SUSY 2018 Barcelona July 23-28

Precision top & electroweak measurements.

Joe Boudreau
University of Pittsburgh
Results from ATLAS & CMS

Top quark precision measurements

- Two processes: $t\bar{t}$ and t-channel single top production
- Two interactions: strong (gtt vertex) and weak (Wtb vertex)
- Only one significant decay channel: W boson + b quark.
- Measurements constrain both the strength of these couplings and their structure.
- Two languages: EFT and anomalous couplings

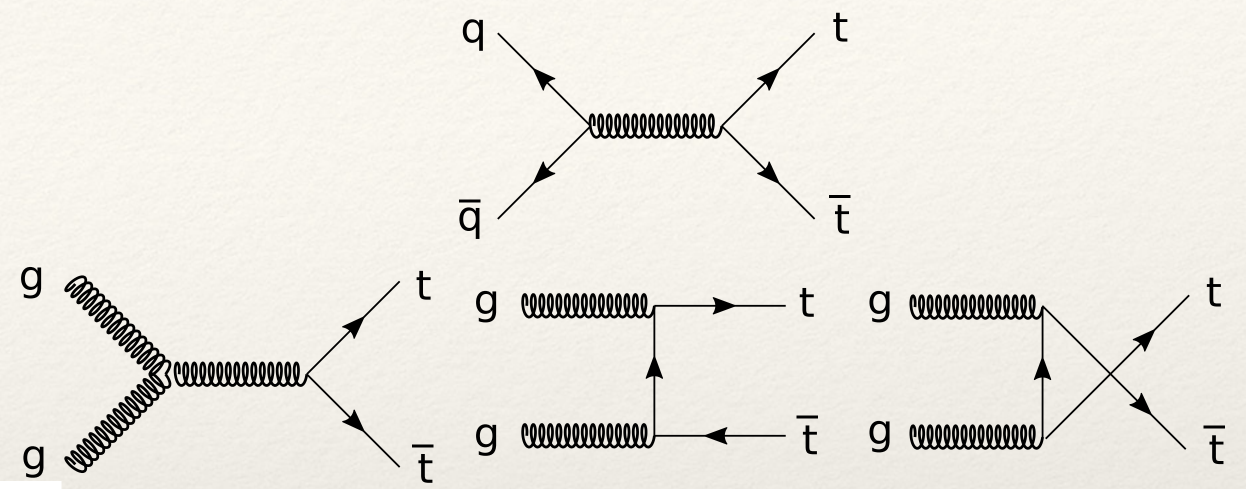
$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^2} O_i + \mathcal{O}(\Lambda^{-4})$$

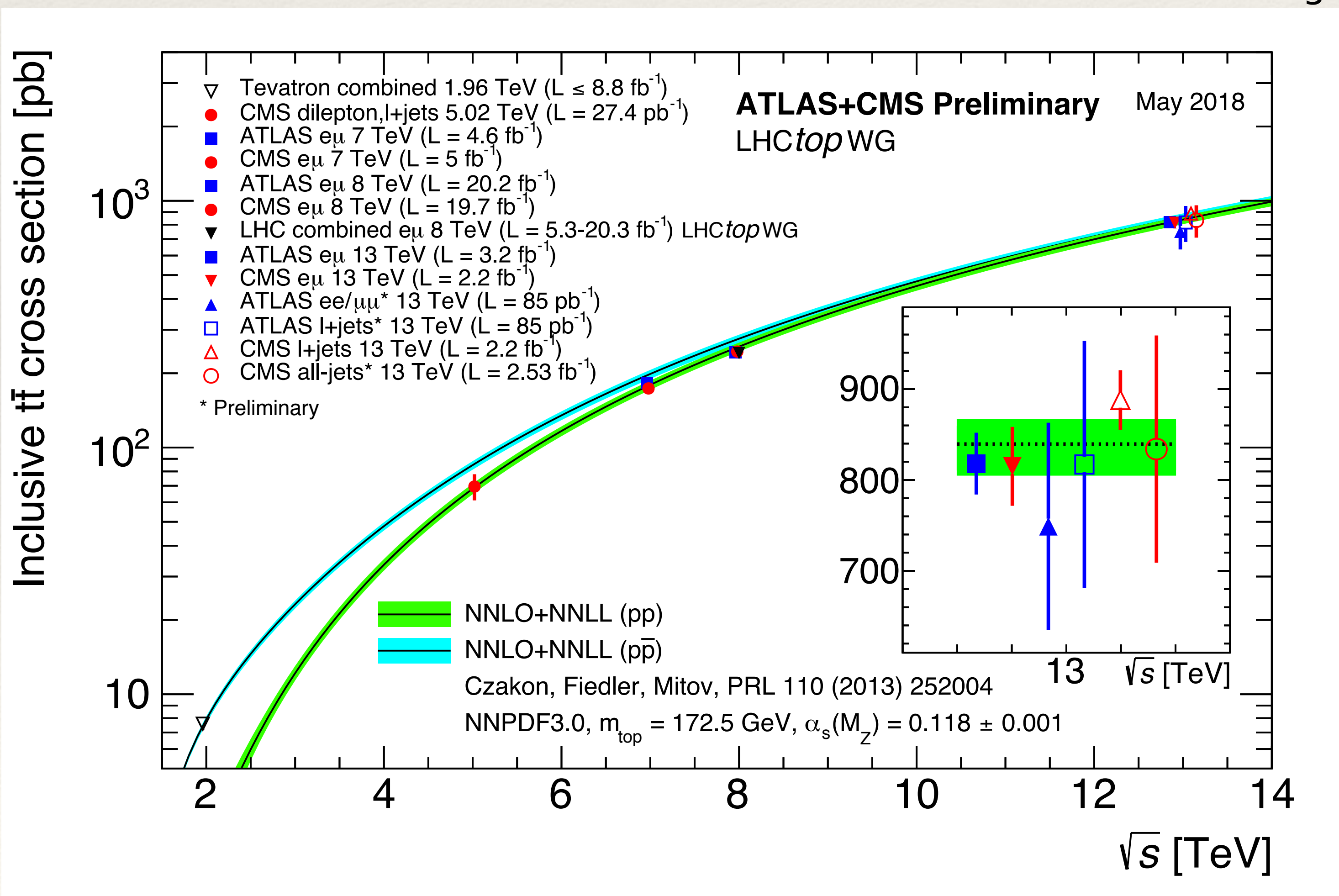
- Precision measurements are based on production cross sections and angular analyses of decay products.

$t\bar{t}$ cross section

Standard model production mechanisms for $q\bar{q}\to t\bar{t}$ and $gg\to t\bar{t}$.

s-channel $q\bar{q}\to t\bar{t}$
s,t, u-channel $gg\to t\bar{t}$.





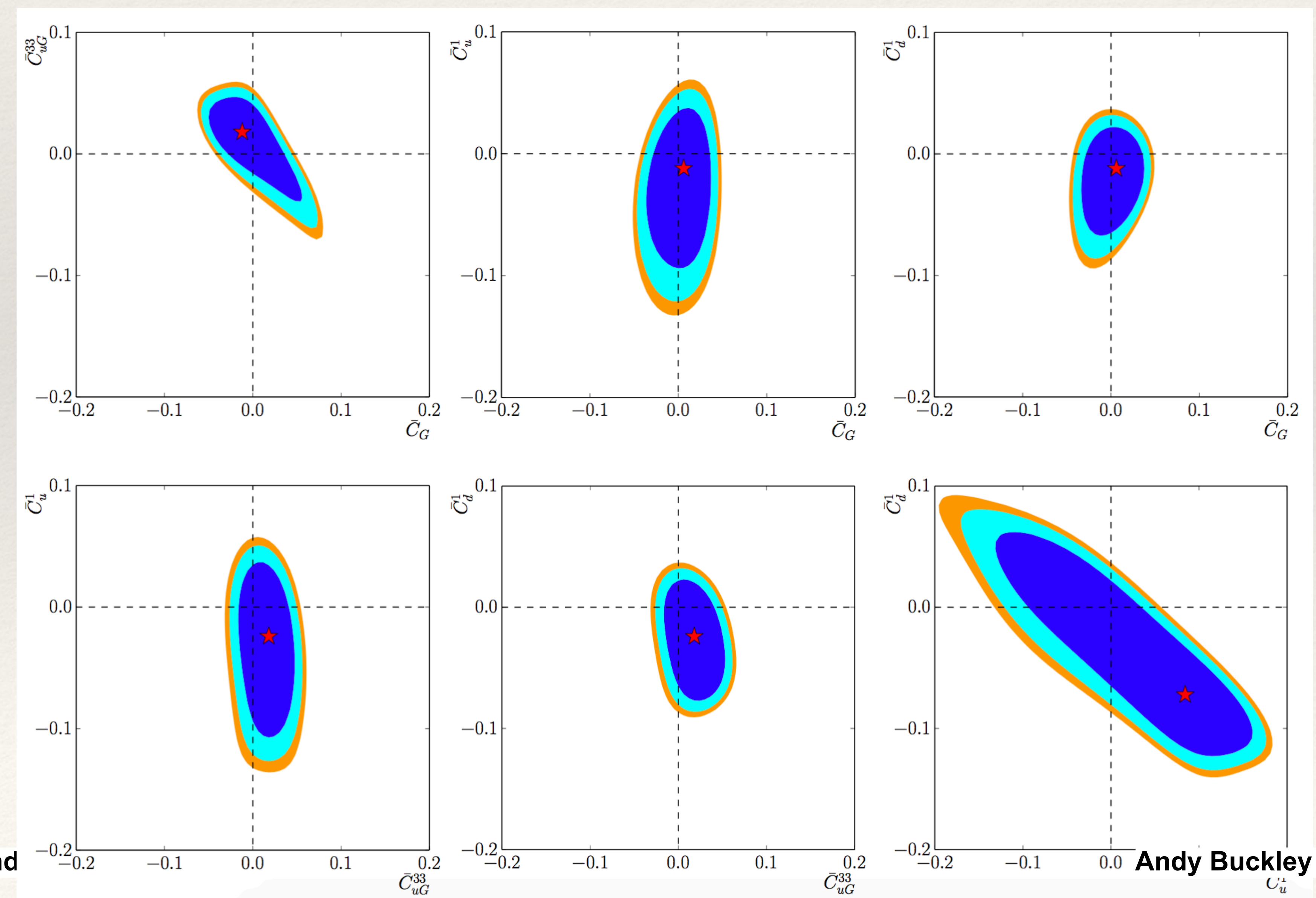
Cyan: $p\bar{p}\to t\bar{t}$ (Tevatron, 1.9 TeV)
Green: $pp\to t\bar{t}$ (LHC,5, 7,8, and 13 TeV)

All measurements in good agreement with SM predictions.

They can be interpreted in the framework of effective field theory

$t\bar{t}$ cross section and effective field theory

$$
\begin{aligned}
\mathcal{L}_{D6} \supset\ & \frac{C_{uG}}{\Lambda^2}\left(\bar{q}\sigma^{\mu\nu}T^A u\right)\tilde{\varphi}G^A_{\mu\nu} + \frac{C_G}{\Lambda^2} f_{ABC} G^{A\nu}_{\mu} G^{B\lambda}_{\nu} G^{C\mu}_{\lambda} + \frac{C_{\varphi G}}{\Lambda^2}\left(\varphi^\dagger\varphi\right) G^A_{\mu\nu}G^{A\mu\nu} \\
& + \frac{C^{(1)}_{qq}}{\Lambda^2}\left(\bar{q}\gamma_\mu q\right)\left(\bar{q}\gamma^\mu q\right) + \frac{C^{(3)}_{qq}}{\Lambda^2}\left(\bar{q}\gamma_\mu \tau^I q\right)\left(\bar{q}\gamma^\mu \tau^I q\right) + \frac{C_{uu}}{\Lambda^2}\left(\bar{u}\gamma_\mu u\right)\left(\bar{u}\gamma^\mu u\right) \\
& + \frac{C^{(8)}_{qu}}{\Lambda^2}\left(\bar{q}\gamma_\mu T^A q\right)\left(\bar{u}\gamma^\mu T^A u\right) + \frac{C^{(8)}_{qd}}{\Lambda^2}\left(\bar{q}\gamma_\mu T^A q\right)\left(\bar{d}\gamma^\mu T^A d\right) + \frac{C^{(8)}_{ud}}{\Lambda^2}\left(\bar{u}\gamma_\mu T^A u\right)\left(\bar{d}\gamma^\mu T^A d\right)
\end{aligned}
$$



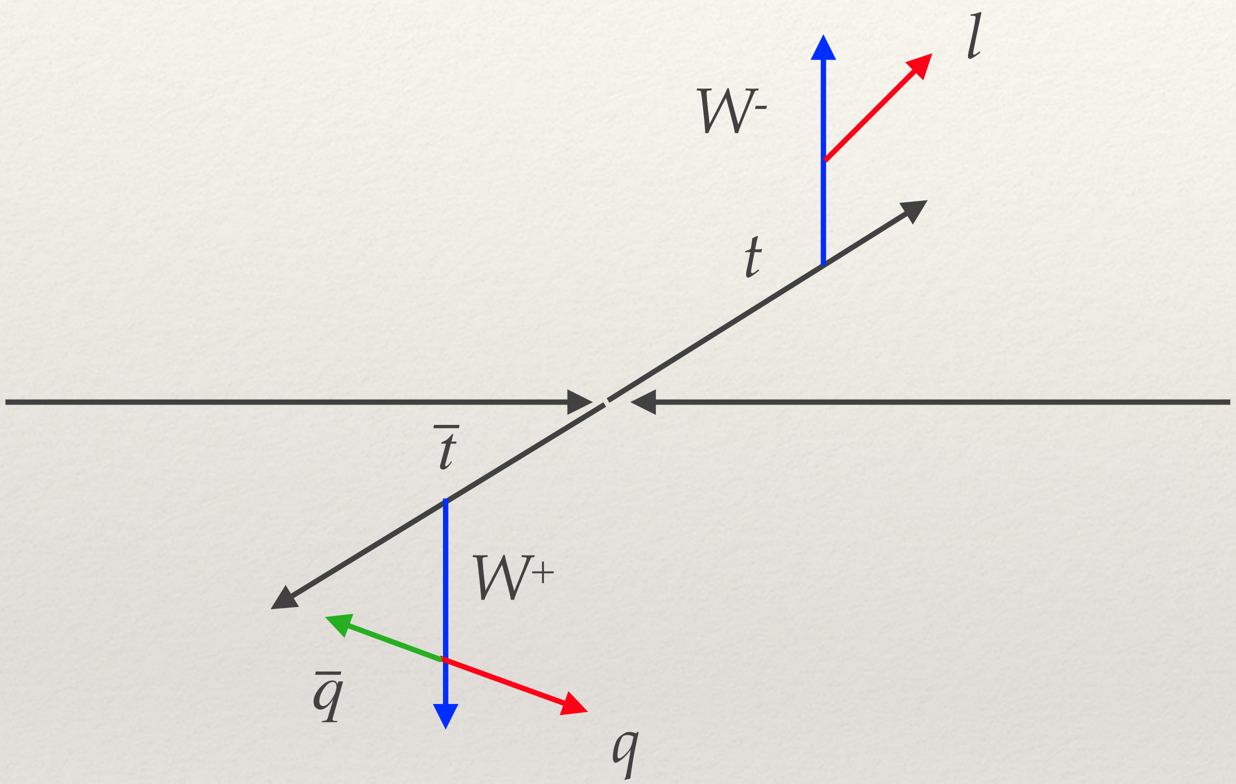
Dimension 6 operators leading to a modification of the production cross section.

The plots show constraints on their Wilson coefficients (or linear combinations).

All other coefficients constrained to zero in these plots.

And[...] Andy Buckley et al. (TOPFitter), JHEP 1604 (2016) 015

Kinematics of $t\bar{t}$ production+decay

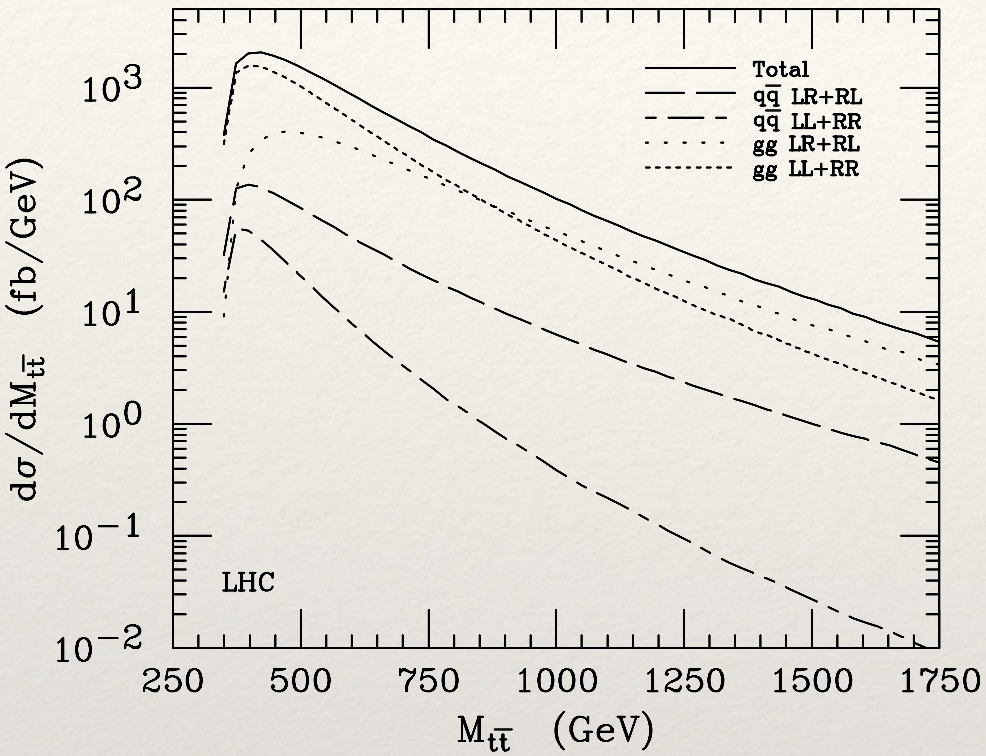


- Rapidity of $t\bar{t}$ system
- Production angle in $t\bar{t}$ rest frame
- Polar and azimuthal angle of W^+ boson
- Polar and azimuthal angle of W^- boson
- Polar and azimuthal angle of the fermion from W^- decay
- Polar and azimuthal angle of the antifermion from the W^+ decay.

