W helicity: latest LHC results

10th Open LHC*Top*WG meeting: Nov. 21st–23rd 2016

María Moreno Llácer

2nd Institute of Physics, Georg-August-Universität Göttingen

Outlook

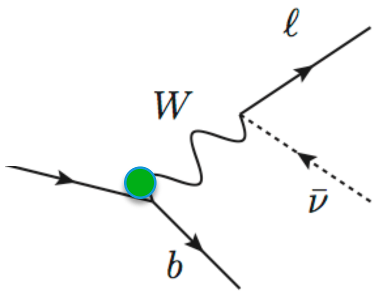
- *Wtb* vertex Lagrangian and sensitive observables to probe it

- *W* helicity using cosθ_l* distributions
    - analysis methods

- Latest LHC results
    * ATLAS 8 TeV: single lepton results
    * CMS 8 TeV: single lepton results
    * Comparisons between them

Wtb vertex Lagrangian:

- Top quark decay: $t \to Wb$ (≈100%)
- SM: Weak coupling with (V-A) structure
  - Only coupling to left-handed fermions



Nucl.Phys. B812 (2009) 181-204
Eur.Phys.J. C50 , 519 (2007)

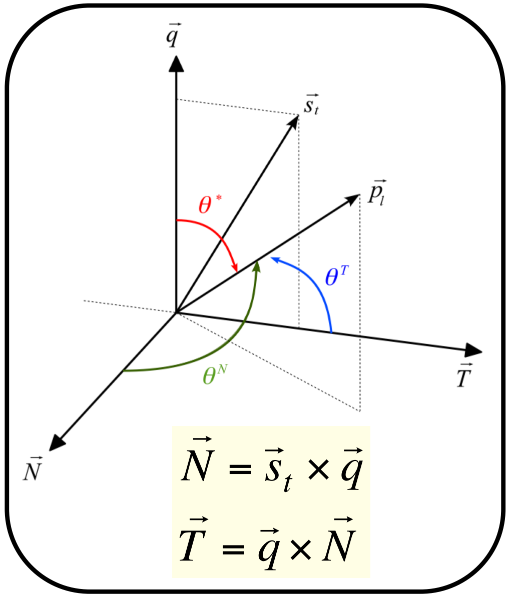
$$L_{Wtb} = -\frac{g}{\sqrt{2}}\bar{u}_b\gamma^\mu (V_L P_L + V_R P_R) u_t W_\mu^+ - \frac{g}{\sqrt{2}}\bar{u}_b \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (g_L P_L + g_R P_R) u_t W_\mu^+ + \text{h.c.}$$

$V_{L,R}$ and $g_{L,R}$
left and right -handed vector and tensor couplings

$SM \Rightarrow V_L = V_{tb} \sim 1$ $\quad V_R = g_L = g_R = 0$

Right-handed contribution?
Tensor couplings?

Angular observables to probe the *Wtb* vertex:



Nucl. Phys. B 840(2010)349

- For unpolarised top quark decays, the only meaningful direction in the top RF is the one of the *W* boson momentum (q)
- For polarised (spin direction s_t) top quarks produced via electroweak interaction, further directions may be considered: N and T.
- Three angular distributions: θ_l^*(q,l), θ_l^N(N,l) and θ_l^T(T,l)

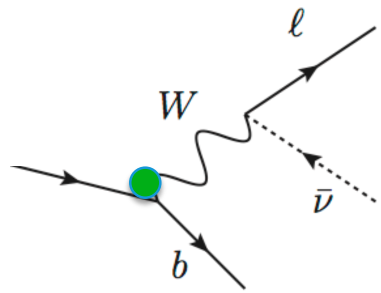
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_l^X} = \frac{3}{8}(1+\cos\theta_l^X)^2 \mathbf{F_+^X} + \frac{3}{8}(1-\cos\theta_l^X)^2 \mathbf{F_-^X} + \frac{3}{4}\sin^2\theta_l^X \mathbf{F_0^X}$$

$$A_{FB}^X = \frac{N(\cos\theta_l^X > 0) - N(\cos\theta_l^X < 0)}{N(\cos\theta_l^X > 0) + N(\cos\theta_l^X < 0)} \propto \left(F_+^X - F_-^X\right)$$

Wtb vertex Lagrangian:

- Top quark decay: $t \to Wb$ (≈100%)
- SM: Weak coupling with (V-A) structure
  - Only coupling to left-handed fermions

Nucl.Phys. B812 (2009) 181-204
Eur.Phys.J. C50 , 519 (2007)



$$L_{Wtb} = -\frac{g}{\sqrt{2}}\,\bar{u}_b \gamma^{\mu}\left(V_L P_L + V_R P_R\right) u_t W^{+}_{\mu} - \frac{g}{\sqrt{2}}\,\bar{u}_b \frac{i\sigma^{\mu\nu} q_{\nu}}{M_W}\left(g_L P_L + g_R P_R\right) u_t W^{+}_{\mu} + \text{h.c.}$$

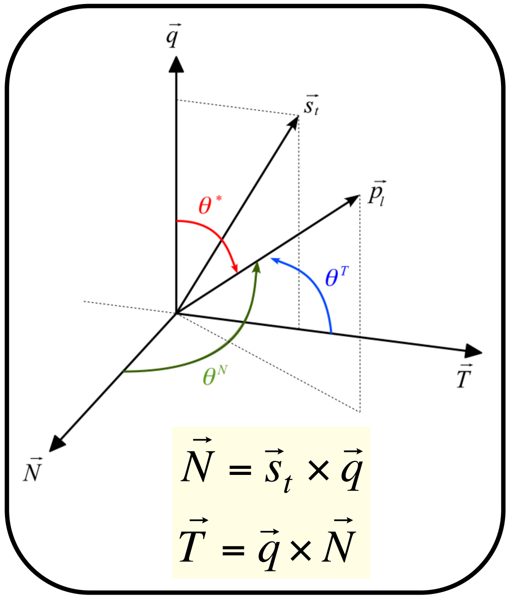
$V_{L,R}$ and $g_{L,R}$

left and right-handed vector and tensor couplings

$SM \Rightarrow$ $V_L = V_{tb} \sim 1$ $\quad V_R = g_L = g_R = 0$

Right-handed contribution?
Tensor couplings?

Angular observables to probe the *Wtb* vertex:



Nucl. Phys. B 840(2010)349

→ For unpolarised top quark decays, the on[...]ection in the top RF is the one of the *W* boson[...]

→ For polarised (spin direction s_t) top [...] produced via electroweak interaction, further directions may be considered: N and T.

More on this in EFT sessions later in the workshop.

→ Three angular distributions: θ_l^*(q,l), θ_l^N(N,l) and θ_l^T(T,l)

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_l^X} = \frac{3}{8}(1+\cos\theta_l^X)^2 \mathbf{F}_+^{\mathbf{X}} + \frac{3}{8}(1-\cos\theta_l^X)^2 \mathbf{F}_-^{\mathbf{X}} + \frac{3}{4}\sin^2\theta_l^X \mathbf{F}_0^{\mathbf{X}}$$

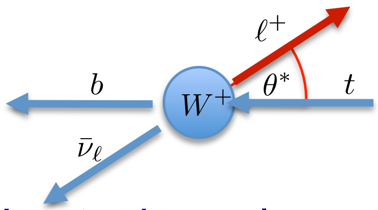
$$A_{FB}^X = \frac{N(\cos\theta_l^X > 0) - N(\cos\theta_l^X < 0)}{N(\cos\theta_l^X > 0) + N(\cos\theta_l^X < 0)} \propto \left(F_+^X - F_-^X\right)$$

W helicity in tt events (cosθ_l*)

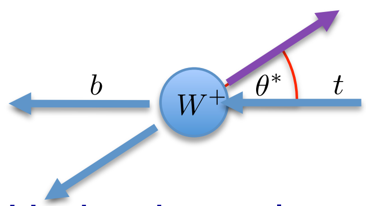
W bosons from top quark decays → 3 possible polarizations (helicity fractions): left-handed F_L, right-handed F_R, longitudinal F_0

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

Sensitive observable: cosθ_l* being θ_l* the angle between the down-type fermion (charged lepton or down-type quark) from the W boson decay and the reversed direction of the top quark, both in the W boson rest frame.

