FCNC, EFT, Anomalous couplings at ATLAS

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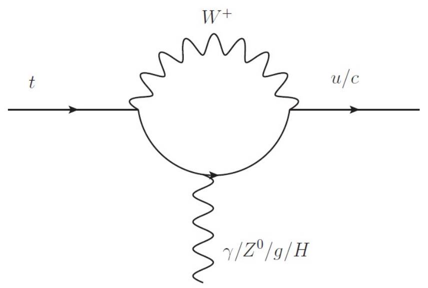
On Behalf of the ATLAS Collaboration

Flavor Changing Neutral Currents

Not allowed at tree level in SM.

Allowed at loop-level, but GIM suppressed.
Branching Ratio ~ $10^{-15} \rightarrow 10^{-12}$



BSM interactions could lead to much larger effects
Branching Ratio up to 10^{-4}

There have been many searches for top FCNC in ATLAS.
I will present the ones that currently provide our best limits

The Lagrangian for top FCNC can be written in terms of a set of anomalous couplings:

$$\mathcal{L} = \sum_{q=u,c} \Big[\sqrt{2} g_s \frac{\kappa_{gqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} T_a (f^L_{Gq} P_L + f^R_{Gq} P_R) q G^a_{\mu\nu} +$$

$$+ \frac{g}{\sqrt{2} c_W} \frac{\kappa_{zqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} (f^L_{Zq} P_L + f^R_{Zq} P_R) q Z_{\mu\nu} + \frac{g}{4 c_W} \zeta_{zqt} \bar{t} \gamma^\mu (f^L_{Zq} P_L + f^R_{Zq} P_R) q Z_\mu -$$

$$-e \frac{\kappa_{\gamma qt}}{\Lambda} \bar{t} \sigma^{\mu\nu} (f^L_{\gamma q} P_L + f^R_{\gamma q} P_R) q A_{\mu\nu} +$$

$$+ \frac{g}{\sqrt{2}} \bar{t} \kappa_{Hqt} (f^L_{Hq} P_L + f^R_{Hq} P_R) q H \Big] + h.c.$$

These couplings can also be expressed in terms of EFT coefficients, or combinations of coefficients

t→qH

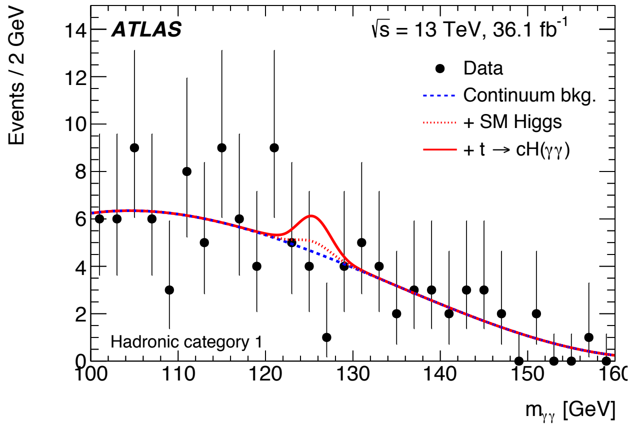
JHEP 10 (2017) 129
arXiv:1707.01404

Search for FCNC in $t\bar{t}$ events.
One top decays to Wb,
the other to qH, H→γγ

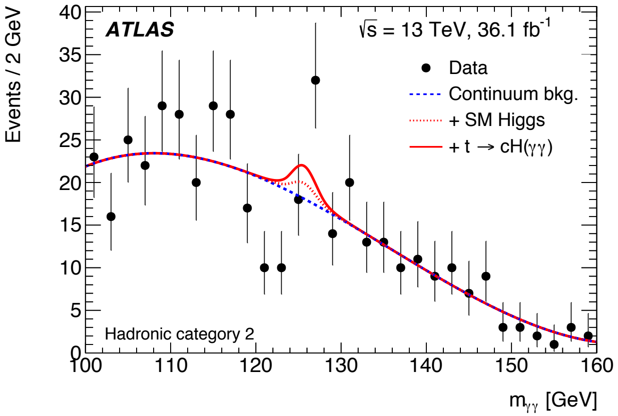
$m_{\gamma\gamma j} \in [152,190]$

Events categorized by whether
1. W decays to jets or leptons.
2. m_{Wb} inside top mass window or not.

