Single Top Quark Properties Measurements

On behalf of the ATLAS and CMS Collaborations

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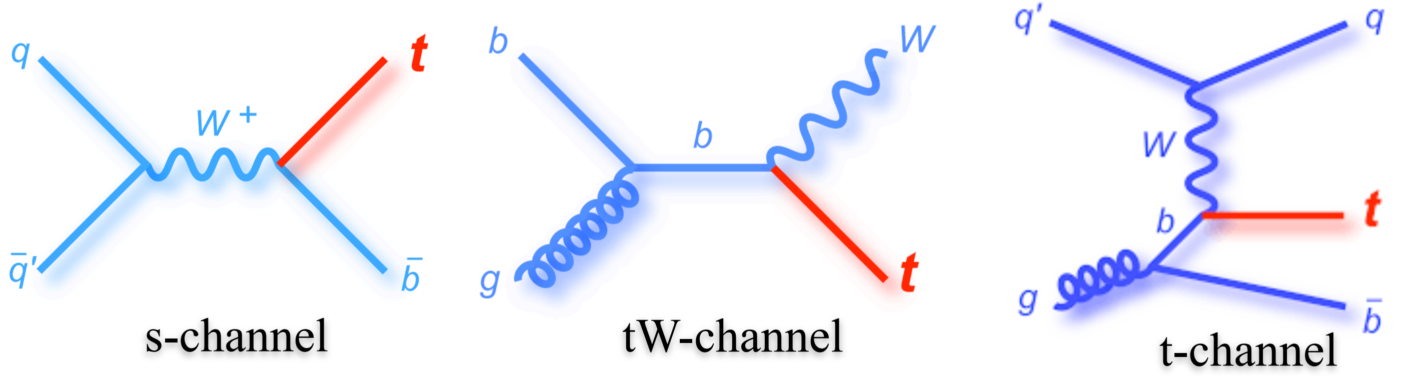
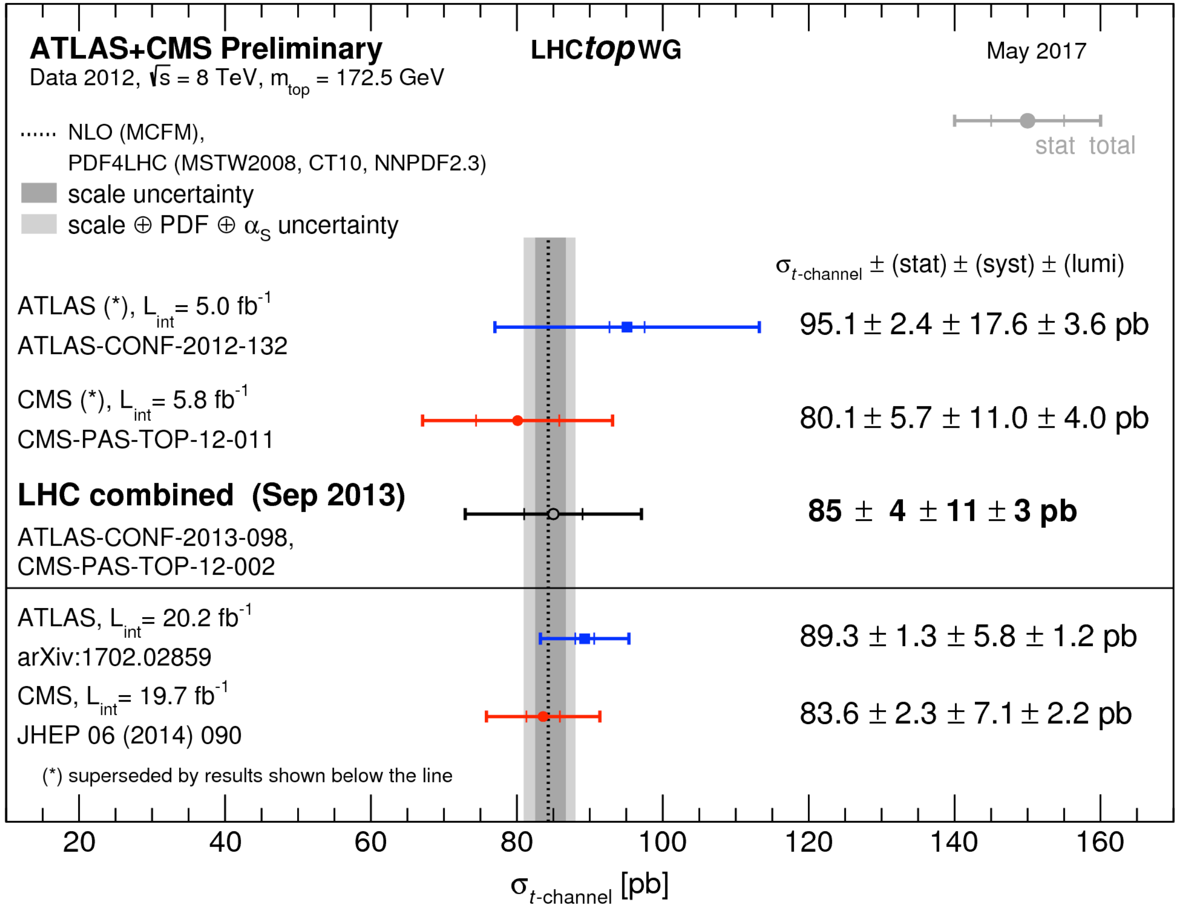
Physics with single top

- Single top-quark production via electroweak interaction, involving a Wtb vertex

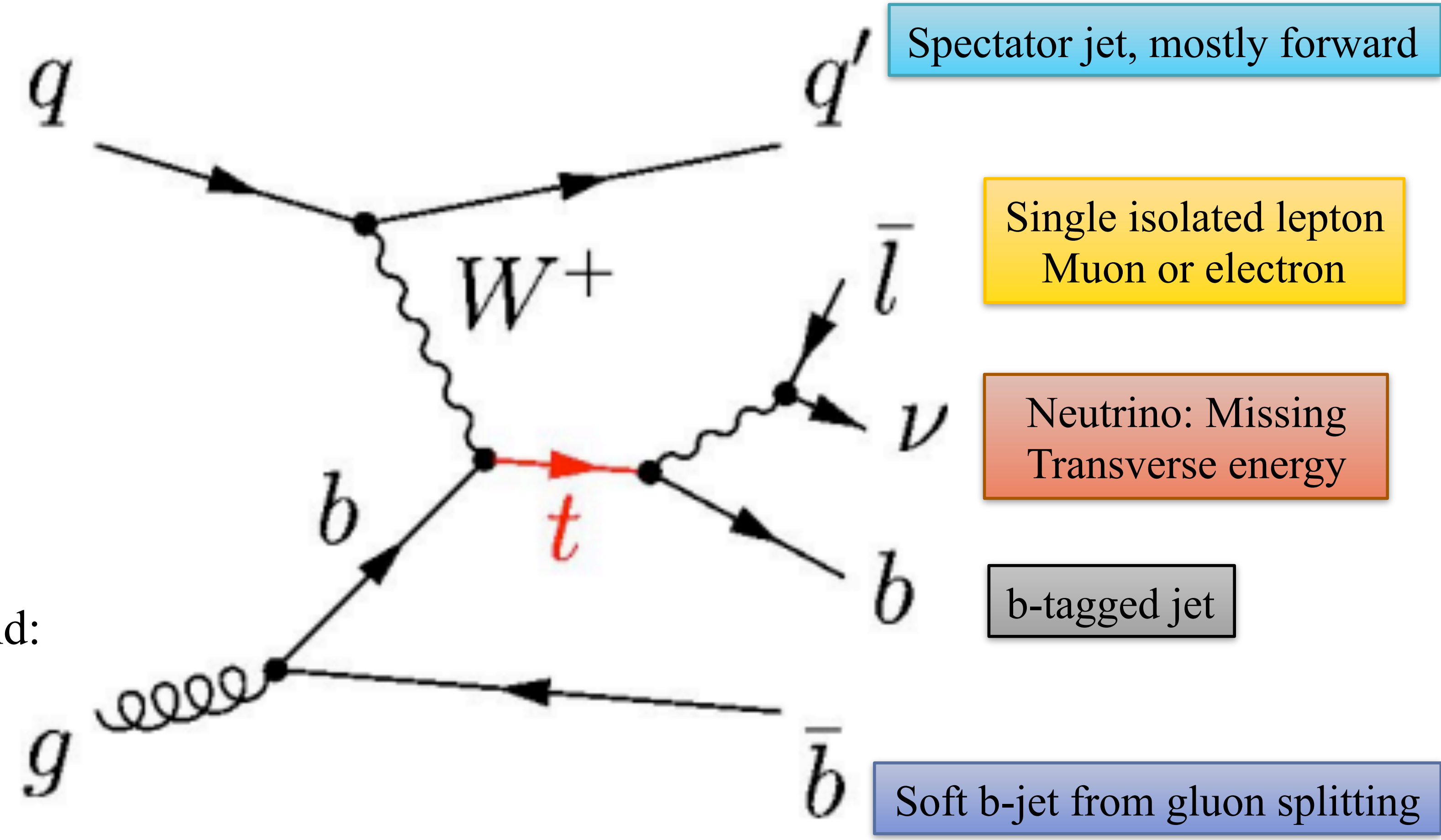


- Single top t-channel process
  - Sensitive to $|V_{tb}|$ (also for tW and s-channel)
  - Ratio top/antitop production is sensitive to the u/d quark ratio in the PDF sets
  - Sensitive to b-quark PDF
  - Sensitive to the top quark mass
  - Sensitive to the Wtb interaction
  - Sensitive to the top and W polarisation
  - Sensitive to the new physics contributions



