Polarisation measurements in single-top-quark production and decay at LHC run-1

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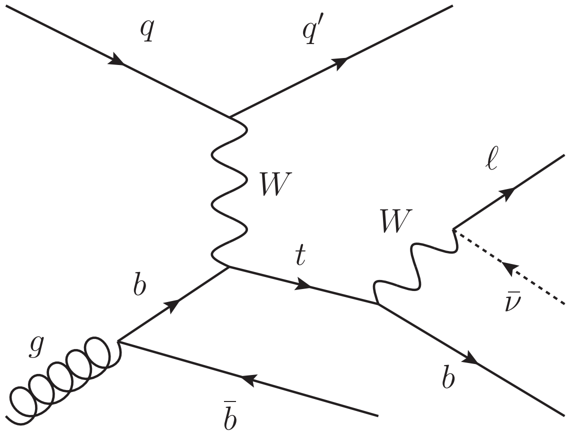
Top LHC-France, 4-5 May 2017, Marseille

Polarisation in single-top-quark production and decay

- The electroweak top-quark production processes lead to polarised top quarks due to the V-A form of the Wtb vertex
- In the t-channel process (exchange of a space-like W boson, dominant mechanism) the produced top quarks are highly polarised along the direction of the spectator quark: predicted degree of polarisation $\sim 90\%$
- The electroweak decay of the produced top quarks $t \to Wb$ leads to real W bosons, also polarised (helicity states)
- The top-quark and W-boson polarisations can be measured from angular distributions of the decay products: W boson, b-quark, or charged lepton (e or μ) from the W-boson leptonic decay $W \to l\nu$
- The charged lepton is the most powerful spin analyser for the measurement of the top-quark and W boson polarisations



Polarisation and anomalous Wtb couplings

- Measuring top-quark and W-boson polarisation observables in the t-channel provides a powerful probe for studying the Wtb vertex in both top-quark production and decay
- New physics effects resulting in corrections to the Wtb vertex would affect the polarisation values Most general form of the Wtb Lagrangian in the effective operator formalism

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}}\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_{W}}\left(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}}\right)tW_{\mu}^{-} + \mathrm{h.c.}$$

- Standard Model (tree level): $V_{\mathrm{L}} = V_{tb} \approx 1$ - all other couplings $V_{\mathrm{R}}, g_{\mathrm{L}}, g_{\mathrm{R}} = 0$ Deviations from these values would provide hints of physics beyond the SM. In particular, complex values would imply that the Wtb vertex has CP-violating components
- The top-quark and W-boson polarisation observables can all be expressed/parametrised as a function of the four couplings (with separation of their real and imaginary parts). This makes possible to set limits/constraints on the anomalous couplings or to directly measure them

J.A. Aguilar-Saavedra et al.: arXiv:1005.5382,1208.6006, 1404.1585, 1508.04592

Top-quark polarisation observable

The top-quark polarisation can be determined from the angular distribution of the charged lepton relatively to the direction of the spectator quark (top-quark spin axis) in the top-quark rest frame: measurement of the longitudinal polarisation P or of the spin asymmetry $A_l = \frac{1}{2}\alpha_l P$

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_\ell} = \frac{1}{2}\{1 + \alpha_\ell P \cos\theta_\ell\}$$

- Spin analysing power for the charged lepton: $\alpha_{l^\pm} = \pm 0.998$ at NLO. This value can be modified in presence of anomalous Wtb couplings
- Different values of P are expected for top-quarks and antitop-quarks: 0.91 for t and -0.86 for $\bar{t}$ at NLO. These two values can be modified differently in presence of anomalous Wtb couplings

W-boson spin observables

The W-boson polarisation is determined from the angular distribution of the charged lepton in the W-boson rest frame relatively to the W-boson direction (W-boson spin axis) and to the spectator-quark direction (top-quark spin axis) in the top-quark rest frame