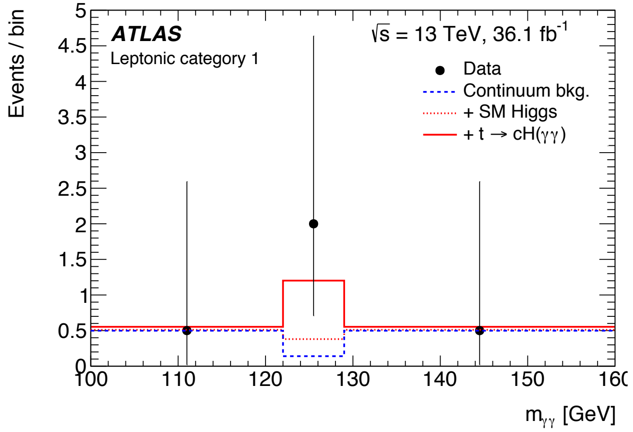
$m_{Wb} \in [120,220]$ GeV



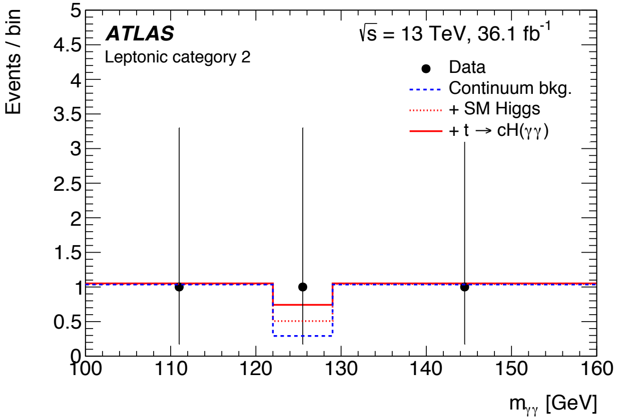
$m_{Wb} \notin [120,220]$ GeV



$m_{Wb} \in [130,210]$ GeV



$m_{Wb} \notin [130,210]$ GeV



t→qH

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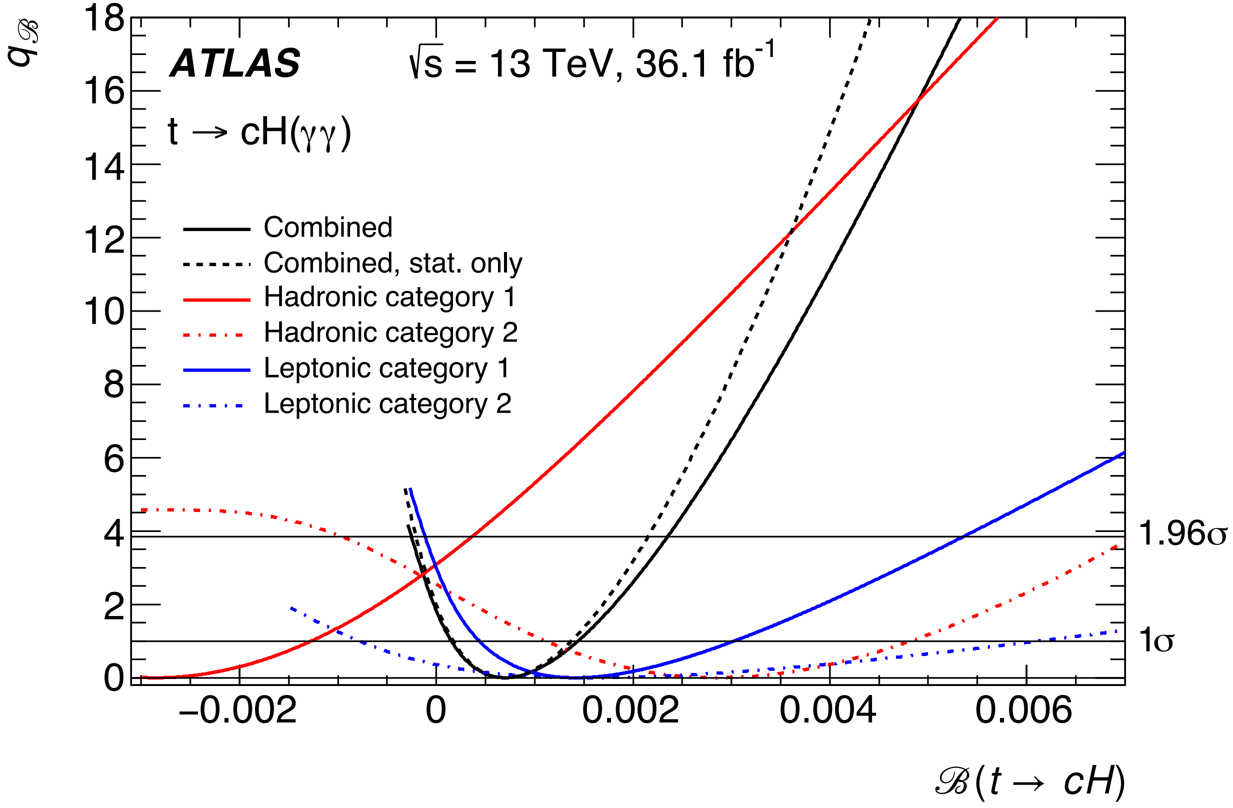
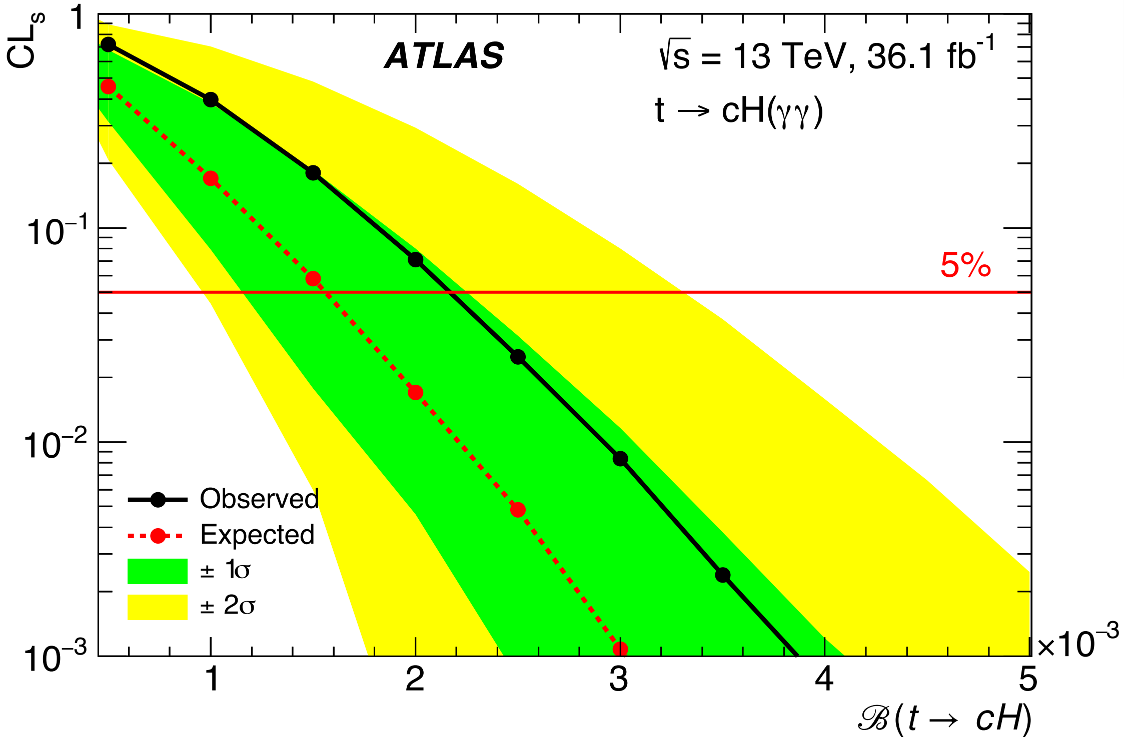
$q_B = -2(\ln L(\mathcal{B}) - \ln L(\hat{\mathcal{B}}))$
Shown for each individual category and the combination.





B(t→Hu) < 0.24% (obs)
< 0.17% (exp)
B(t→Hc) < 0.22% (obs)
< 0.16% (exp)

limits extracted from t→qH

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The branching ratio limits have been used to obtain limits on the off-diagonal Yukawa couplings

$$\sqrt{|\lambda_{tcH}|^2 + 0.92|\lambda_{tuH}|^2} < 0.090$$

Where each λ is the quadratic sum of the two possible chirality couplings.

This could be recast as a limit on a quadratic combination of all the relevant EFT coefficients $C_{u\phi}^{13}$, $C_{u\phi}^{31*}$, $C_{u\phi}^{23}$, and $C_{u\phi}^{32*}$.