BASIC SELECTION (LEPTONIC DECAY)

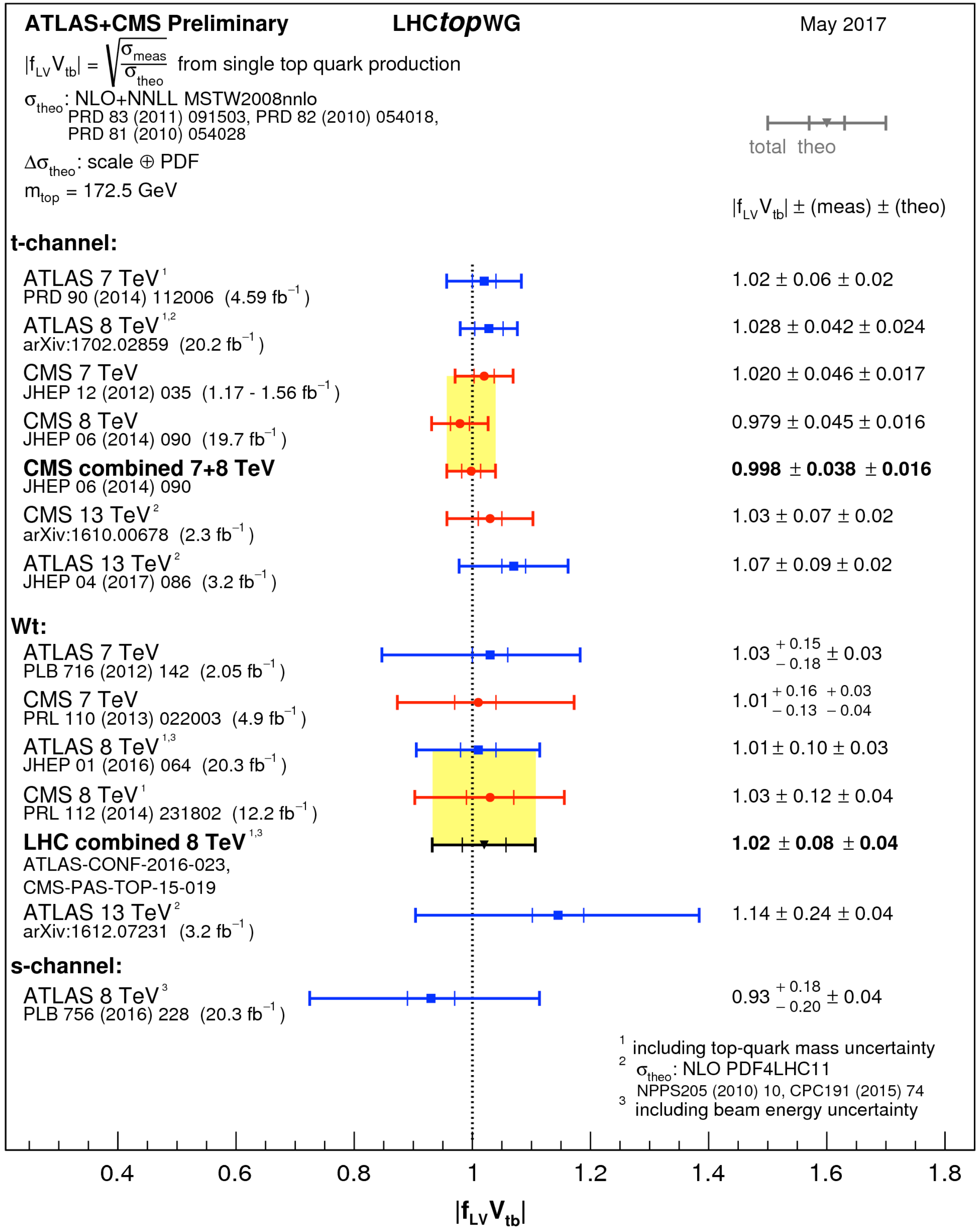
- Event selection (t-channel)
  - One isolated lepton
  - Two jets, one b-tagged
  - MET
- Background
  - Top pair production
  - QCD multijet
  - W+jets and Z+jets
- Specific techniques to suppress background:
  - Boosted decision trees
  - Neural networks
  - Cut based techniques



$|V_{tb}|$ measurement

- Single top quark productions has direct access to V_{tb}
- V_{tb} has been constrained in all t-channel and tW channel measurements
- Assumptions:
  - $BR(t \rightarrow Wb) \approx 1$
  - $|V_{tb}| >> |V_{td}|, |V_{ts}|$
  - $F_{LV} = 1$ for the SM

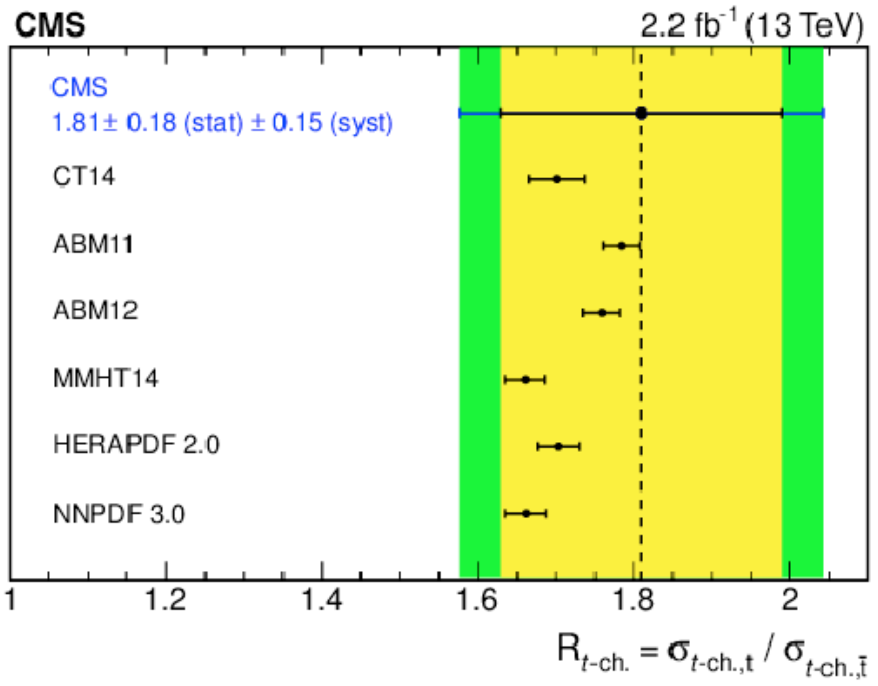
$$|f_{LV} \cdot V_{tb}| = \sqrt{\frac{\sigma^{meas.}_{t-chan.}}{\sigma^{theo.}_{t-chan.}}}$$



R_t measurements

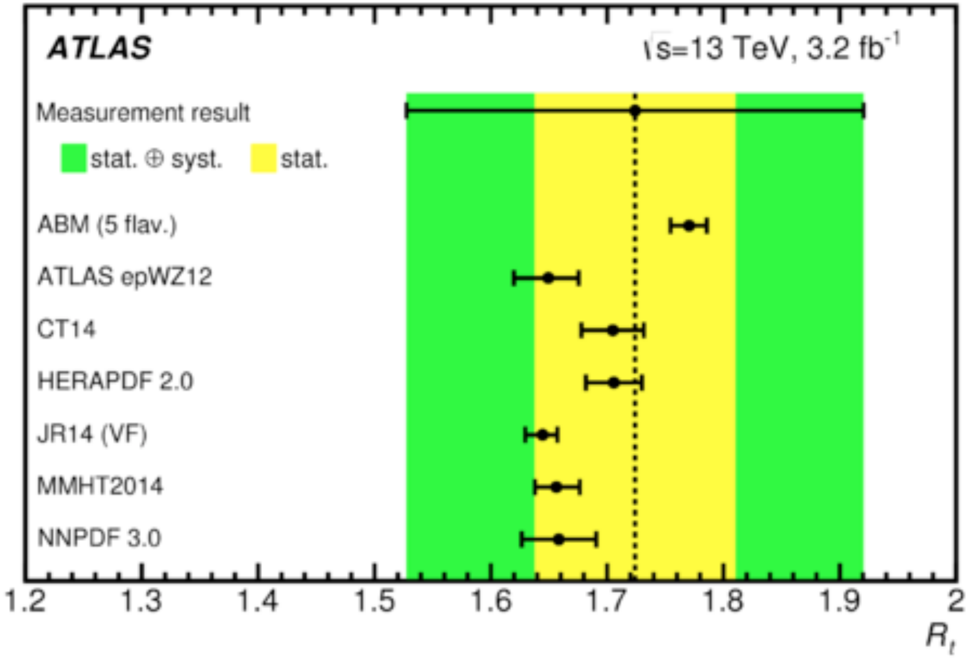
JHEP04(2017)086, Phys.Lett. B772 (2017) 752-776