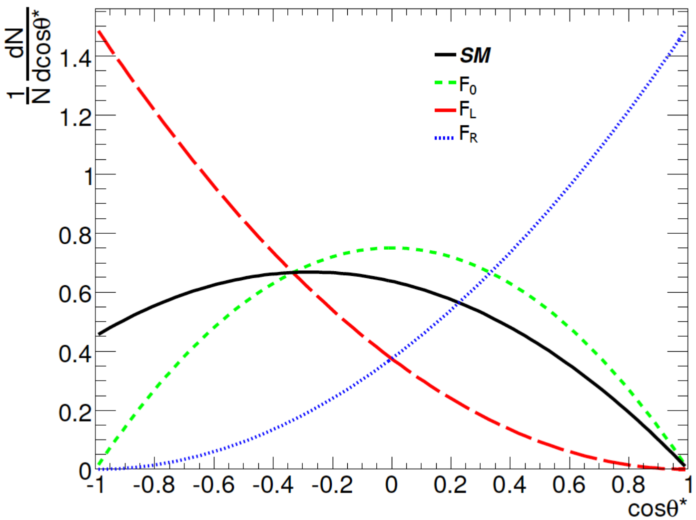


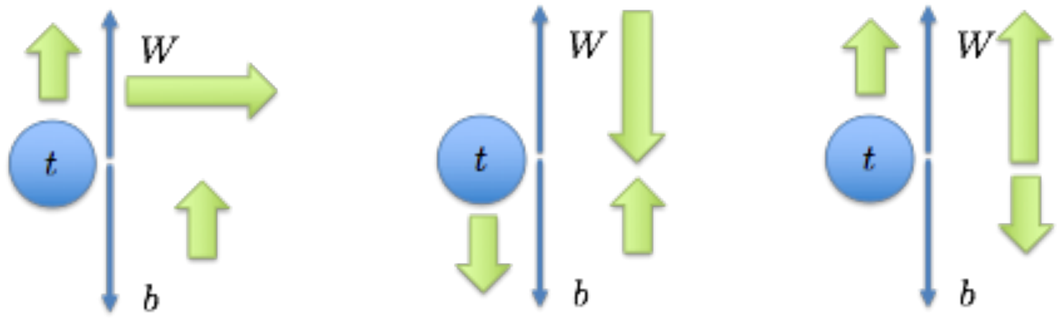
Leptonic analyser



Hadronic analyser

→ two measurements per event.



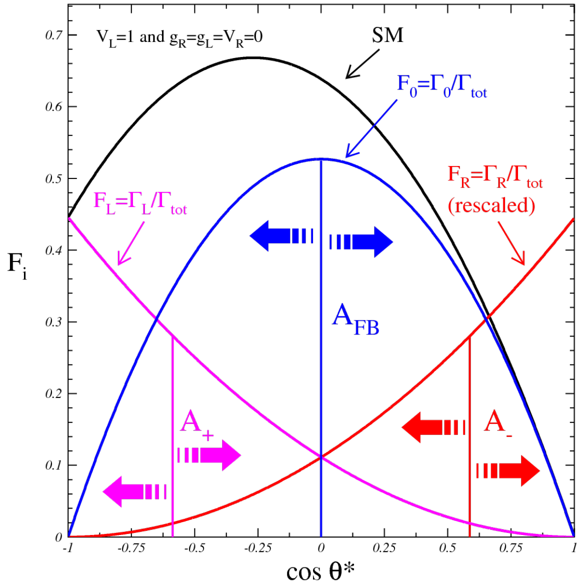


F_0 = 0.687 ± 0.005 F_L = 0.311 ± 0.005 F_R = 0.0017 ± 0.0001

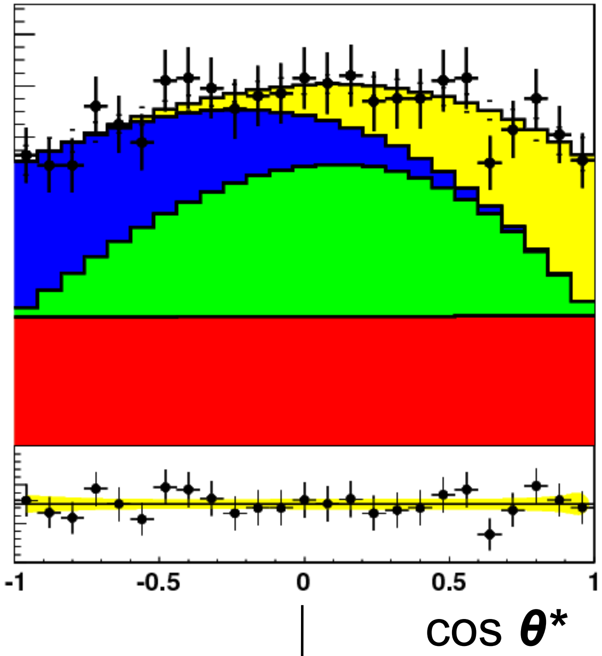
SM NNLO calc. (m_t = 172.8 ± 1.3 GeV): Phys. Rev. D81 11503 (2010)

Analysis methods

Angular asymmetries



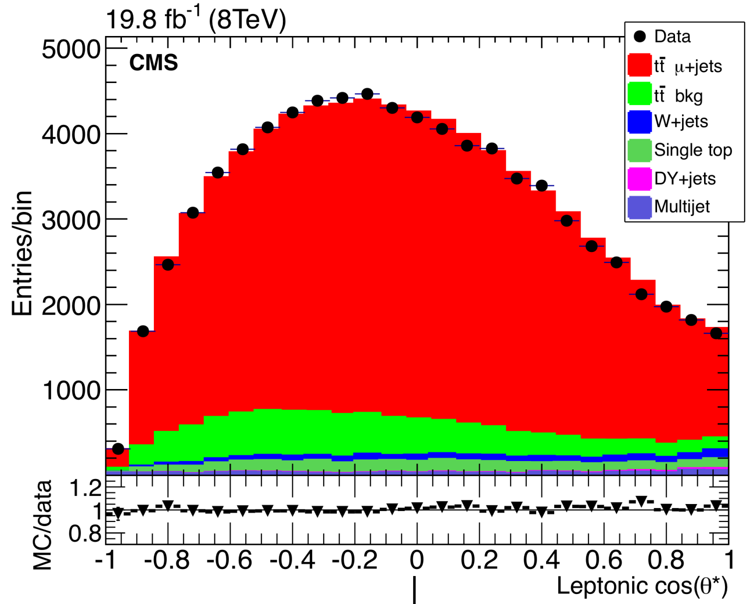
Templates



Dedicated tt signal templates for a specific F_i are created.

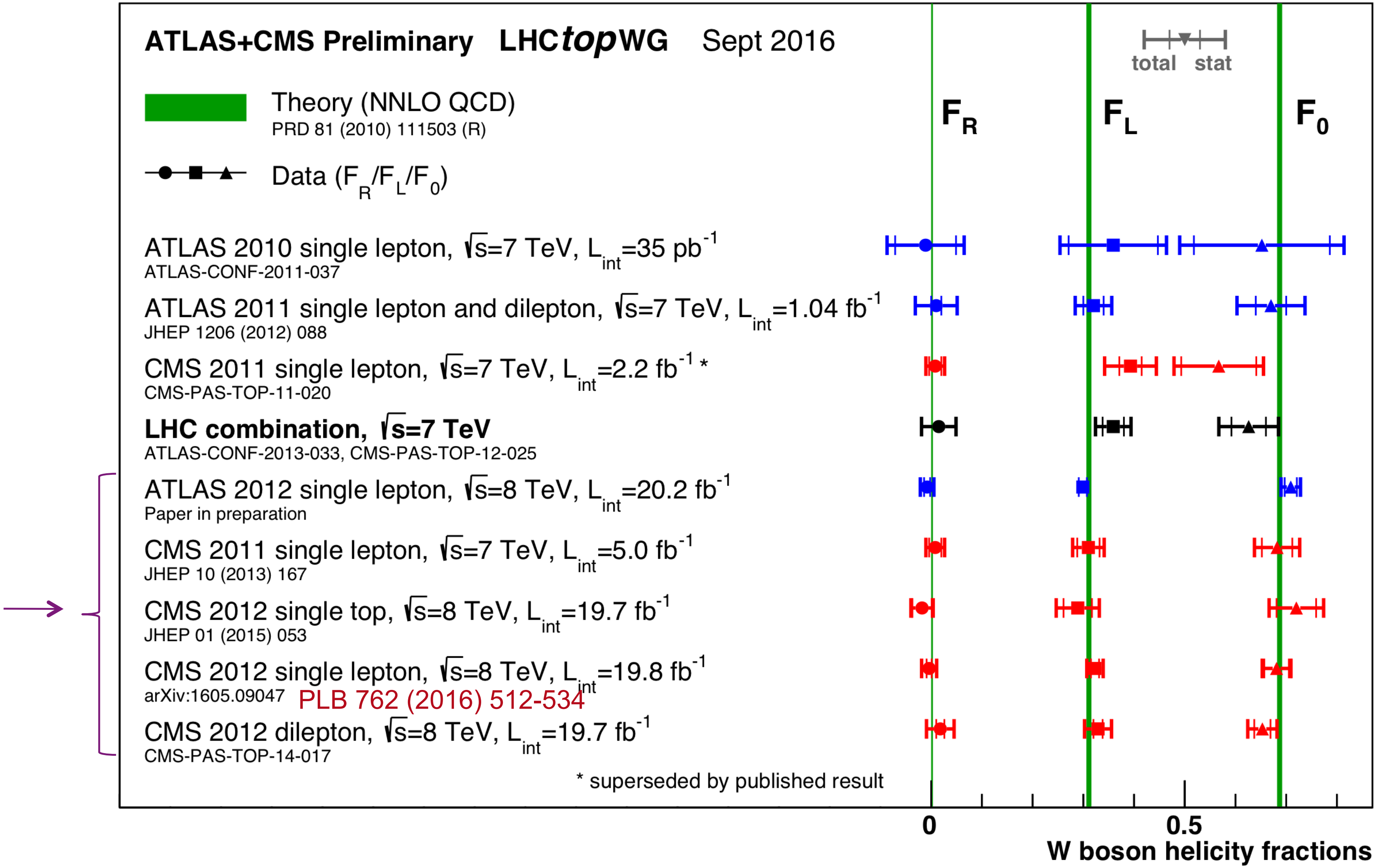
* ATLAS 7 TeV: dedicated F_0, F_R & F_L MC samples at LO
* ATLAS 8 TeV: by reweighting MC SM tt events

Reweighting



The number of expected events in a given bin is modified by reweighting each event in that bin by a factor *w*.