$t \to qZ$

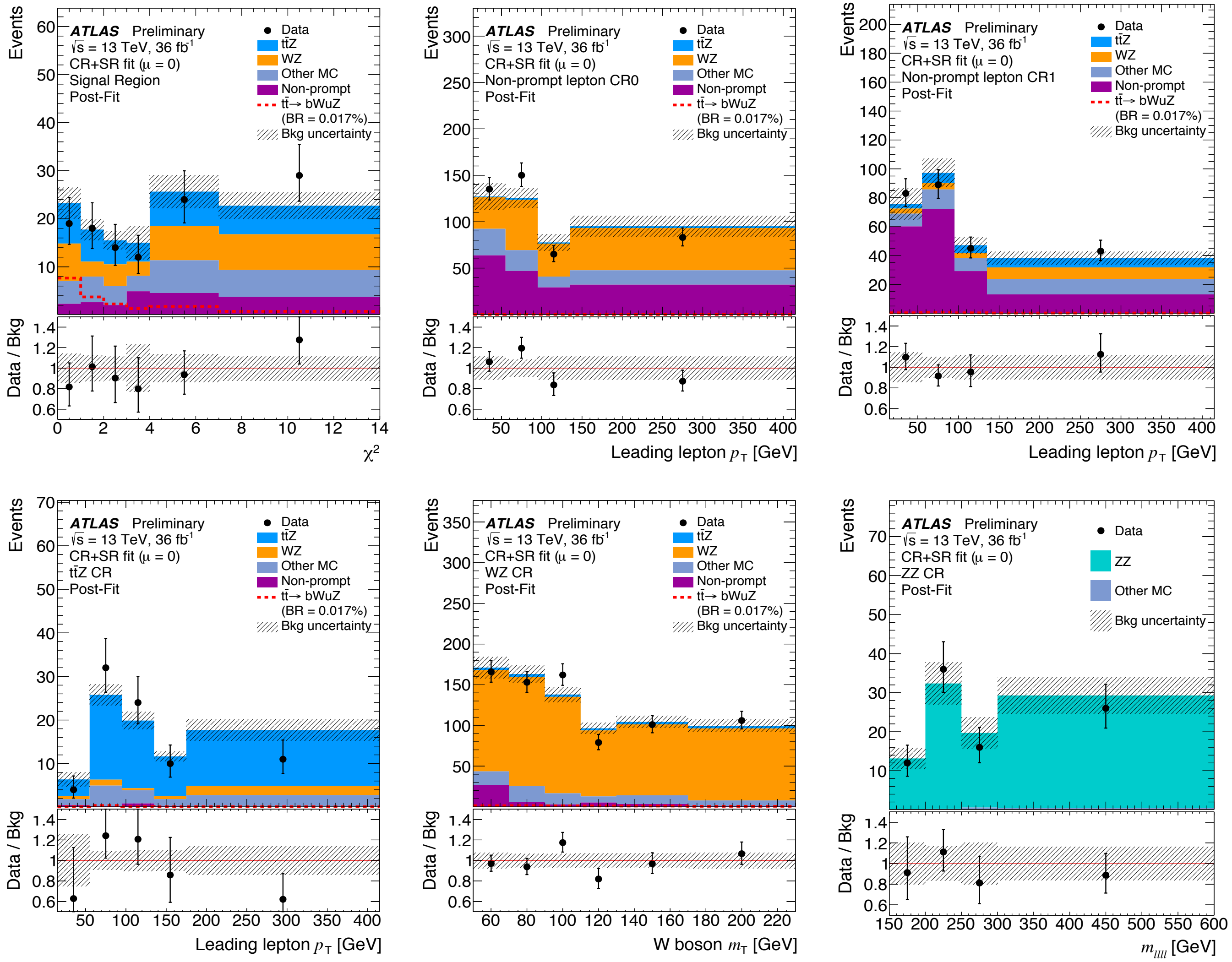
ATLAS-CONF-2017-070

Search for FCNC in $t\bar{t}$ events.
One top decays to Wb, $W \to l\nu$
the other to qZ, $Z \to l^+ l^-$
3 leptons plus 2 jets; 1 b-tagged, plus MET.

Form χ^2 based on reconstructed m_{jll}, $m_{bl\nu}$, and $m_{l\nu}$.

Simultaneous fit to 6 distributions in Signal and Control Regions

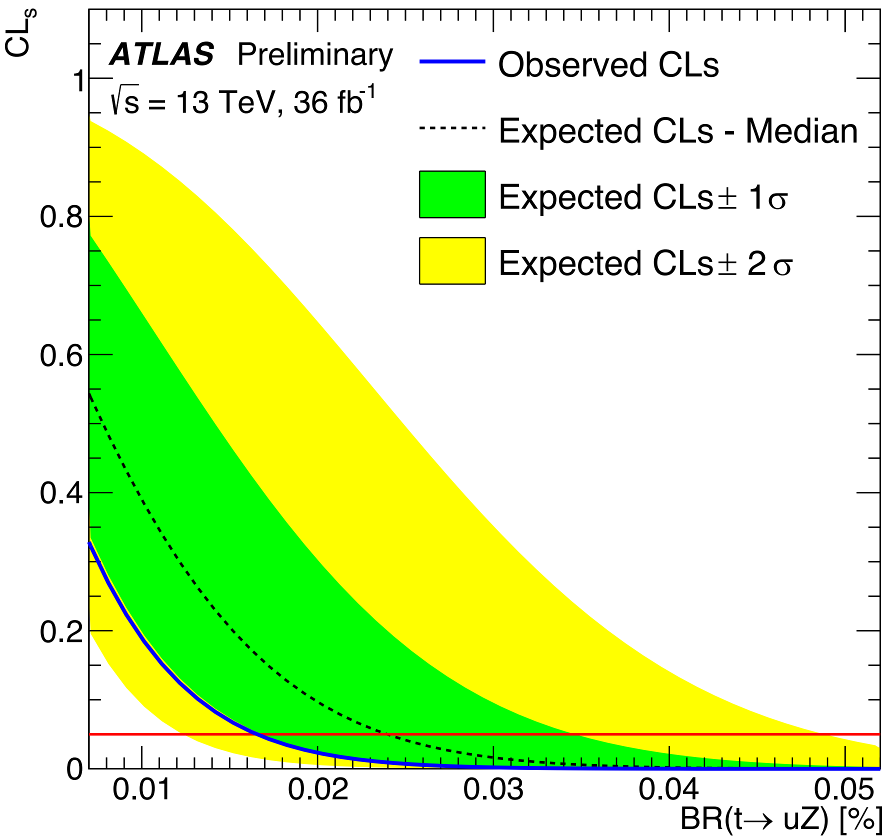
Main syst due to background Modeling

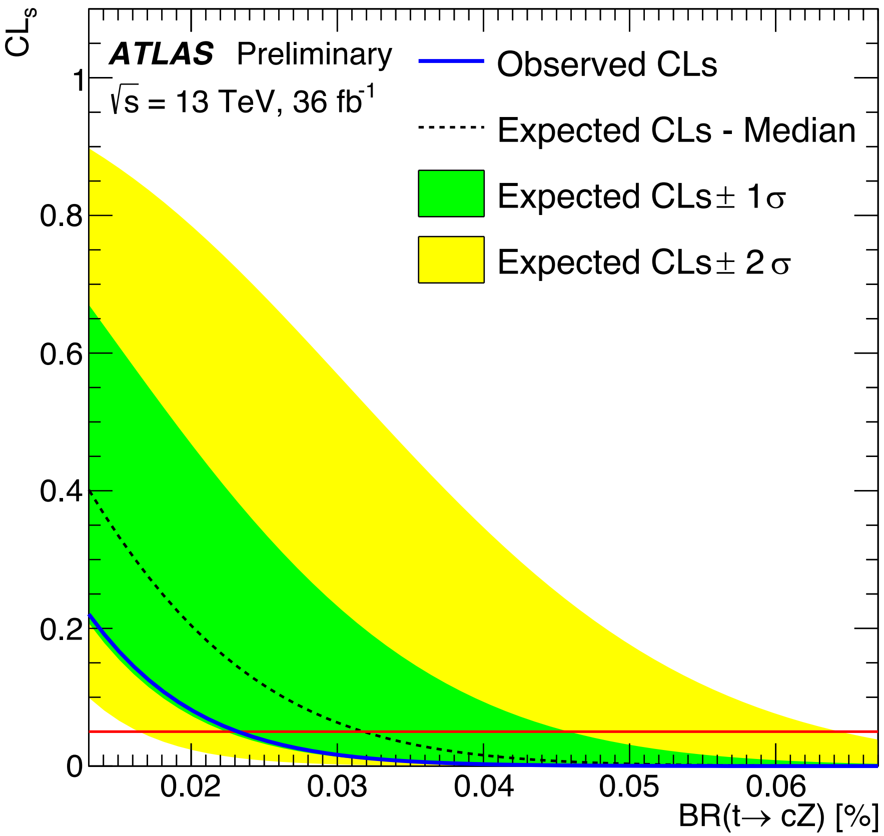


t→qZ

Results

ATLAS-CONF-2017-070





B(t→Zu) < 0.017% (obs)
< 0.024% (exp)
B(t→Zc) < 0.023% (obs)
< 0.032% (exp)

EFT limits from t→qZ

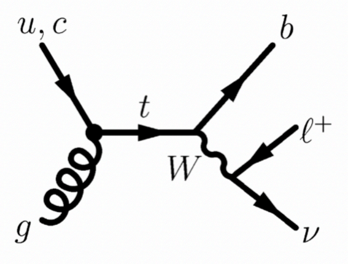
Eur. Phys. J. C (2016) 76:55
arXiv:1509.00294

- Limits on EFT coefficients related to the tensor *Ztq* couplings have also been extracted from the branching ratio limits.
- Each limit assumes all other coefficients are 0.
  - Since the tensor couplings depend on linear combinations of C_{uW} and C_{uB}, it would be best to show these correlations.
  - The *γtq* couplings depend on a different combination of couplings, so a combined analysis would be more powerful.
- This also assumes the vector *Ztq* couplings are zero. How does this affect limits obtained on the tensor couplings?

