fractions
- All in agreement with SM

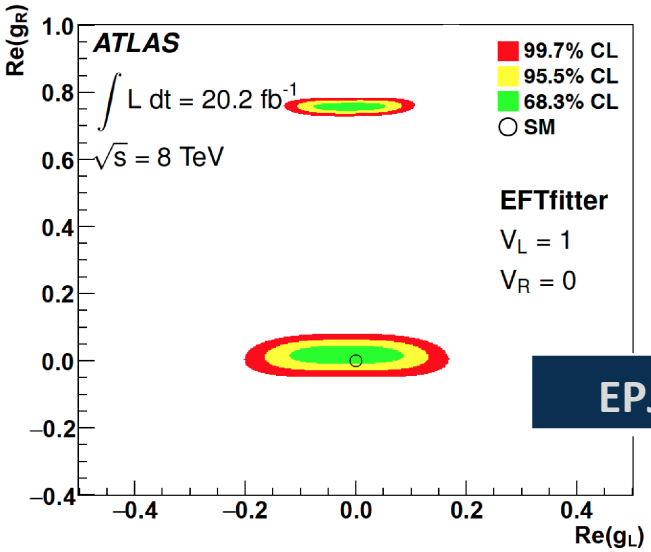


tt̄ (l+jets)

PLB 762 (2016) 512



JHEP 02 (2017) 028



tt̄ (l+jets)

EPJ C 77 (2017) 264

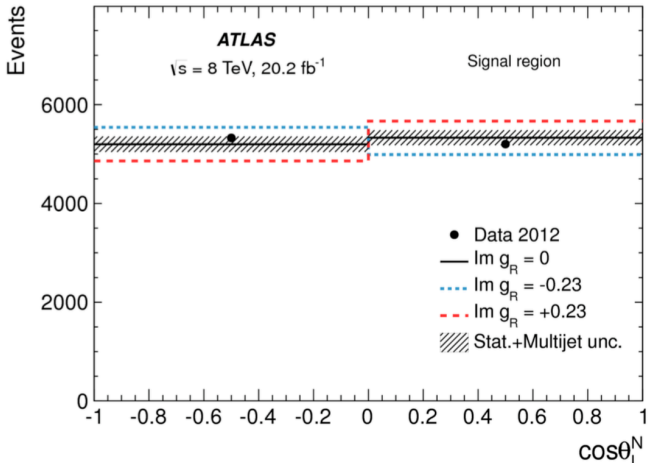
AC constraints from additional angular information

JHEP 04 (2017) 124

20 fb^{-1} @ 8 TeV

- Angular distributions in (t-channel) single top events used to measure top polarization and W spin asymmetries, constrain ACs

Angular Distributions → Unfolding Technique → Top and W spin measurements / AC Constraints

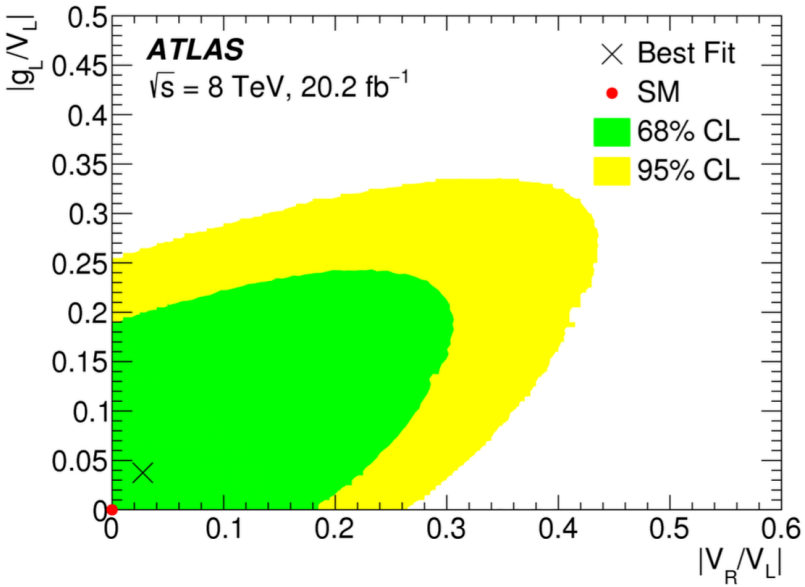


Assuming V_L=1: $\mathrm{Im}(g_R) \in [-0.18, 0.06]$

JHEP 12 (2017) 017

20 fb^{-1} @ 8 TeV

- Description of the Wtb vertex using normalized triple-differential $(\theta,\theta^*,\varphi^*)$ decay rate of top quarks
- Constraints on extended amplitudes and phases (f_1, f_1^+, f_0^+, δ_+, δ_-) translated into limits on coupling ratios



EFT

Effective Field Theory

- ***Model-independent expansion*** of the SM Lagrangian
- (Dimension-4) SM Lagrangian extended with higher-order operators
  - Dimension-5 operators typically excluded as they do not conserve lepton number
  - Effective Lagrangian is thus a series expansion of dimension-6 operators, in the inverse of the energy scale of the NP, $1/\Lambda$
  - Dimensionless Wilson Coefficients (WCs) c_i parameterize the strength of a given NP interaction
- Proposal for common standards + prescriptions for EFT interpretations by LHCtopWG: [arXiv:1802.07237].