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

- The coefficients of the various angular terms define six spin observables for the W boson
- The two spin observables $\langle T_0\rangle, \langle S_3\rangle$ are related to the well-known three helicity fractions $F_\mathrm{R}, F_\mathrm{L}, F_0$. They are mainly sensitive to $\mathrm{Re}g_\mathrm{R}$
- The four other spin observables $\langle S_{1,2}\rangle, \langle A_{1,2}\rangle$ combine the longitudinal top-quark polarisation P and the W-boson polarisation. The SM prediction is 0 for $\langle S_2\rangle$ and $\langle A_2\rangle$. They are only sensitive to $\mathrm{Im}g_\mathrm{R} \Longrightarrow$ observables of great interest to search for a CP-violating contribution
- Integrations of the two-dimensional decay rate over appropriately chosen angles or combinations of angles lead to angular distributions containing only one or two of the six spin observables as angular coefficients. Integration over ϕ_l^* gives

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_\ell^*} = \frac{1}{2}+\frac{3}{4\sqrt{6}}\langle T_0\rangle(3\cos^2\theta_\ell^*-1)+\frac{3}{4}\langle S_3\rangle\cos\theta_\ell^* = \frac{3}{4}F_0\sin^2\theta_\ell^*+\frac{3}{8}F_\mathrm{L}(1-\cos\theta_\ell^*)^2+\frac{3}{8}F_\mathrm{R}(1+\cos\theta_\ell^*)^2$$

Polarisation observable measurements

Various methods used to measure the top-quark and W-boson polarisation observables after applying event selection, reconstructing the four-momenta of the W-boson and top-quark candidates, and taking into account the background

- Unfolding technique applied to obtain the distribution of a given angular observable at parton level from the measured one
  - Applied unfolding corrections (resolution, efficiency) determined from simulation (SM parameters)
  - Polarisation observable associated with a given angular observable extracted either from a χ^2-fit or from a particular asymmetry of the unfolded distribution
- Folding technique applied to fit the measured angular distribution using detector-level templates corresponding to the different angular terms
  - Template distributions determined from simulation (SM parameters) by re-weighting the parton-level angular distribution (templates including the resolution and selection effects)
  - Polarisation observables extracted from a binned likelihood fit: coefficients associated with the re-weighted templates are parameters of the fit
- Analytic folding procedure applied to fit directly the measured differential decay rate
  - Signal and $t\bar{t}$ background distributions, efficiency and resolution functions modelled via series in spherical harmonics
  - Polarisation observables extracted from a unbinned likelihood fit. Direct measurement of the couplings also performed
- The measurements of several polarisation observables can be combined to extract limits on anomalous couplings. The most commonly used tool is the TopFit program (arXiv:1005.5382): it is based on a χ^2 test statistic and implements the various polarisation observables as a function of the $V_{\mathrm{L,R}}, g_{\mathrm{L,R}}$ couplings

Measurement of the W-boson helicity fractions at $8\ \mathrm{TeV}$

JHEP01 (2015) 053

- Events selected with t-channel single-top-quark topology: 1 electron or 1 muon, 2 jets with 1 b-jet among them
- Template-fit of the measured distribution in $cos\theta_l^*$ to extract the three helicity fractions. Templates computed with a POWHEG (NLO) + PYTHIA sample of t-channel events
- Background shapes taken from simulation, except data-driven multijet
- Best fit values and exclusion limits at 68% and 95% CL set on $\mathrm{Re}g_L$ and $\mathrm{Re}g_R$, assuming $V_L = 1, V_R = \mathrm{Im}g_L = \mathrm{Im}g_R = 0$ (TopFit)