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

t→qg

Search for FCNC in exclusive single-top events.
isolated lepton, MET, exactly 1 b-tagged jet.



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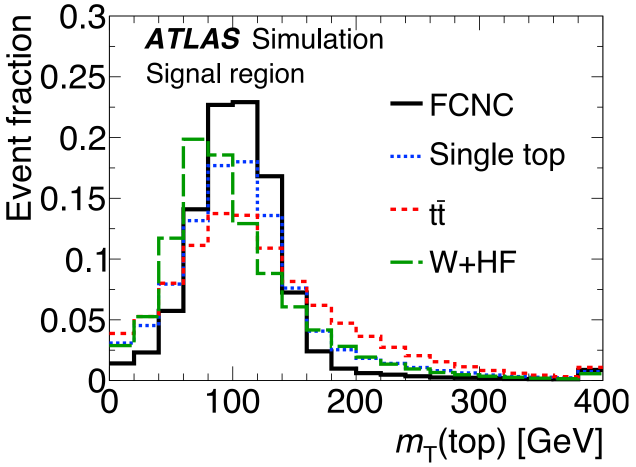
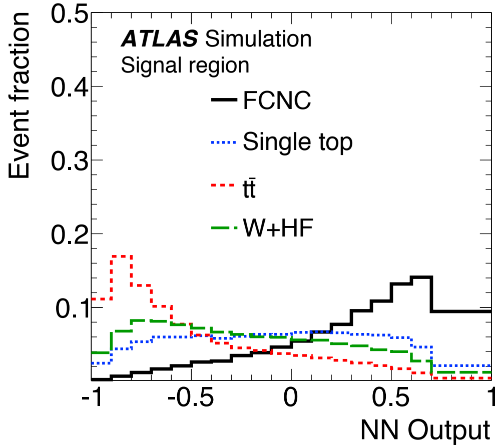
arXiv:1509.00294

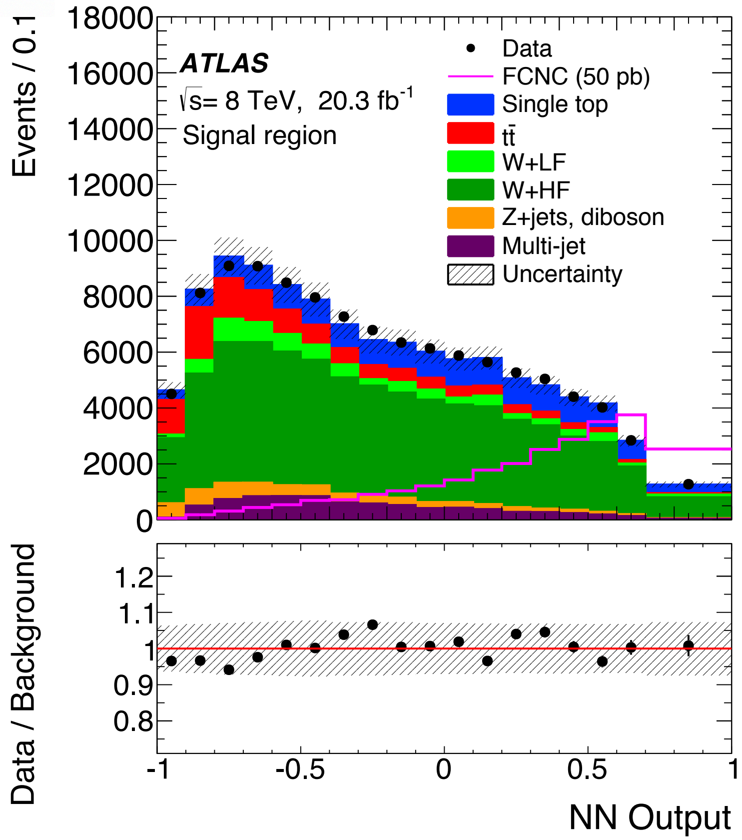
W+jets suppressed with Neural Net.

13 variables, most important:

Transverse mass of reconstructed top







t→qg

[Eur. Phys. J. C (2016) 76:55](#)
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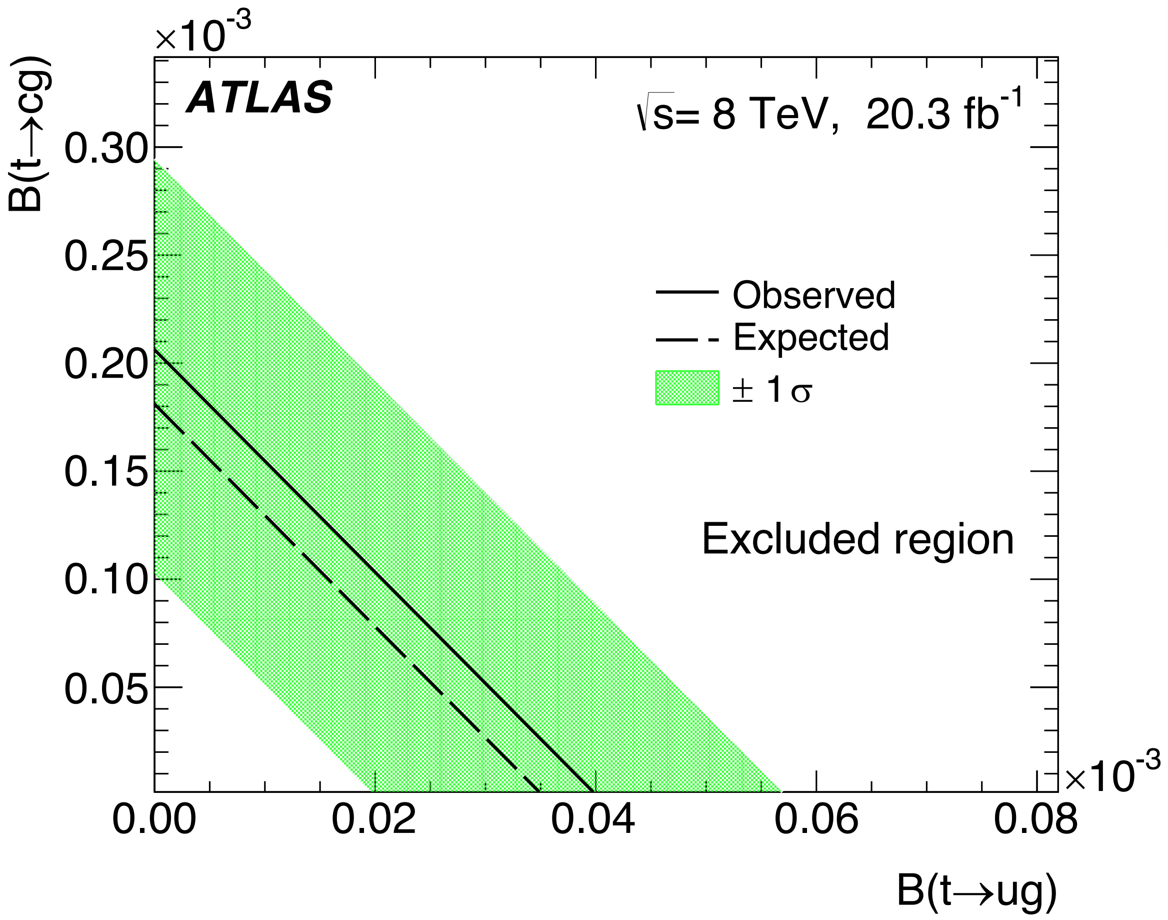
Result shows excluded region in plane of Branching Ratios.
Shaded region shows one-sigma variation of expected limit.