- R_t: ratio of top and anti-top in t-channel
- Due to the different u and d quark density of the proton, top cross section is higher than anti top cross section
- R_t is sensitive to PDF



ATLAS: $R_t = 1.72 \pm 0.09(\text{stat.}) \pm 0.18(\text{syst.})$

CMS: $R_t = 1.81 \pm 0.18(\text{stat.}) \pm 0.15(\text{syst.})$



See Matthias's and Lidia's talks for more detail

Top mass measurement

ATLAS-CONF-2014-055, EPJC 77 (2017) 354

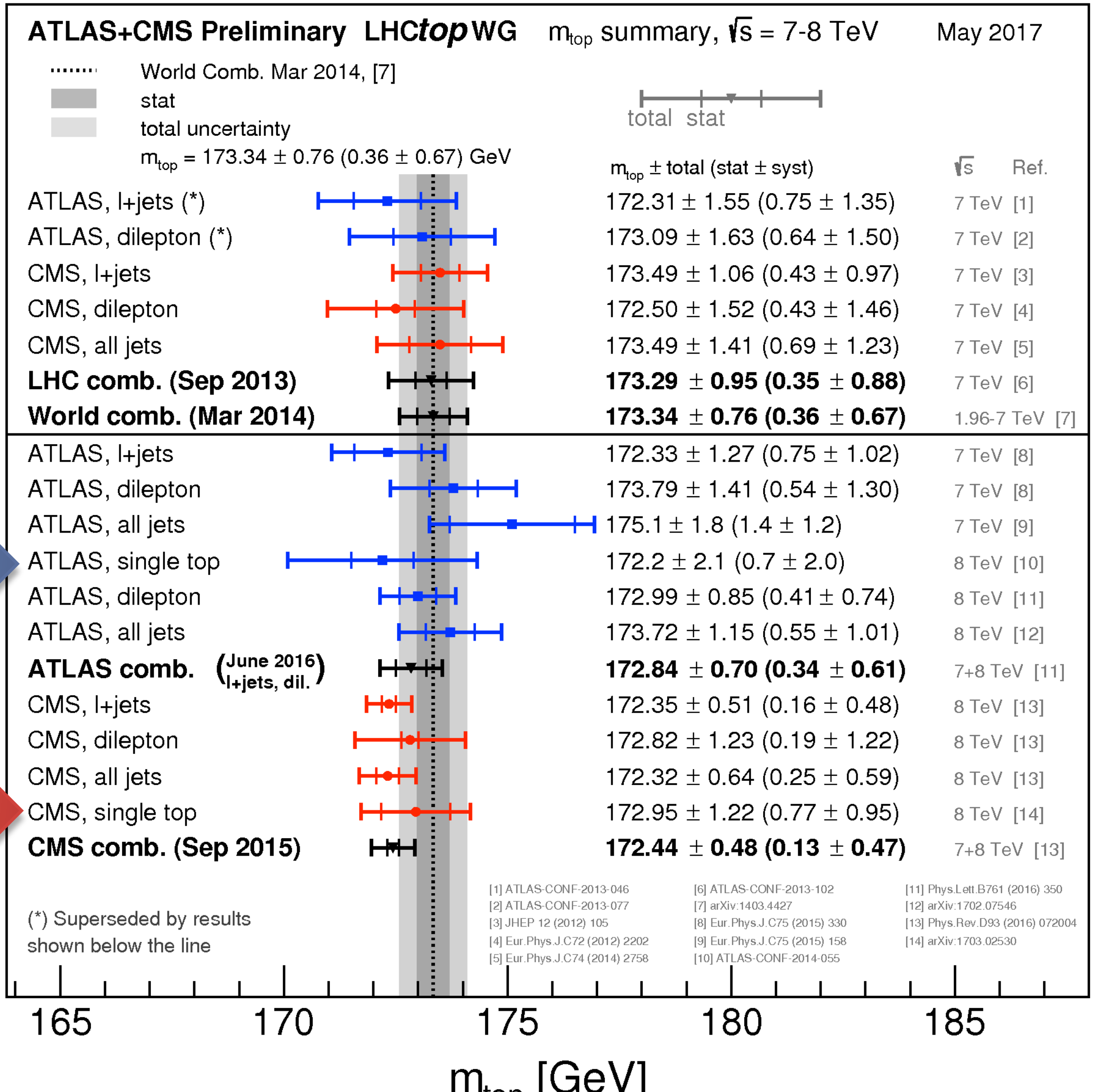
2012 data: $\sqrt{s}$ = 8 TeV, L = 20.3 fb^{-1} (ATLAS), 19.7 fb^{-1} (CMS)

- Top quark mass is measured in topologies enhanced with single top t-channel
- The reconstructed lνb (lb) invariant mass distribution is fitted to extract the top mass in CMS (ATLAS) analysis

M_{top} = 172.2 ± 0.7(stat.) ± 2.0(syst.) GeV

M_{top} = 172.95 ± 0.77(stat.) ± 0.95(syst.) GeV

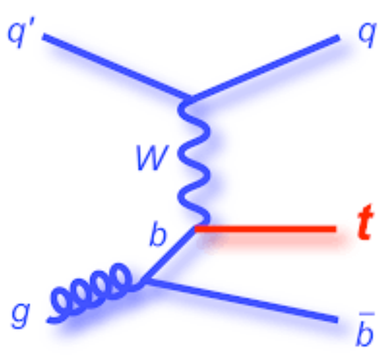
See Andrea's and Ben's talks for more detail

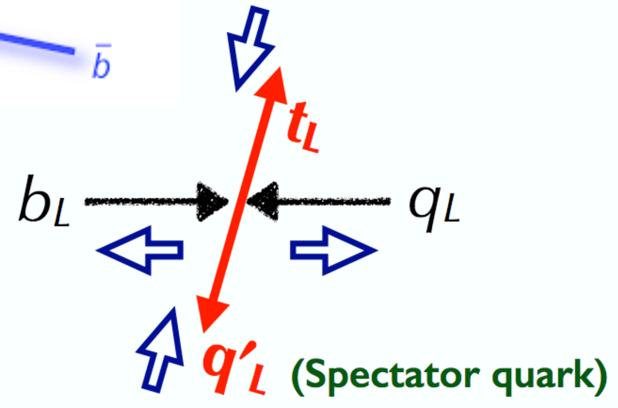


Top quark polarization

JHEP 04 (2016) 073

2012 data: $\sqrt{s}$ = 8 TeV, L = 19.7 fb^{-1}





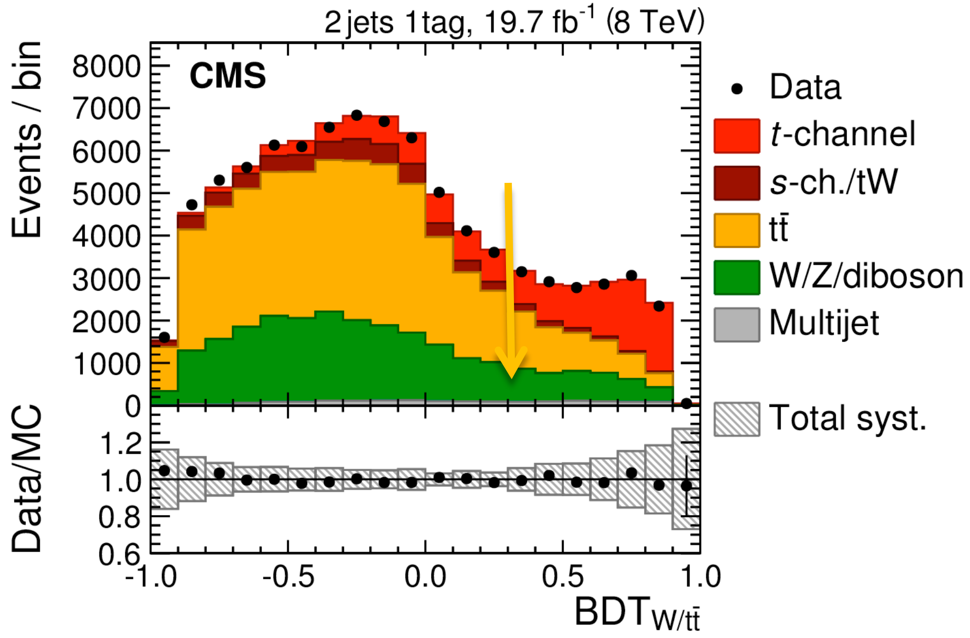
- V-A nature of the SM predicts large top polarization, P, along the direction of momentum of the spectator quark in the top rest frame
- Distribution of top decay product with respect to this direction follows