Latest LHC results



Latest LHC results

	7 TeV	8 TeV
ATLAS	**ttbar single lepton & dilepton** **1.04 fb^{-1} [JHEP 1206 (2012) 088]** F_0 = 0.67 ± 0.03 (stat.) ± 0.06 (syst.) F_L = 0.32 ± 0.02 (stat.) ± 0.03 (syst.) F_R = 0.01 ± 0.01 (stat.) ± 0.04 (syst.)	**ttbar single lepton** **20.2 fb^{-1} [Paper in preparation]** F_0 = 0.709 ± 0.012 (stat.*) ± 0.015 (syst.) F_L = 0.299 ± 0.008 (stat.*) ± 0.013 (syst.) F_R = -0.008 ± 0.006 (stat.*) ± 0.012 (syst.)
CMS	**ttbar single lepton** **5.0 fb^{-1} [JHEP 1310 (2013) 167]** F_0 = 0.682 ± 0.030 (stat.) ± 0.033 (syst.) F_L = 0.310 ± 0.022 (stat.) ± 0.022 (syst.) F_R = 0.008 ± 0.012 (stat.) ± 0.014 (syst.)	**ttbar single lepton** **19.8 fb^{-1} [PLB 762 (2016) 512-534]** 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.) **ttbar dilepton** **19.7 fb^{-1} [CMS-PAS-TOP-14-017]** F_0 = 0.653 ± 0.016 (stat.) ± 0.024 (syst.) F_L = 0.329 ± 0.009 (stat.) ± 0.025 (syst.) F_R = 0.018 ± 0.008 (stat.) ± 0.026 (syst.) **Single top** **19.7 fb^{-1} [JHEP 01 (2015) 053]** F_0 = 0.720 ± 0.039 (stat.) ± 0.037 (syst.) F_L = 0.298 ± 0.028 (stat.) ± 0.032 (syst.) F_R = -0.018 ± 0.019 (stat.) ± 0.011 (syst.)

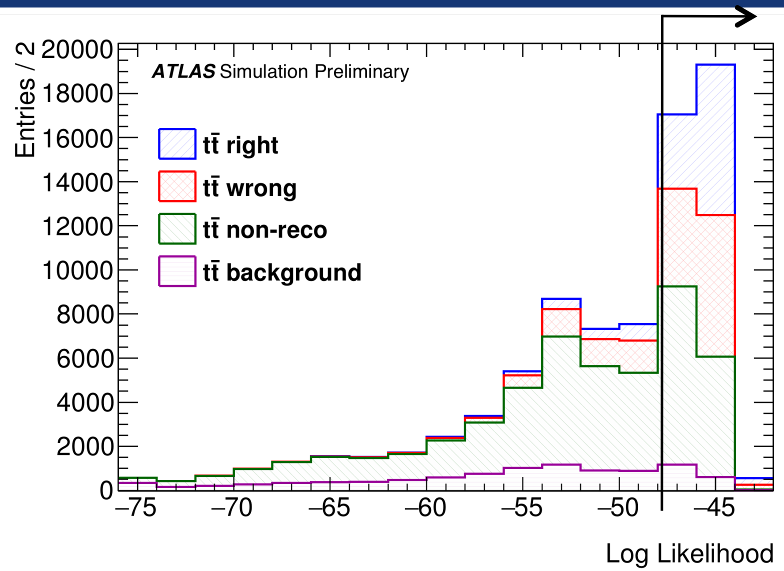
Latest LHC results

	7 TeV	8 TeV
ATLAS	**ttbar single lepton & dilepton** **1.04 fb^{-1} [JHEP 1206 (2012) 088]** F_0 = 0.67 ± 0.03 (stat.) ± 0.06 (syst.) F_L = 0.32 ± 0.02 (stat.) ± 0.03 (syst.) F_R = 0.01 ± 0.01 (stat.) ± 0.04 (syst.)	**ttbar single lepton** **20.2 fb^{-1} [Paper in preparation]** F_0 = 0.709 ± 0.012 (stat.*) ± 0.015 (syst.) F_L = 0.299 ± 0.008 (stat.*) ± 0.013 (syst.) F_R = -0.008 ± 0.006 (stat.*) ± 0.012 (syst.)
CMS	**ttbar single lepton** **5.0 fb^{-1} [JHEP 1310 (2013) 167]** F_0 = 0.682 ± 0.030 (stat.) ± 0.033 (syst.) F_L = 0.310 ± 0.022 (stat.) ± 0.022 (syst.) F_R = 0.008 ± 0.012 (stat.) ± 0.014 (syst.)	**ttbar single lepton** **19.8 fb^{-1} [PLB 762 (2016) 512-534]** 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.) **ttbar dilepton** **19.7 fb^{-1} [CMS-PAS-TOP-14-017]** F_0 = 0.653 ± 0.016 (stat.) ± 0.024 (syst.) F_L = 0.329 ± 0.009 (stat.) ± 0.025 (syst.) F_R = 0.018 ± 0.008 (stat.) ± 0.026 (syst.) **Single top** **19.7 fb^{-1} [JHEP 01 (2015) 053]** F_0 = 0.720 ± 0.039 (stat.) ± 0.037 (syst.) F_L = 0.298 ± 0.028 (stat.) ± 0.032 (syst.) F_R = -0.018 ± 0.019 (stat.) ± 0.011 (syst.)

ATLAS 8 TeV single lepton

Event selection

- Single lepton triggers
- Exactly one lepton (e/μ) with p_T > 25 GeV and $|\eta|<2.5$
- ≥ 4 jets with p_T > 25 GeV and $|\eta|<2.5$
  - ≥ 1 b-tagged
- E_T^{miss} > 20 GeV and $E_T^{miss} + m_T^W$ > 60 GeV for $N_{b\text{-}tag}=1$
- Cut on likelihood of reconstruction algorithm: Log $\mathcal{L}$ > -48



Event reconstruction

using an "extended kinematic likelihood fit" with KLFitter (referred to as "normalized event probability p_i) including p_T and *b*-tag weight of jets (for up/down-type quark separation):

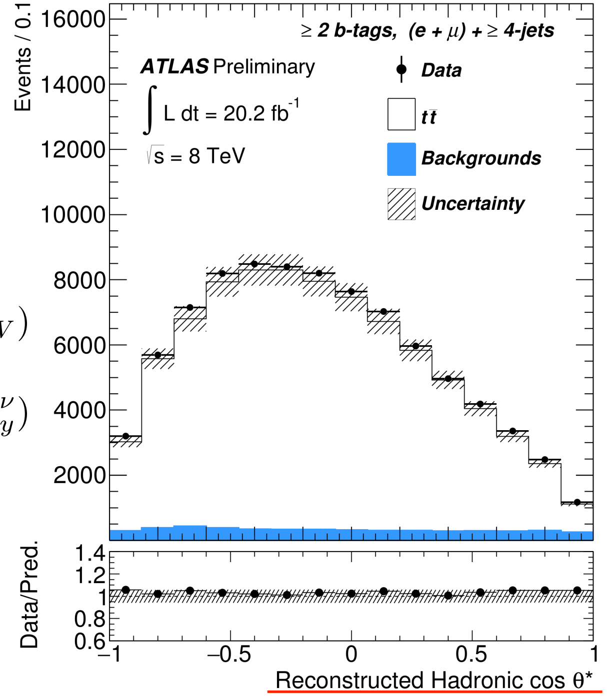
→ Optimized jet feeding:

- 2 jets with highest b-tag weight
- 2/3 further jets with highest p_T
- Best of 5! = 120 (24 for n_{jet} = 4) permutations is selected

$$\mathcal{L} = BW(m_{q1q2q3}|m_t,\Gamma_t)\cdot BW(m_{q1q2}|m_W,\Gamma_W)\cdot BW(m_{q4\ell\nu}|m_t,\Gamma_t)\cdot BW(m_{\ell\nu}|m_W,\Gamma_W)$$
$$\cdot\prod_{i=1}^{4} W_{\rm jet}(E_i^{\rm meas}|E_i)\cdot W_\ell(E_\ell^{\rm meas}|E_\ell)\cdot W_{\rm miss}(E_x^{\rm miss}|p_x^\nu)\cdot W_{\rm miss}(E_y^{\rm miss}|p_y^\nu)$$

$$p_i = \frac{\mathcal{L}_i \prod_j \Delta p_{i,j}}{\sum_i \mathcal{L}_i \prod_j \Delta p_{i,j}}$$

→ **leptonic analyzer**
→ **hadronic analyzer**



ATLAS 8 TeV single lepton

Template fit method (using reweighting)

- Signal templates (3: one for each helicity state)
  No dedicated F_i simulated samples available.
  Instead, reweighting SM ttbar sample using analytic expression.
- Background templates (5: W+light, c, bb/cc jets, QCD, rem.bkg.)