B(t→ug) < 4x10^{-5} (obs)
B(t→cg) < 20x10^{-5} (obs)

Largest systematic uncertainties due to
- Missing E_T modeling
- Jet Energy resolution

coupling limits extracted from t→qg

Eur. Phys. J. C (2016) 76:55
arXiv:1509.00294

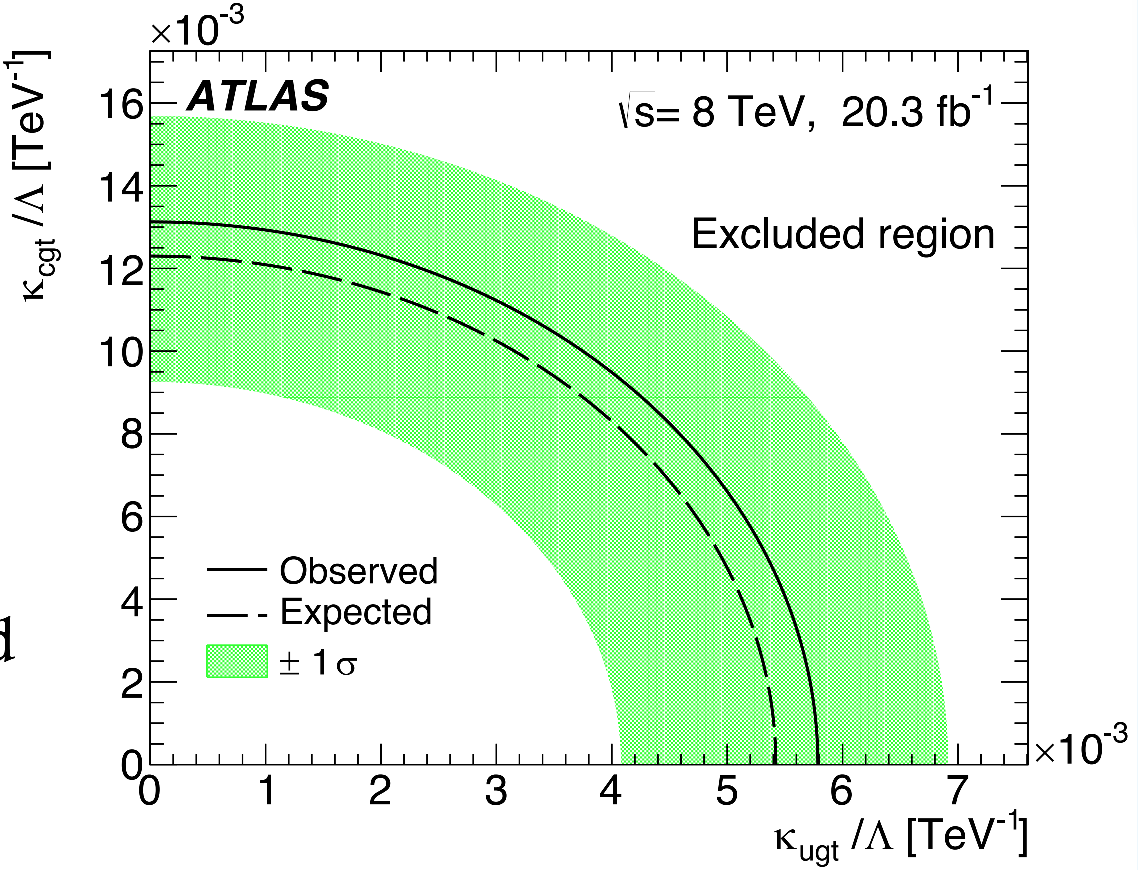
Assumes only left-handed couplings.

Conservative limit as right-handed couplings would be easier to distinguish from SM top production.

Assuming all other couplings are SM, one can quote

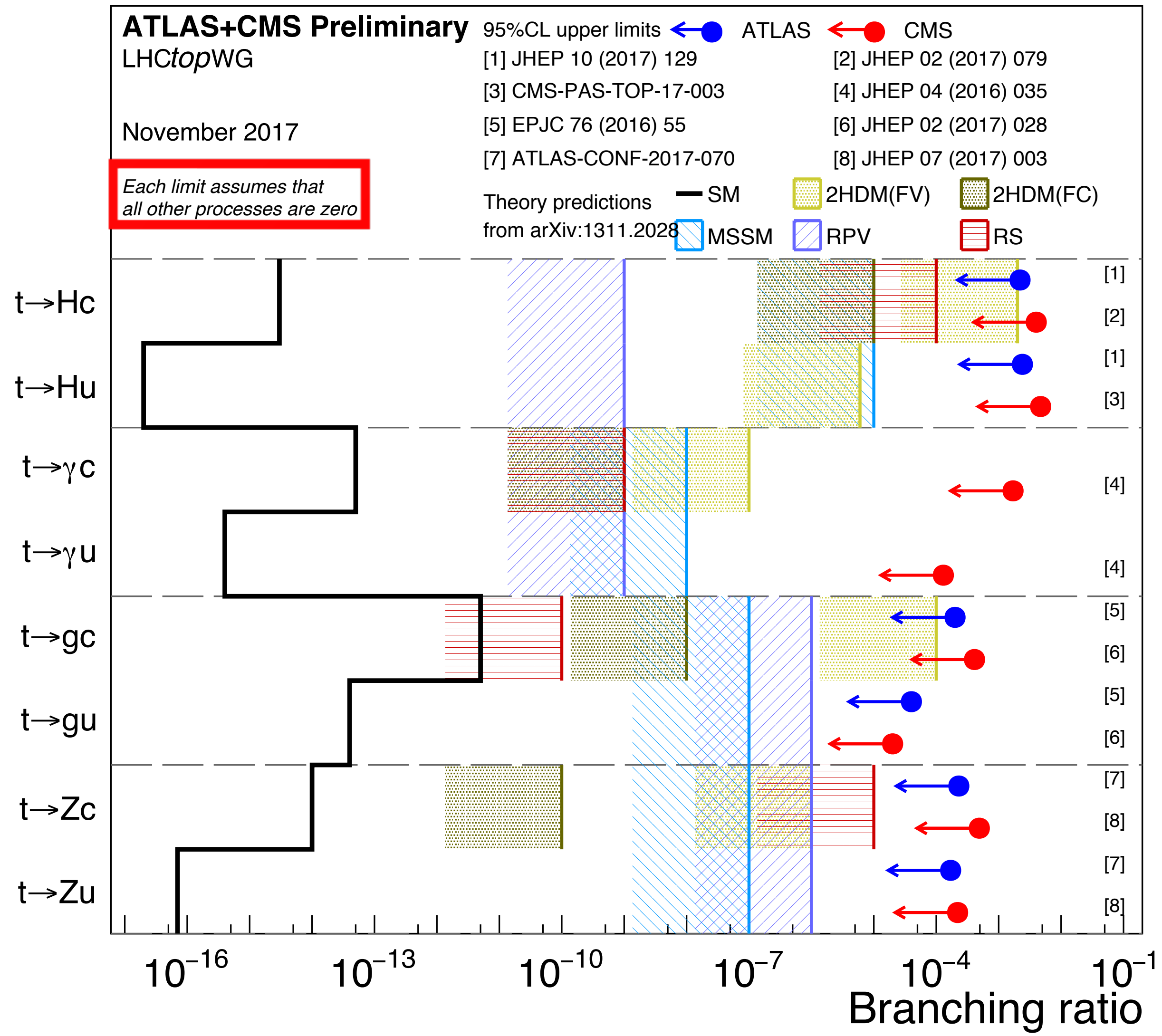
$\kappa_{ugt}/\Lambda < 5.8\text{x}10^{-3}$, $\kappa_{cgt}/\Lambda < 13\text{x}10^{-3}$

In future, perhaps we can quote how limits vary with assumed right- vs left-handed couplings.