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*_X} = \left(\frac{1}{2} + A_X\cos\theta^*_X\right)$$

  - Where $A_X = \frac{1}{2} P_t \alpha_X$
    - P_t: degree of polarization ~ 90% for spectator jet direction
    - α_X: spin analyzing power ~1 for lepton
- Top polarization can be extracted from asymmetries (A_x)

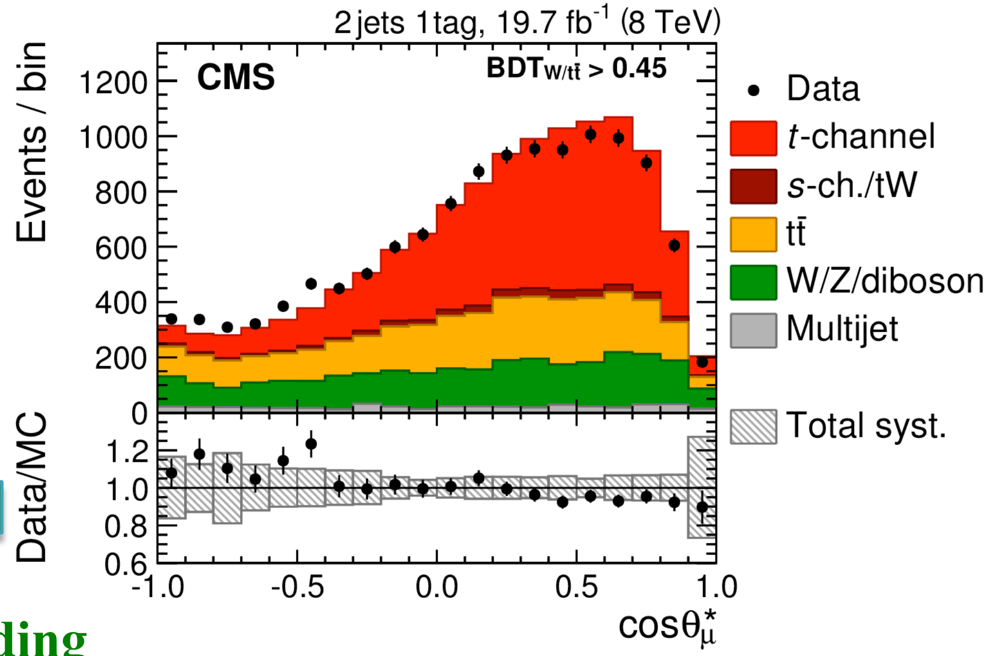
$$A_X \equiv \frac{1}{2} P_t \alpha_X = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

- BDT selects ~50% pure t-channel sample

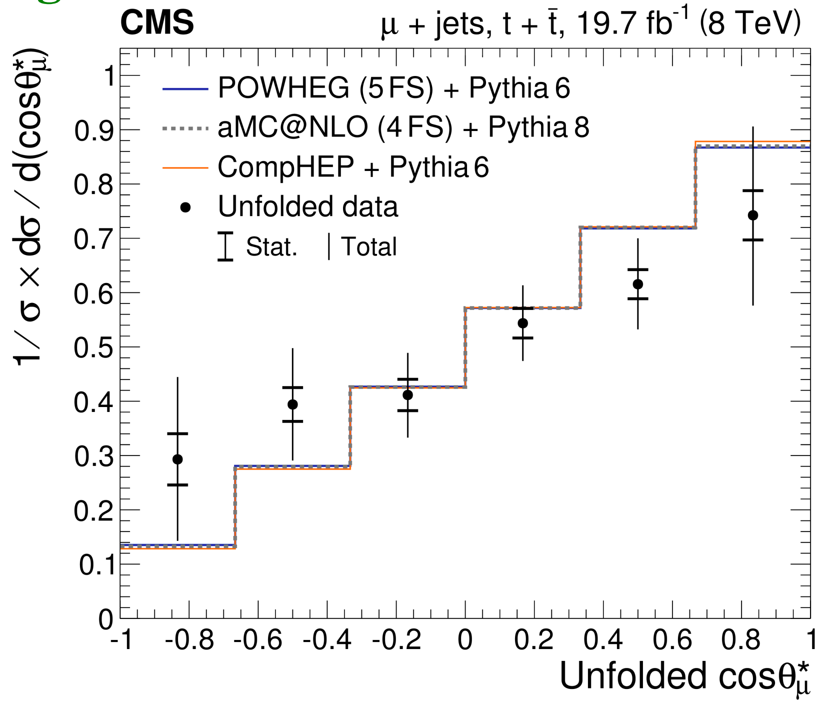


Top quark polarization

- Reconstruct cos(θ*), subtract background (W+jets largest)
- Data is unfolded at parton level to correct for efficiency and resolution.
- Dominant systematics from JES and background subtraction
- A smaller slope than expected is observed (SM predicts Aμ = 0.44)



unfolding



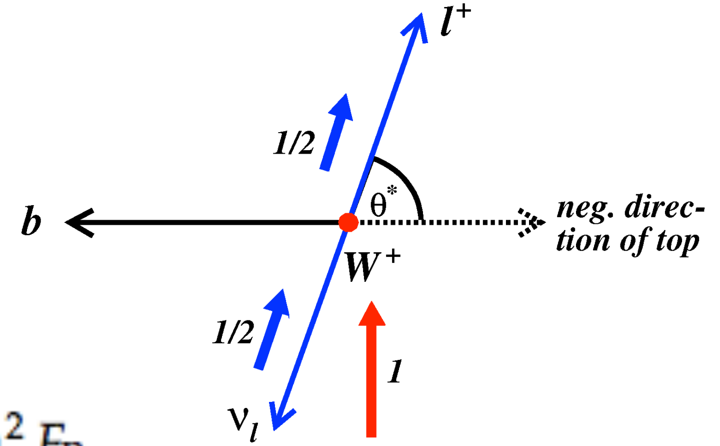
$$A_\mu = 0.26 \pm 0.03(\text{stat.}) \pm 0.10(\text{syst.})$$

- Compatible with a p-value of 4.6% (equiv. to 2 sigma)