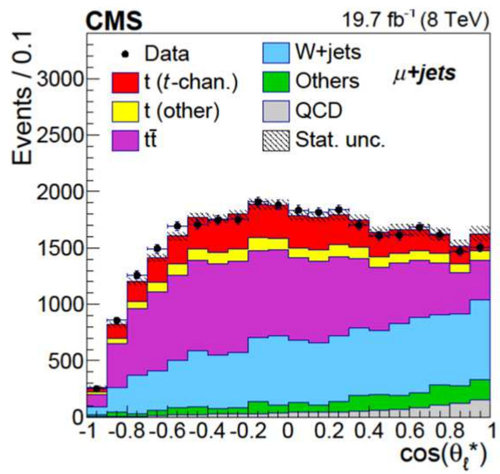
Results consistent with the SM expectations

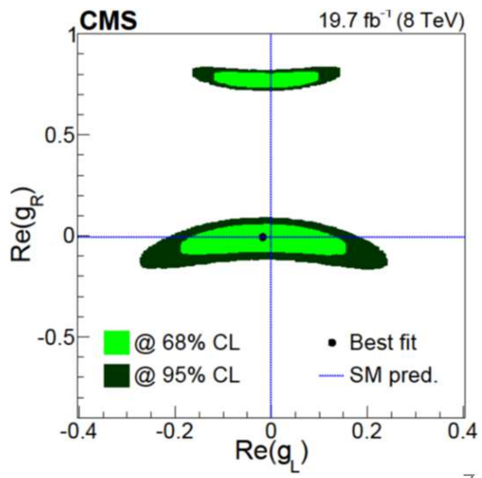
$F_{\mathrm{L}} = 0.298 \pm 0.028(\mathrm{stat}) \pm 0.032(\mathrm{syst})$

$F_0 = 0.720 \pm 0.039(\mathrm{stat}) \pm 0.037(\mathrm{syst})$

$F_{\mathrm{R}} = -0.018 \pm 0.019(\mathrm{stat}) \pm 0.011(\mathrm{syst})$

Best fit: $\mathrm{Re}g_L = -0.017, \quad \mathrm{Re}g_R = -0.008$





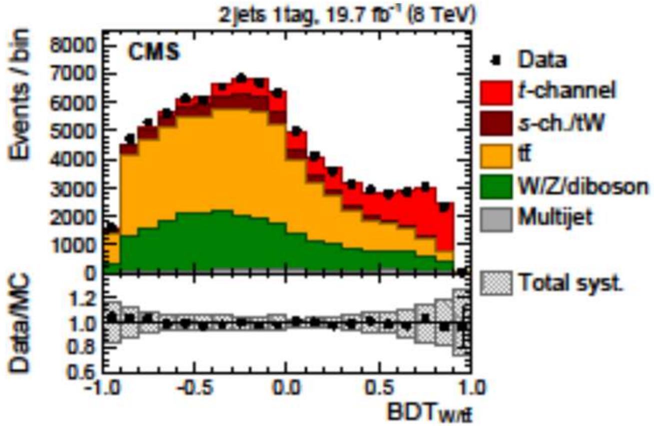
Measurement of top-quark polarisation in t-channel at $8\ \mathrm{TeV}$

JHEP04 (2016) 073

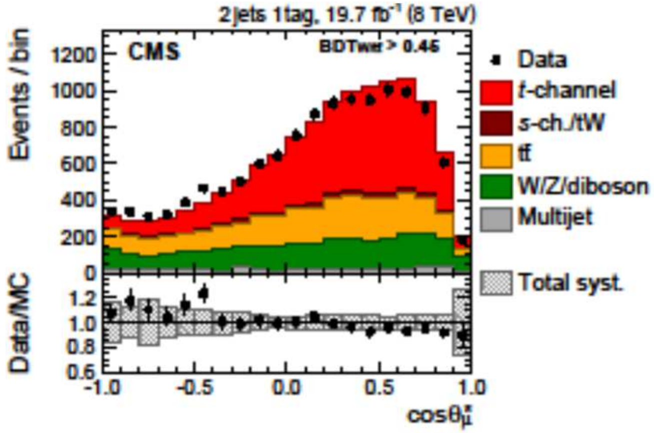
- Only muon as top-quark spin analyser
- Multivariate discriminants (BDTs) used to reject background events and to select signal events. Signal region $BDT_{W/t\bar{t}} > 0.45$
- Unfolding to parton level of the measured distribution in $cos\theta_\mu$ followed by a χ^2-fit to extract the spin asymmetry A_μ
- Unfolding corrections computed with POWHEG + PYTHIA Measurement bias test performed by using COMPHEP samples generated with anomalous Wtb couplings: small bias accounted for as a systematic uncertainty