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i + \cdots$$

NP energy scale — WCs — Dim-6 operators

- 59 Dimension-6 operators that conserve baryon and lepton number
- (not all relevant for Top physics)

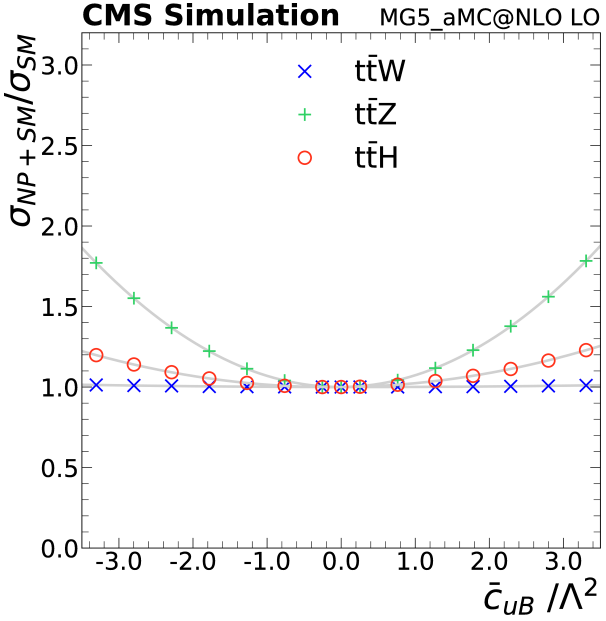
EFT interpretation: ttW/Z cross section

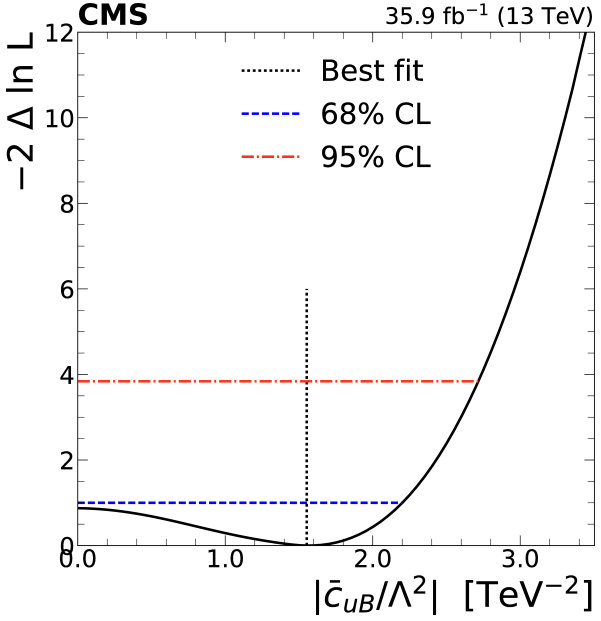
Multilepton ttW and ttZ xsec measurement, with additional interpretation in context of EFT

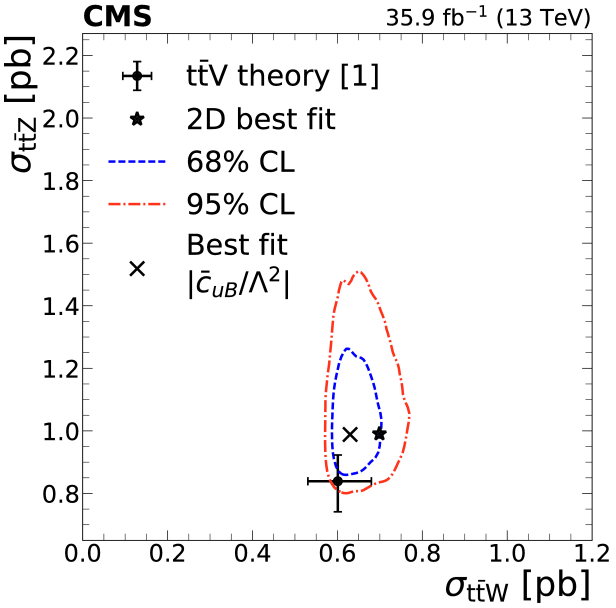
JHEP 08 (2018) 011

35.9 fb^{-1} @ 13 TeV

- Eight operators selected that impact expected ttZ/W/H cross section w/o significantly impacting expected backgrounds (mainly tt)
- Constraints on the individual operators obtained by fitting to one operator at a time
- Full results in backup







EFT interpretation: other results NEW!

ATLAS-CONF-2018-047

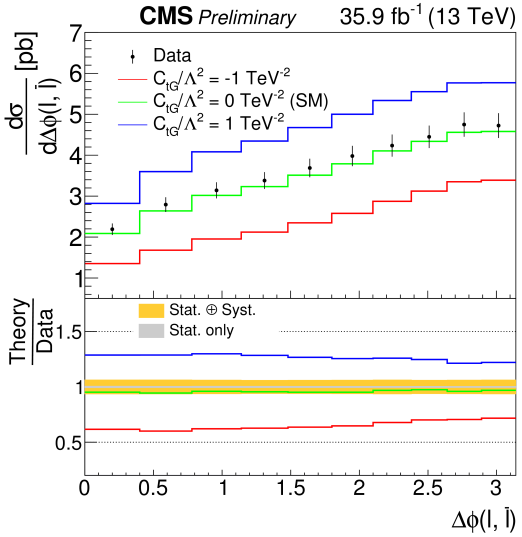
36.1 fb^{-1} @ 13 TeV

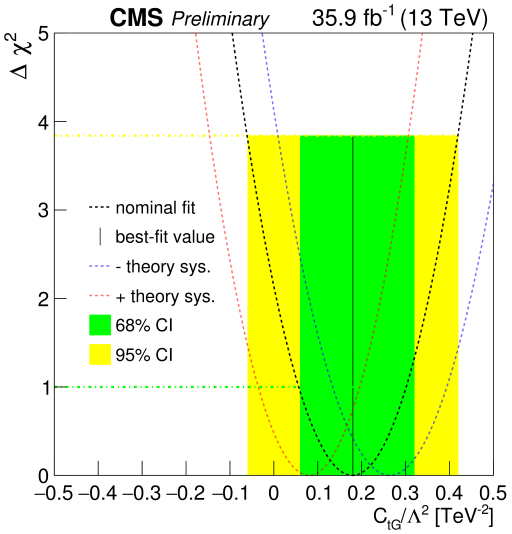
- ttV+tttt cross section analysis in multilepton final states
  - Details in talk yesterday by Clara Nellist
- ttV measurement used to place limits on 5 EFT operators that would affect ttZ
- Results in backup

CMS PAS TOP-17-014

35.9 fb^{-1} @ 13 TeV

- Top chromomagnetic dipole moment constrained from differential tt xsec as function of $\Delta\phi(ll)$ at particle level
- Compared expected yields after varying C_{tG} operator strength using EFT predictions at NLO (PRD 91 (2015) 114010)
- Limit consistent with SM and improves previous results on C_{tG}/Λ^2
- See talk by K. Kousouris