Decays are classified as dilepton (10.5%), lepton + jets (43.8%), and fully hadronic (45.7%, not used for precision measurement).

Measurements are based upon distributions of observables — projections of the joint PDF for the production+decay process. Sensitive to the structure of the gtt vertex (production) and the Wtb vertex (decay)

Spin correlations



LL+RR partons produce $t\bar{t}$ pairs w/ opposite spins

LR+RL partons produce $t\bar{t}$ pairs w/ aligned spins

New physics can alter the spin correlation:

- Via exotic production mechanisms (Z′, heavy Higgs, SUSY)
- *Via virtual effects (anomalous couplings) at the ggt vertex.*

Stephen J. Parke, arXiv:1202.2345

Decay time of the top quark (10^{-25} s) shorter than the hadronization time (10^{-24} s)

==> spin information is transferred to the decay products of the top quark.

The weak decay of the top quark t→Wb is a spin analyzer.

$$\frac{1}{\Gamma_T}\frac{d\Gamma}{d\cos\chi_i} = (1+\alpha_i\cos\chi_i)/2$$

$$\alpha_i = \begin{cases} +0.998 & l^+ \\ +0.966 & \bar{d} \\ -0.314 & \bar{\nu} \\ -0.317 & \bar{u} \\ -0.393 & b \end{cases} \quad \text{(NLO)}$$

Angle between decay product and spin axis, top rest frame.

Old news: spin correlations established in 2012

Simplest observable is Δϕ, the difference in azimuth of two leptons in the laboratory frame:

- Does not require the reconstruction of full event kinematics
- Can easily be applied to top dilepton events, the cleanest sample of $t\bar{t}$ events

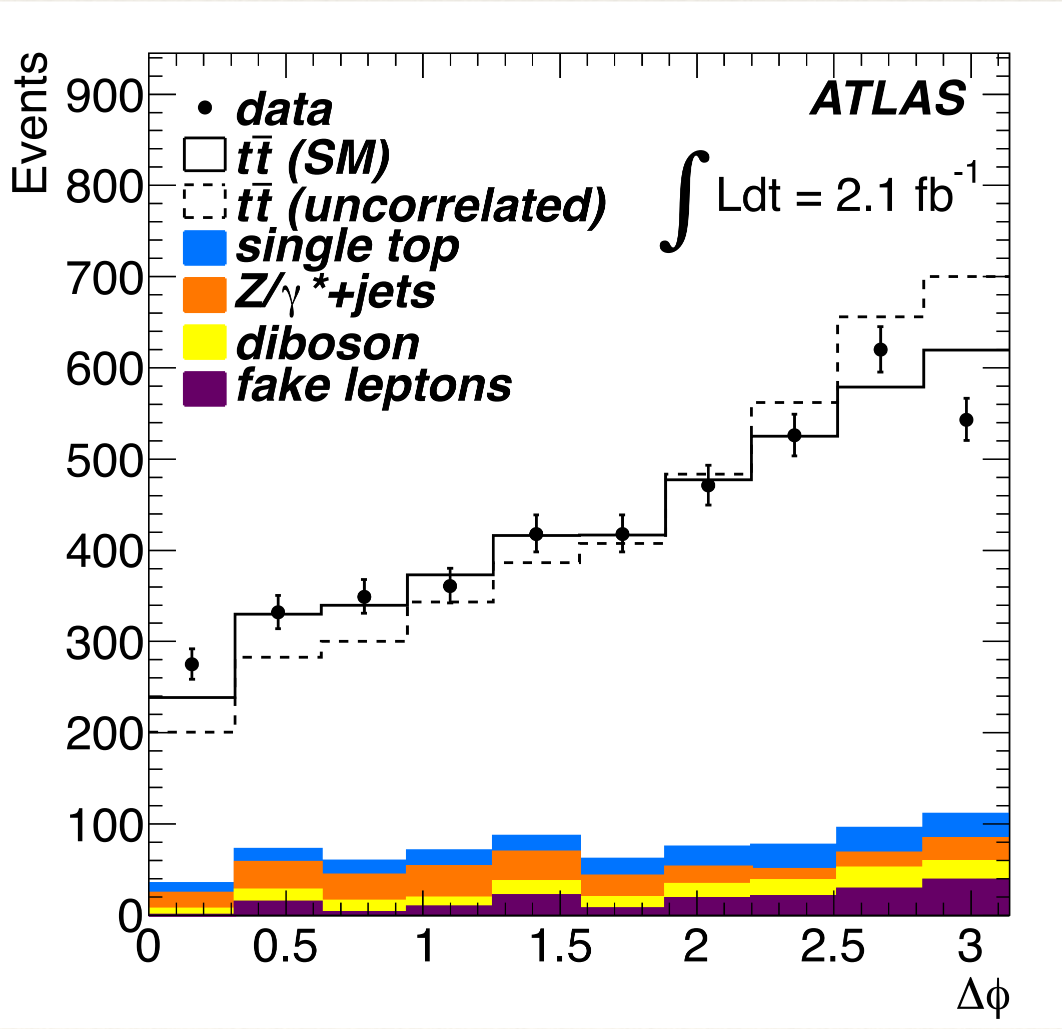
These correlations are established experimentally in 2012 using the distribution of Δϕ==>

$$n_i = f_{\mathrm{SM}} n_{\mathrm{spin}} + (1 - f_{\mathrm{SM}}) n_{\mathrm{nospin}}$$

f_{SM} factor has SM expectation of 1.0

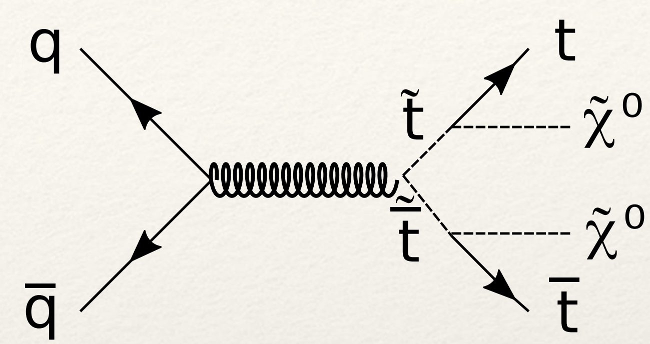
$f_{SM}=1.30 \pm 0.14 \, ^{+0.27}_{-0.22}$ Phys. Rev. Lett. 108 (2012) 212001

5.1 σ observation of spin correlations (ATLAS),

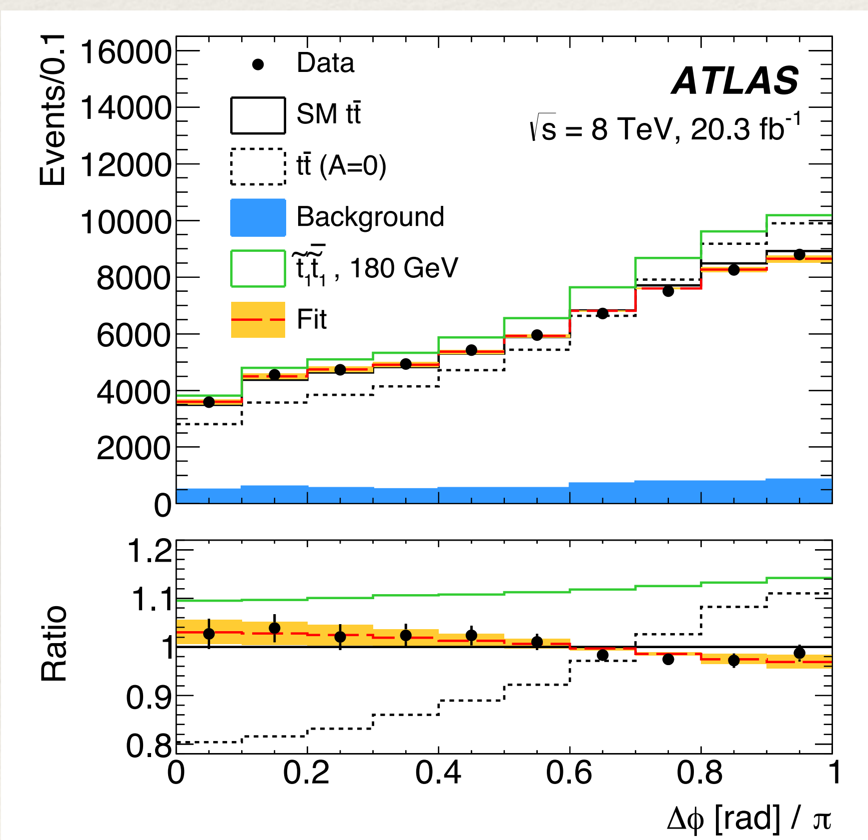


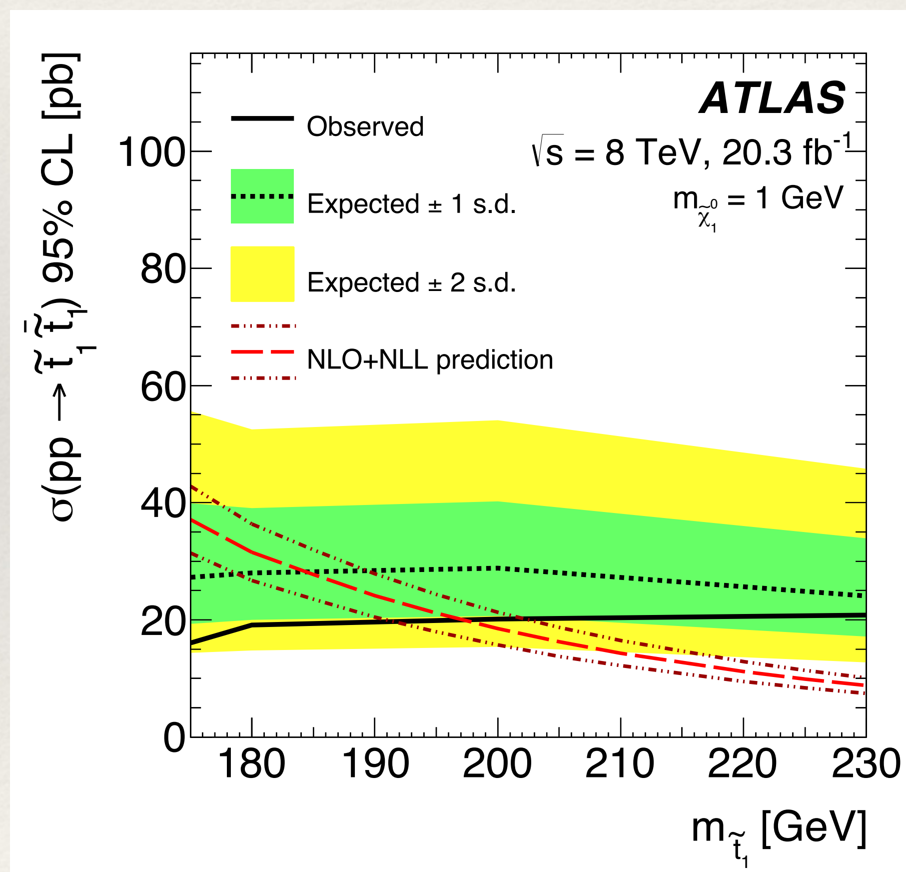
Spin Correlations in 8 TeV data and limits on the $m_{\tilde{t}_1}$

- dilepton events used
- Spin correlation strength $A_{helicity}=(N_{like}-N_{unlike})/(N_{like}+N_{unlike})$ extracted
- Bounds on the mass of the lightest stop inferred.
- The search looks for right-handed tops from the lightest stop.



Phys. Rev. Lett. 114 (2015) 142001





From cross section only, limits are weaker:

$m_t < m_{t_1} < 177$ GeV

see

Eur. Phys. J. C **74** 3109 (2014)

$A_{helicity} = 0.38 \pm 0.04$

$A^{SM}_{helicity} = 0.318 \pm 0.006$

compare with

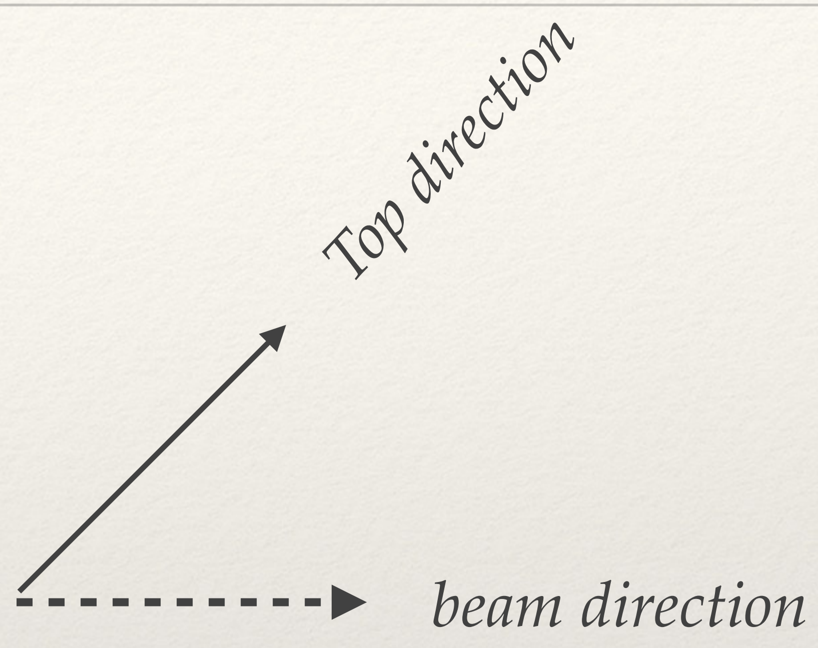
[Nucl. Phys. B **725** 115 (2013)]

$$m_t < m_{\tilde{t}_1} < 191 \text{ GeV} \qquad (95\%)$$

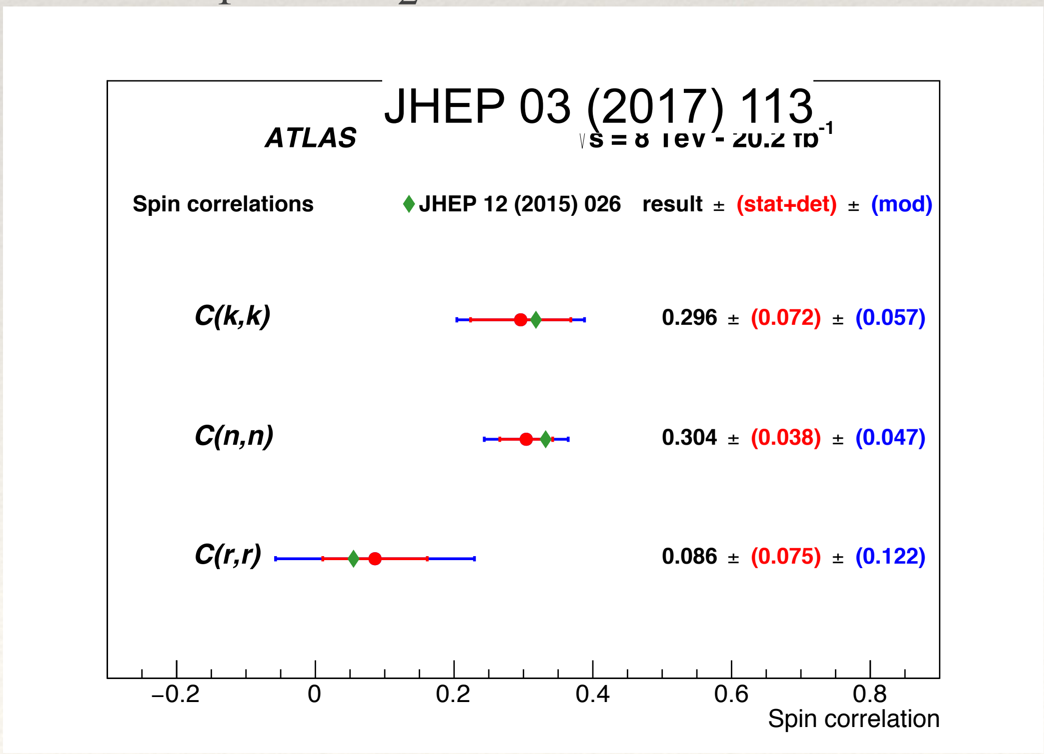
Spin correlations in all three directions

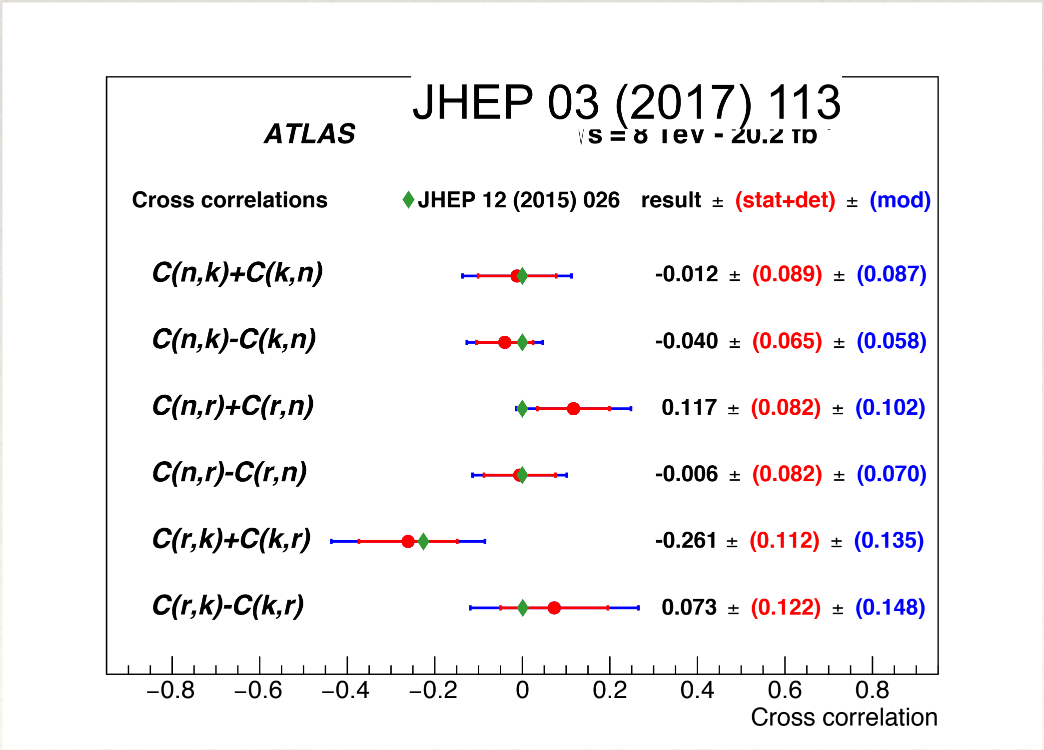
In the Zero Momentum Frame (ZMF), we identify three angles:

- Helicity angle θ
- Transverse angle, ⊥ production plane
- "R-axis angle", third orthogonal direction
- All components of the $t\bar{t}$ pair spin-density matrix measured in the analysis from ATLAS.