$$W_L = \frac{\frac{3}{8}(1-\cos\theta^*_{gen})^2}{f_L\cdot\frac{3}{8}(1-\cos\theta^*_{gen})^2 + f_0\cdot\frac{3}{4}(1-\cos^2\theta^*_{gen}) + f_R\cdot\frac{3}{8}(1+\cos\theta^*_{gen})^2}$$

$$W_0 = \frac{\frac{3}{4}(1-\cos^2\theta^*_{gen})}{f_L\cdot\frac{3}{8}(1-\cos\theta^*_{gen})^2 + f_0\cdot\frac{3}{4}(1-\cos^2\theta^*_{gen}) + f_R\cdot\frac{3}{8}(1+\cos\theta^*_{gen})^2}$$

$$W_R = \frac{\frac{3}{8}(1+\cos\theta^*_{gen})^2}{f_L\cdot\frac{3}{8}(1-\cos\theta^*_{gen})^2 + f_0\cdot\frac{3}{4}(1-\cos^2\theta^*_{gen}) + f_R\cdot\frac{3}{8}(1+\cos\theta^*_{gen})^2}$$

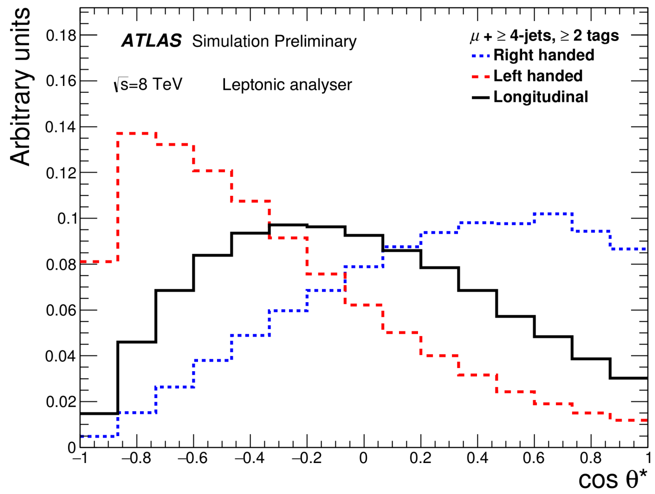
- Binned likelihood fit:

$$\mathscr{L} = \prod_{k=1}^{N_{\rm bins}} {\rm Poisson}(n_{{\rm data},k}, n_{{\rm exp},k}) \prod_{j=1}^{N_{\rm bkg}} \frac{1}{\sqrt{2\pi}\sigma_{{\rm bkg},j}} \exp\left(\frac{-(n_{{\rm bkg},j}-\hat{n}_{{\rm bkg},j})^2}{2\sigma^2_{{\rm bkg},j}}\right)$$

$$n_{\rm exp} = n_0 + n_{\rm L} + n_{\rm R} + n_{W+{\rm light}} + n_{W+c} + n_{W+bb/cc} + n_{\rm fake} + n_{\rm rem.\ bkg.}$$

- Fit parameters:
Yields of signal (n_0, n_L, n_R) and backgrounds (W+jets, fakes, rem.bkg.) allowed to float within their norm. unc.

Background	Norm. unc.
W + light jets	5 %
W + c	25 %
W + cc/bb	7 %
Fake leptons	30 %
Remaining background (Single top, Z+jets, VV)	16 % / 17 % (≥ 2b, ≥1b)



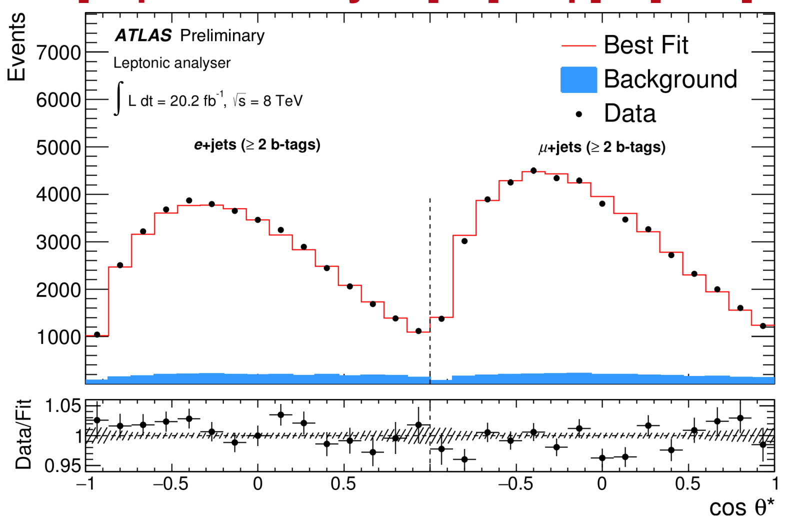
- Fractions are extracted as:

$$F_{\rm i} = \frac{N_i}{N_0+N_L+N_R}, \qquad n_i = \epsilon_i^{\rm sel} N_i \qquad \text{for i= 0, L, R.}$$

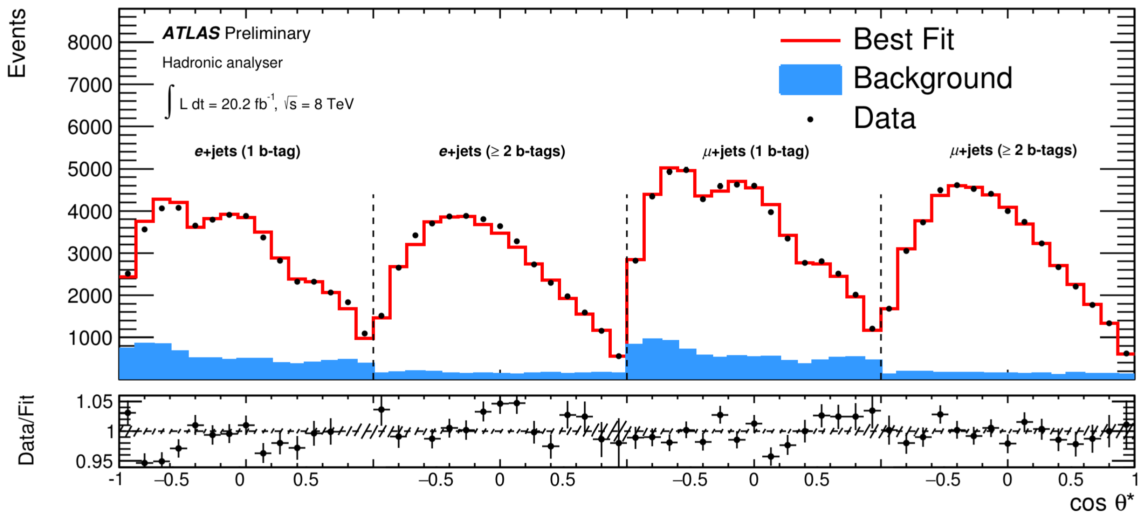
Results

- In total, 8 orthogonal channels; all possible combinations studied.
- Channel combination using simultaneous fit on the “glued-templates” (more bins).
- Best results obtained for each analyzer:
    - Leptonic: [e + μ] x [≥ 2b] → most sensitive / best result
    - Hadronic: [e + μ] x [1b + ≥ 2b]
    - Overall best combination: same as leptonic
    - Main syst. unc.: jet energy scale and resolution, ttbar modelling

[Leptonic analyzer] x [e + μ] x [≥ 2b]



[Hadronic analyzer] x [e + μ] x [1b + ≥2b]



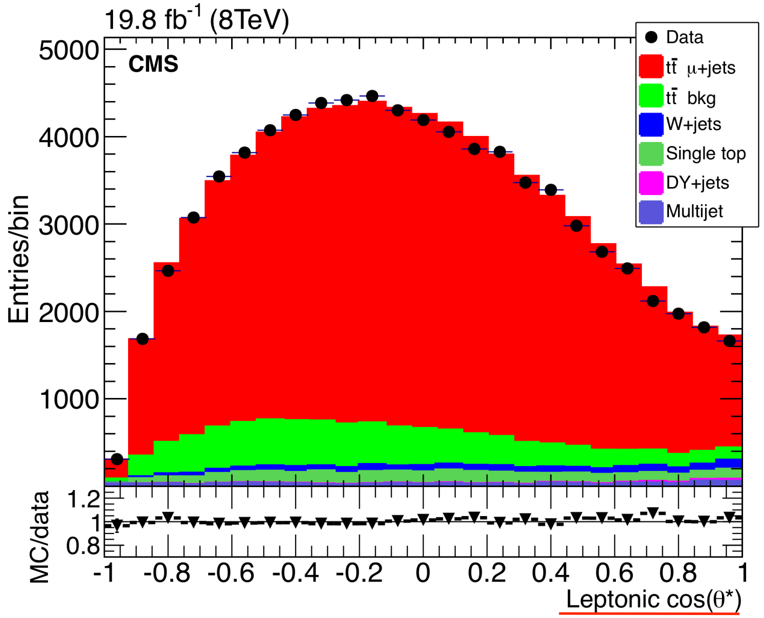
F_0 = 0.709 ± 0.012 (stat.+bkg.norm) ± 0.015 (syst.)
F_L = 0.299 ± 0.008 (stat.+bkg.norm) ± 0.013 (syst.)
F_R = -0.008 ± 0.006 (stat.+bkg.norm) ± 0.012 (syst.)