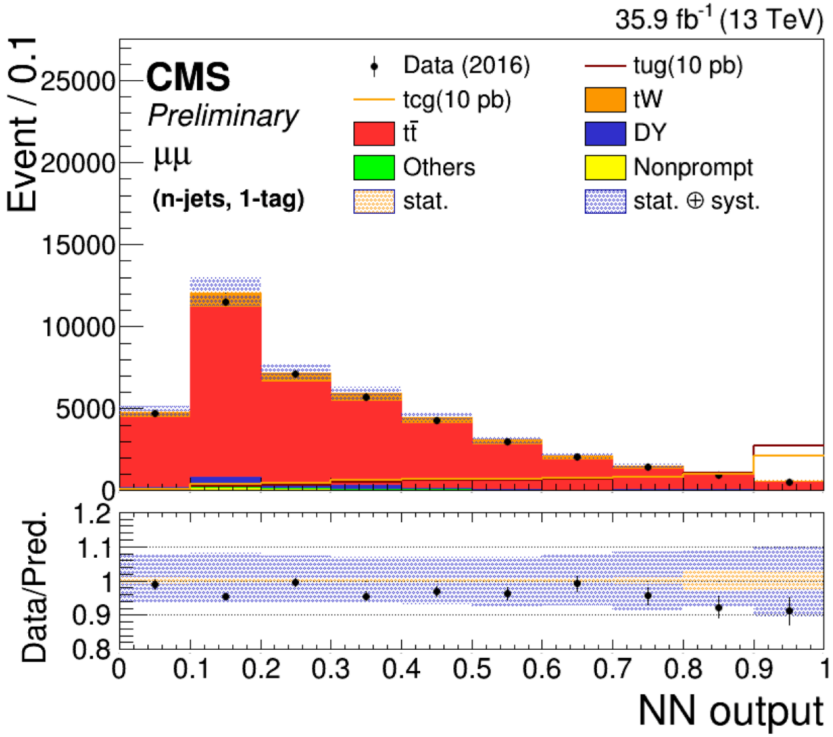


EFT: Direct search for New Physics NEW!

CMS PAS TOP-17-020

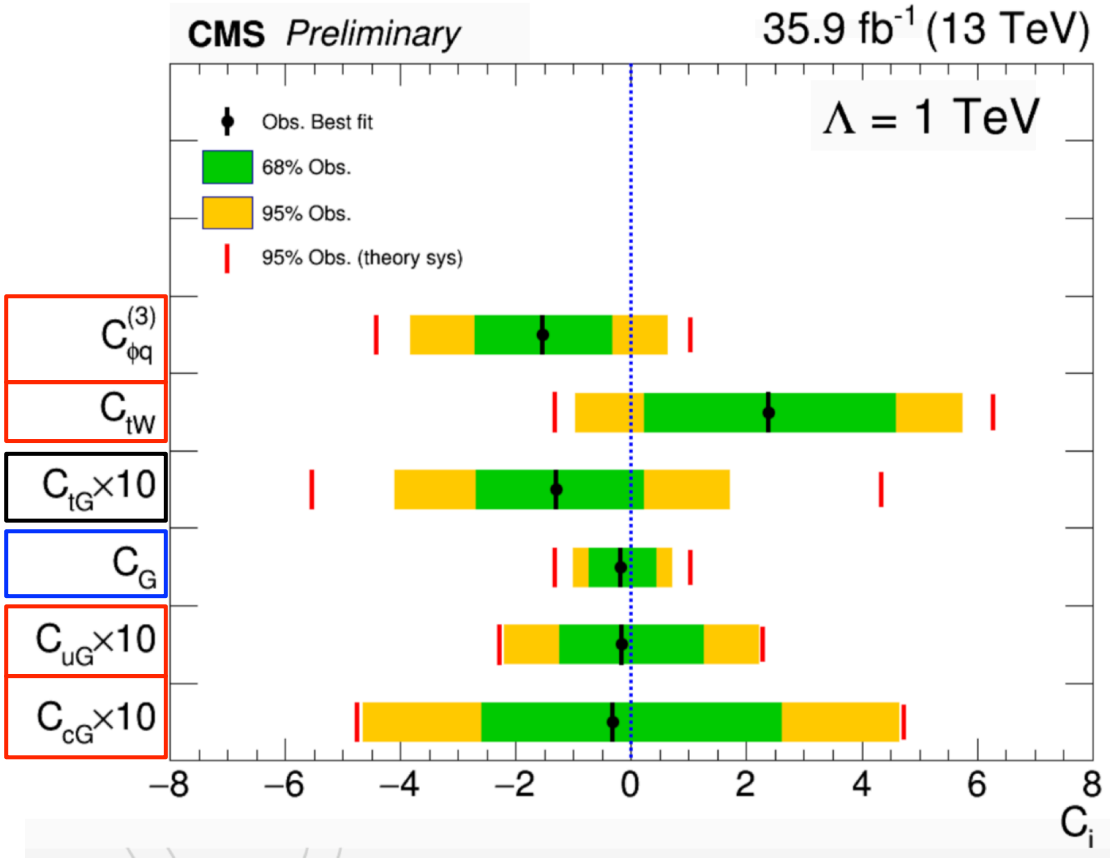
35.9 fb^{-1} @ 13 TeV

Search for deviations from the SM in single top (tW) and tt̄ production



- Event selection targeting dilepton + jets events
  - Separated by lepton flavor
  - tt̄: >=2 jets (2 b jets)
  - tW: 1-2 jets (0-1 b jet).
- Signal extraction via neural networks (training dependent on analysis channel)

EFT: Direct search for New Physics NEW!