W helicity

JHEP 01 (2015) 053

2012 data: $\sqrt{s}$ = 8 TeV, L = 19.7 fb^{-1}

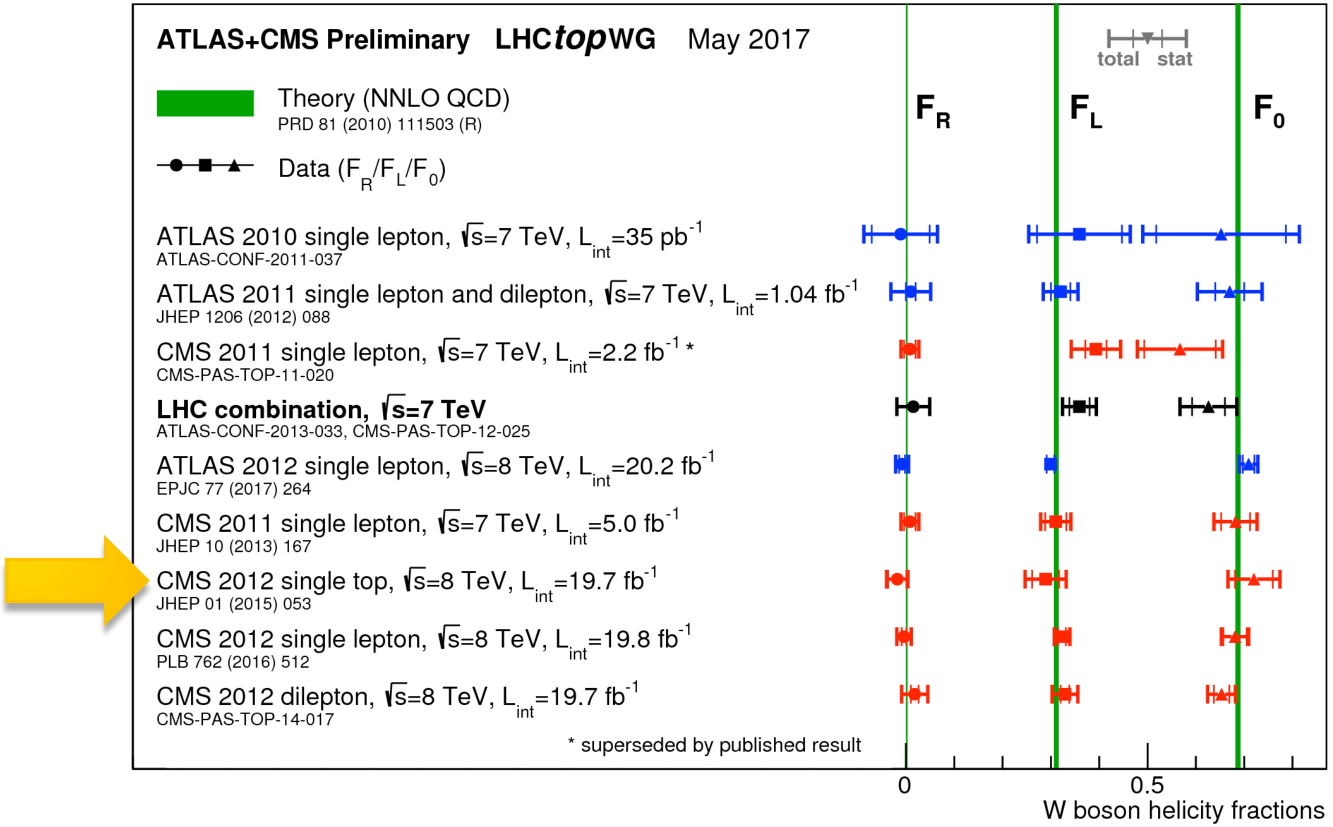


- W from top decay is produced with different helicities, can be measured by θ_l^*: angle between W in top frame and lepton in W frame

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

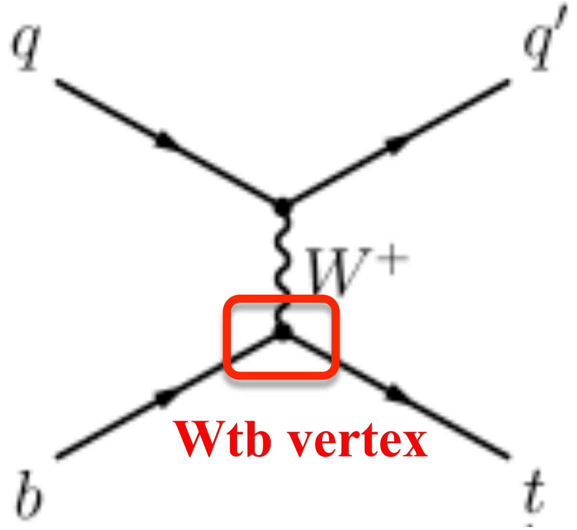
- In SM, $F_0 \sim 70\%$, $F_L \sim 30\%$, $F_R \sim 0$
- F_0, F_R and F_L can be extracted through a fit to the $\cos(\theta_l^*)$ distribution
- The left-handed and longitudinal polarizations are treated as free parameters in the fit
- Right-handed polarisation fraction is extracted from the condition: $F_L+F_0+F_R=1$

$$F_L = 0.298 \pm 0.028\,(\text{stat}) \pm 0.032\,(\text{syst}),$$
$$F_0 = 0.720 \pm 0.039\,(\text{stat}) \pm 0.037\,(\text{syst}),$$
$$F_R = -0.018 \pm 0.019\,(\text{stat}) \pm 0.011\,(\text{syst}),$$



Anomalous Wtb interaction

- Single top quark production process can be used to search for new physics
- General effective Lagrangian of Wtb vertex



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

- Anomalous couplings in the SM: $V_L = V_{tb}$; $V_R = g_L = g_R = 0$
- If anomalous couplings are non zero: evidence of new physics
- If imaginary part of anomalous coupling is non zero: evidence of CP violation
- The increased statistics for single-top at LHC allows measurement of multi differential decay rates of the top quark.

Spin observables and asymmetries

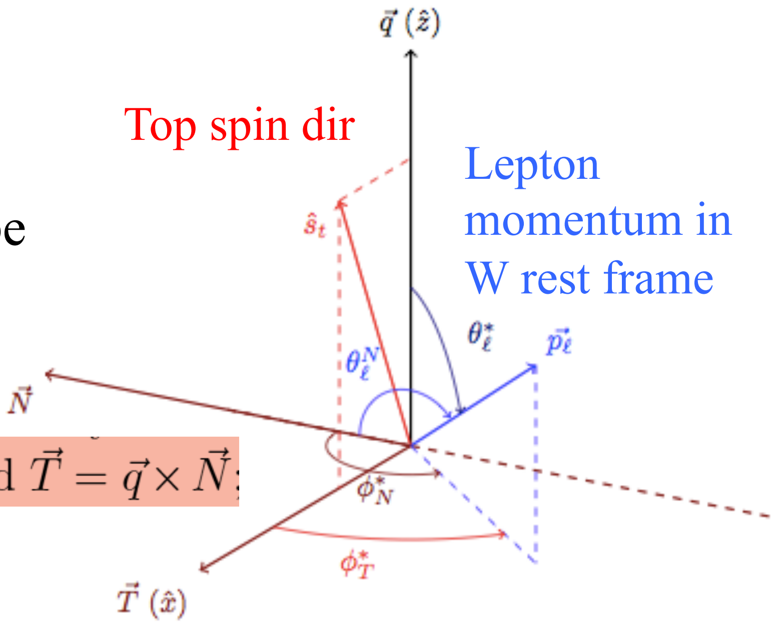
JHEP04 (2017) 124

2012 data: $\sqrt{s}$ = 8 TeV, L = 20.2 fb^{-1}

- Top and W polarization observables can be extracted from asymmetries in various angular distributions of the decay products.

- the spin-density matrix elements for the W-boson helicity components can be parameterised in terms of expectation values of six independent spin observables
- In the SM
  - $\langle S_3 \rangle = -0.31$ and $\langle T_0 \rangle = -0.43$ (related to W helicity)
  - $\langle S_1 \rangle = 0.46$ and $\langle A_1 \rangle = 0.23$ (related to top polarization)
  - $\langle S_2 \rangle = 0$ and $\langle A_2 \rangle = 0$ (related to top polarization – sensitive to Img$_R$)

$\vec{N} = \hat{s}_t \times \vec{q}$ and $\vec{T} = \vec{q} \times \vec{N}$



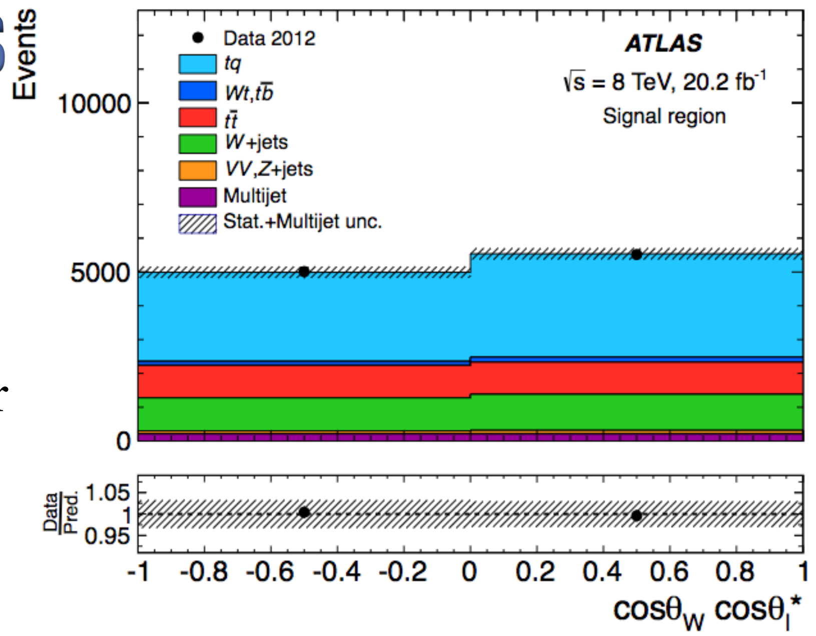
$$
\begin{aligned}
\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_\ell^*)d\phi_\ell^*} = & \frac{3}{8\pi}\left\{\frac{2}{3} + \frac{1}{\sqrt{6}}\langle T_0\rangle\left(3\cos^2\theta_\ell^* - 1\right) + \langle S_3\rangle\cos\theta_\ell^*\right. \\
& + \langle S_1\rangle\cos\phi_\ell^*\sin\theta_\ell^* + \langle S_2\rangle\sin\phi_\ell^*\sin\theta_\ell^* \\
& \left. - \langle A_1\rangle\cos\phi_\ell^*\sin 2\theta_\ell^* - \langle A_2\rangle\sin\phi_\ell^*\sin 2\theta_\ell^*\right\}.
\end{aligned}
$$