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}\left(1 - C\cos\theta_1\cos\theta_2\right)$$ *Simplest form.*





CMS 8 TeV (dilepton analysis)

CMS collaboration, PRD D **93** 052007 (2016). The main reference and roadmap for this work is Bernreuther and Si PLB 725 (2013) 115, examining the effect of anomalous top chromo-magnetic and chromo-electric dipole moments.

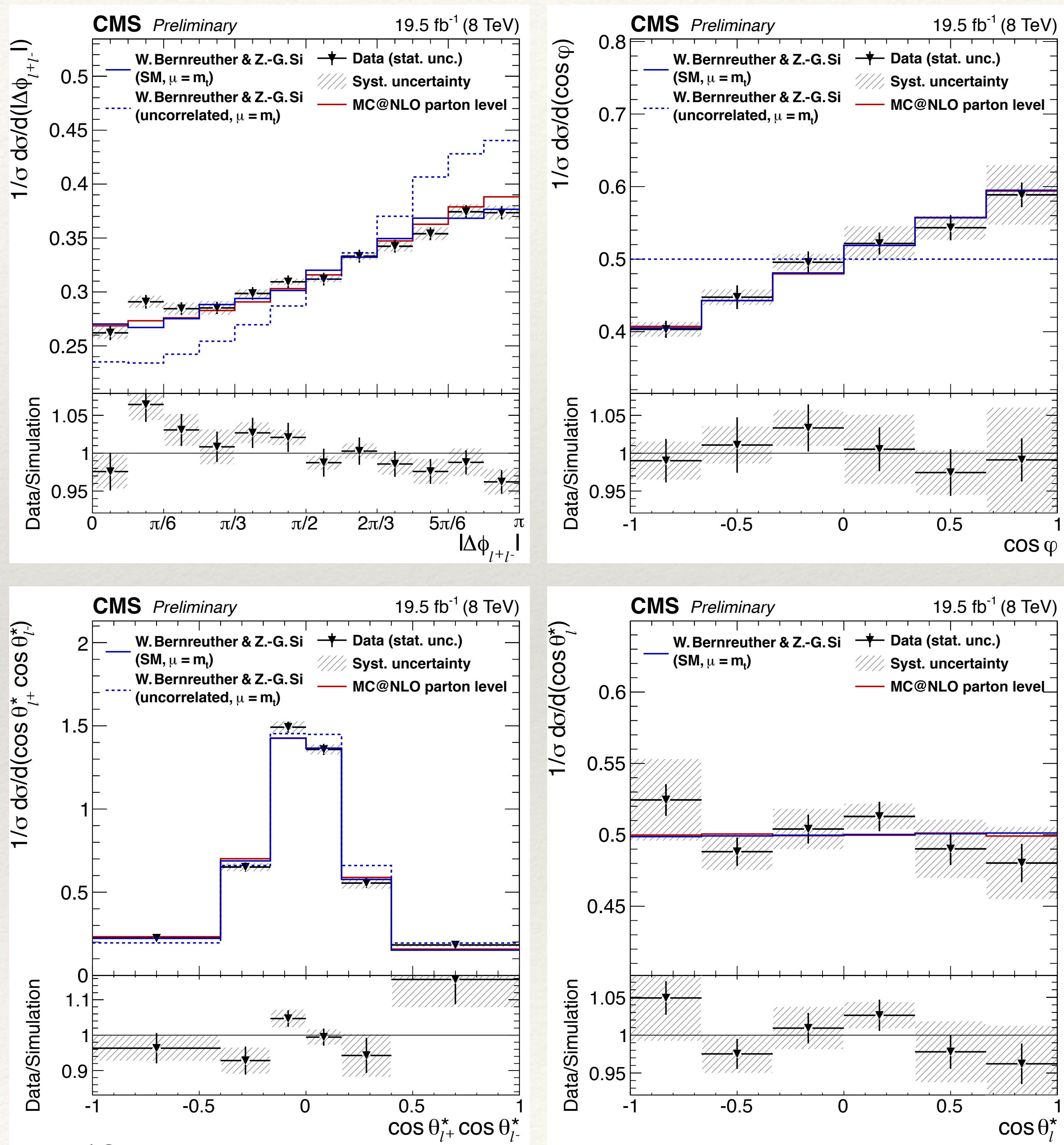
$$A_{\Delta\phi} = \frac{N\left(|\Delta\phi_{\ell^+\ell^-}| > \pi/2\right) - N\left(|\Delta\phi_{\ell^+\ell^-}| < \pi/2\right)}{N\left(|\Delta\phi_{\ell^+\ell^-}| > \pi/2\right) + N\left(|\Delta\phi_{\ell^+\ell^-}| < \pi/2\right)}$$

$$A_{c_1c_2} = \frac{N\left(c_1c_2 > 0\right) - N\left(c_1c_2 < 0\right)}{N\left(c_1c_2 > 0\right) + N\left(c_1c_2 < 0\right)}$$

$$A_{\cos\varphi} = \frac{N\left(\cos\varphi > 0\right) - N\left(\cos\varphi < 0\right)}{N\left(\cos\varphi > 0\right) + N\left(\cos\varphi < 0\right)}$$

$$A_{P^\pm} = \frac{N\left(\cos\theta^*_{\ell^\pm} > 0\right) - N\left(\cos\theta^*_{\ell^\pm} < 0\right)}{N\left(\cos\theta^*_{\ell^\pm} > 0\right) + N\left(\cos\theta^*_{\ell^\pm} < 0\right)}$$

CPV: $A_{CPV} = A_{P+} - A_{P-}$



Chromo-moments at the gtt vertex

Variable	$f_{\text{SM}} \pm \text{(stat)} \pm \text{(syst)} \pm \text{(theor)}$	Total uncertainty
$A_{\Delta\phi}$	$1.14 \pm 0.06 \pm 0.13\,^{+0.08}_{-0.11}$	$^{+0.16}_{-0.18}$
$A_{\cos\varphi}$	$0.90 \pm 0.09 \pm 0.10 \pm 0.05$	± 0.15
$A_{c_1 c_2}$	$0.87 \pm 0.17 \pm 0.21 \pm 0.04$	± 0.27
$A_{\Delta\phi}$ (vs. $M_{t\bar{t}}$)	$1.12 \pm 0.06 \pm 0.08\,^{+0.08}_{-0.11}$	$^{+0.12}_{-0.15}$

CMS PRD **93** 052007 (2016)

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

$$\hat{\mu}_t \equiv \frac{m_t}{g_s}\tilde{\mu}_t \qquad \hat{d}_t \equiv \frac{m_t}{g_s}\tilde{d}_t$$

The CMS analysis is sensitive to Re($\hat{\mu}_t$) and Im($\hat{d}_t$)

Dimensionless anomalous chromo-magnetic & electric dipole moment parameters.

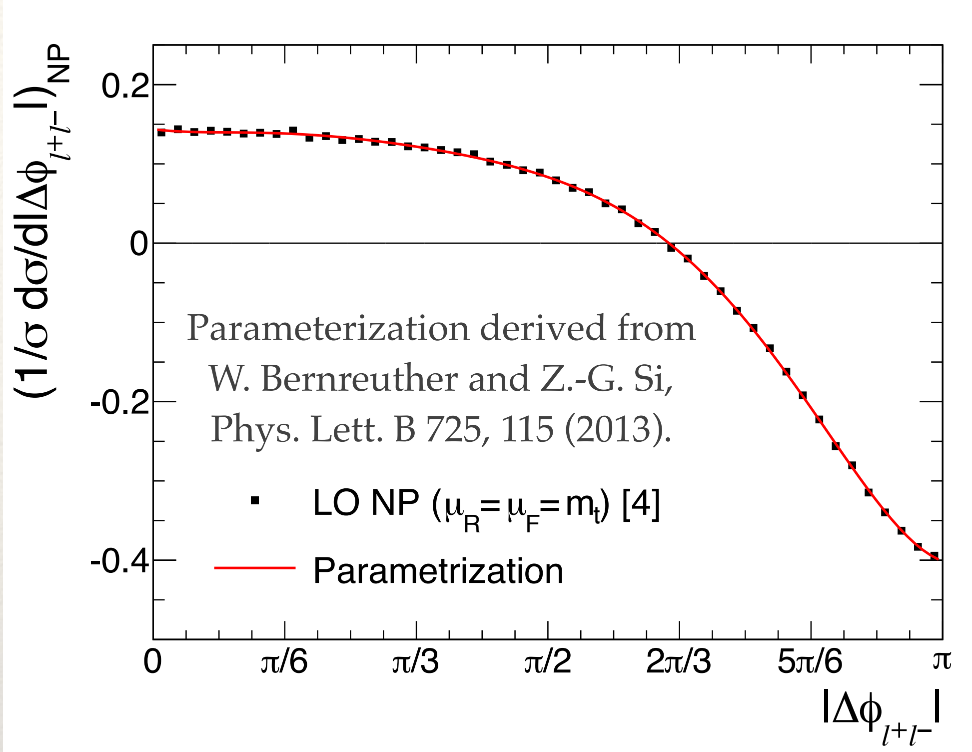
$$\delta\hat{\mu}_t = \frac{\sqrt{2}}{g_s}\text{Re}C^{33}_{uG\phi}\frac{vm_t}{\Lambda^2} \qquad \delta\hat{\mu}_t = \frac{\sqrt{2}}{g_s}\text{Re}C^{33}_{uG\phi}\frac{vm_t}{\Lambda^2}$$

Relation to Wilson coefficients

J.A. Aiguilar-Saveedra, Nucl.Phys.B812:181-204,2009

Re($\hat{\mu}$) & Im($\hat{d}$) from spin correlations (CMS)

$$\frac{1}{\sigma}\frac{d\sigma}{d|\Delta\phi_{\ell^+\ell^-}|} = \left(\frac{1}{\sigma}\frac{d\sigma}{d|\Delta\phi_{\ell^+\ell^-}|}\right)_{\mathrm{SM}} + \mathrm{Re}\left(\hat{\mu}_t\right)\left(\frac{1}{\sigma}\frac{d\sigma}{d|\Delta\phi_{\ell^+\ell^-}|}\right)_{\mathrm{NP}}$$



Fit to Re($\hat{\mu}_t$) assuming all other parameters have SM values ==>

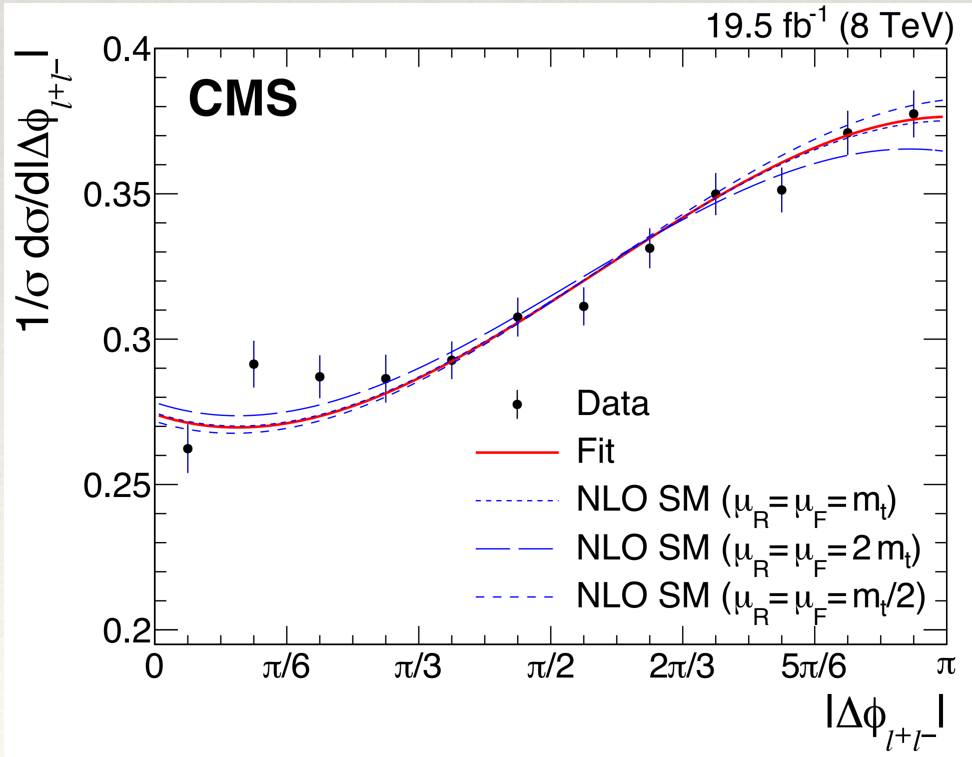
$-0.053 < \mathrm{Re}(\hat{\mu}_t) < 0.042$ (95%)

Using the asymmetry in cosϕ ==>

$-0.053 < \mathrm{Re}(\hat{\mu}_t) < 0.026$ (95%)

CP violation in $t\bar{t}$ production? From $A_{CPV}=A_{P+}-A_{P-}$

$-0.068 < \mathrm{Im}\,(\hat{d}_t) < 0.067$ (95%)

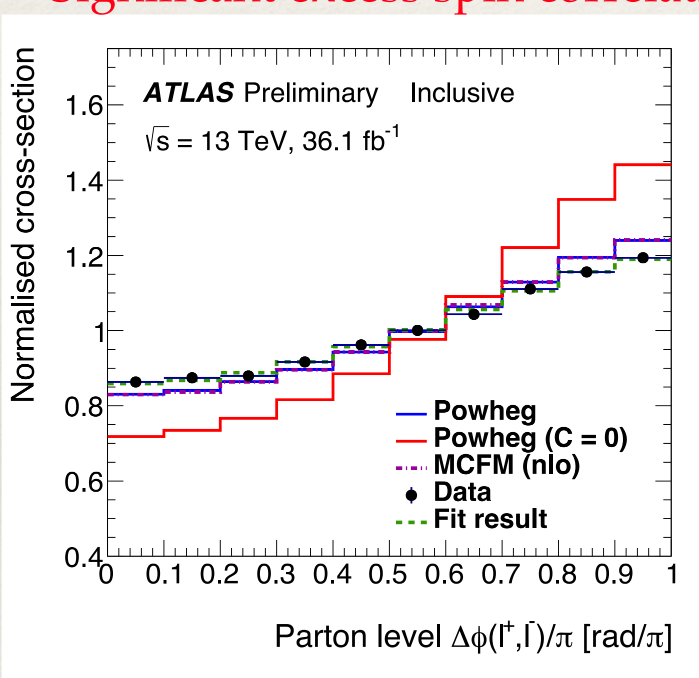


(Chromomagnetic moment is also constrained by differential cross section in CMS; see talk by Xin Chen in parallel session.)

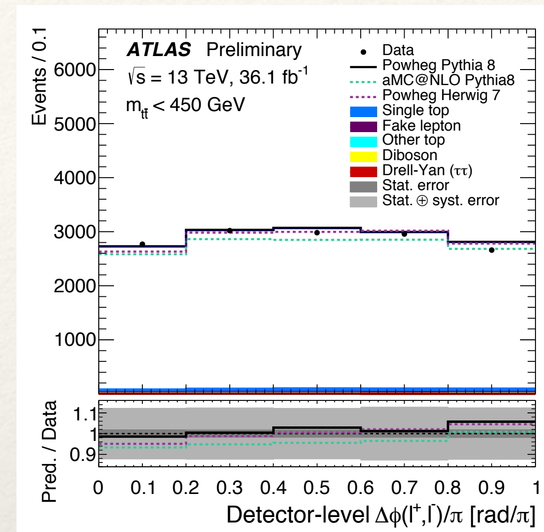
Latest word on spin correlations (ATLAS, 13 TeV)

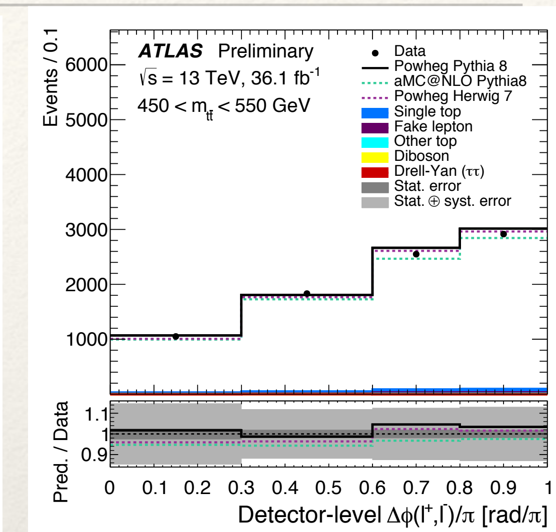
[ATLAS-CONF-2018-027]

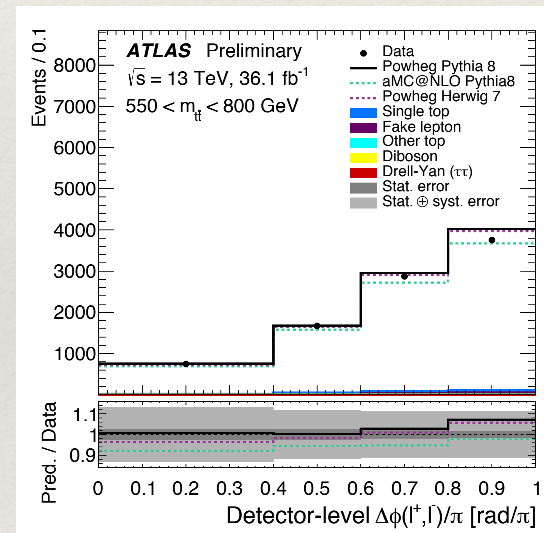
- Spin correlation in eμ channel.
- Δϕ distribution unfolded to parton level
- Absolute and normalized cross sections measured.
- f_{SM} from normalized cross section
- Signal modeling uncertainties dominant
- Significant excess spin correlation observed:

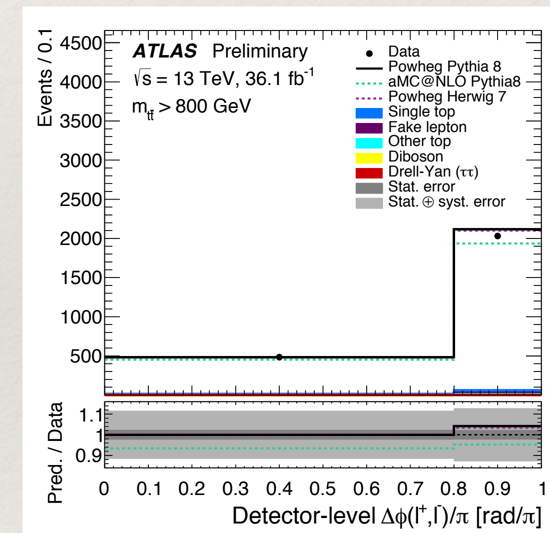


Excess spin correlation increases m(tt̄) but significance is limited by the sample size when divided into bins —>









Region	$f_{\rm SM}$	Significance (incl. theory uncertainties)
$m_{t\bar{t}} < 450$ GeV	$1.11 \pm 0.04 \pm 0.13$	0.85 (0.84)
$450 < m_{t\bar{t}} < 550$ GeV	$1.17 \pm 0.09 \pm 0.14$	1.00 (0.91)
$550 < m_{t\bar{t}} < 800$ GeV	$1.60 \pm 0.24 \pm 0.35$	1.43 (1.37)
$m_{t\bar{t}} > 800$ GeV	$2.2 \pm 1.8 \pm 2.3$	0.41 (0.40)
inclusive	$1.250 \pm 0.026 \pm 0.063$	3.70 (3.20)

The only hint so far of an anomaly in tt̄ production…

SUSY interpretation in progress

← *The trend was present in past measurements*

The Wtb vertex

The previous results are probes of the gtt vertex, assuming a SM Wtb vertex.