$$A_\mu(t) = 0.29 \pm 0.03(\mathrm{stat}) \pm 0.10(\mathrm{syst})$$
$$A_\mu(\bar{t}) = 0.21 \pm 0.05(stat) \pm 0.13(\mathrm{syst})$$
$$A_\mu(t+\bar{t}) = 0.26 \pm 0.03(\mathrm{stat}) \pm 0.10(\mathrm{syst})$$

Compatible with a p-value of 4.6% (2.0σ) with the SM prediction of 0.44



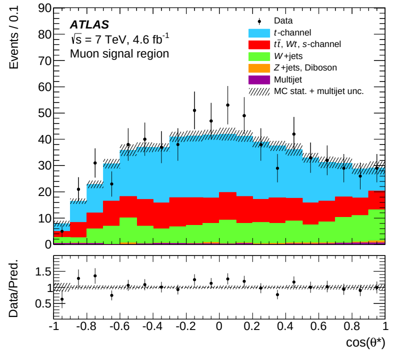
Signal region: $BDT_{W/t\bar{t}} > 0.45$

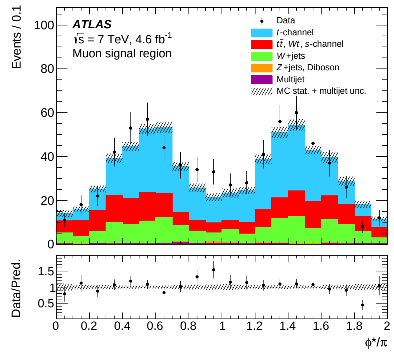


Search for anomalous couplings in t-channel at $7\ \mathrm{TeV}$

JHEP04 (2016) 023

- One lepton (e or μ) and 2 jets with 1 b-tag - Cut-based analysis
- Signal angular distribution modelled through a series in spherical harmonics in θ_l^* and ϕ_l^* with coefficients parameterised in terms of polarisation observables or of combinations of the Wtb couplings (with V_{R} and g_L assumed to be 0)
- Efficiency and resolution modelling also as a series of spherical harmonics
  Background modelling also through a series in spherical harmonics
- Efficiency and resolution corrections derived from $\mathrm{PROTOS} + \mathrm{PYTHIA}$ t-channel samples - The background model uses $\mathrm{PROTOS}\ t\bar{t}$ events
- Efficiency, resolution and background models constructed such that any dependences on the polarisation/coupling values are removed
- Maximum-likelihood fit to extract coupling values or polarisation parameters: fraction $f_1 = F_{\mathrm{R}} + F_{\mathrm{L}}$, mainly sensitive to $\mathrm{Re}g_{\mathrm{R}}$, and phase $\delta_- = arctan\frac{\langle S_2\rangle + 2\langle A_2\rangle}{\langle S_1\rangle + 2\langle A_1\rangle}$, only sensitive to $\mathrm{Im}g_{\mathrm{R}}$





Results compatible with the SM expectations at LO

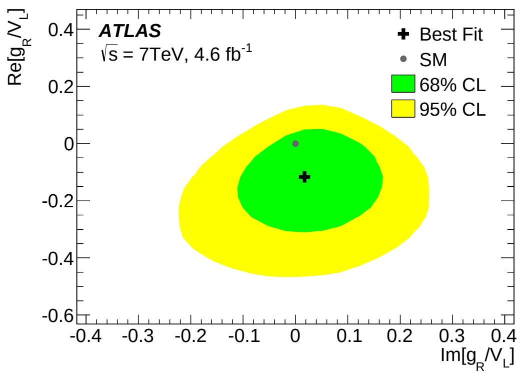
$f_1 = 0.37 \pm 0.07\ (0.304 \text{ in SM})$, $\delta_- = -0.014\pi \pm 0.036\pi\ (0 \text{ in SM})$