Spin observables and asymmetries

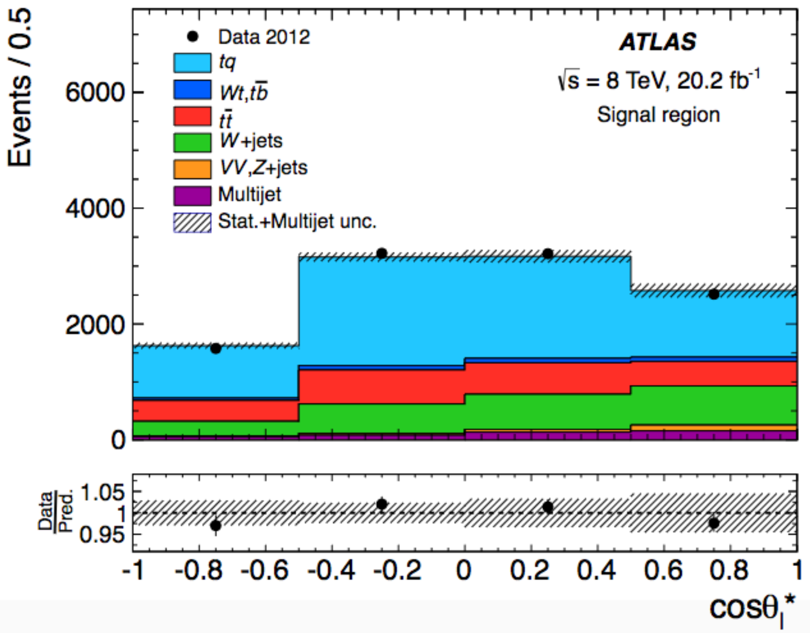
- Selection cuts on $|\eta_j|$, $\Delta\eta(j,b)$, $m(l\nu b)$, $H_T(l,j,MET)$ are use to enrich the signal region
- The polarisation observables are extracted from asymmetries in angular distributions

$$A_{\mathrm{FB}} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}, \qquad A_{\mathrm{EC}} = \frac{N(|\cos\theta| > \frac{1}{2}) - N(|\cos\theta| < \frac{1}{2})}{N(|\cos\theta| > \frac{1}{2}) + N(|\cos\theta| < \frac{1}{2})}.$$

Asymmetry	Angular observable	Polarisation observable	SM prediction
A^{ℓ}_{FB}	$\cos\theta_\ell$	$\frac{1}{2}\alpha_\ell P$	0.45
A^{tW}_{FB}	$\cos\theta_W \cos\theta^*_\ell$	$\frac{3}{8}P(F_R + F_L)$	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^{T}_{FB}	$\cos\theta^T_\ell$	$\frac{3}{4}\langle S_1\rangle$	0.34
A^{N}_{FB}	$\cos\theta^N_\ell$	$-\frac{3}{4}\langle S_2\rangle$	0
$A^{T,\phi}_{\mathrm{FB}}$	$\cos\theta^*_\ell \cos\phi^*_T$	$-\frac{2}{\pi}\langle A_1\rangle$	−0.14
$A^{N,\phi}_{\mathrm{FB}}$	$\cos\theta^*_\ell \cos\phi^*_N$	$\frac{2}{\pi}\langle A_2\rangle$	0



(b)



Spin observables and asymmetries

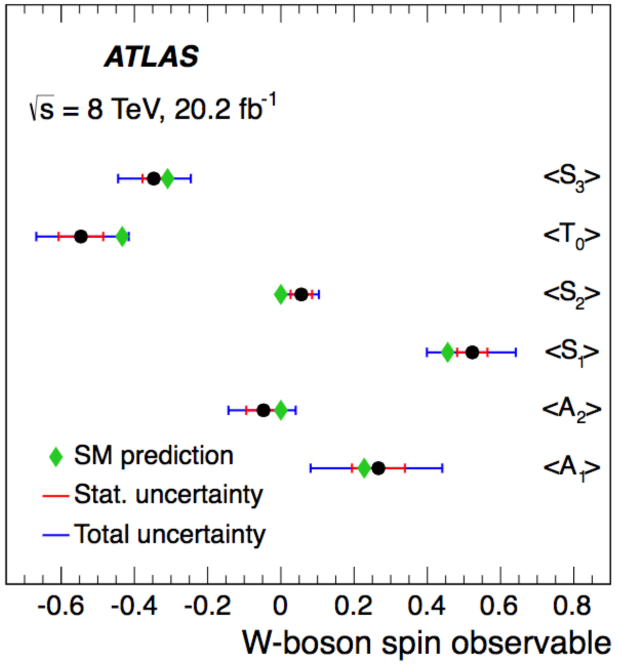
- Measured angular distributions are unfolded at parton level after subtracting the background contributions
- Angular asymmetries extracted from the unfolded distributions.
- Dominant sources of uncertainty: data statistics, t-channel and ttbar modeling and jet energy scale.
- Results in agreement with the Standard Model predictions.

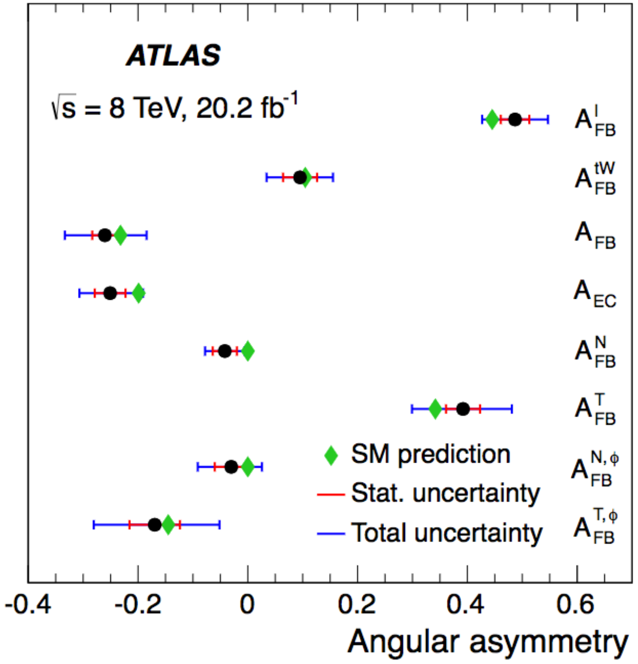
$$\alpha_\ell P = 0.97 \pm 0.05(\text{stat.}) \pm 0.11(\text{syst.}) = 0.97 \pm 0.12\,,$$
$$P(F_\text{R} + F_\text{L}) = 0.25 \pm 0.08(\text{stat.}) \pm 0.14(\text{syst.}) = 0.25 \pm 0.16\,.$$

- Limits on Im (g_R) extracted by combining two particular asymmetries: A_{FB}^{l} and A_{FB}^{N}

Im (g_R): [-0.18, 0.06]