Experiment also can probe the Wtb vertex, as we will show in the next slides.

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

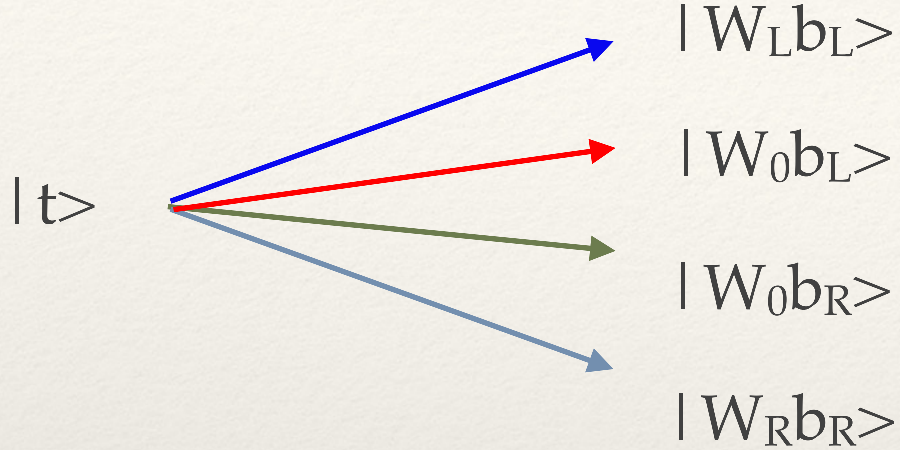
Language of anomalous couplings

$$\delta V_L = C_{\phi q}^{(3,33)*}\frac{v^2}{\Lambda^2} \qquad \delta g_L = \sqrt{2}C_{dW}^{33*}\frac{v^2}{\Lambda^2}$$

$$\delta V_R = \frac{1}{2}C_{\phi\phi}^{33}\frac{v^2}{\Lambda^2} \qquad \delta g_R = \sqrt{2}C_{uW}^{33}\frac{v^2}{\Lambda^2}$$

Language of effective field theory

W Boson Helicity Fractions

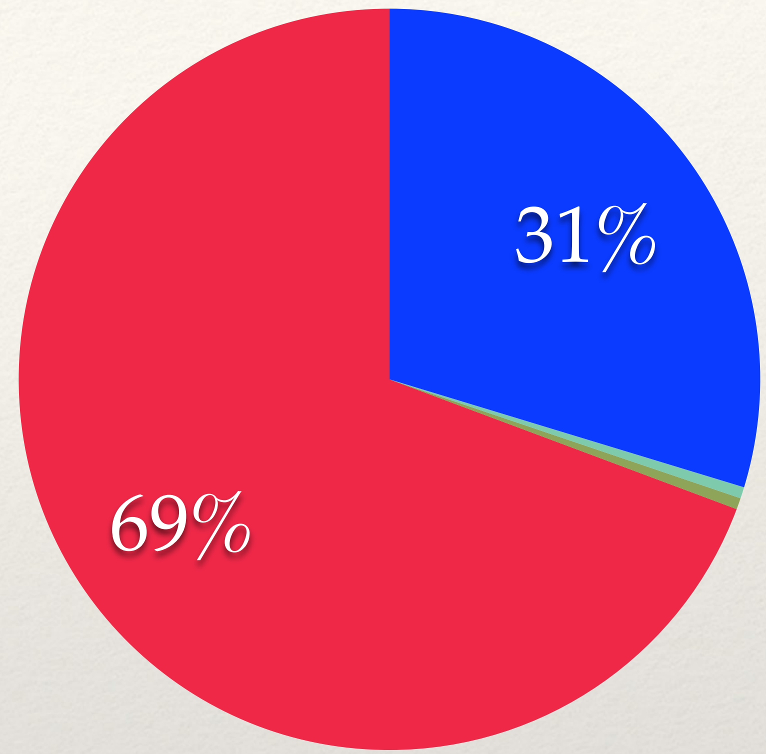


$F_L = 0.311(5)$

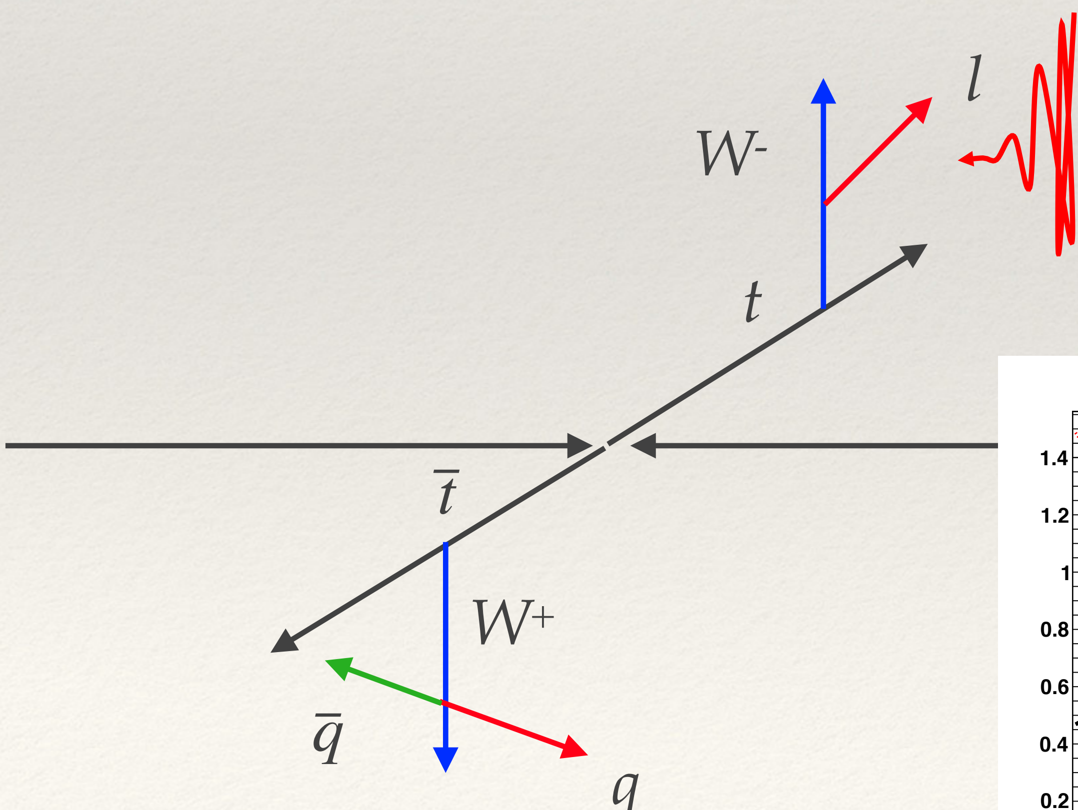
$F_0 = 0.687(5)$

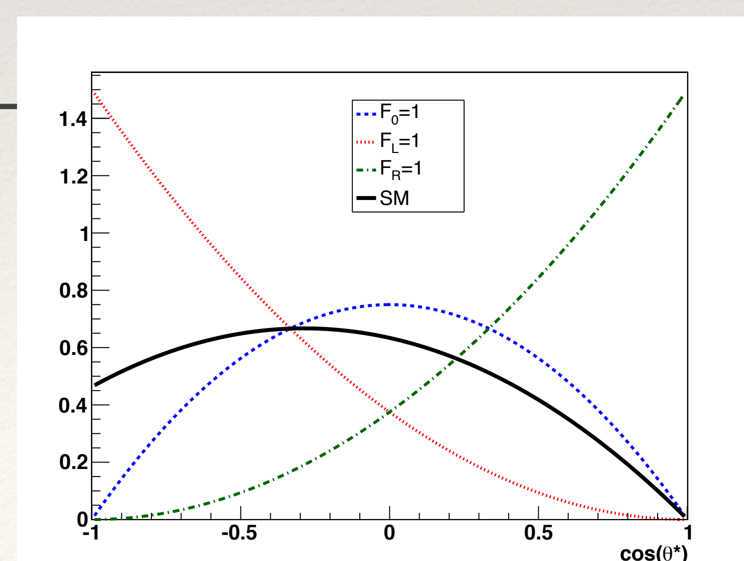
$F_R = 0.0017(1)$

(NNLO QCD) Phys. Rev. D **81**, 111503 (2010)



Helicity fractions are determined from an analysis of the angle θ* : angle between the W boson in the top quark frame and the charged lepton in the W frame.



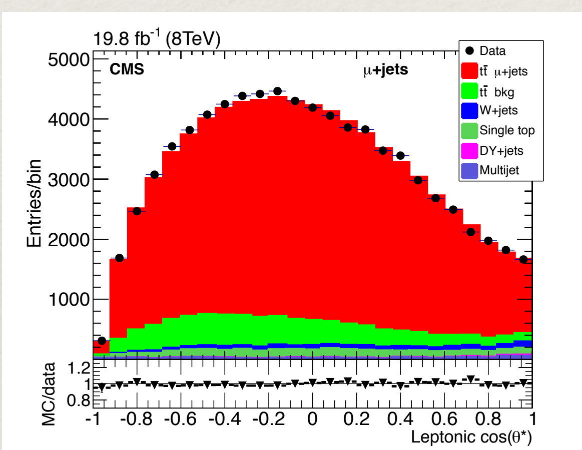


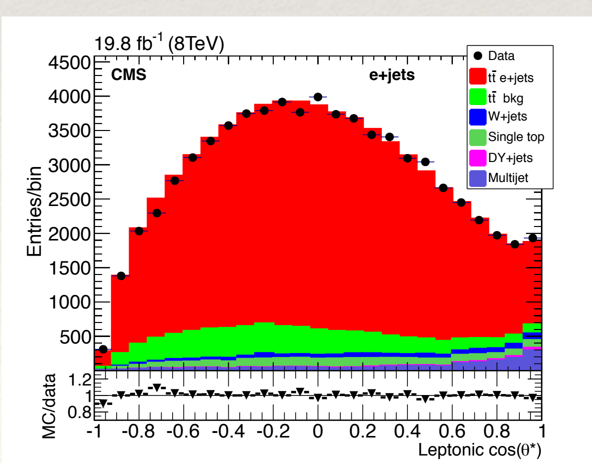
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{4}\left(\sin\theta^*\right)^2 F_0 + \frac{3}{8}(1+\cos\theta^*)^2 F_R$$

Helicity fractions from $t\bar{t}$ events (CMS)

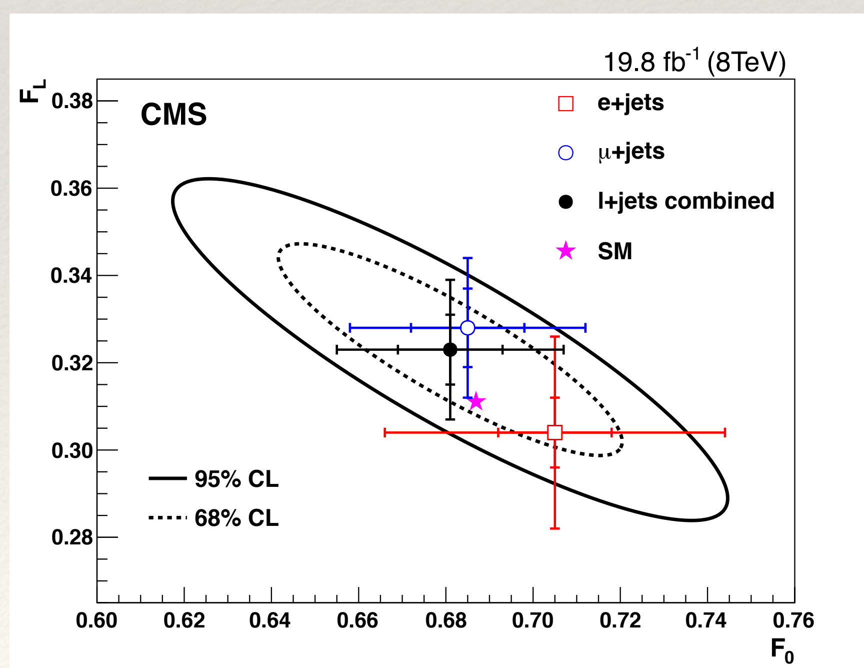
- Lepton+jet events
- Require 1 lepton (e or μ) + 4 jets events, two of which are b-tagged.
- Reconstruct neutrino momentum, $t\bar{t}$ system, angles θ* on hadronic and leptonic side
- Binned likelihood fit to θ* on leptonic side extracts helicity fractions.

Channel	F_0 ± (stat) ± (syst)	F_L ± (stat) ± (syst)	F_R ± (stat) ± (syst)	$\rho_{0,L}$
e+jets	0.705 ±0.013±0.037	0.304±0.009±0.020	−0.009 ± 0.005±0.021	−0.950
μ+jets	0.685 ±0.013±0.024	0.328±0.009±0.014	−0.013 ± 0.005±0.017	−0.957
ℓ+jets	0.681 ±0.012±0.023	0.323±0.008±0.014	−0.004 ± 0.005±0.014	−0.959