F_0 = 0.659 ± 0.010 (stat.+bkg.norm) ± 0.053 (syst.)
F_L = 0.281 ± 0.021 (stat.+bkg.norm) ± 0.065 (syst.)
F_R = 0.061 ± 0.022 (stat.+bkg.norm) ± 0.105 (syst.)

CMS 8 TeV single lepton

Event selection

- Single lepton triggers
- Exactly one lepton (e/μ) with p_T > 30/26 GeV and $|\eta|$<2.5/2.1
- At least 4 jets with $|\eta|$<2.4
  - increased p_T cut for first 4 jets: 55, 45, 25 and 20 GeV
  - at least two of them b-tagged (with p_T > 20 GeV)
- Cut on m_T^W: 30 < m_T^W < 200 GeV

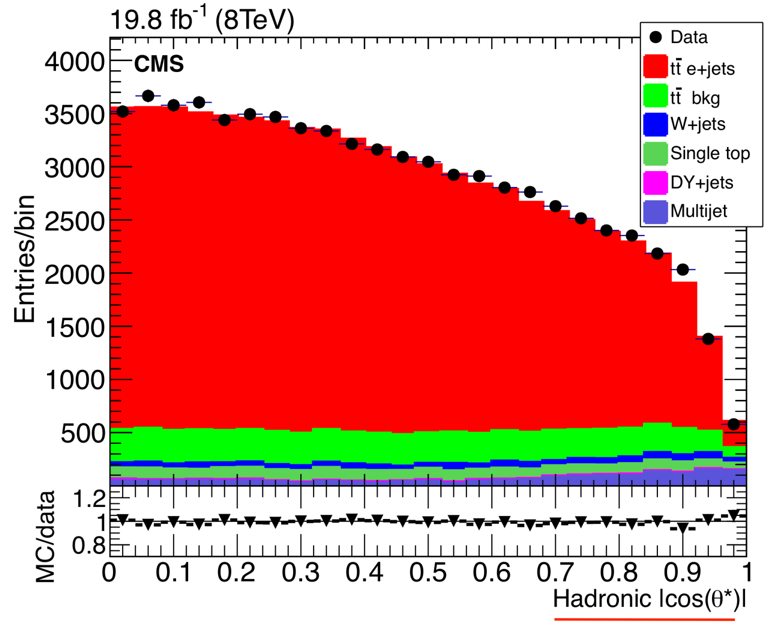


Event reconstruction

- using a kinematic fit:
  - p_z^ν determination using top & W masses constraints
  - jets and lepton momentum resolution taken into account

→ Final sample composition: 82% (e/μ+jets), 10% (other ttbar decays, with τ), 3.5% (single top), rest (other bkgs.)

→ Build $\cos\theta_l^*$ for the leptonic analyzer (for illustration, absolute value for hadronic analyzer also shown).



Reweighting method & binned likelihood fit

- Binned likelihood fit:

$$\mathcal{L}(\vec{F}) = \prod_i \frac{N_{MC}(i;\vec{F})^{N_{data}(i)}}{\left[N_{data}(i)\right]!} \exp\left[-N_{MC}(i;\vec{F})\right]$$

$$\begin{aligned} N_{MC}(i;\vec{F}) = \; & N_{t\bar{t}}(i;\vec{F}) \\ & + N_{single\text{-}t}(i;\vec{F}) \\ & + N_{W+jets}(i) \\ & + N_{DY+jets}(i) \\ & + N_{multijet}(i), \end{aligned}$$

where

$$N_{t\bar{t}}(i;\vec{F}) = \mathcal{F}_{t\bar{t}} \left[\sum_{t\bar{t}\text{ events in bin } i} w_{lep}(\cos\theta^*_{gen};\vec{F}) \times w_{had}(\cos\theta^*_{gen};\vec{F}) \right],$$

$$N_{single\text{-}t}(i;\vec{F}) = \sum_{\text{single-t events in bin } i} w_{single\text{-}t}(\cos\theta^*_{gen};\vec{F})$$

- Fit parameters: $\mathcal{F}_{tt}$, F_0, F_L ($F_R=1-F_0-F_L$)
- Background normalisation is fixed (its uncertainty is included as syst. unc.)

$$w_{lep/had/single\text{-}t}(\cos\theta^*_{gen};\vec{F}) \equiv \left[\frac{3}{8}F_L(1-\cos\theta^*_{gen})^2 + \frac{3}{4}F_0\sin^2\theta^*_{gen} + \frac{3}{8}F_R(1+\cos\theta^*_{gen})^2\right] \Big/ \left[\frac{3}{8}F_L^{SM}(1-\cos\theta^*_{gen})^2 + \frac{3}{4}F_0^{SM}\sin^2\theta^*_{gen} + \frac{3}{8}F_R^{SM}(1+\cos\theta^*_{gen})^2\right],$$

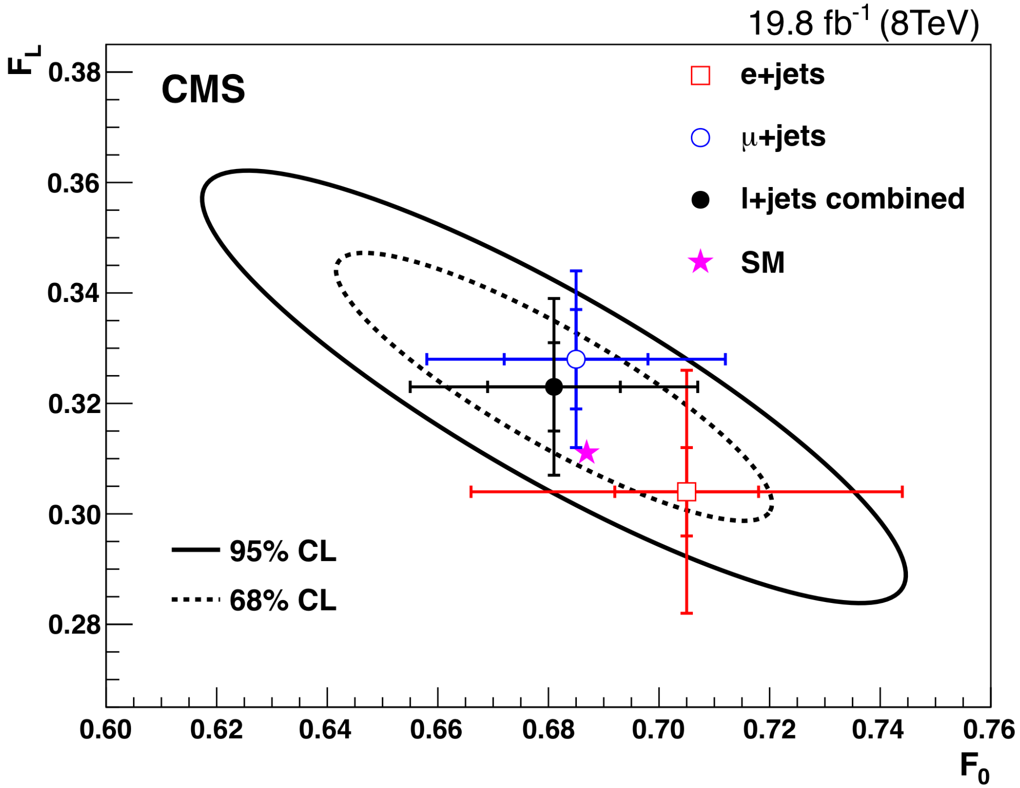
Background	Norm. unc.
Z + jets	±30 %
W + light jets	±30 %
W + heavy flavour	+100% / -50 %
Fake leptons	±50% (e), $^{+40\%}_{-50\%}$ (μ)
Single top	±30 %

Results

- Electron & muon channel are combined using BLUE.

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

with syst. $\rho_{0,L} = -0.87$



Systematic uncertainties

Main syst. unc.	ΔF_0	ΔF_L
Jet energy scale	0.005	0.003
W+jets bkg.	0.007	0.001
Fake leptons bkg.	0.008	0.001
top quark mass	0.010*	0.007*
tt ME scales	0.012*	0.007*
tt PS scale	0.009*	0.007*
tt ME, PS & hadr. MC	0.006	0.004
Total	0.023	0.014

* Stat. precision of the limited sample size is assigned as syst. variation.

Comparisons: results

Start with the combination in the single lepton channel.

- Both analyses use the same sensitive variable and channel: **leptonic analyzer with ≥ 2b jets**.
- Central values are quite close.
- Both comparable within the uncertainties with the SM predictions.
- Differences in the treatment and list of syst. unc. → differences in correlations btw. fractions and size of the uncertainties.
- Syst. uncertainty for ATLAS is smaller.

ttbar single lepton

20.2 fb^{-1} [Paper in preparation]

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.)

$\rho_{0,L} = -0.55$, $\rho_{0,R} = -0.75$, $\rho_{L,R} = +0.16$

ttbar single lepton

19.6 fb^{-1} [PLB 762, 2016] 512-534

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.)