See Nuno's talk for more details

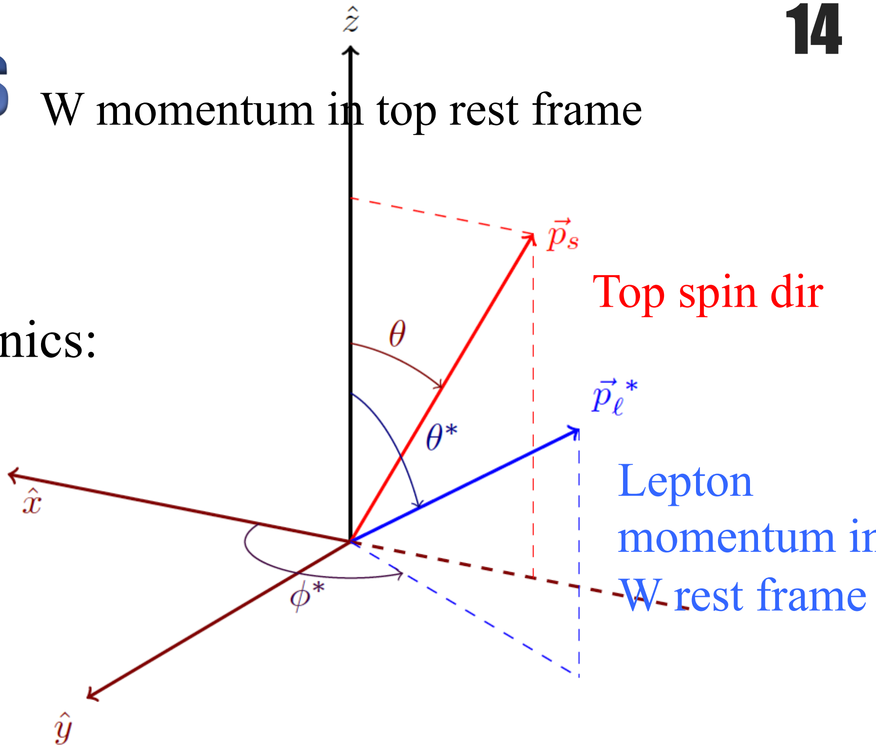




Triple-differential angular decay rates

arXiv:1707.05393 - submitted to JHEP

2012 data: $\sqrt{s}$ = 8 TeV, L = 20.2 fb^{-1}

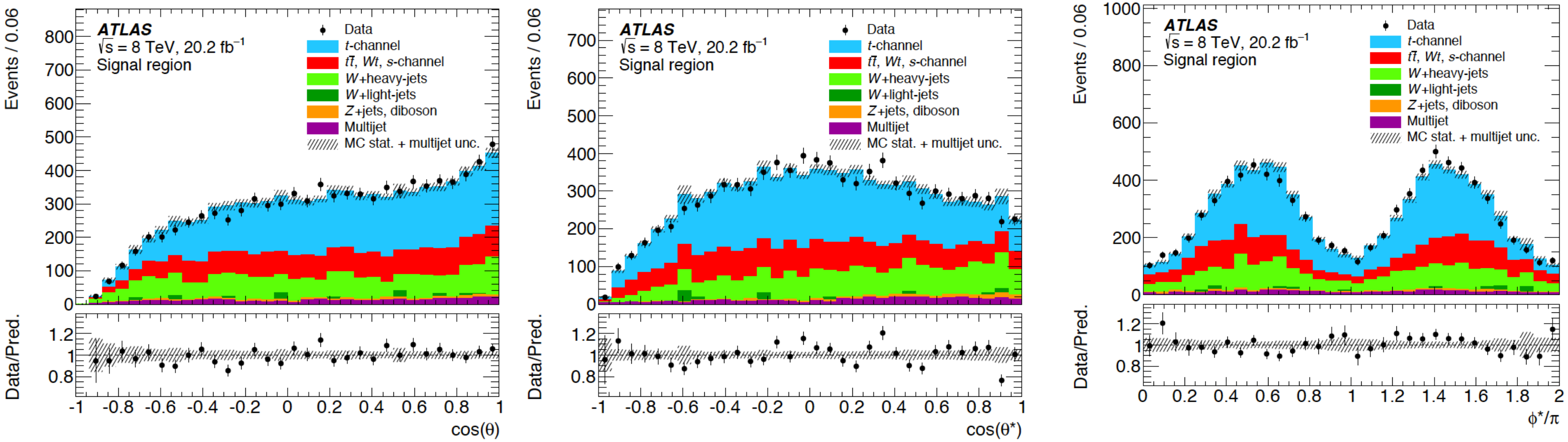


- t-channel cross section can be written as a finite series of Spherical Harmonics:

$$\varrho(\theta,\theta^*,\phi^*;P) = \frac{1}{N}\frac{\mathrm{d}^3N}{\mathrm{d}(\cos\theta)\mathrm{d}\Omega^*} = \sum_{k=0}^{1}\sum_{l=0}^{2}\sum_{m=-k}^{k} a_{k,l,m}M_{k,l}^m(\theta,\theta^*,\phi^*),$$

$$M_{k,l}^m(\theta,\theta^*,\phi^*) = \sqrt{2\pi}Y_k^m(\theta,0)Y_l^m(\theta^*,\phi^*).$$

- The model is based on the angles θ, θ* and φ*
- An angular analysis of the triple-differential decay rate is performed in order to determine generalised helicity fractions and phases, as well as the polarisation of the produced top quark.



Spin observables and asymmetries

- Systematics are dominated by MC event generators and JES
- Statistics are also dominating the total error
- Search is only sensitive to coupling ratios
- All of the measured values are in agreement with the SM expectations.

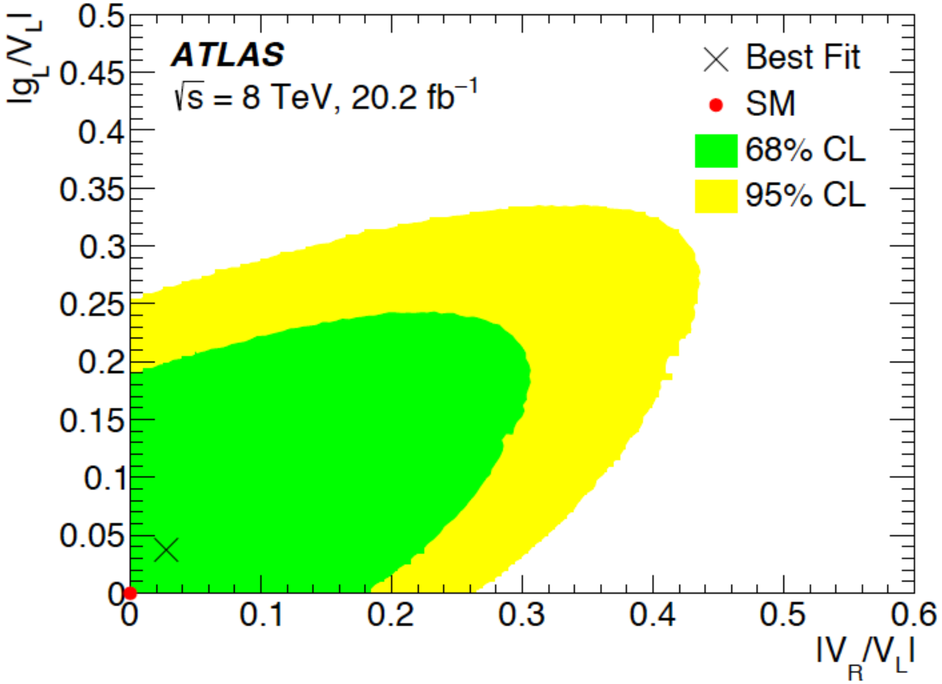
$$\mathrm{Re}\left[\frac{g_R}{V_L}\right] \in [-0.12, 0.17] \quad \text{and} \quad \mathrm{Im}\left[\frac{g_R}{V_L}\right] \in [-0.07, 0.06]\,.$$

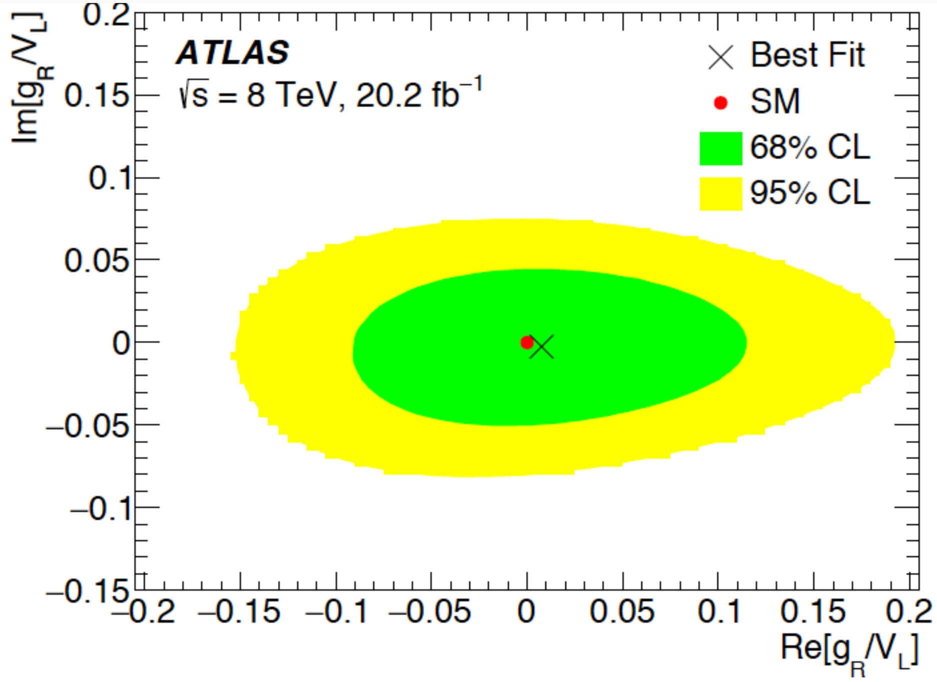
$$|V_R/V_L| < 0.37 \qquad (95\%\ \mathrm{CL})\,,$$

$$|g_L/V_L| < 0.29 \qquad (95\%\ \mathrm{CL})\,,$$

- A three angle analysis is needed to fully describe the top production (polarization) and decay