CMS PAS TOP-17-020

35.9 fb^{-1} @ 13 TeV

- Analysis sets limits on 6 EFT operators that affect $t\bar{t}$ and/or tW
- Limits on C_{uG} and C_{cG} translated to observed (expected) limits on FCNC BRs
- First experimental bound on C_G coupling

Single Top (tW) $t\bar{t}$
Single Top (tW) + $t\bar{t}$

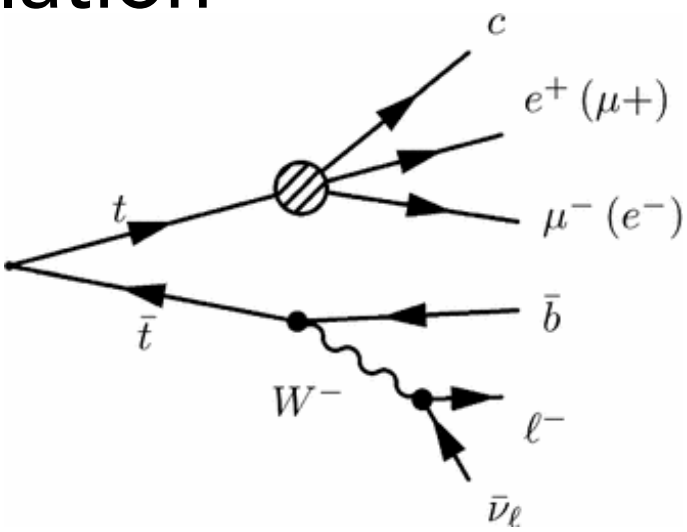
B(t → ug) < 0.12 (0.22)% obs (exp)
B(t → cg) < 0.53 (1.05)% obs (exp)

Search for cLFV Top decays NEW!

Charged Lepton Flavor Violation

ATLAS-CONF-2018-044

79.8 fb^{-1} @ 13 TeV

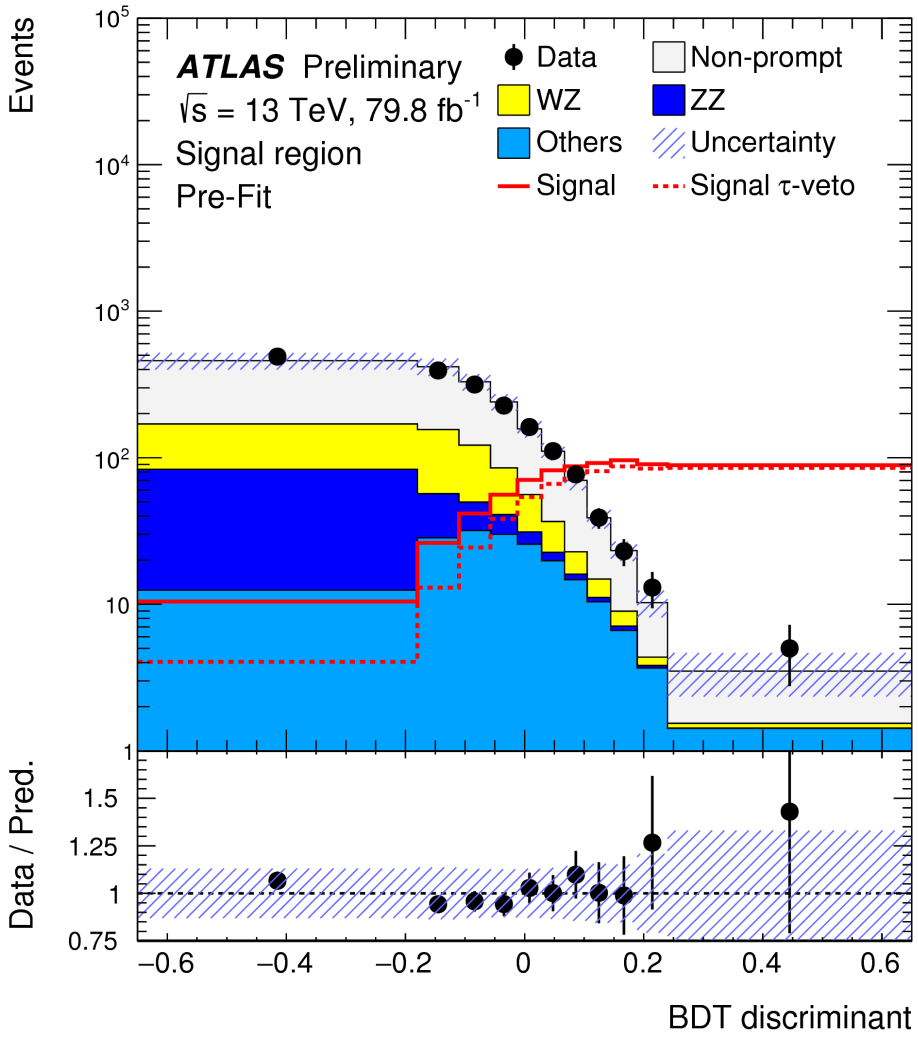


[diagram: EPJ C (2015) 75: 450]

See poster by Carlo Gottardo!

- Top-quark pair production with the decays:
  - Different-flavor, opposite-sign dilepton + 1 up-type quark
  - SM leptonic decay
- Event signature: 3l + >=2 jets (1 b-jet)
- Main background: non-prompt leptons
  - Estimated using data-driven matrix method (tag-and-probe approach in control regions enriched in non-prompt leptons)

Search for cLFV Top decays NEW!



ATLAS-CONF-2018-044

79.8 fb^{-1} @ 13 TeV

- Event reconstruction in signal region to reconstruct cLFV top quark
- Invariant mass of reconstructed cLFV top, other kinematic quantities used to train BDT → final discriminant to set limits on Top cLFV BR

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

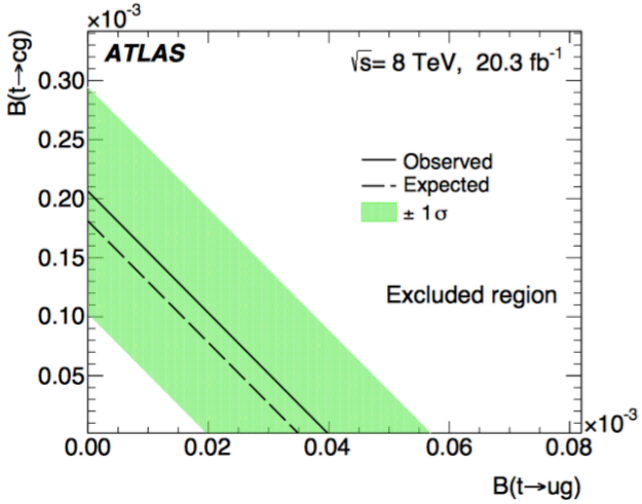
$B(t\to e\mu q) < 6.6(4.8)\times10^{-6}$ obs (exp)