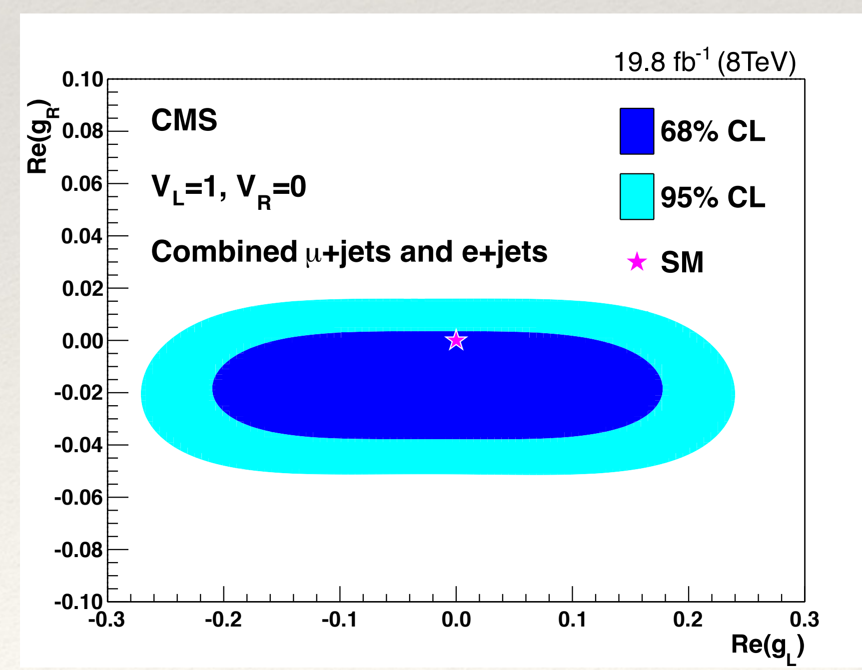




Helicity fractions



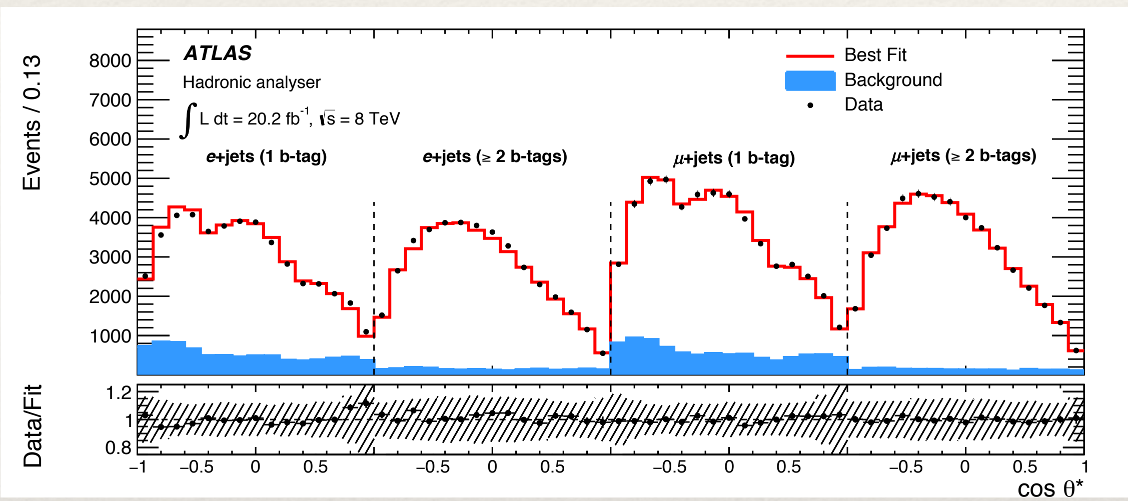
Anomalous couplings

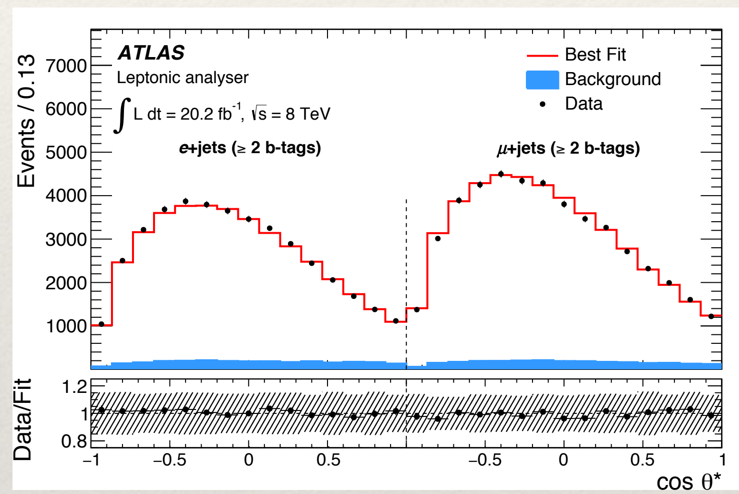


PLB 762 (2016) 512

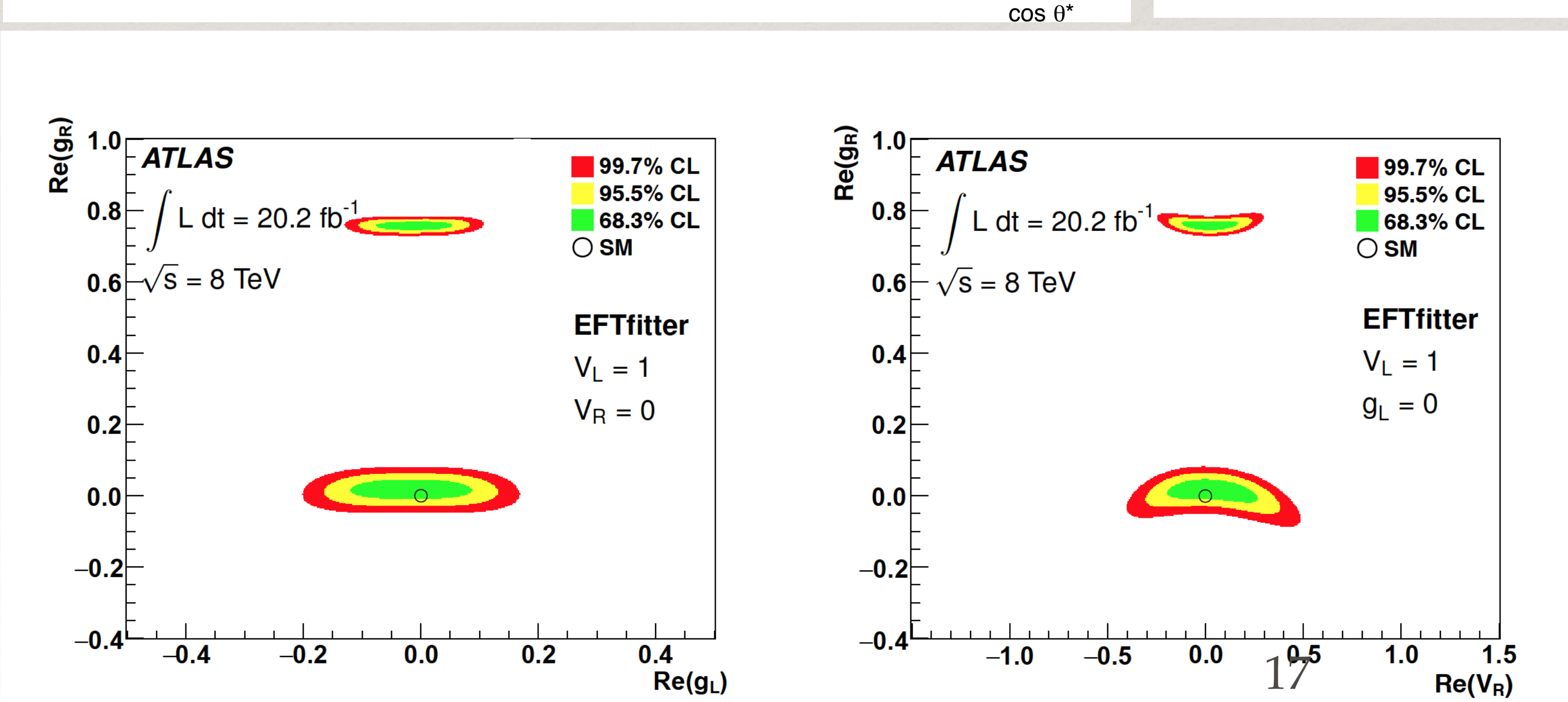
Helicity fractions from $t\bar{t}$ events (ATLAS)

- Lepton+jet events
- Require 1 lepton (e or μ) + 4 jets events, at least one of which are b-tagged.
- Kinematic fit (KLFitter, NIM A 748 18 2014) to reconstruct $t\bar{t}$ system
- Binned likelihood fit to θ* from both leptonic & hadronic side used
  - How is that possible? ==> b-tagging on the hadronic side to identify (anti)fermion from W decay!





EPJ 77 (2017) 264

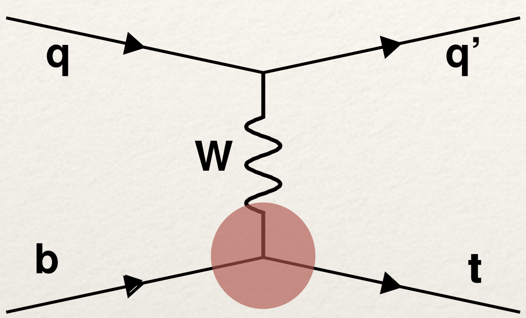


F_0=0.709±0.012 (stat+bkg.norm)±0.015 (syst)
F_L=0.299±0.008 (stat+bkg.norm)±0.013 (syst)
F_R=-0.008±0.006 (stat+bkg.norm)±0.012 (syst)

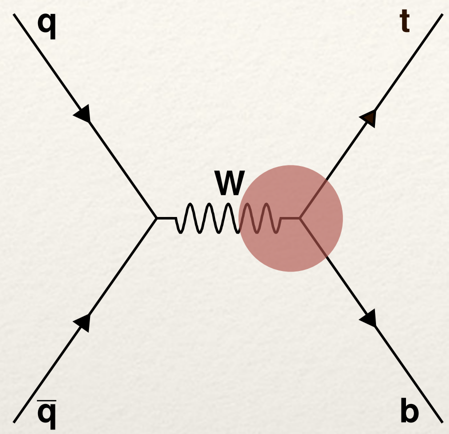
Jet reconstruction and signal modeling dominant systematic errors.

Single top processes and the Wtb vertex

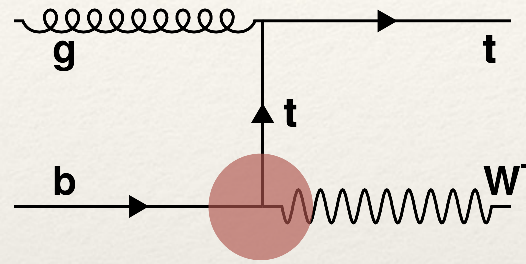
t-channel



s-channel

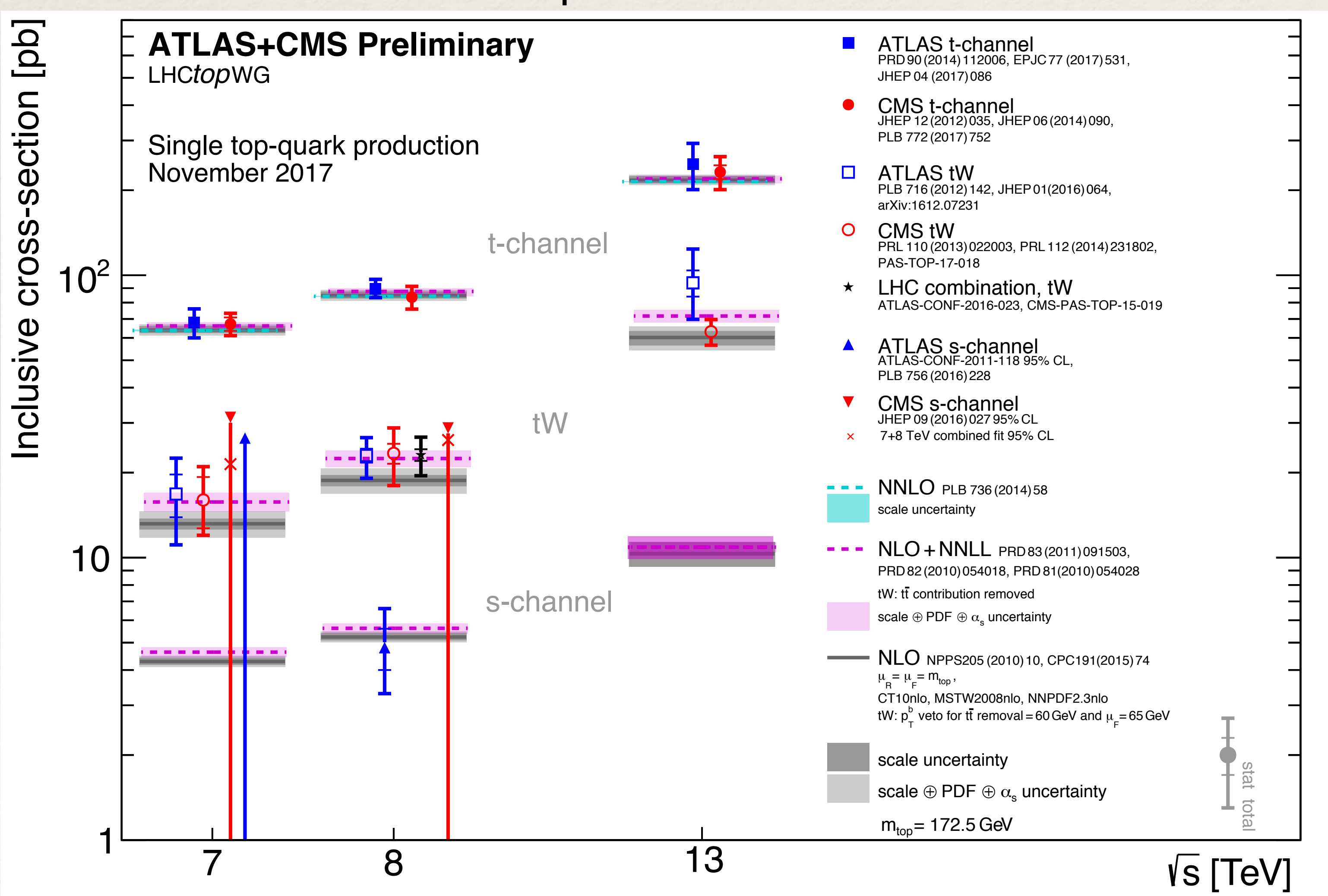


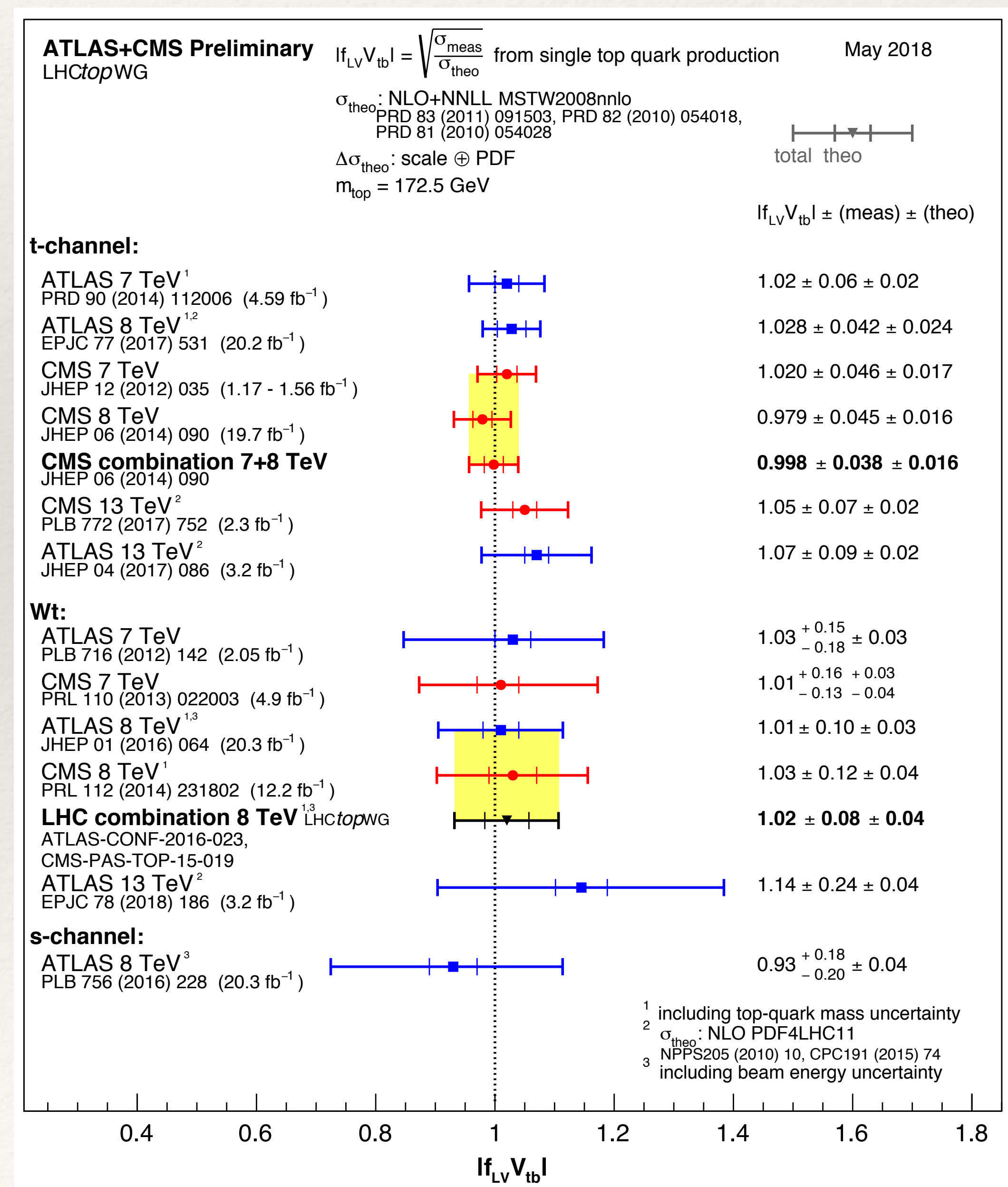
tW-channel



The Wtb vertex occurs both at production and decay in all single top processes. Direct measurement of $|V_{tb}|$