See Nuno's talk for more details





Anomalous Wtb interaction

JHEP 02 (2017) 028

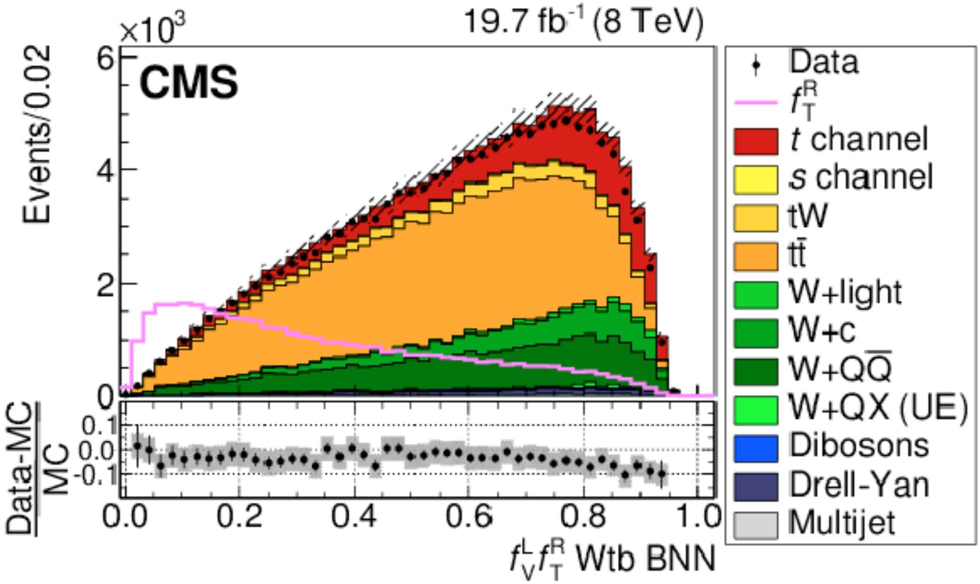
2011 data: √s = 7 TeV, L = 5 fb^{-1}

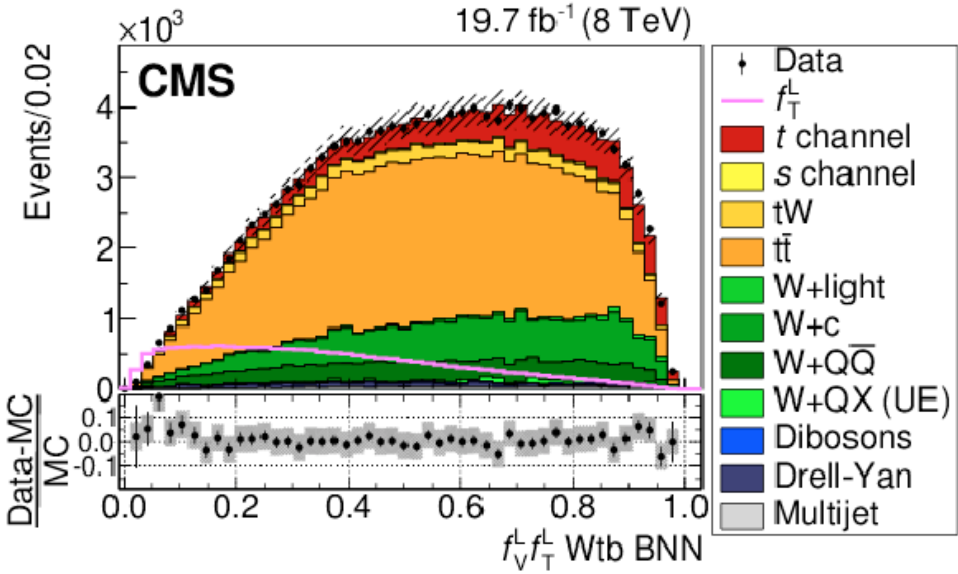
2012 data: √s = 8 TeV, L = 19.7 fb^{-1}

- A search for anomalous Wtb interactions at 7 and 8 teV

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

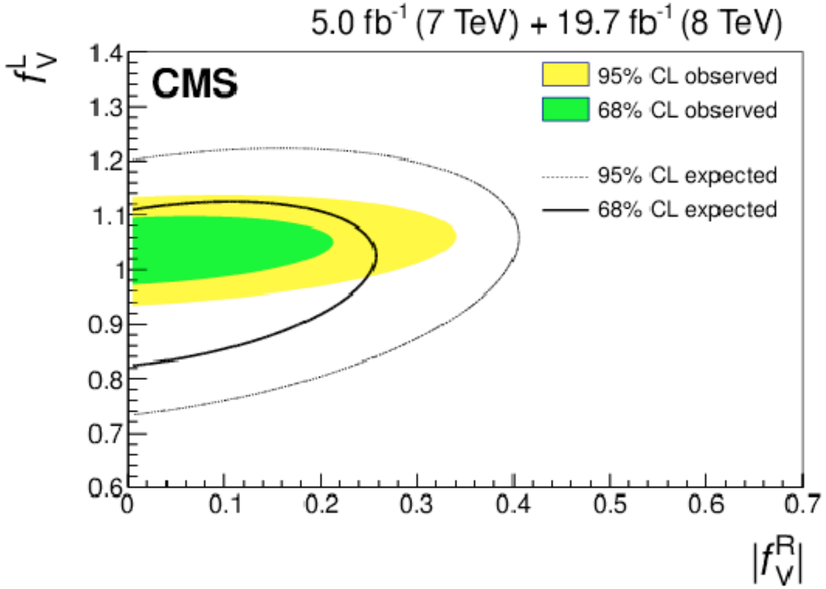
- Only muon channel is analyzed
- A neural network for rejecting QCD events is used
- Three dedicated neural network for separating events from anomalous interaction from SM events are used
  - (f_V^L, f_V^R)
  - (f_V^L, f_T^L)
  - (f_V^L, f_T^R)
- Also stringent limits on top-quark-gluon FCNC couplings are set using dedicated neural networks (See Kirill's talk).



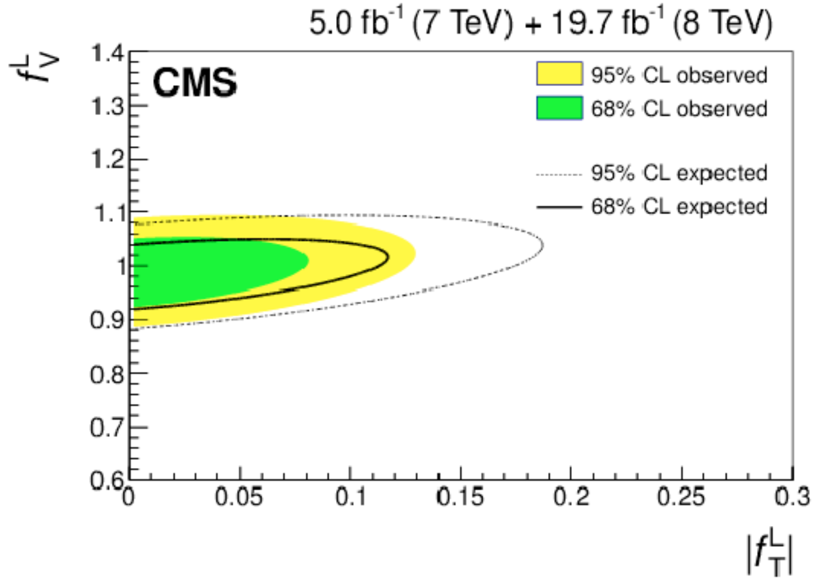


Anomalous Wtb interaction

- The presence of anomalous Wtb couplings in both the production and decay of the top quark is considered
- Two and three of four anomalous couplings are considered simultaneously in two and three dimensional scenarios
- Limits are extracted from a simultaneous fit to the SM BNN and anomalous Wtb BNNs outputs
- Only real parts are constrained



Scenario	$f_V^L >$	$\lvert f_V^R\rvert <$	$\lvert f_T^L\rvert <$	$< f_T^R <$	
$\sqrt{s} = 7$ and 8 TeV					
(f_V^L, f_V^R)	0.97 (0.92)	0.28 (0.31)			
(f_V^L, f_T^L)	0.92 (0.92)		0.10 (0.14)		
(f_V^L, f_T^R)	0.94 (0.93)			–0.046 (–0.050)	0.046 (0.041)
(f_V^L, f_T^L, f_T^R)	0.98 (0.97)		0.057 (0.10)	–0.049 (–0.051)	0.048 (0.046)
(f_V^L, f_V^R, f_T^R)	0.98 (0.97)	0.16 (0.22)		–0.049 (–0.049)	0.039 (0.037)



summary

- The ATLAS and CMS experiments have deeply studied the top quark properties in single-top production
- Unique features of the electroweak top quark production are exploited in order to search for new physics in Wtb interaction
- Strong limits are set to the Wtb anomalous couplings, especially imaginary part of g_R coupling
- The top-quark polarization has been measured by both experiments using single top events
- Large cross section of the single top t-channel and tW-channel at the 13 TeV LHC and larger statistics in Run-2 datasets allow us to measure top properties more precisely.

Thanks for your attention