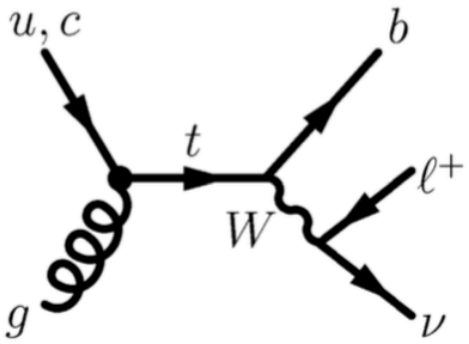
Summary

- No clear evidence (yet) for BSM effects in the Top sector
- Lots of activity in FCNC, AC and EFT Top analyses
  - Constraints on NP continue to tighten as more data is analyzed
  - See talk by K. Finelli tomorrow for tqH FCNC update!
- EFT gaining in popularity in BSM top physics
  - When appropriate, relatively straightforward to include constraints on EFT parameters in Top analyses
  - Way to do apples-to-apples comparison of BSM/NP constraints across different analyses

Backup

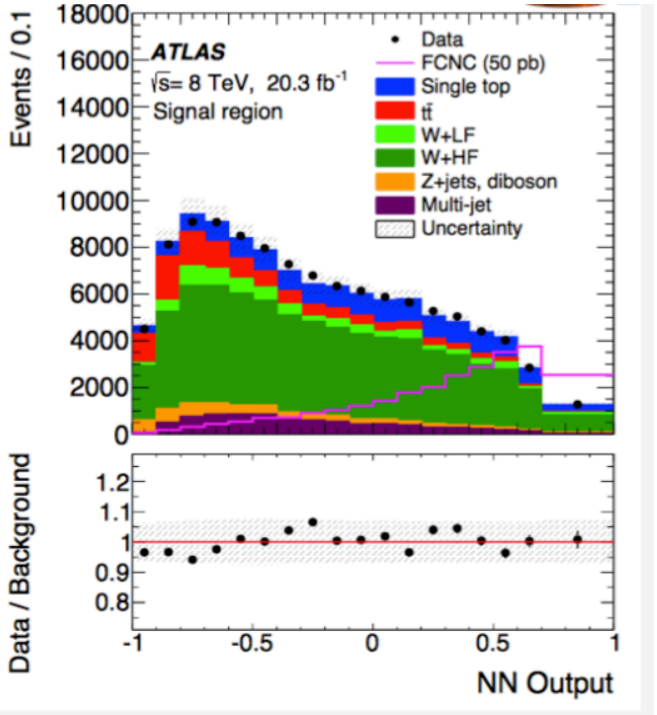
Top-gluon FCNC





EPJ C (2016) 76:55

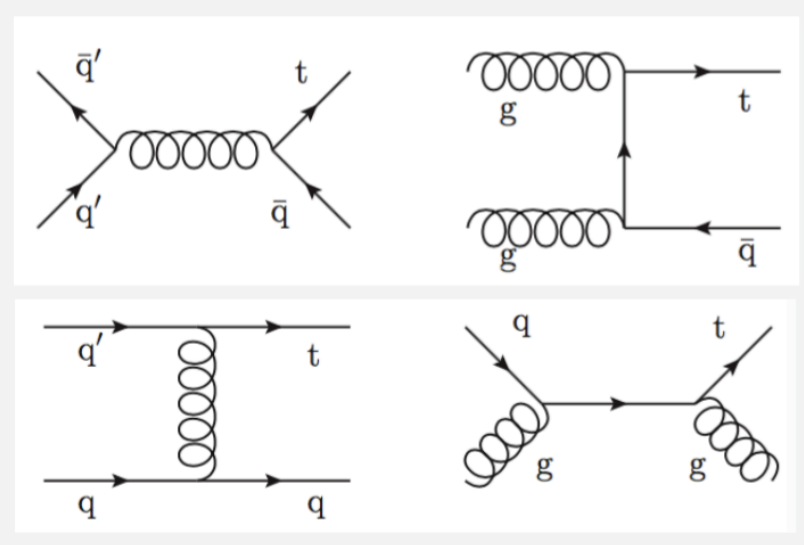
20.3 fb^{-1} @ 8 TeV



- Search for tqg FCNC in single top events (specifically W→lν)
- Topology: isolated lepton, missing transverse energy, ==1 b jet
- NN to separate signal from W+jets
- Constraints on tqg couplings translated to limits on B(t→gq)
  - Best limits on B(t→gc)

B(t→**g**u) < 0.0040 % (obs)
0.0035 % (exp)
B(t→**g**c) < 0.020 % (obs)
0.018 % (exp)

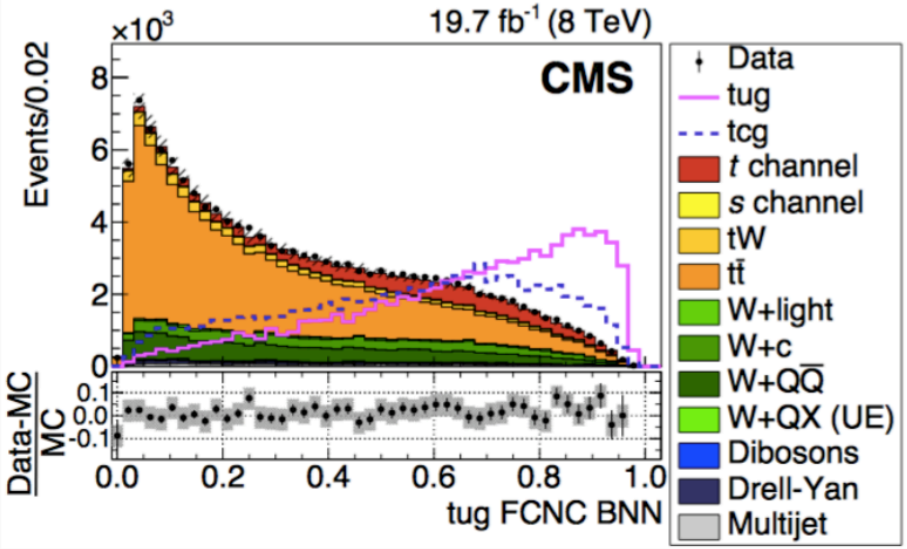
Top-gluon FCNC



- Search for tqg FCNC in single top events
- Topology: isolated lepton, missing transverse energy, ==0 or ==1 b jets
- Bayesian NN to separate signal from $t\bar{t}$
- Best limits on B(t→gu)