$\rho_{0,L} = -0.87$

NNLO QCD calculation
Phys.Rev.D81:111503,2010

F_0 = 0.687 ± 0.005
F_L = 0.311 ± 0.005
F_R = 0.0017 ± 0.0001

Comparisons: strategy

ATLAS

- el/μ channel combination using simultaneous fit on the "glued-templates" (more bins).
- Bkg. normalisations: free floating parameters in the fit (unc. in table below).
- Syst. unc. estimated using ensemble tests: repeat fit using nominal templates and syst. varied pseudo-data.

CMS

- Reweighting also for single top quark events.
- el/μ channel combination with BLUE.
- Bkg. normalisations are fixed in the fit.
- Syst. effects* estimated changing the signal and bkg. templates and fitting to (nominal) data.

- Some differences in list of MC samples and syst. unc.

* ttbar signal modelling → ATLAS: Powheg(NLO)+Py6, CMS: MG5 (LO≤3p)+Py6
* bkg. norm. unc.
* jet vertex fraction (to suppress pile-up jets), jet reco. eff.

Background	Norm. unc.
W + light jets	5 %
W + c	25 %
W + cc/bb	7 %
Fake leptons	30 %
Remaining background (Single top, Z+jets, VV)	16 % / 17 % (≥ 2b, ≥1b)

Background	Norm. unc.
Z + jets	±30 %
W + light jets	±30 %
W + heavy flavour	+100% / -50 %
Fake leptons	±50% (e), $^{+40\%}_{-50\%}$ (μ)
Single top	±30 %

* Stat. precision of the limited sample size is assigned as syst. variation if it is larger than the latter.

Comparisons: systematic unc.

Source	ATLAS		CMS	
	F_0	F_L	F_0	F_L
Reconstructed objects				
Jet energy scale	+0.0063 / -0.0033	+0.0028 / -0.0025	±0.005	±0.003
Jet energy resolution	+0.0062 / -0.0059	+0.0048 / -0.0018	±0.003	±0.003
b-tagging efficiency	+0.0017 / -0.0021	+0.0012 / -0.0013	±0.001	<0.001
Electron/Muon efficiency	+0.0028 / -0.0030 +0.0024 / -0.0029	+0.0018 / -0.0020 +0.0013 / -0.0015	±0.001	±0.001
Jet vertex fraction	+0.0036 / -0.0017	+0.0019 / -0.0013	--	--
Jet reconstruction efficiency	+0.0002 / -0.0002	<0.0001 / <0.0001	--	--
Signal modelling				
Top quark mass	±0.0017	±0.0050	±0.010*	±0.007*
Showering & hadronisation	±0.0019 (P+P6 vs. P+HW)	±0.0019	±0.006 (MG5+Py6 vs. MC@NLO+HW)	±0.004
ME generator	±0.0025 (P+HW vs. MC@NLO+HW)	±0.0032		
PDF	±0.0033	±0.0042	±0.002	±0.001
ISR/FSR (PP6 with varied h_{damp}, μ_R & μ_F, P2012 tune)	±0.0033	±0.0058	--	--
μ_R & μ_F scales (MG5 LO)	--	--	±0.012*	±0.007*
Matching scale (MG5+Py6)	--	--	±0.009*	±0.007*
Method uncertainty				
MC statistics	±0.0091	±0.0056	±0.002	±0.001
Total systematics	+0.015 / -0.014	+0.013 / -0.012	±0.023** (w. bkg. norm.) ±0.020 (wo. bkg. norm.)	±0.014** (w. bkg. norm.) ±0.014 (wo. bkg. norm.)
Stat. + bkg. norm.	±0.012	±0.008	±0.012** (stat.) ±0.016 (stat.+bkg.norm)	±0.008** (stat.) ±0.008 (stat.+bkg.norm)

Limits on anomalous couplings

ATLAS:

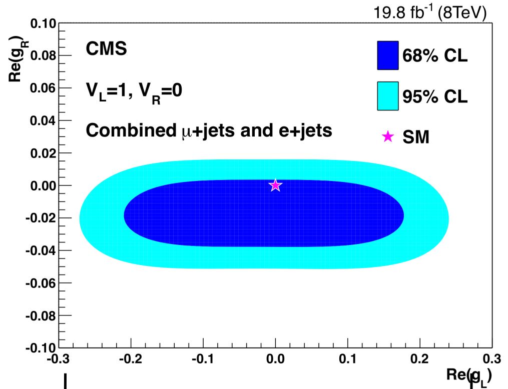
F_0 = 0.709 ± 0.012 (stat.+bkg.norm) ± 0.015 (syst.)
F_L = 0.299 ± 0.008 (stat.+bkg.norm) ± 0.013 (syst.)
F_R = -0.008 ± 0.006 (stat.+bkg.norm) ± 0.012 (syst.)

$\rho_{0,L} = -0.55,\ \rho_{0,R} = -0.75,\ \rho_{L,R} = +0.16$

CMS:

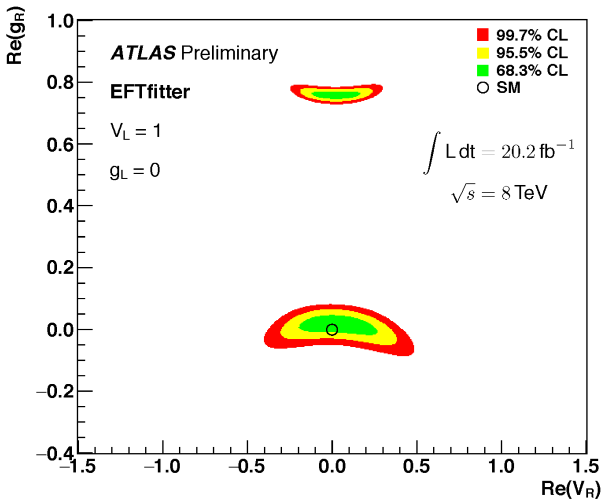
F_0 = 0.681 ± 0.012 (stat.) ± 0.023 (syst.)
F_L = 0.323 ± 0.008 (stat.) ± 0.014 (syst.)
F_R = -0.004 ± 0.005 (stat.) ± 0.014 (syst.)

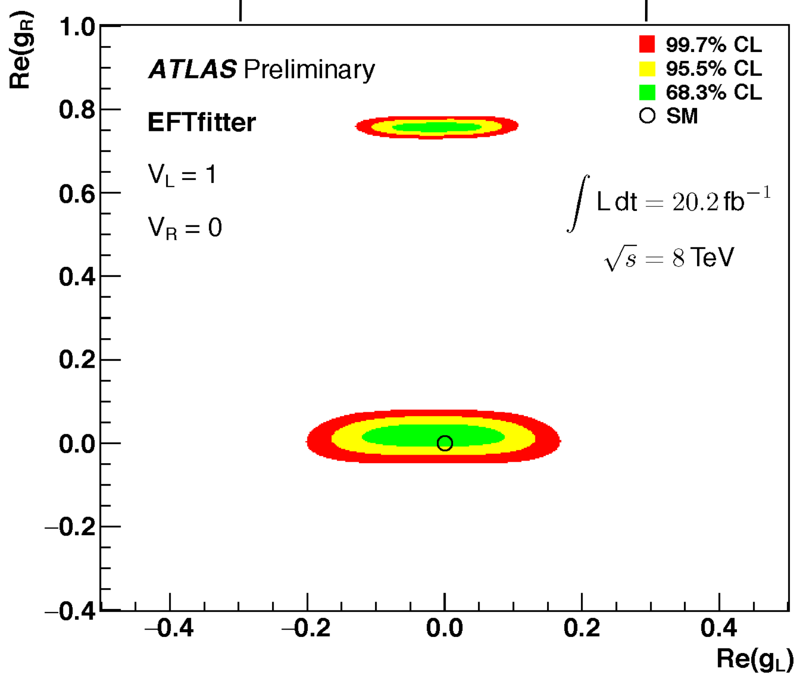
$\rho_{0,L} = -0.87$



ATLAS:

Coupling	95% CL limit
V_R	[-0.24, 0.31]
g_L	[-0.14, 0.11]
g_R	[-0.02, 0.06], [0.74, 0.78]





Summary

- Both ATLAS and CMS have new results in ttbar lepton+jets using leptonic analyzer
→ combination exercise could be started soon (person power?)

- Both comparable within the uncertainties with the SM predictions.
- Differences in strategy, correlations btw. fractions and size of the uncertainties:

ATLAS
- el/μ channel combination using simultaneous fit on the "glued-templates" (more bins).
- Bkg. norm.: free floating parameters in the fit

CMS
- Reweighting also for single top quark events.
- el/μ channel combination with BLUE.
- Bkg. normalisations are fixed in the fit.

- Differences in estimation of syst. unc.:
  * strategy
  * ttbar signal modelling
  * bkg. normalisation uncertainties
  * jet vertex fraction (to suppress pile-up jets), jet reco. eff.