Left handed couplings could also be expressed in terms of C_{uG}^{31*}, C_{uG}^{32*}; right-handed: C_{uG}^{13}, C_{uG}^{23}

Summary of all Branching Ratio limits



Other constraints on couplings

The angular correlations, mentioned by Ben yesterday, have also been used to extract anomalous couplings associated with the Wtb vertex.

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

These can be associated with the V_{tb} from the SM plus four EFT coefficients.

$$V_L = V_{tb} + C_{\phi q}^{(3,3+3)}\frac{v^2}{\Lambda^2};\ V_R = \frac{1}{2}C_{\phi\phi}^{3,3*}\frac{v^2}{\Lambda^2};\ g_L = \sqrt{2}C_{dW}^{3,3*}\frac{v^2}{\Lambda^2};\ g_R = \sqrt{2}C_{uW}^{3,3}\frac{v^2}{\Lambda^2}$$

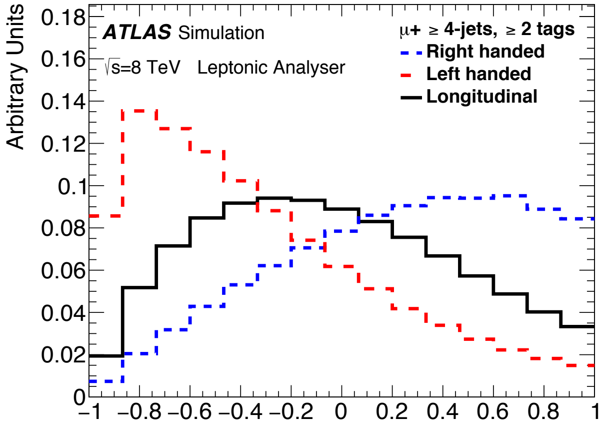
W Helicity Fractions

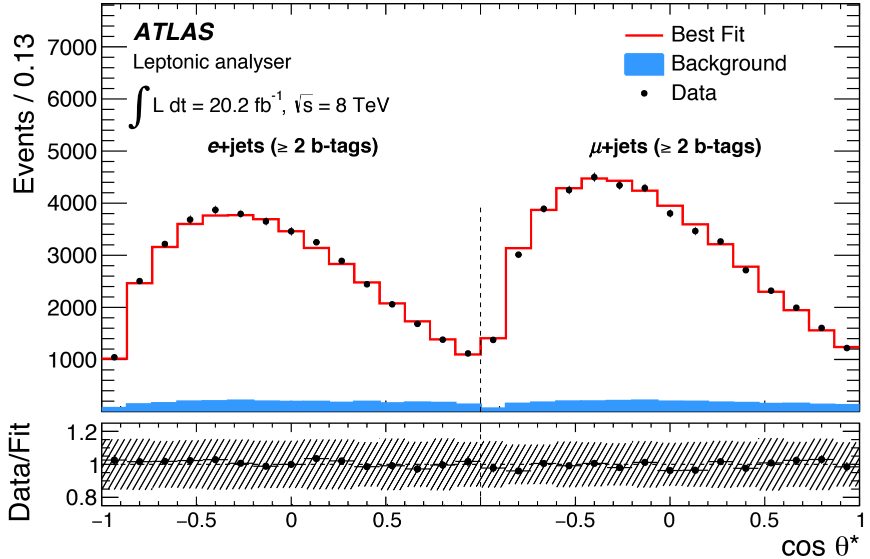
Eur. Phys. J. C 77 (2017) 264
arXiv:1612.02577

The standard W Helicity fractions are extracted in $t\bar{t}$ events.
1 lepton plus 4 jets (2 b-tagged) plus missing E_T.

Template fit to distribution in angle between lepton and helicity axis in W rest frame.

Systematic uncertainty somewhat larger than statistical.
Largest systematic for F_0 is MC template statistics.



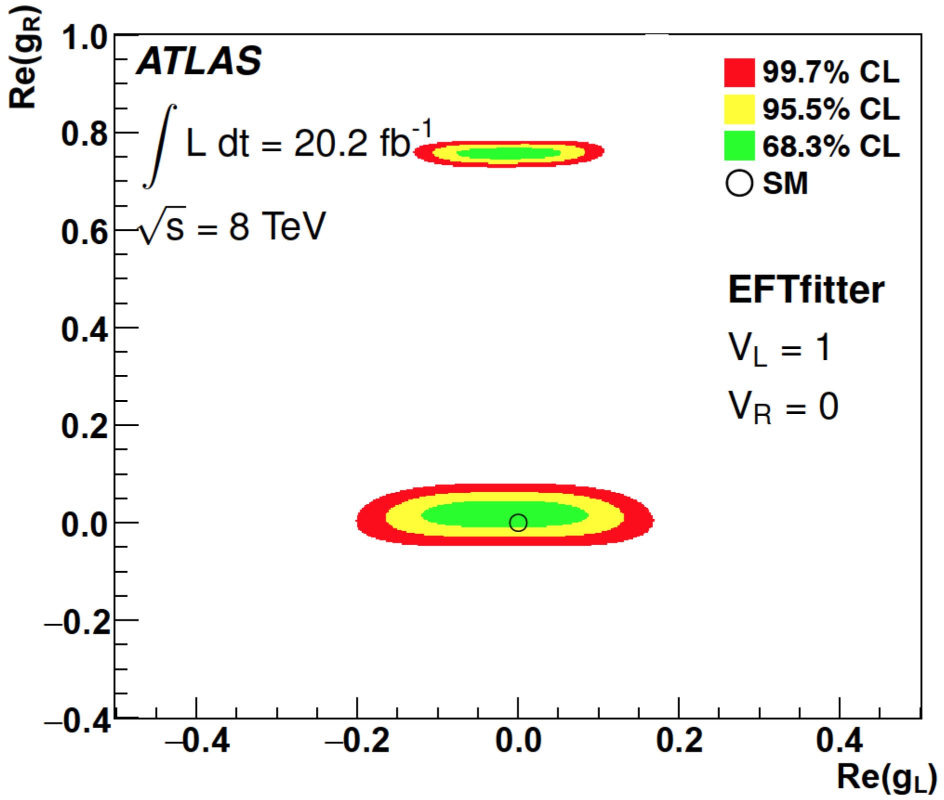


$$F_0 = 0.709 \pm 0.012\ (\text{stat.+bkg. norm.})^{+0.015}_{-0.014}\ (\text{syst.})$$

$$F_L = 0.299 \pm 0.008\ (\text{stat.+bkg. norm.})^{+0.013}_{-0.012}\ (\text{syst.})$$

$$F_R = -0.008 \pm 0.006\ (\text{stat.+bkg. norm.}) \pm 0.012\ (\text{syst.})$$

Constraints from W-Helicity Fractions



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arXiv:1612.02577

W-helicity measurements can be used to constrain anomalous couplings. This plot shows tight constraints in g_R vs g_L.

There are assumptions that the two coupling not shown are fixed to their SM values, and the ones shown are purely real. If these assumptions are removed, most of the plane is allowed.