JHEP 02 (2017) 028

5+20 fb^{-1} @ 7+8 TeV



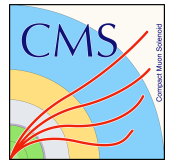
B(t→gu) < 0.0020 % (obs)
0.0028 % (exp)
B(t→gc) < 0.041 % (obs)
0.028 % (exp)

Top-Z FCNC

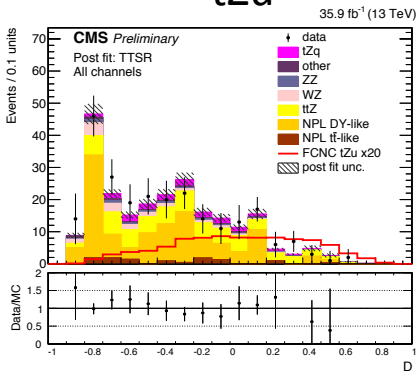
Search for top-Z FCNC in single top and tt̄ production (backup)

CMS PAS TOP-17-017

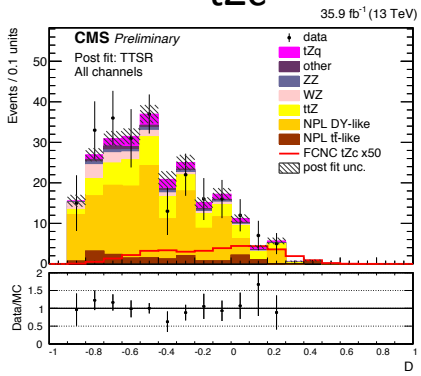
35.9 fb^{-1} @ 13 TeV



tZu

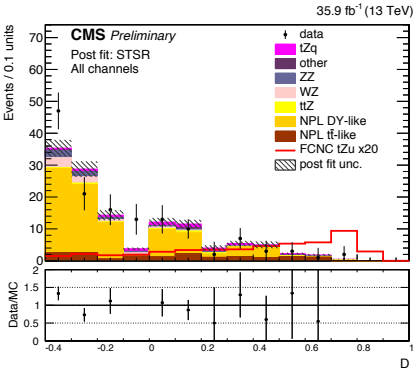


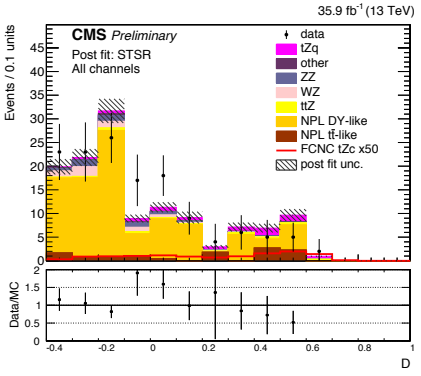
tZc

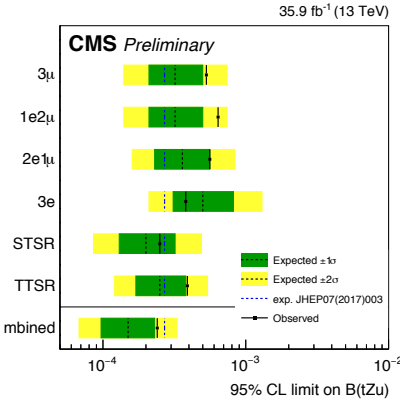


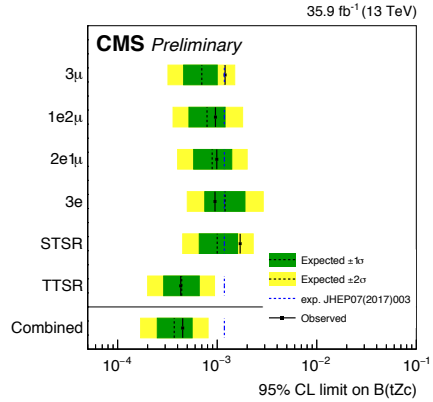
ttbar

Single top



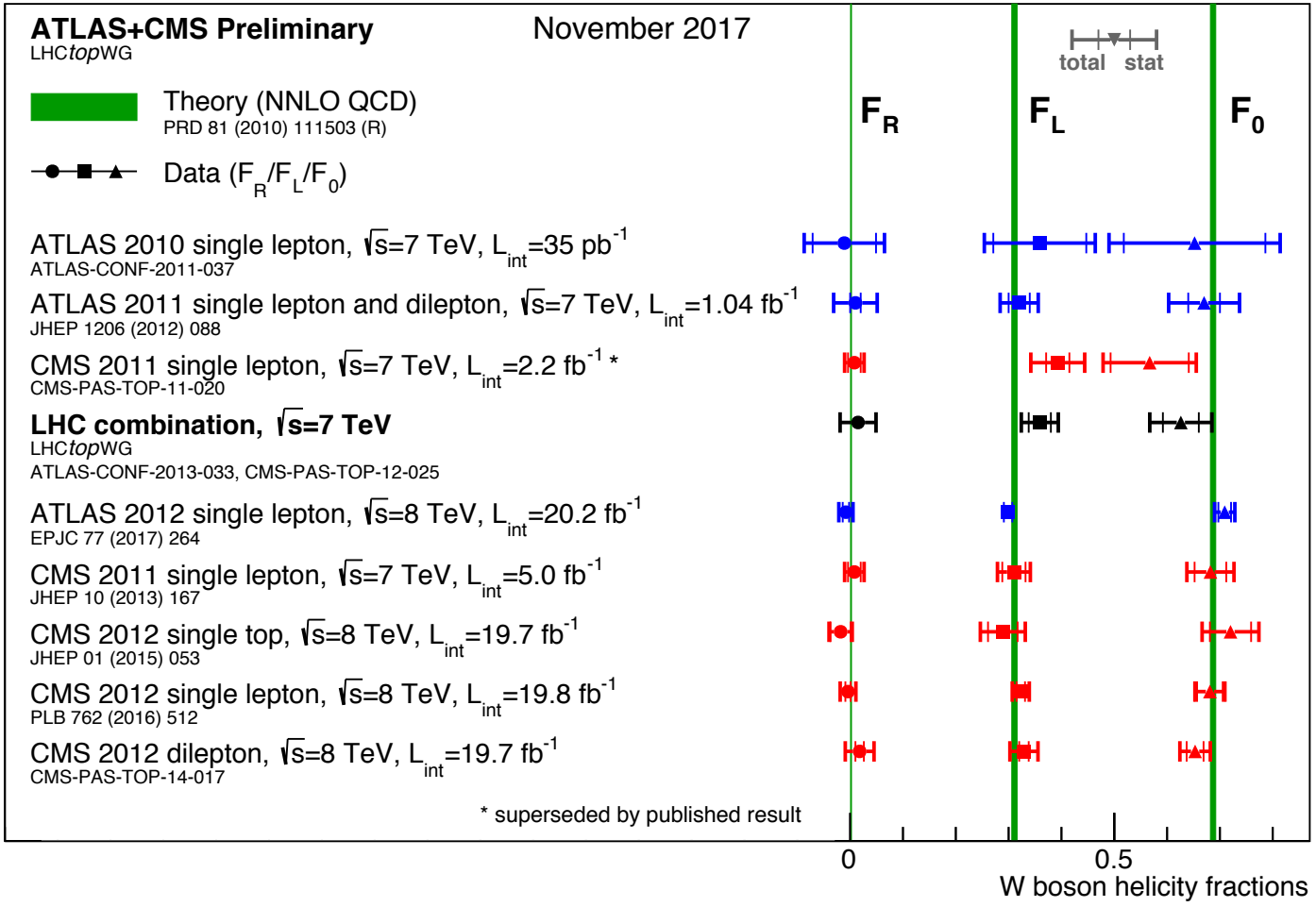






- Above: upper limits broken down by analysis channel
- Left: BDTs used as inputs to the fit

Summary of W helicity measurements



See also talk by Petra

EFT with Top Quarks

- To investigate effects of NP on a given process using EFT, one must calculate the expected cross section as a function of the WCs:

Matrix element SM EFT expansion

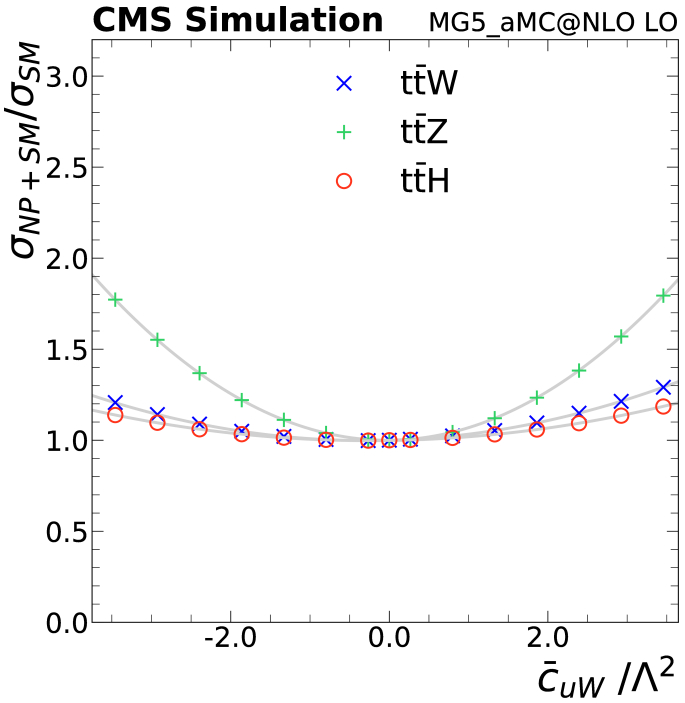
$$\mathcal{M} = \mathcal{M}_0 + \sum_i c_i \mathcal{M}_i$$

- Xsec scales quadratically with WC strength:

$$\sigma_{\mathrm{SM+NP}}(c_i) \propto |\mathcal{M}|^2$$

$$\propto s_0 + s_{1i} c_i + s_{2i} c_i^2$$

c.f. JHEP 08 (2018) 011

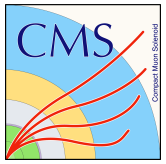


EFT interpretation: ttW/Z cross section

Results: limits placed on 8 EFT operators

JHEP 08 (2018) 011

35.9 fb^{-1} @ 13 TeV



Wilson coefficient	68% CL [TeV^{-2}]	95% CL [TeV^{-2}]
$\bar{c}_{\mathrm{uW}}/\Lambda^2$	$[-1.6, 1.5]$	$[-2.2, 2.2]$
$\lvert\bar{c}_{\mathrm{H}}/\Lambda^2 - 16.8\,\mathrm{TeV}^{-2}\rvert$	$[3.7, 23.4]$	$[0, 28.7]$
$\widetilde{c}_{3\mathrm{G}}/\Lambda^2$	$[-0.5, 0.5]$	$[-0.7, 0.7]$
$\bar{c}_{3\mathrm{G}}/\Lambda^2$	$[-0.3, 0.7]$	$[-0.5, 0.9]$
$\bar{c}_{\mathrm{uG}}/\Lambda^2$	$[-0.9, -0.8]$ and $[-0.3, 0.2]$	$[-1.1, 0.3]$
$\lvert\bar{c}_{\mathrm{uB}}/\Lambda^2\rvert$	$[0, 1.5]$	$[0, 2.1]$
$\bar{c}_{\mathrm{Hu}}/\Lambda^2$	$[-9.2, -6.5]$ and $[-1.6, 1.1]$	$[-10.1, 2.0]$
$\bar{c}_{2\mathrm{G}}/\Lambda^2$	$[-0.7, 0.4]$	$[-0.9, 0.6]$

EFT interpretation: ttX measurement

From talk by C. Nellist

ATLAS-CONF-2018-047

36.1 fb^{-1} @ 13 TeV

ATLAS EXPERIMENT

Interpretations of the inclusive cross-section measurement in terms of Effective Field Theory (EFT).