All consistent with SM value $|V_{tb}|=1$





Helicity fraction measurements in single top t-channel

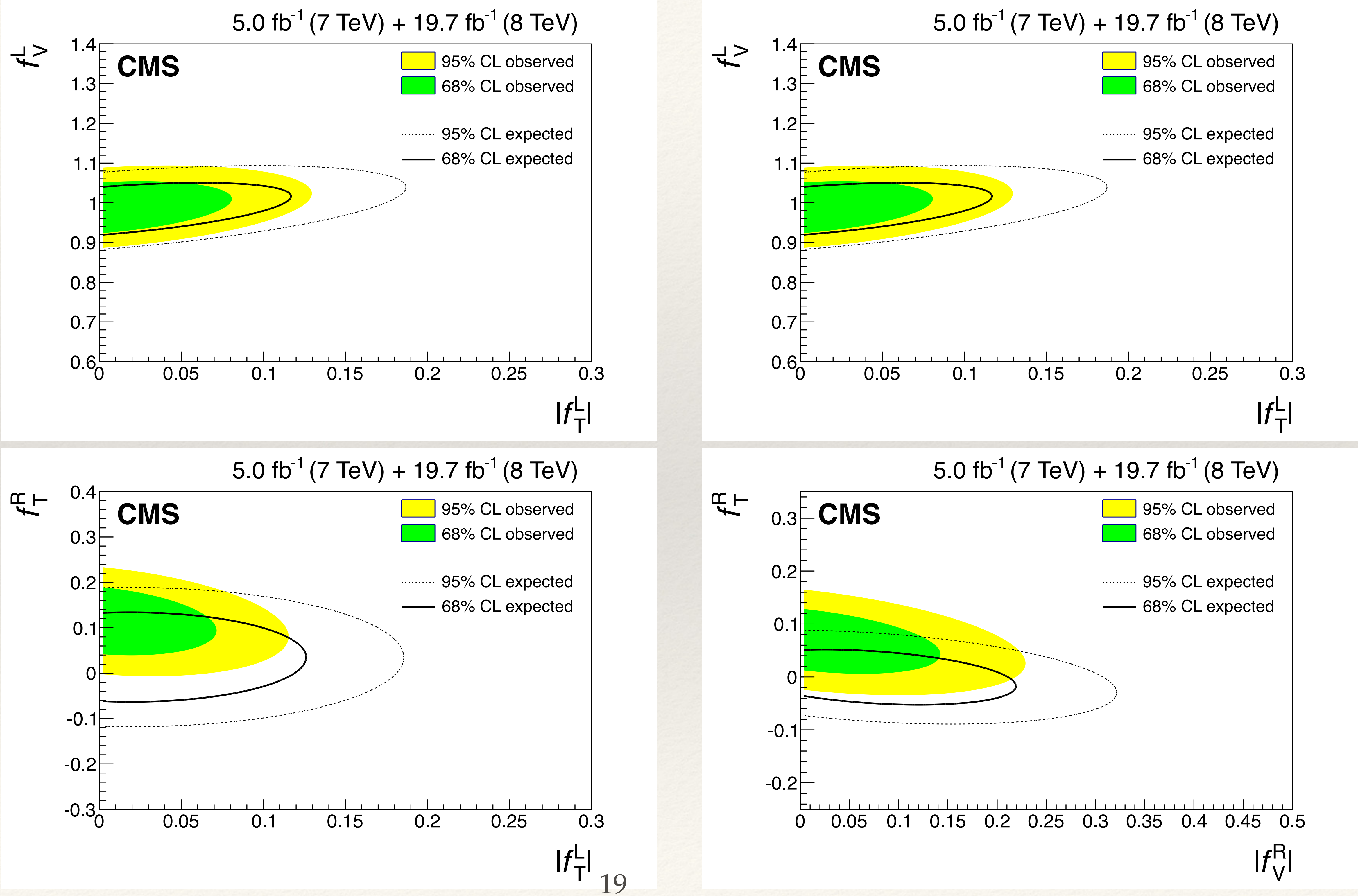
JHEP 02 (2017) 028

$f^L_V = V_L$

$f^R_V = V_R$

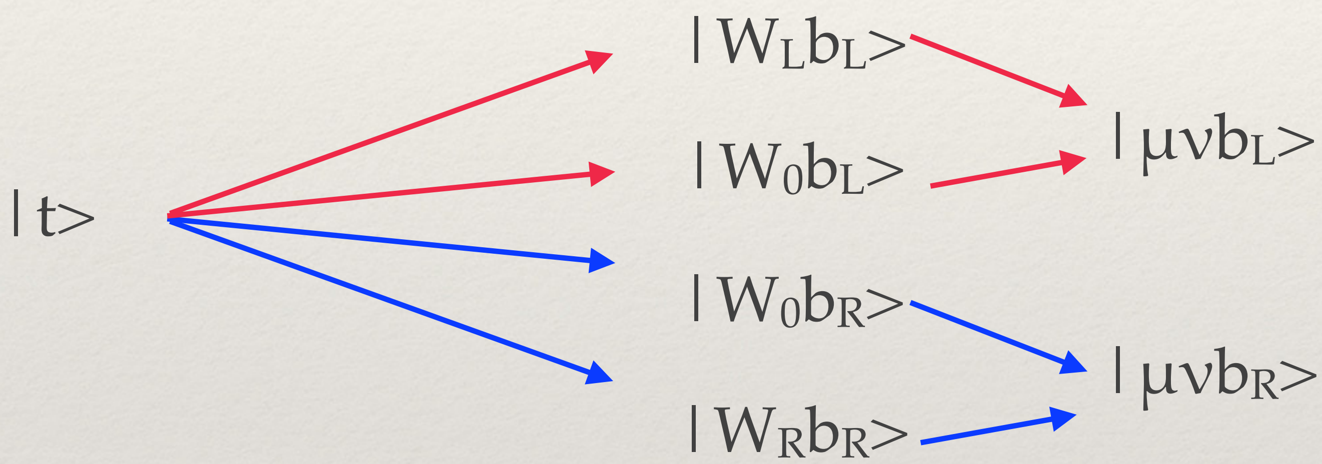
$f^R_T = g_R$

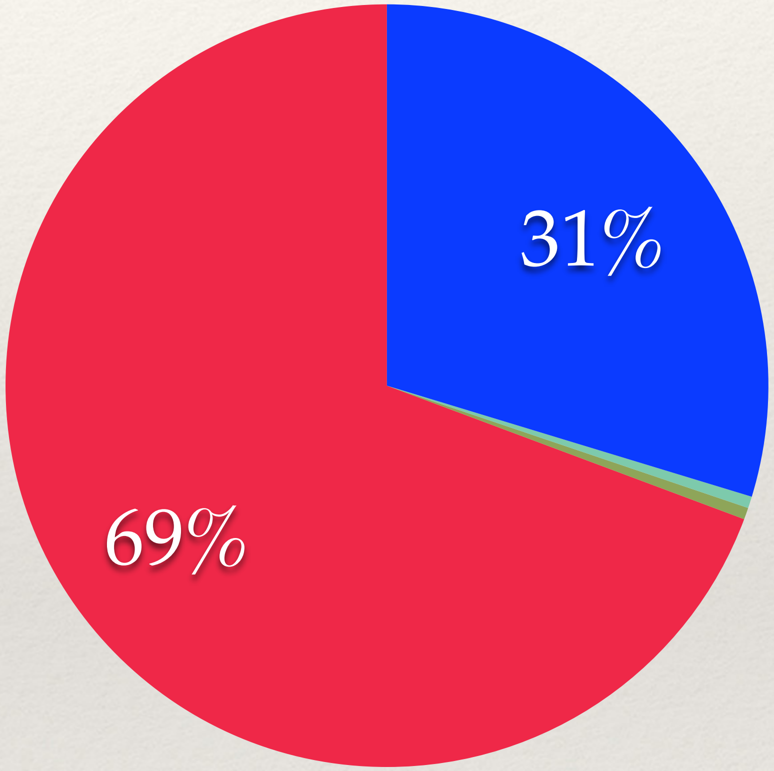
$f^L_T = g_L$



Beyond helicity fractions in single top t-channel

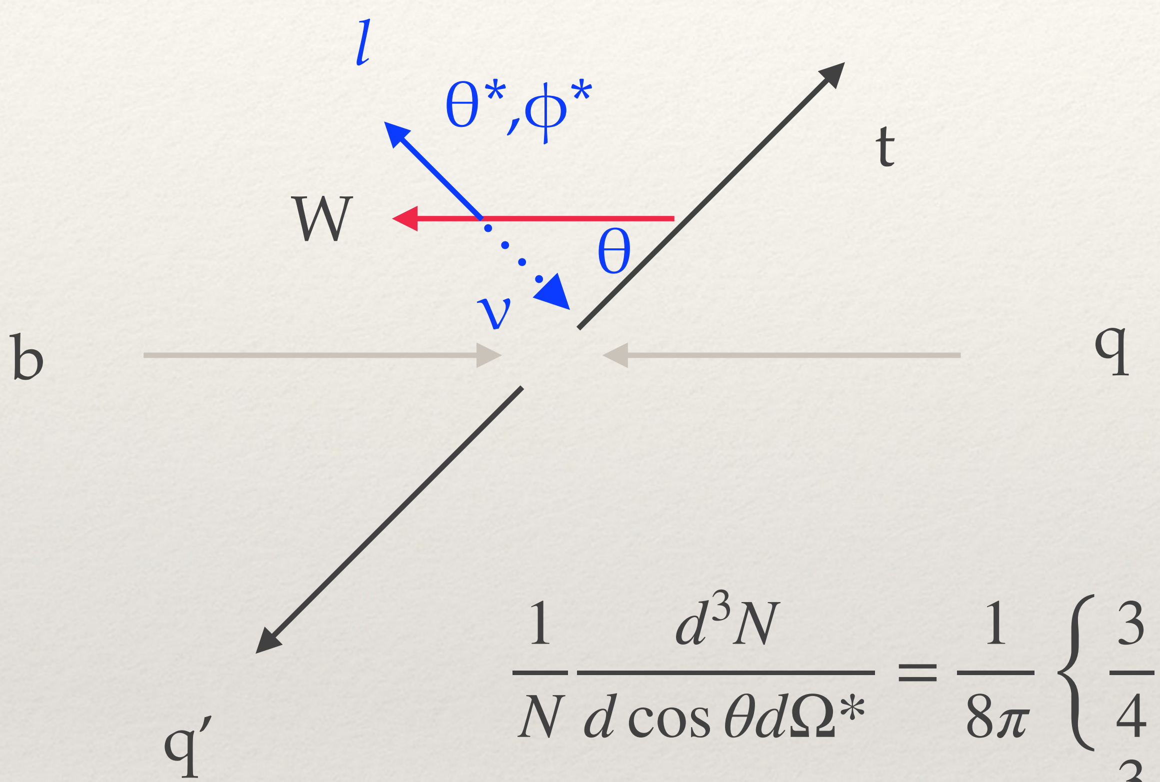
Single top t-channel events have high (~90%) polarization along the spectator quark direction to the V-A structure of the weak interaction. This makes possible a unique set of measurements





Helicity fraction measurements determine the relative strength of three categories (L,R, 0). One can also separate four categories and determine a relative phase. From there go to constraints on V_R, g_L, g_R

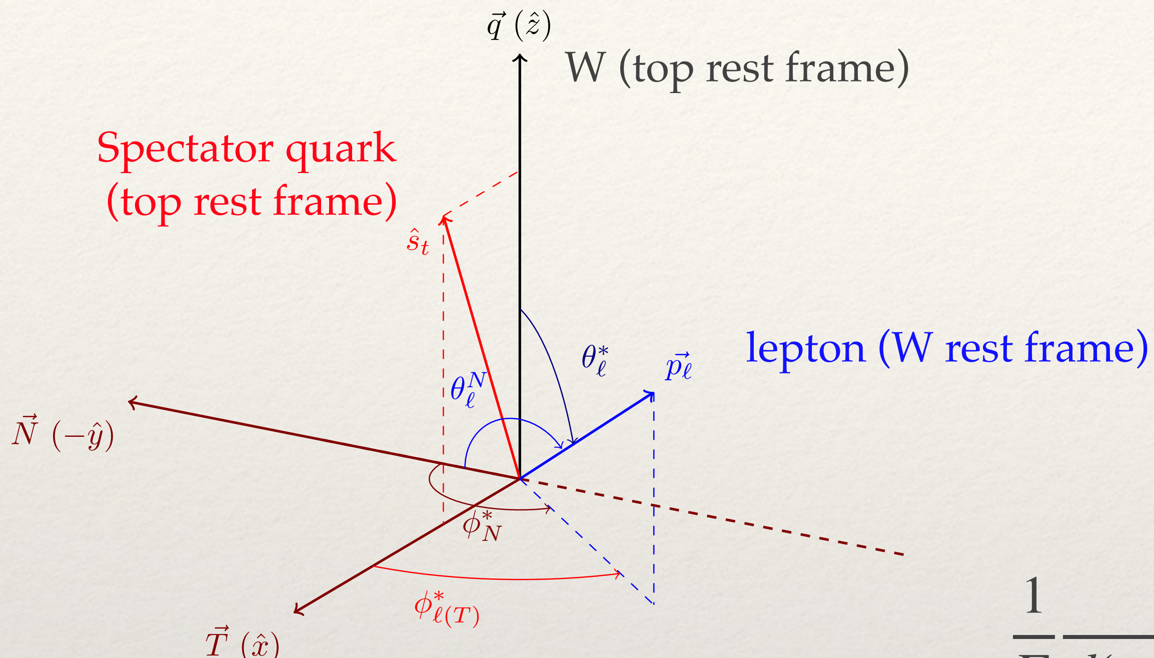
Decay kinematics depend on 3 angles.



θ: t decay polar angle
θ: W decay polar angle
ϕ*: W decay azimuthal angle

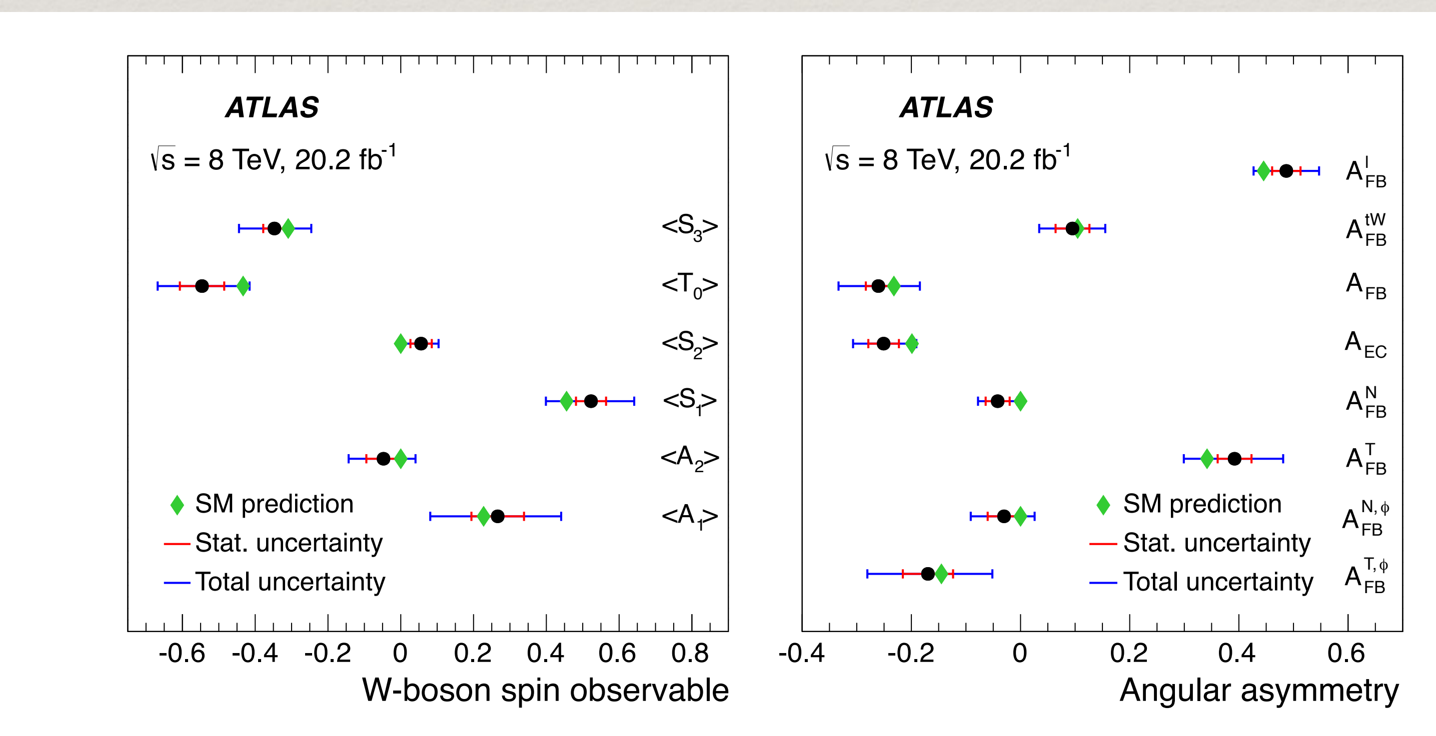
$$
\begin{aligned}
\frac{1}{N}\frac{d^3N}{d\cos\theta d\Omega^*} = \frac{1}{8\pi}\Bigg\{ &\frac{3}{4}|A_{1,\frac{1}{2}}|^2(1+P\cos\theta)(1+\cos\theta^*)^2 \\
&+\frac{3}{4}|A_{-1,-\frac{1}{2}}|^2(1-P\cos\theta)(1-\cos\theta^*)^2 \\
&+\frac{3}{2}\Big(|A_{0,\frac{1}{2}}|^2(1-P\cos\theta)+|A_{0,-\frac{1}{2}}|^2(1+P\cos\theta)\Big)\sin^2\theta^* \\
&-\frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*(1+\cos\theta^*)\,\mathrm{Re}\left[e^{i\phi^*}A_{1,\frac{1}{2}}A^*_{0,\frac{1}{2}}\right] \\
&-\frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*(1-\cos\theta^*)\,\mathrm{Re}\left[e^{-i\phi^*}A_{-1,-\frac{1}{2}}A^*_{0,-\frac{1}{2}}\right]
\end{aligned}
$$

Asymmetries in single top t-channel



Asymmetry	Angular observable	Polarisation observable	SM prediction
A_{FB}^{ℓ}	$\cos\theta_\ell$	$\frac{1}{2}\alpha_\ell P$	0.45
A_{FB}^{tW}	$\cos\theta_W \cos\theta_\ell^*$	$\frac{3}{8}P(F_R+F_L)$	0.10
A_{FB}	$\cos\theta_\ell^*$	$\frac{3}{4}\langle S_3\rangle = \frac{3}{4}(F_R - F_L)$	-0.23
A_{EC}	$\cos\theta_\ell^*$	$\frac{3}{8}\sqrt{\frac{3}{2}}\langle T_0\rangle = \frac{3}{16}(1-3F_0)$	-0.20
A_{FB}^{T}	$\cos\theta_\ell^T$	$\frac{3}{4}\langle S_1\rangle$	0.34
A_{FB}^{N}	$\cos\theta_\ell^N$	$-\frac{3}{4}\langle S_2\rangle$	0
$A_{FB}^{T,\phi}$	$\cos\theta_\ell^* \cos\phi_T^*$	$-\frac{2}{\pi}\langle A_1\rangle$	-0.14
$A_{FB}^{N,\phi}$	$\cos\theta_\ell^* \cos\phi_N^*$	$\frac{2}{\pi}\langle A_2\rangle$	0

$$\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_\ell^*)d\phi_\ell^*} = \frac{3}{8\pi}\Bigg\{\frac{2}{3} + \frac{1}{\sqrt{6}}\langle T_0\rangle\Big(3\cos^2\theta_\ell^* - 1\Big) + \langle S_3\rangle\cos\theta_\ell^*$$
$$+\langle S_1\rangle\cos\phi_\ell^*\sin\theta_\ell^* + \langle S_2\rangle\sin\phi_\ell^*\sin\theta_\ell^*$$
$$-\langle A_1\rangle\cos\phi_\ell^*\sin 2\theta_\ell^* - \langle A_2\rangle\sin\phi_\ell^*\sin 2\theta_\ell^*\Bigg\}$$



Multiple angular asymmetries measured.
All consistent with SM.
CP violation parameter:

$$\mathrm{Im}(g_R) \in [-0.18, 0.06] \qquad 95\%\text{C.L.}$$

If all other anomalous couplings zero and VL=1

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Series of analyses from ATLAS

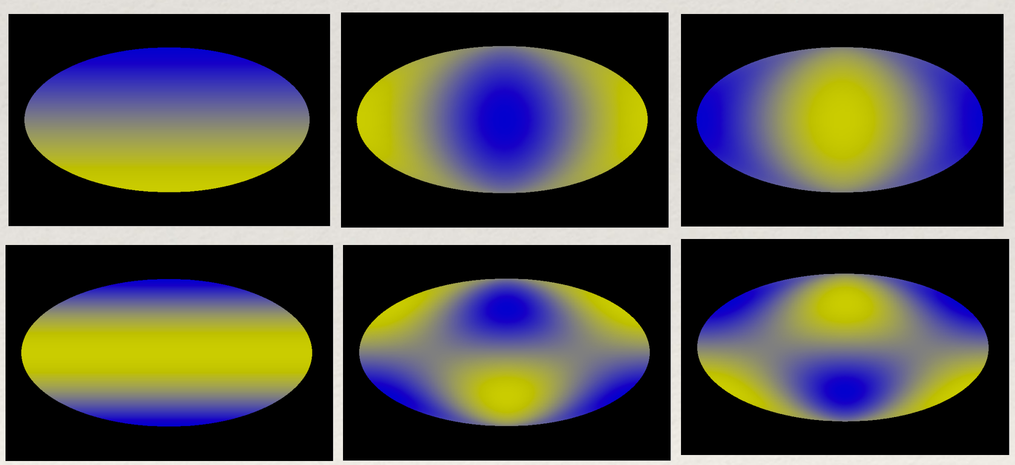
Double [JHEP 04 (2016) 023] and triple [JHEP 12 (2017) 017] differential decay rates.