$\mathrm{Re}[g_{\mathrm{R}}/V_{\mathrm{L}}] = -0.13 \pm 0.07(\mathrm{stat}) \pm 0.10(\mathrm{syst})$

$\mathrm{Im}[g_{\mathrm{R}}/V_{\mathrm{L}}] = 0.03 \pm 0.06(\mathrm{stat}) \pm 0.07(\mathrm{syst})$

95% CL exclusion limits

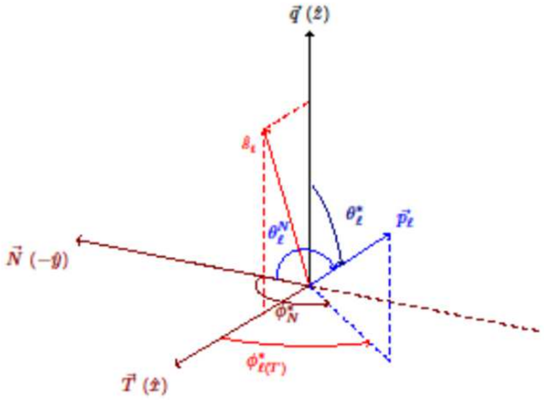
$\mathrm{Re}[g_{\mathrm{R}}/V_{\mathrm{L}}] \in [-0.36, 0.10]$, $\mathrm{Im}[g_{\mathrm{R}}/V_{\mathrm{L}}] \in [-0.17, 0.23]$



Probing the Wtb structure in t-channel at $8\ \mathrm{TeV}$

JHEP04 (2017) 124

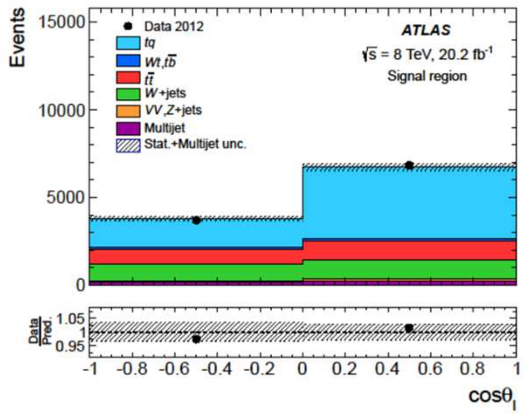
- One lepton (e or μ) and 2 jets with 1 b-tag - Cut-based analysis
- Unfolding to parton level of the measured distribution in various angular observables - Extraction of the corresponding polarisation observable from its forward-backward or edge-central asymmetry