- Set constraints on the five operators which modify the ttZ vertex: $O_{\phi Q}^{(3)}$, $O_{\phi Q}^{(1)}$, $O_{\phi t}$, O_{tW}, O_{tB}
- First two enter the ttZ vertex as a linear combination
  - measurement is sensitive to the difference: $C_{\phi Q}^{(3)} - C_{\phi Q}^{(1)}$
- Only one operator is considered at a time.

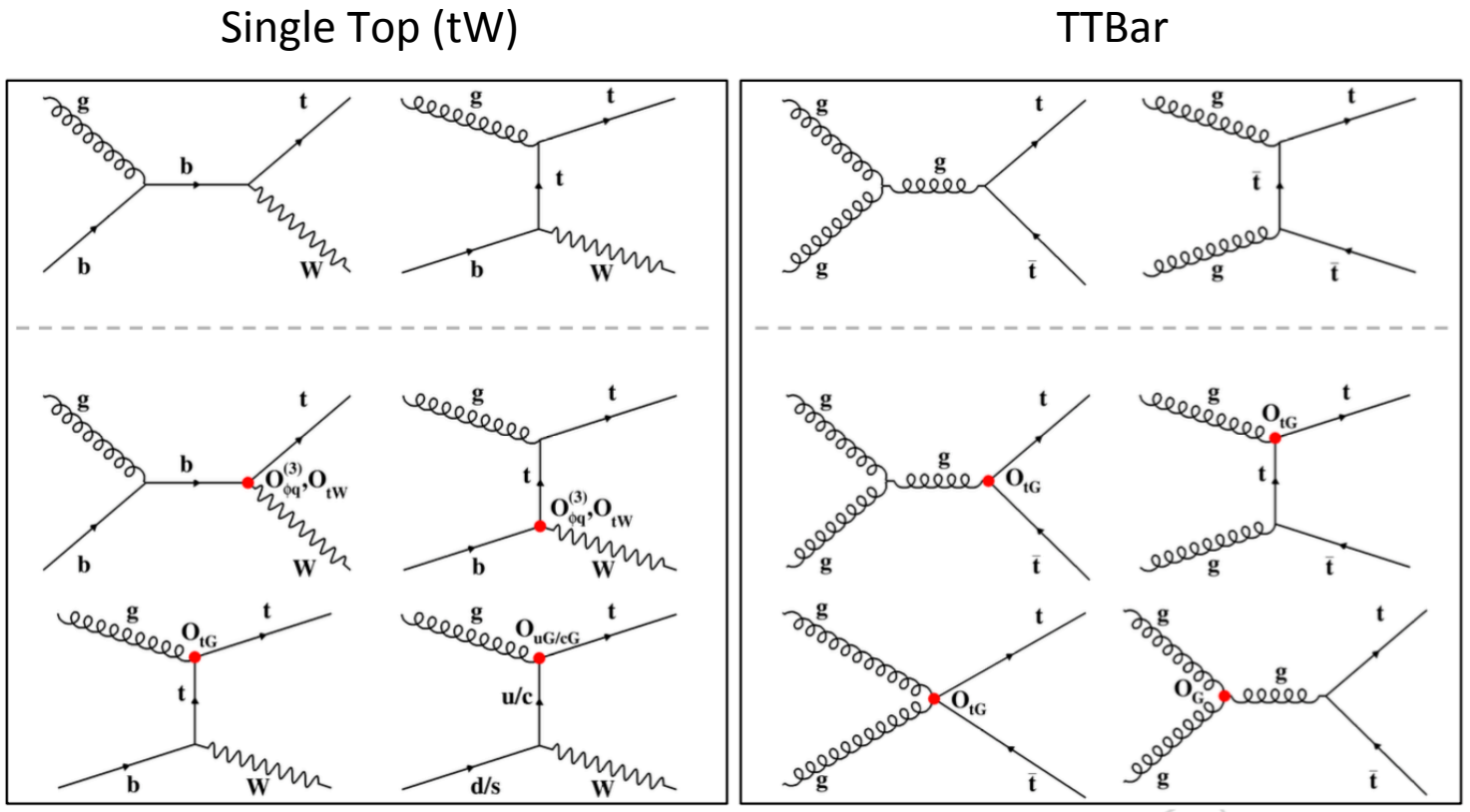
Coefficient	Expected limits at 68% and 95 % CL	Observed limits at 68% and 95 % CL	Previous constraints at 95 % CL JHEP **05** (2016) 052
$(C_{\phi Q}^{(3)} - C_{\phi Q}^{(1)})/\Lambda^2$	[-2.1, 1.9], [-4.6, 3.7]	[-1.0, 2.7], [-3.4, 4.3]	[-3.4, 7.5]
$C_{\phi t}/\Lambda^2$	[-3.8, 2.8], [-23, 5.0]	[-2.0, 3.6], [-27, 5.7]	[-2.0, 5.7]
C_{tB}/Λ^2	[-8.3, 8.6], [-12, 13]	[-11, 10], [-15, 15]	[-16, 43]
C_{tW}/Λ^2	[-2.8, 2.8], [-4.0, 4.1]	[-2.2, 2.5], [-3.6, 3.8]	[-0.15, 1.9]

EFT: Search for New Physics

Search for new physics in top quark dilepton final states (backup)

CMS PAS TOP-17-020

35.9 fb^{-1} @ 13 TeV



Search for cLFV Top decays

Ranked list of variables used in BDT

ATLAS-CONF-2018-044

79.8 fb^{-1} @ 13 TeV

ATLAS EXPERIMENT

Variable	Separation (%)
OSSF lepton pair invariant mass	11
cLFV top mass	10
p_T of the electron associated to the cLFV decay	9.1
p_T of the muon associated to the cLFV decay	8.5
p_T of the lepton associated to the SM decay	8.3
Scalar mass of all jets and leptons in the event	7.6
Same-sign electron pair invariant mass	6.9
Missing transverse momentum	6.8
Number of b-jets	6.7
W transverse mass associated to the SM top lepton	6.6
ΔR between the cLFV electron and the cLFV light jet	6.5
SM top mass	6.4
ΔR between the cLFV muon and the cLFV light jet	6.3
BDT discriminant	44