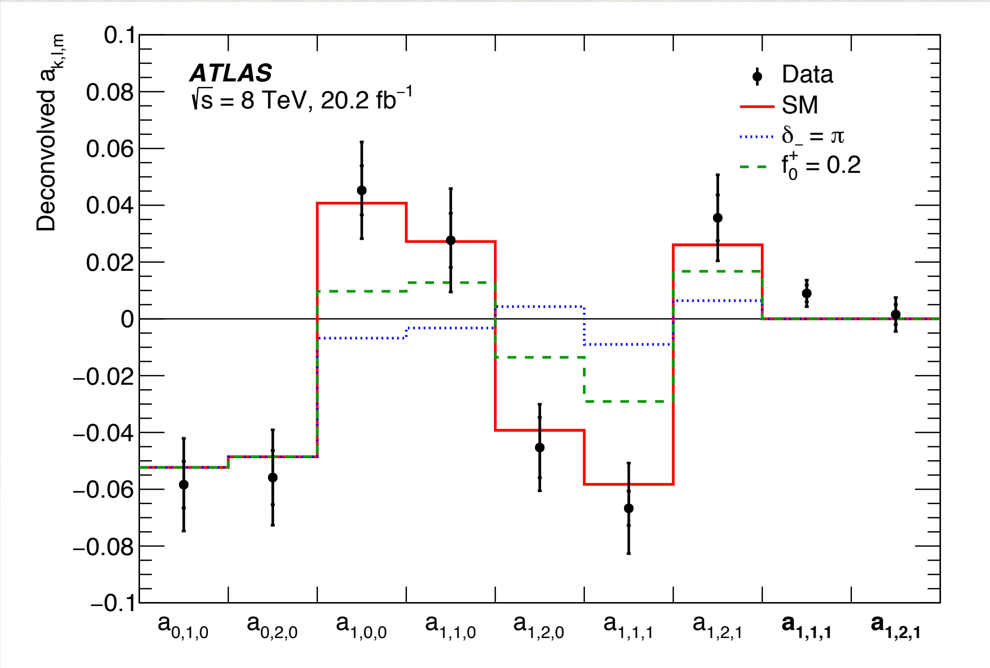
Triple differential cross section:

$$\rho(\theta, \theta^*, \phi^*) \equiv \frac{1}{\Gamma}\frac{d\Gamma}{d\Omega_3} = a^m_{k,l} M^m_{k,l}(\theta, \theta^*, \phi^*)$$

$$M^m_{k,l}(\theta_1, \theta_2, \phi) = \sqrt{2\pi}\, Y^m_k(\theta_1, 0) Y^m_l(\theta_2, \phi) = \sqrt{2\pi}\, Y^m_k(\theta_1, \phi) Y^m_l(\theta_2, 0)$$

Decompose the differential decay rate into orthogonal functions and perform Fourier analysis.





[JHEP 12 (2017) 017]

Use Fourier techniques to deconvolve the detector.

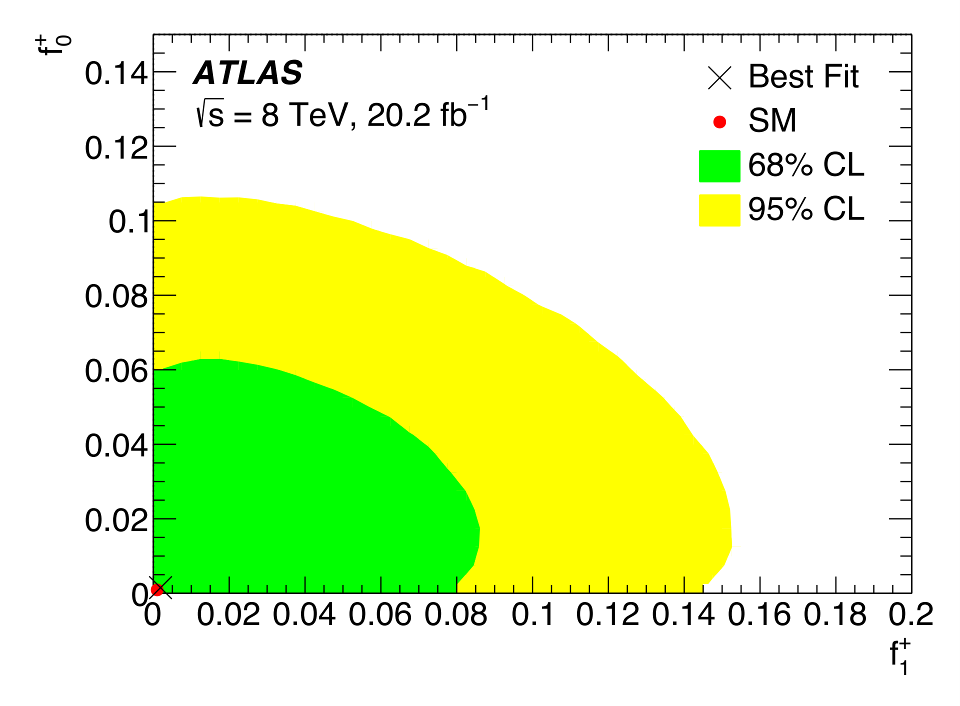
Helicity fractions & phases with *no assumptions on other parameters*

f_0^+: the fraction of b's which are right-handed in events with longitudinal W's

$f_0^+ < 0.041$ (68% CL)
$f_0^+ < 0.085$ (95% CL) *unique measurement*

f_1^+: the fraction of b's which are right-handed in events with transverse W's.

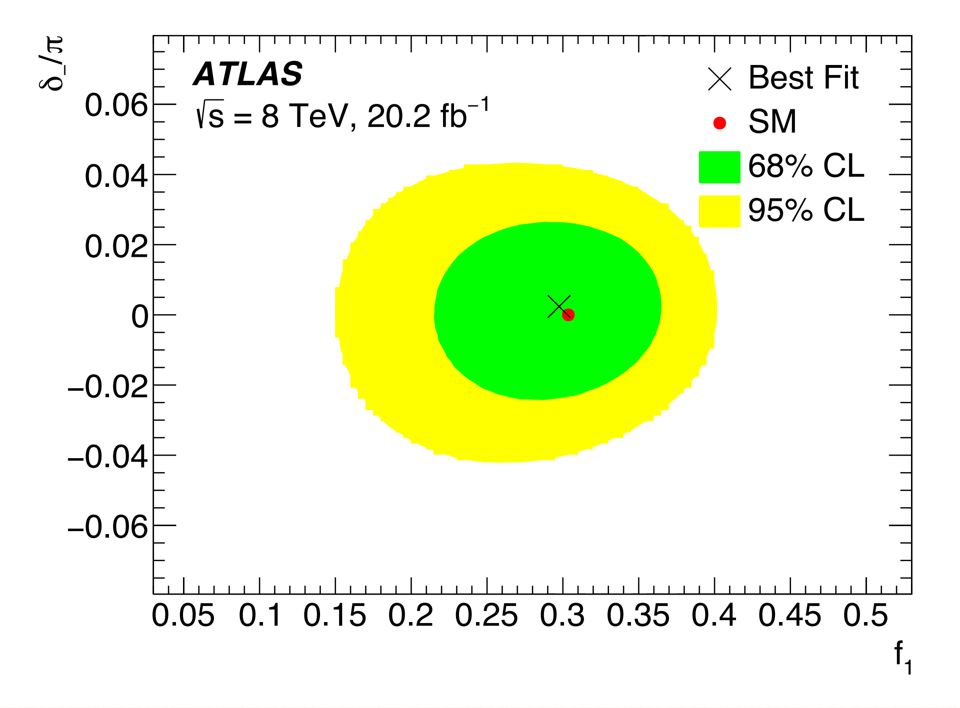
$f_1^+ < 0.053$ (68% CL)
$f_1^+ < 0.120$ (95% CL)



$f_1 = 1 - F_L$: Also measured in standard W boson polarization analyses.

δ_-: If nonzero, could signify CP violation in top quark decay.

$$f_1 = 0.296^{+0.020}_{-0.023}\,(\text{stat.})\,{}^{+0.043}_{-0.046}\,(\text{syst.}) = 0.296^{+0.048}_{-0.051}\,,$$
$$\delta_- = 0.002\pi^{+0.013\pi}_{-0.014\pi}\,(\text{stat.})\,{}^{+0.010\pi}_{-0.011\pi}\,(\text{syst.}) = 0.002\pi^{+0.016\pi}_{-0.017\pi}\,.$$



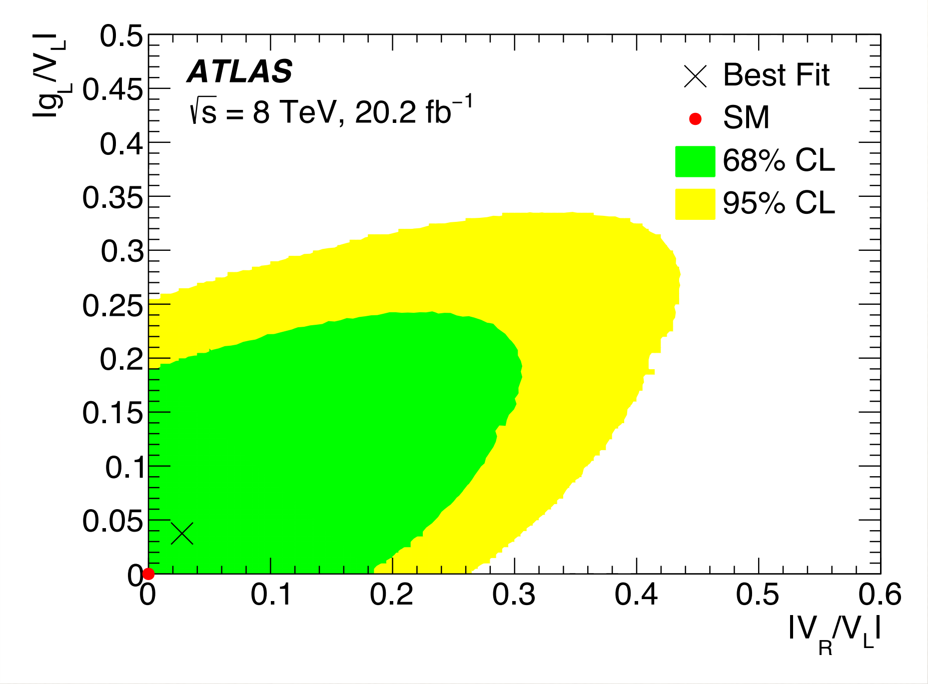
[JHEP 12 (2017) 017]

Anomalous couplings with *no assumptions on other parameters.*

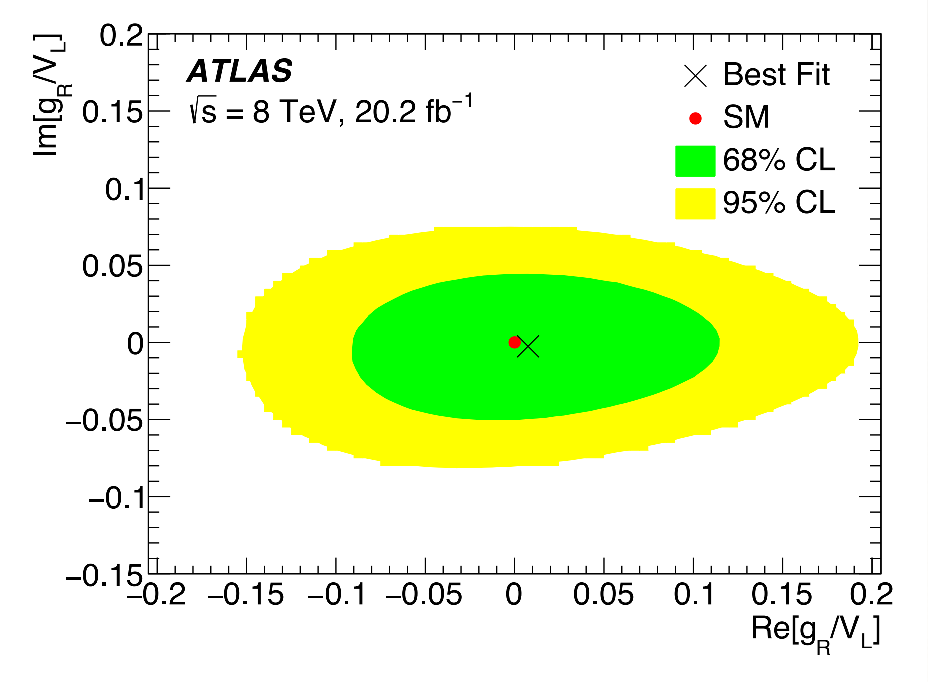
- $|V_R/V_L| < 0.23$ (68% CL)
- $|V_R/V_L| < 0.37$ (95% CL)

- $|g_L/V_L| < 0.19$ (68% CL)
- $|g_L/V_L| < 0.29$ (95% CL)

- Tighter limits exist from $b \to s\gamma$ and from W helicity fractions in $t\bar{t}$ events, but with assumptions on other parameters.



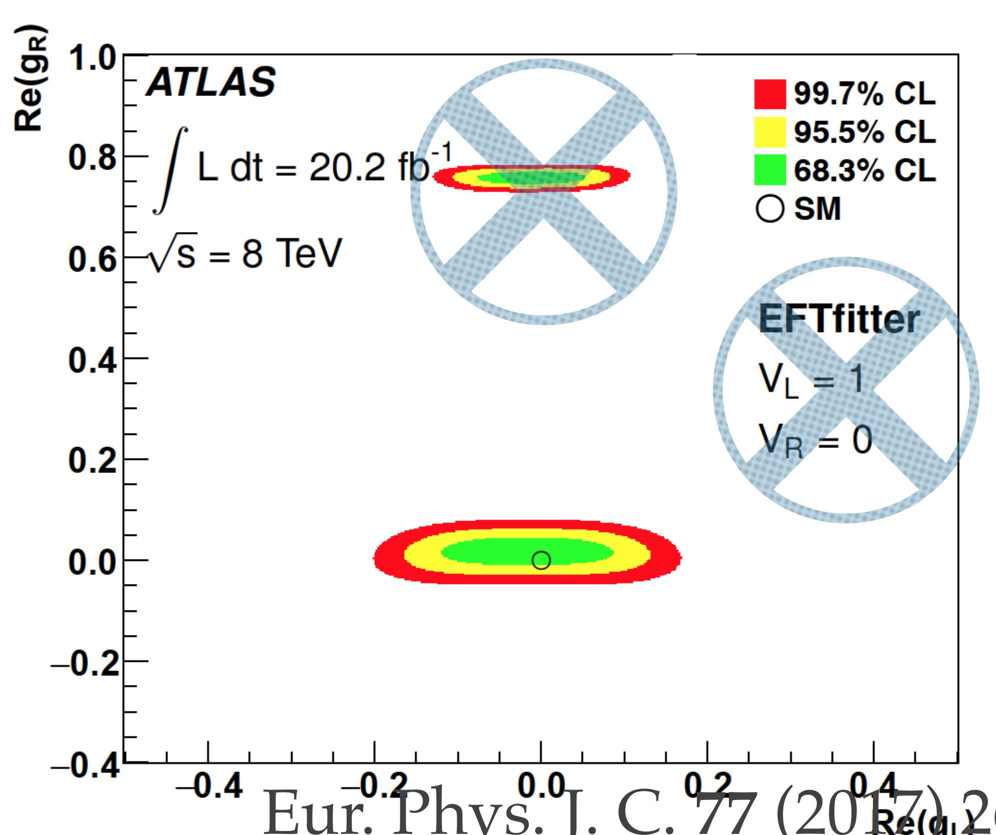
$$\mathrm{Re}\left[\frac{g_R}{V_L}\right] \in [-0.12, 0.17] \quad \text{and} \quad \mathrm{Im}\left[\frac{g_R}{V_L}\right] \in [-0.07, 0.06]\,.$$



[JHEP 12 (2017) 017]

Triple-differential decay rate removes ambiguity from W-boson helicity fraction measurements in $t\bar{t}$ events:

The triple differential decay rate measurement [JHEP 12 (2017) 017] eliminates the secondary, BSM solution of the standard helicity fraction measurement and does so without assumptions on any parameters of the Wtb vertex.