BACK-UP

Comparisons: signal & bkg. modelling

ATLAS

Process	MC sample (ME+PS)	Normalisation
tt	Powheg (NLO, CT10 PDF)+Pythia6	NNLO+NNLL
Single top	Powheg (NLO, CT10 PDF)+Pythia6	aNNLO
W+jets	Alpgen (LO multileg ≤5p, CTEQ6L1 PDF) + Pythia6	Data-driven: ttbar charge asym. K_light = 0.80 +- 0.04 (5%) K_c = 1.07 +- 0.27 (25%) K_bb/K_cc = 1.50 +- 0.11 (7%)
Z+jets	Alpgen (LO multileg ≤5p, CTEQ6L1 PDF) + Pythia6	NNLO
Dibosons	Sherpa (LO multileg ≤3p, CT10 PDF) + Sherpa	NLO
Fake leptons	----	Data-driven: matrix method

CMS

Process	MC sample (ME+PS)	Normalisation
tt	MadGraph (LO multileg ≤3p, CTEQ6L1 PDF) +Pythia6	NNLO+NNLL
Single top	Powheg (NLO, CTEQ6M PDF)+Pythia6	aNNLO
W+jets	MadGraph (LO multileg ≤?p, CTEQ6L1 PDF) +Pythia6	NNLO
Z+jets	MadGraph (LO multileg ≤?p, CTEQ6L1 PDF) +Pythia6	NNLO
Fake leptons	Pythia6	Data-driven

Comparisons: systematic unc.

ATLAS

Uncertainties

Source	Leptonic analyzer ≥ 2 b-tags		
	F_0	F_L	F_R
Reconstructed objects			
Jet energy scale	+0.0063 / -0.0033	+0.0028 / -0.0025	+0.0037 / -0.0014
Jet energy reso.	+0.0062 / -0.0059	+0.0048 / -0.0018	+0.0071 / -0.0067
b tagging eff.	+0.0017 / -0.0021	+0.0012 / -0.0013	+0.0011 / -0.0012
Ele/Muon eff	+0.0028 / -0.0030 +0.0024 / -0.0029	+0.0018 / -0.0020 +0.0013 / -0.0015	+0.0011 / -0.0011 +0.0010/ -0.0015
Jet vertex fraction	+0.0036 / -0.0017	+0.0019 / -0.0013	+0.0017 / -0.0006
Jet reco. Eff.	+0.0002 / -0.0002	<0.0001 / <0.0001	+0.0002 / -0.0002
Signal modelling			
Top quark mass	±0.0017	±0.0050	±0.0033
PS & Hadr.	±0.0019	±0.0019	±0.0037
ME generator	±0.0025	±0.0032	±0.0057
ISR/FSR	±0.0033	±0.0058	±0.0034
PDF	±0.0033	±0.0042	±0.0009
Method uncertainty			
Template statistics	±0.0091	±0.0056	±0.0044
Total systematics	+0.015 / -0.014	+0.013 / -0.012	+0.013 / -0.012
Stat. + bkg. norm.	±0.012	±0.008	±0.006

CMS

	$\ell+$jets	
	$\pm\Delta F_0$	$\pm\Delta F_L$
JES	0.005	0.003
JER	0.003	0.003
b tagging eff.	0.001	$<10^{-3}$
Lepton eff.	0.001	0.001
Single top normal	0.003	0.001
$W+$jets bkg.	0.007	0.001
$DY+$jets bkg.	0.001	$<10^{-3}$
Multijet bkg.	0.008	0.001
Pileup	0.001	$<10^{-3}$
Top quark mass	0.010	0.007
$t\bar{t}$ scales	0.012	0.007
$t\bar{t}$ match. scale	0.009	0.007
$t\bar{t}$ MC and hadron	0.006	0.004
$t\bar{t}$ p_T reweight	$<10^{-3}$	0.002
Limited MC size	0.002	0.001
PDF	0.002	0.001
Total	0.023	0.014

Systematic unc.
- using ensemble tests
- pseudo-data for each systematic variation
- repeat fit using nominal templates and syst. varied pseudodata
- bkg. norm. directly evaluated in the fit

Uncertainties

Source	Leptonic analyzer ≥ 2 b-tags			Hadronic analyzer 1 b + ≥ 2 b-tags		
	F_0	F_L	F_R	F_0	F_L	F_R
Reconstructed objects						
Jet energy scale	+0.0063 / -0.0033	+0.0028 / -0.0025	+0.0037 / -0.0014	+0.0069 / -0.0070	+0.012 / -0.008	+0.014 / -0.005
Jet energy reso.	+0.0062 / -0.0059	+0.0048 / -0.0018	+0.0071 / -0.0067	+0.027 / -0.031	+0.033 / -0.041	+0.057 / -0.071
b tagging eff.	+0.0017 / -0.0021	+0.0012 / -0.0013	+0.0011 / -0.0012	+0.029 / -0.031	+0.013 / -0.014	+0.034 / -0.035
Ele/Muon eff	+0.0028 / -0.0030 +0.0024 / -0.0029	+0.0018 / -0.0020 +0.0013 / -0.0015	+0.0011 / -0.0011 +0.0010/ -0.0015	+0.0025 / -0.0021 +0.0026/ -0.0037	+0.0028 / -0.0038 +0.0046 / -0.0035	+0.0051 / -0.0058 +0.0072 / -0.0072
Jet vertex fraction	+0.0036 / -0.0017	+0.0019 / -0.0013	+0.0017 / -0.0006	+0.013 / -0.009	+0.0012 / -0.0046	+0.011 / -0.005
Jet reco. Eff.	+0.0002 / -0.0002	<0.0001 / <0.0001	+0.0002 / -0.0002	+0.0008 / -0.0008	+0.0004 / -0.0004	+0.0011 / -0.0011
Signal modelling						
Top quark mass	±0.0017	±0.0050	±0.0033	±0.0033	±0.0100	±0.0068
PS & Hadr.	±0.0019	±0.0019	±0.0037	±0.015	±0.001	±0.014
ME generator	±0.0025	±0.0032	±0.0057	±0.016	±0.024	±0.040
ISR/FSR	±0.0033	±0.0058	±0.0034	±0.018	±0.039	±0.057
PDF	±0.0033	±0.0042	±0.0009	±0.0010	±0.0020	±0.0020
Method uncertainty						
Template statistics	±0.0091	±0.0056	±0.0044	±0.0076	±0.0016	±0.0016
Total systematics	+0.015 / -0.014	+0.013 / -0.012	+0.013 / -0.012	+0.052 / -0.054	+0.063 / -0.067	+0.100 / -0.110
Stat. + bkg. norm.	±0.012	±0.008	±0.006	±0.010	±0.021	±0.022

Systematic uncertainties

	e + jets		μ + jets		ℓ + jets	
	$\pm\Delta F_0$	$\pm\Delta F_L$	$\pm\Delta F_0$	$\pm\Delta F_L$	$\pm\Delta F_0$	$\pm\Delta F_L$
JES	0.004	0.003	0.005	0.003	0.005	0.003
JER	0.001	0.002	0.004	0.003	0.003	0.003
b tagging eff.	0.001	$<10^{-3}$	0.001	$<10^{-3}$	0.001	$<10^{-3}$
Lepton eff.	0.001	0.002	0.001	0.001	0.001	0.001
Single top normal.	0.002	$<10^{-3}$	0.003	0.001	0.003	0.001
W + jets bkg.	0.008	0.001	0.007	0.001	0.007	0.001
DY + jets bkg.	0.002	$<10^{-3}$	0.001	$<10^{-3}$	0.001	$<10^{-3}$
Multijet bkg.	0.023	0.007	0.007	0.003	0.008	0.001
Pileup	0.001	0.001	$<10^{-3}$	$<10^{-3}$	0.001	$<10^{-3}$
Top quark mass	0.012	0.008	0.010 (*)	0.008 (*)	0.010	0.007
$t\bar{t}$ scales	0.011	0.008 (*)	0.014	0.007 (*)	0.012	0.007
$t\bar{t}$ match. scale	0.011 (*)	0.007 (*)	0.010	0.007	0.009	0.007
$t\bar{t}$ MC and hadronisation	0.015	0.009	0.005	0.003	0.006	0.004
$t\bar{t}$ p_T reweight	0.011	0.010	$<10^{-3}$	0.001	$<10^{-3}$	0.002
Limited MC size	0.002	0.001	0.002	0.001	0.002	0.001
PDF	0.004	0.001	0.002	0.001	0.002	0.001
Total	0.037	0.020	0.024	0.014	0.023	0.014

W helicity: CMS 8 TeV ttbar dilepton

Systematics uncertainty	ΔF_L	ΔF_0
Lepton ID and trigger	< 0.001	< 0.001
b tagging	0.001	0.002
Background normalisations	0.002	0.005
Jet energy resolution	0.003	0.002
Jet energy scale	0.002	0.009
Top p_T reweighting	0.007	0.010
Factorization/renormalization scales (signal)	0.013	0.010
Factorization/renormalization scales (DY)	0.004	0.007
Hadronization model	0.006	0.008
Jet-parton matching	0.017	0.012
Top mass ($\pm 1 \text{GeV}/c^2$)	0.004	0.005
Pileup	0.001	< 0.001
PDF	< 0.001	< 0.001
Integrated luminosity	0.001	< 0.001
Limited simulated signal statistics	0.003	0.004
Total uncertainty	0.025	0.024