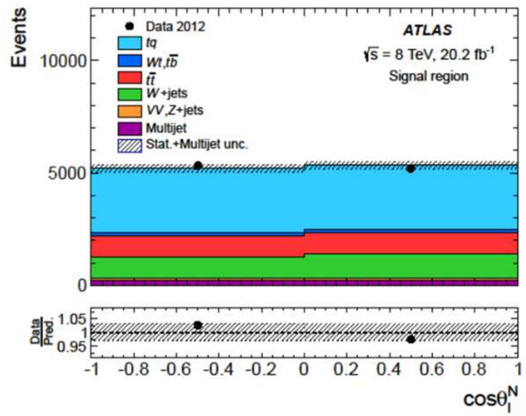


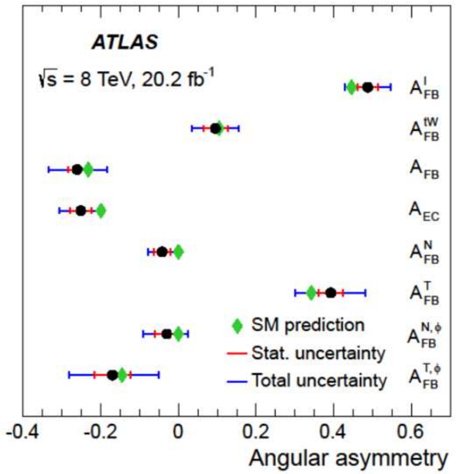
Asymmetry	Angular observable	Polarisation observable	SM prediction
A_{FB}^{ℓ}	$\cos\theta_\ell$	$\frac{1}{2}\alpha_\ell P$	0.45
A_{FB}^{tW}	$\cos\theta_W \cos\theta_\ell^*$	$\frac{3}{8}P(F_{\mathrm{R}}+F_{\mathrm{L}})$	0.10
A_{FB}	$\cos\theta_\ell^*$	$\frac{3}{4}\langle S_3\rangle = \frac{3}{4}(F_{\mathrm{R}}-F_{\mathrm{L}})$	−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
$A_{\mathrm{FB}}^{T,\phi}$	$\cos\theta_\ell^* \cos\phi_T^*$	$-\frac{2}{\pi}\langle A_1\rangle$	−0.14
$A_{\mathrm{FB}}^{N,\phi}$	$\cos\theta_\ell^* \cos\phi_N^*$	$\frac{2}{\pi}\langle A_2\rangle$	0

- Unfolding corrections computed with $\mathrm{PROTOS\ (LO) + PYTHIA}$ t-channel samples. SM parametrisation used for all observables except for $\langle S_2\rangle$ - Interpolation procedure in that case with PROTOS samples generated with varied values of $\mathrm{Im}g_{\mathrm{R}}$, in order to measure $\langle S_2\rangle$ independently of any assumption. Negligible dependence upon the couplings found in the measurement of $\alpha_l P$

Probing the Wtb structure in t-channel at 8 TeV







Measured asymmetries and polarisation observables in agreement with SM predictions: overall compatibility of all asymmetries with a p-value of 0.94 (0.83 for the W-boson spin observables)

Limits at 95% CL (TopFit) by combining $\alpha_l P(A_{\mathrm{FB}}^{l})$ and $\langle S_2\rangle(A_{\mathrm{FB}}^{N})$

$$\mathrm{Im}\, g_{\mathrm{R}} \in [-0.18, 0.06]$$

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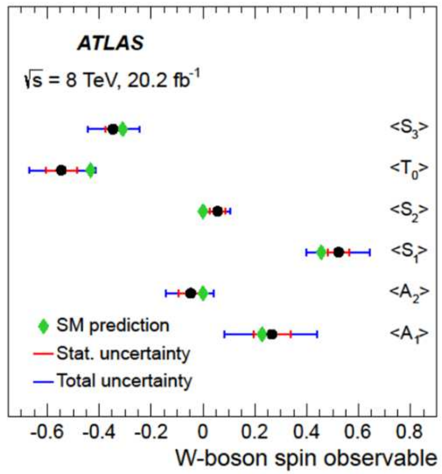

Conclusions and perspectives

- First « precision » polarisation measurements in single-top-quark production and decay at run-1 provided by the ATLAS and CMS collaborations
- Powerful probe to constrain anomalous Wtb contributions, in particular CP-violating ones through the measurements of observables only sensitive to $\mathrm{Im}g_{\mathrm{R}}$
- Include these measurements and the future run-2 ones in more global fits: all single-top-quark cross-sections and polarisation results together with W-boson helicity fraction measurements from $t\bar{t}$ analyses. This needs to properly take into account measurement correlations and dependences of the efficiency corrections on the couplings
- Interpretation will be extended to the more general framework of effective field theories (EFTs). Will include the four-fermion contributions in single-top-quark production