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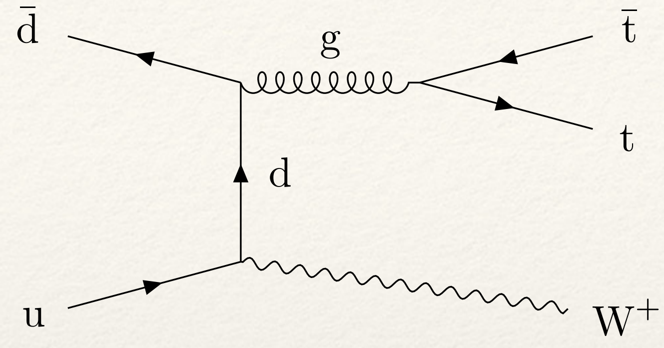
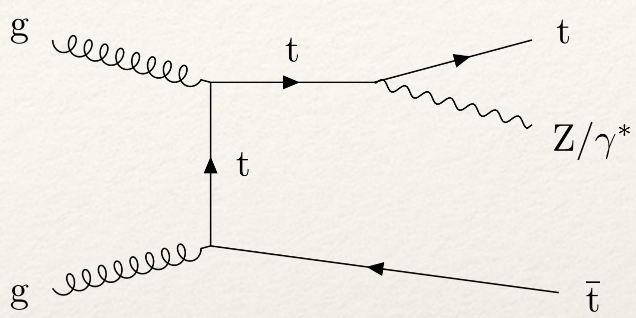
Sources of systematic error:

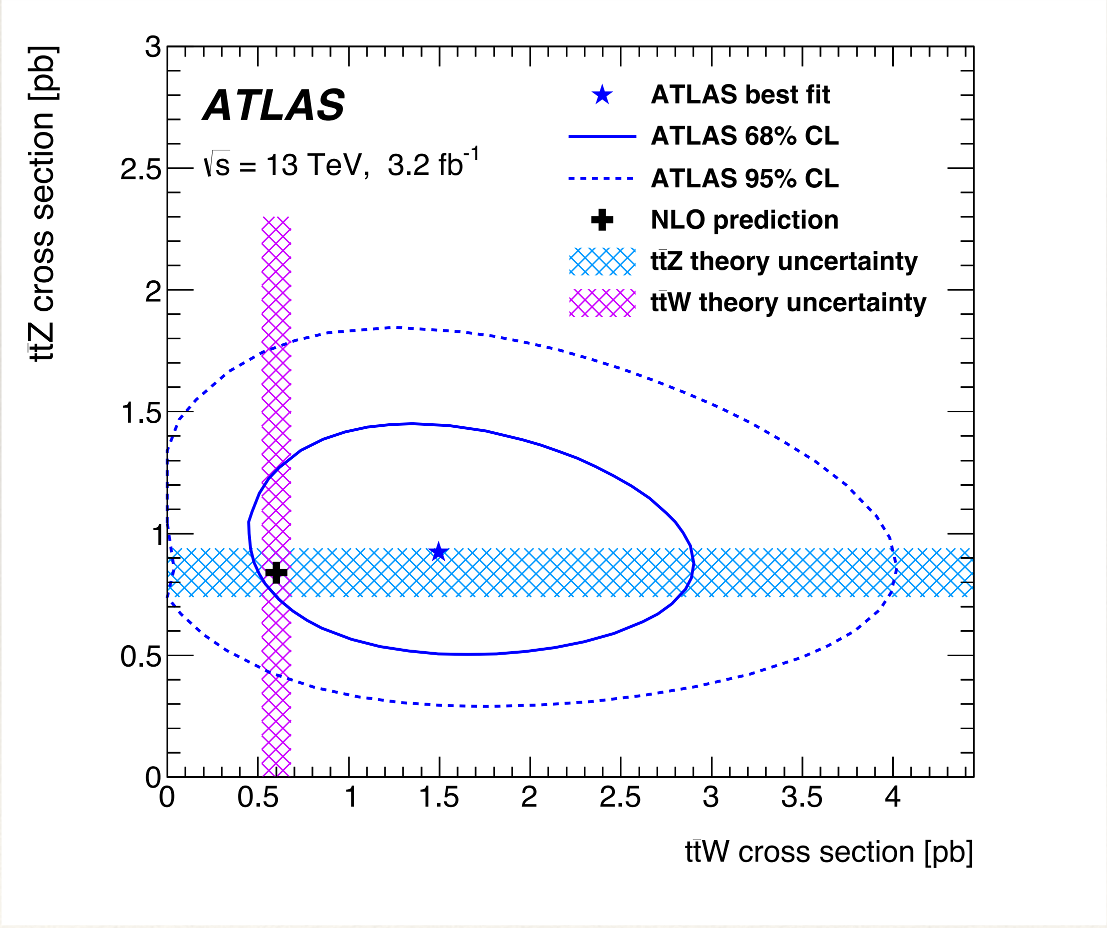
Source	Helicity parameters		Coupling ratios	
	$\sigma(f_1)$	$\sigma(\delta_-)/\pi$	$\sigma(\mathrm{Re}\,[g_R/V_L])$	$\sigma(\mathrm{Im}\,[g_R/V_L])$
Statistical	0.022	0.013	0.030	0.027
Jets	0.029	0.007	0.039	0.009
Leptons	0.014	0.002	0.017	<0.001
E_T^{miss}	<0.001	<0.001	<0.001	<0.001
Generator	0.027	0.006	0.030	0.010
Parton shower and hadronisation	0.004	0.003	<0.001	0.003
PDF variations	0.008	0.004	<0.001	<0.001
Background normalisation	<0.001	<0.001	<0.001	<0.001
Multijet normalisation	<0.001	<0.001	<0.001	<0.001
W+jets shape	0.015	0.005	0.007	0.009
Luminosity	<0.001	<0.001	<0.001	<0.001
MC sample sizes	0.009	0.006	<0.001	0.013
Other	<0.001	<0.001	<0.001	<0.001
Total systematic uncertainty	0.044	0.010	0.061	0.017
Total	0.049	0.017	0.068	0.032

New information on the ttZ, ttW± interactions

Signal:
dilepton (ttW)
trilepton, 4-lepton (ttZ)







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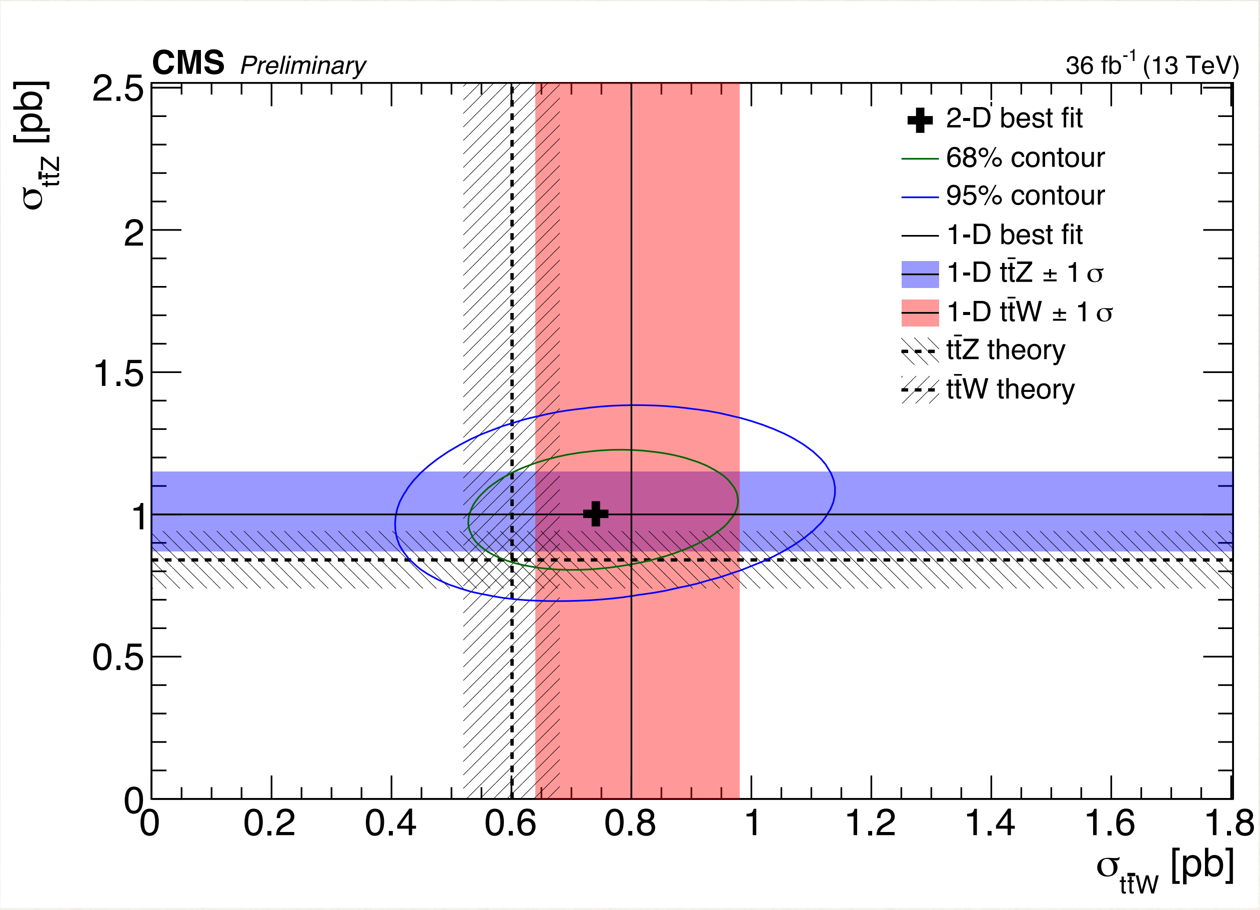
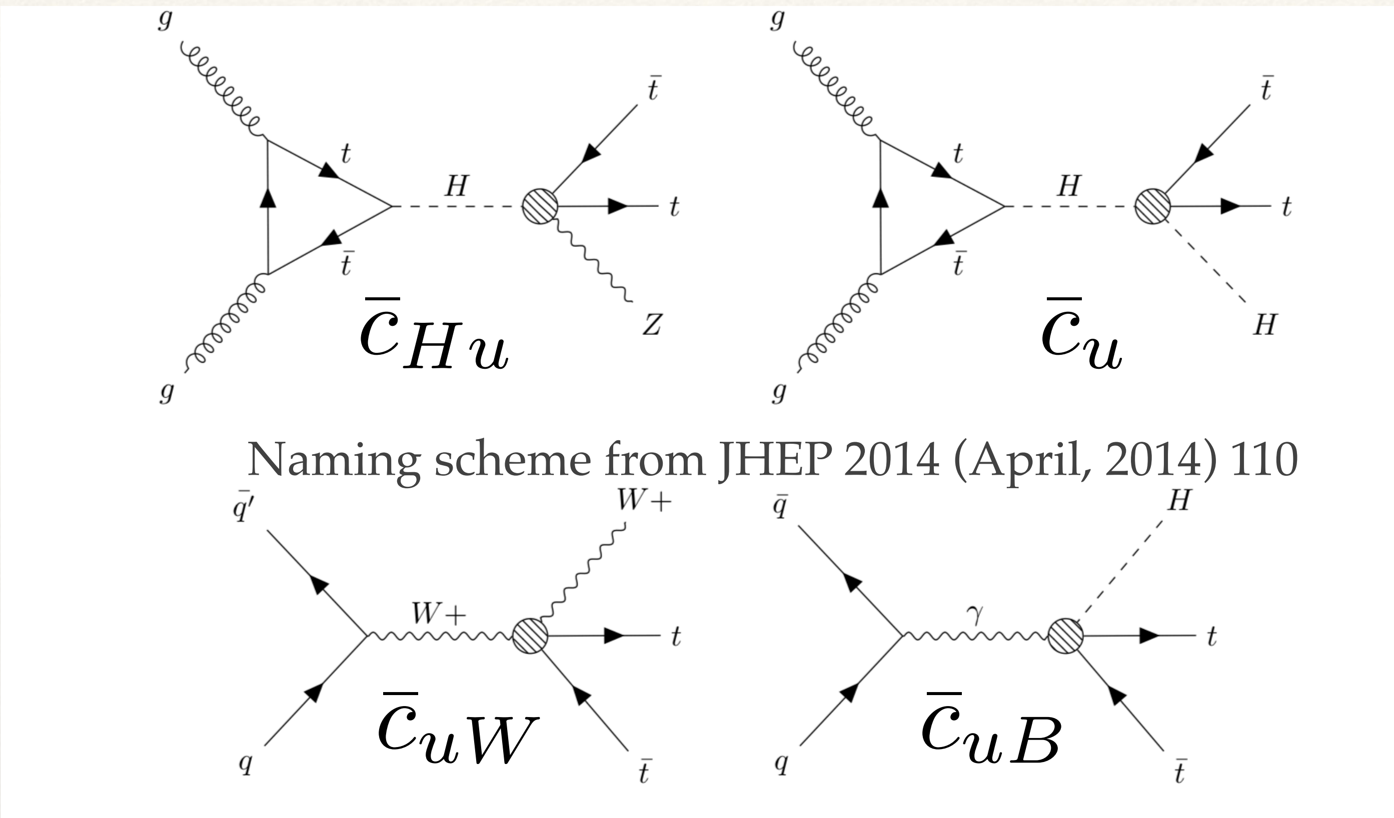
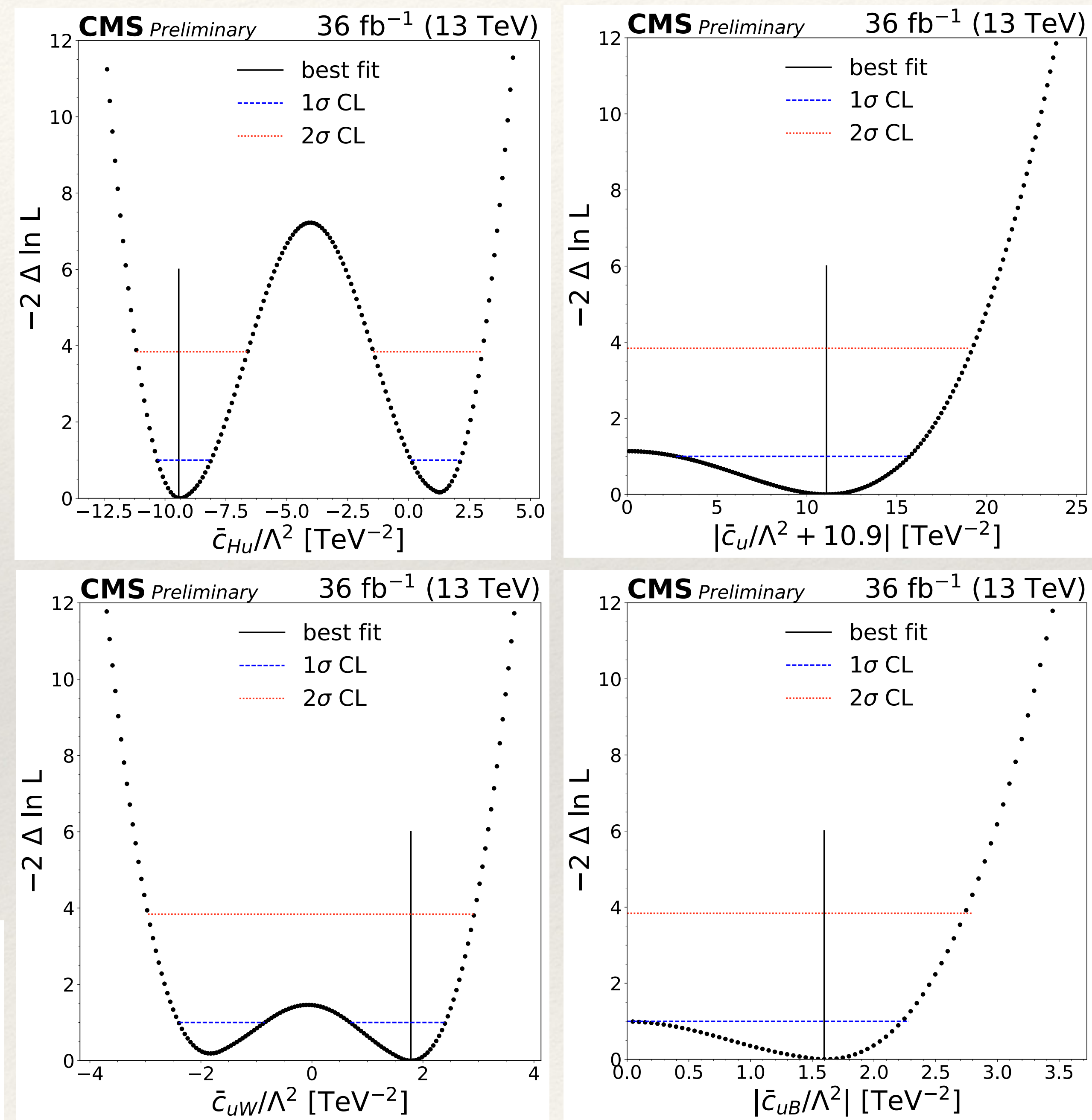


CMS-PAS-TOP-17-005

CMS ttZ & ttW analysis



Naming scheme from JHEP 2014 (April, 2014) 110



CMS-PAS-TOP-17-005

Wilson coefficient	Best fit [TeV^{-2}]	1σ CL [TeV^{-2}]	2σ CL [TeV^{-2}]
$\lvert\bar{c}_{uB}/\Lambda^2 + 0.1\,\text{TeV}^{-2}\rvert$	3.2	[0.0, 4.4]	[0.0, 5.4]
$\lvert\bar{c}_{u}/\Lambda^2 + 18.5\,\text{TeV}^{-2}\rvert$	19.1	[5.0, 26.4]	[0.0, 32.5]
$\bar{c}_{uW}/\Lambda^2$	3.0	[-4.1, -1.5] and [1.2, 4.1]	[-5.1, 5.0]
$\bar{c}_{Hu}/\Lambda^2$	-9.4	[-10.3, -8.1] and [0.1, 2.1]	[-11.1, -6.6] and [-1.4, 3.0]

Discussed in more detail in the talk of Olga Bylund in parallel session

(Likelihood contours assume all other Wilson coefficients are zero.)

Conclusions

- Measurement of $t\bar{t}$, single top, ttZ and ttW processes are yielding precision information on gtt, Wtb, ttZ, $ttW^{\pm}$ interactions in a corner of the standard model not fully explored till now.
- All measurements consistent with the standard model, but hints of an anomaly at the 3.2 σ level in the ATLAS measurement of spin correlations at 13 TeV
- Measurements are now being cast in the form of constraints on Wilson coefficients of EFT operators.
- More precision to come with the full 13 TeV dataset, Run 3, and the HL-LHC
  - Spin correlation measurement at 13 TeV with full dataset
  - EFT approach becoming more common.
  - More complete analyses of single top and $t\bar{t}$ angular distributions
  - Greater sensitivity to rare decay modes ttW and ttZ.
  - Challenge: gain control over systematic errors.