W helicity: CMS 8 TeV single top

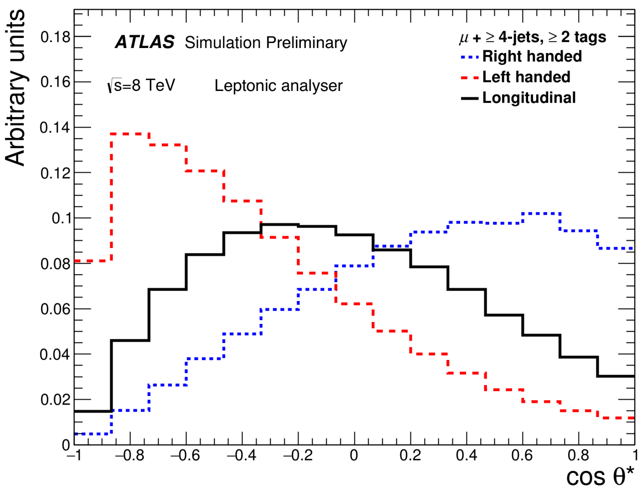
	Muon channel		Electron channel		Combination	
	ΔF_0	ΔF_L	ΔF_0	ΔF_L	ΔF_0	ΔF_L
Experimental	0.010	0.009	0.008	0.005	0.010	0.010
Modeling	0.025	0.017	0.025	0.022	0.025	0.020
Normalization	0.002	0.008	0.012	0.014	0.011	0.012
SM W helicities	0.007	0.004	0.005	0.003	0.007	0.004
MC sample size	0.026	0.012	0.025	0.015	0.020	0.012
tWb in prod.	0.014	0.016	0.010	0.018	0.011	0.014
Total	0.041	0.030	0.040	0.036	0.037	0.032

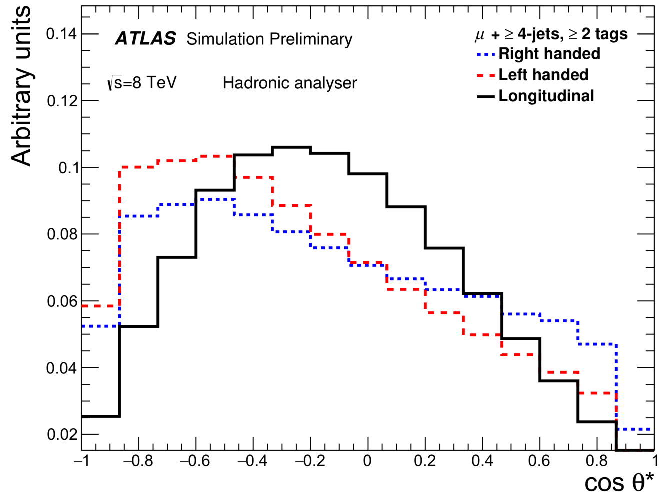
$$F_L = 0.298 \pm 0.028\,(\text{stat}) \pm 0.032\,(\text{syst}),$$
$$F_0 = 0.720 \pm 0.039\,(\text{stat}) \pm 0.037\,(\text{syst}),$$

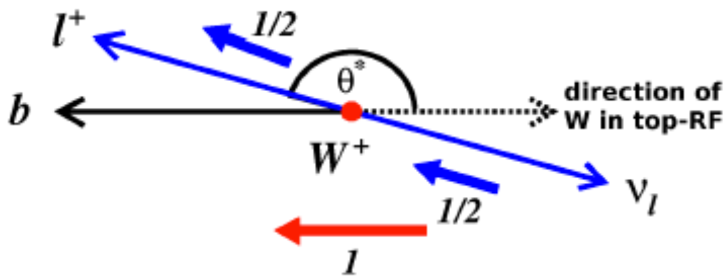
total correlation of **−0.80**

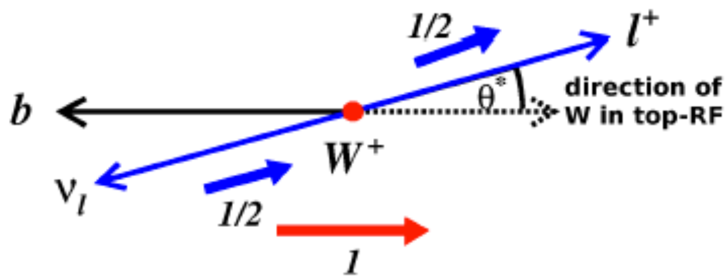
$$F_R = -0.018 \pm 0.019\,(\text{stat}) \pm 0.011\,(\text{syst}),$$

W helicity







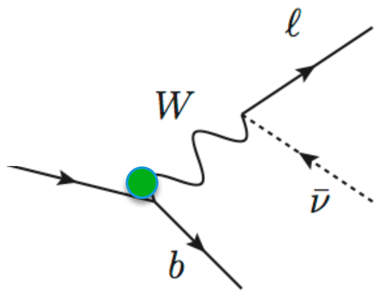


- cosθ* ~ -1: corresponds to events in which the charged lepton is emitted backward to the direction of motion of the W boson and thus parallel to the b-quark momentum.
The strong suppression of events after event selection can be linked to the event-selection requirements on the charged lepton candidates: isolation and the cut on its momentum.

- cosθ* ~ +1 corresponds to events in which the neutrino is emitted backward with respect to the direction of motion of the W boson and thus in the same direction as the b-quark. Therefore the momentum of the neutrino (and thus also the missing transverse energy) decreases and these events are more likely to fail the missing transverse energy cut. Mismeasurements on this also affect the angular distribution.

The *Wtb* vertex Lagrangian:

$$SM \Rightarrow \qquad L_{Wtb}^{SM} = -\frac{g}{\sqrt{2}} \bar{u}_b \gamma^\mu V_{tb} P_L u_t W_\mu^+ + \text{h.c.}$$



A general extension:

Nucl.Phys. B812 (2009) 181-204
Eur.Phys.J. C50 , 519 (2007)

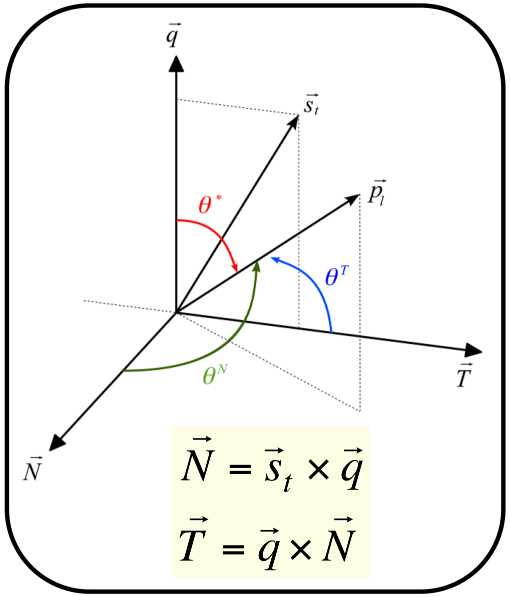
$$L_{Wtb} = -\frac{g}{\sqrt{2}} \bar{u}_b \gamma^\mu (V_L P_L + V_R P_R) u_t W_\mu^+ - \frac{g}{\sqrt{2}} \bar{u}_b \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (g_L P_L + g_R P_R) u_t W_\mu^+ + \text{h.c.}$$

$SM \Rightarrow$ $V_L = V_{tb} \sim 1$ $\quad V_R = g_L = g_R = 0$

$V_{L,R}$ and $g_{L,R}$

left and right - handed vector and tensor couplings

Angular observables to probe the *Wtb* vertex:



Nucl. Phys. B 840(2010)349

- For unpolarised top quark decays, the only meaningful direction in the top RF is the one of the *W* boson momentum (q)

- For polarised (spin direction s_t) top quarks produced via electroweak interaction, further directions may be considered: N and T.

- Three angular distributions: θ_l^*(q,l), θ_l^N(N,l) and θ_l^T(T,l)

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_l^X} = \frac{3}{8}(1+\cos\theta_l^X)^2 \mathbf{F}_+^\mathbf{X} + \frac{3}{8}(1-\cos\theta_l^X)^2 \mathbf{F}_-^\mathbf{X} + \frac{3}{4}\sin^2\theta_l^X \mathbf{F}_0^\mathbf{X}$$

$$A_{FB}^X = \frac{N(\cos\theta_l^X > 0) - N(\cos\theta_l^X < 0)}{N(\cos\theta_l^X > 0) + N(\cos\theta_l^X < 0)} \propto \left(F_+^X - F_-^X\right)$$

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

$$W_L = \frac{\frac{3}{8}(1-cos\theta^*_{gen})^2}{f_L\cdot\frac{3}{8}(1-cos\theta^*_{gen})^2 + f_0\cdot\frac{3}{4}(1-cos^2\theta^*_{gen}) + f_R\cdot\frac{3}{8}(1+cos\theta^*_{gen})^2}$$

$$W_0 = \frac{\frac{3}{4}(1-cos^2\theta^*_{gen})}{f_L\cdot\frac{3}{8}(1-cos\theta^*_{gen})^2 + f_0\cdot\frac{3}{4}(1-cos^2\theta^*_{gen}) + f_R\cdot\frac{3}{8}(1+cos\theta^*_{gen})^2}$$

$$W_R = \frac{\frac{3}{8}(1+cos\theta^*_{gen})^2}{f_L\cdot\frac{3}{8}(1-cos\theta^*_{gen})^2 + f_0\cdot\frac{3}{4}(1-cos^2\theta^*_{gen}) + f_R\cdot\frac{3}{8}(1+cos\theta^*_{gen})^2}$$