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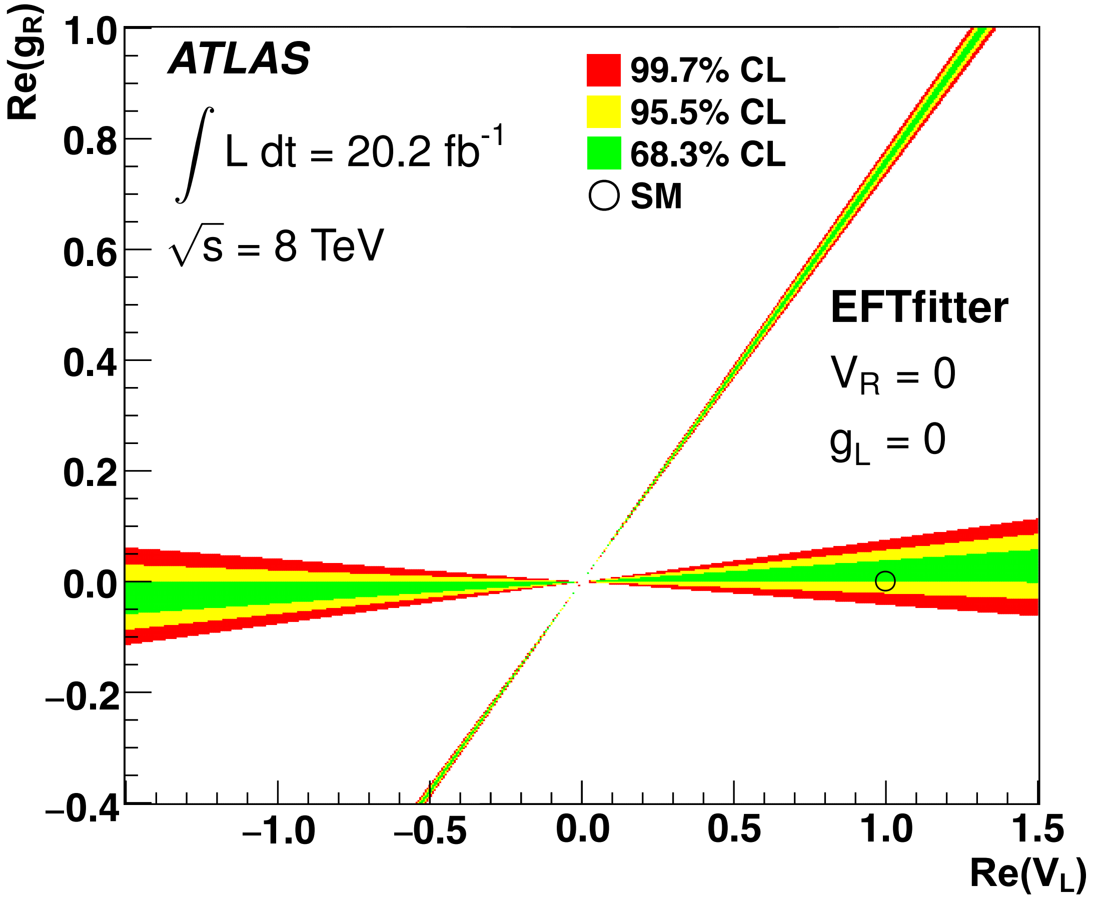
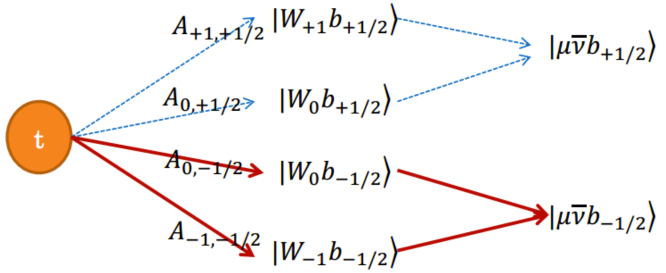
arXiv:1612.02577

If one examines a different set, of couplings one see that helicity *fractions* are sensitive to ratios of couplings. They very precisely determine two allowed regions in g_R/V_L.

Again, if one releases the assumptions on the other two couplings, the interpretation becomes more complicated.

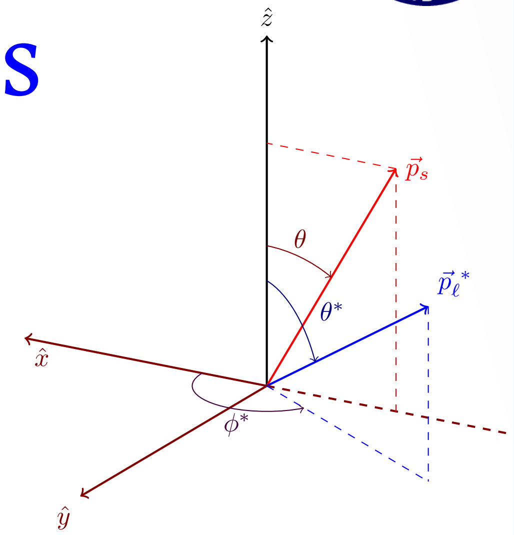


Top decay distribution can be fully expressed in terms of 4 Helicity amplitudes



$A_{\lambda w, \lambda b} =$ { $\lambda_b=1/2, \lambda_w=0,1.$; $\lambda_b=-1/2, \lambda_w=0,-1.$ }

λ represents the helicity fractions of b quark and W boson. $A_{\lambda w,\lambda b}$ is the decay amplitude.



F_R, F_L, F_0

$$\frac{1}{N}\frac{dN}{d\Omega d\Omega^*} = \frac{1}{(4\pi)^2}\Bigg[\frac{3}{4}\left|A_{1,\frac{1}{2}}\right|^2(1+P\cos\theta)(1+\cos\theta^*)^2$$
$$+\frac{3}{4}\left|A_{-1,-\frac{1}{2}}\right|^2(1-P\cos\theta)(1-\cos\theta^*)^2$$
$$+\frac{3}{2}\left(\left|A_{0,\frac{1}{2}}\right|^2(1-P\cos\theta)+\left|A_{0,-\frac{1}{2}}\right|^2(1+P\cos\theta)\right)\sin^2\theta^*$$
$$-\frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*(1+\cos\theta^*)\,\Re\left(e^{i\phi^*}A_{1,\frac{1}{2}}A^*_{0,\frac{1}{2}}\right)$$
$$-\frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*(1-\cos\theta^*)\,\Re\left(e^{-i\phi^*}A_{-1,-\frac{1}{2}}A^*_{0,-\frac{1}{2}}\right)\Bigg],$$

Terms in Black: measured by W-Helicity analyses

Terms in Green: also measure relative phase between amplitudes

Terms in Red: measures polarization and different combinations of amplitudes

The full triple differential decay distribution is determined in t-channel single-top events by measuring coefficients of orthogonal functions of θ, θ^*, and ϕ^*.

JHEP 12 (2017) 017
arXiv:1707.05393

Extracted Observables

JHEP 12 (2017) 017
arXiv:1707.05393

Likelihood is calculated numerically in full 6-d space of parameters

Two 2-d and one 1-d profiles shown here

$$f_1 = \frac{|A_{-1,-\frac{1}{2}}|^2 + |A_{1,\frac{1}{2}}|^2}{|A_{-1,-\frac{1}{2}}|^2 + |A_{0,-\frac{1}{2}}|^2 + |A_{0,\frac{1}{2}}|^2 + |A_{1,\frac{1}{2}}|^2} = F_R + F_L = 1 - F_0$$

$$f_1^+ = \frac{|A_{1,\frac{1}{2}}|^2}{|A_{-1,-\frac{1}{2}}|^2 + |A_{1,\frac{1}{2}}|^2} = \frac{F_R}{F_R + F_L}$$

$$f_0^+ = \frac{|A_{0,\frac{1}{2}}|^2}{|A_{0,-\frac{1}{2}}|^2 + |A_{0,\frac{1}{2}}|^2}$$

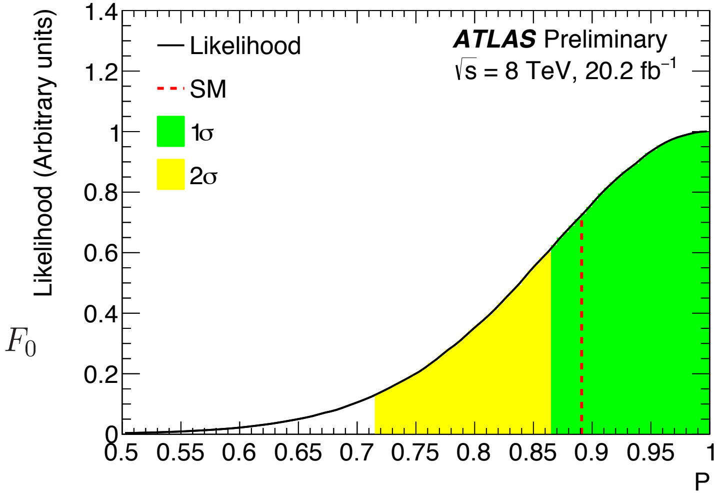
Not previously measured

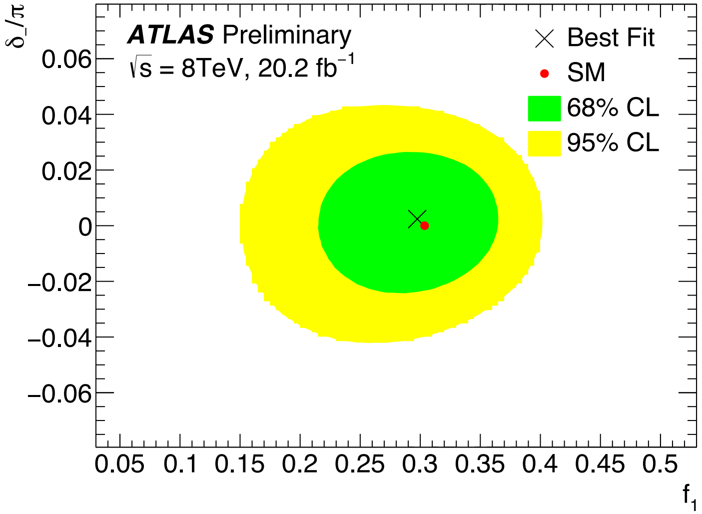
$$\delta_- = \arg A_{-1,-\frac{1}{2}} A^*_{0,-\frac{1}{2}}$$

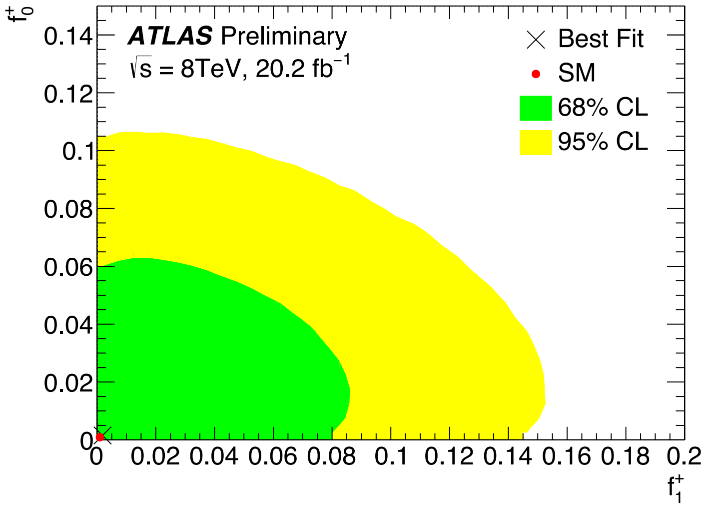
Non-zero phase could imply CP-violation

$$\delta_+ = \arg A_{1,-\frac{1}{2}} A^*_{0,\frac{1}{2}}$$

P = top polarization







Constraints from triple-differential top decay

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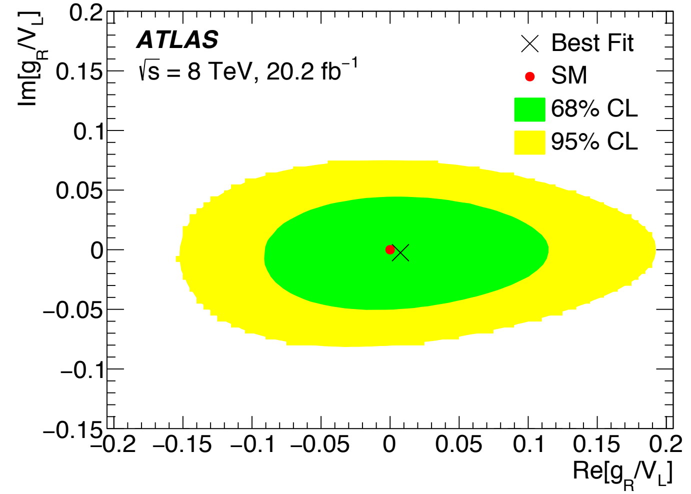
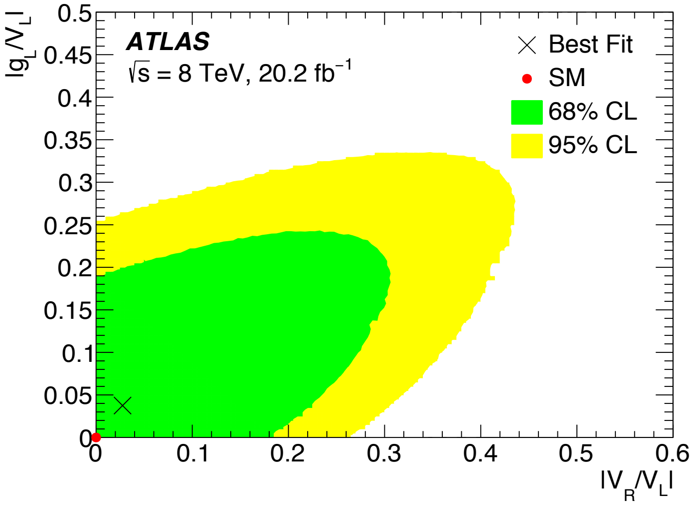


In the analysis with single-top, all assumptions on the couplings are removed, we explicitly state the result as ratios of couplings, and V_R, g_L, and g_R. are allowed to be complex.



f_1^+ and f_0^+ are determined by different linear combinations of g_L and V_R. In this case it is not conservative to fix one to its SM value when setting limits on the other. One needs the full correlation.

Summary

- ATLAS has many top FCNC results.
  - The full Run 2 data set will allow for more sensitivity to BSM physics.
    - Will need to keep control of systematics for t→Zq and t→gq
- The FCNC results have been used to provide constraints on couplings/EFT coefficients.
- Anomalous couplings/EFT also extracted from W Helicity measurements in $t\bar{t}$ events and from triple differential decay distributions in single-top events.
  - Correlations are important.
- A top sub-group has been formed in ATLAS to more fully examine ways to extract EFT coefficients from the wealth of top data to be extracted in Run 2 and beyond.