Top quark pair property measurements and $t\bar{t}+X$, using the ATLAS detector at the LHC

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Top quark properties at ATLAS

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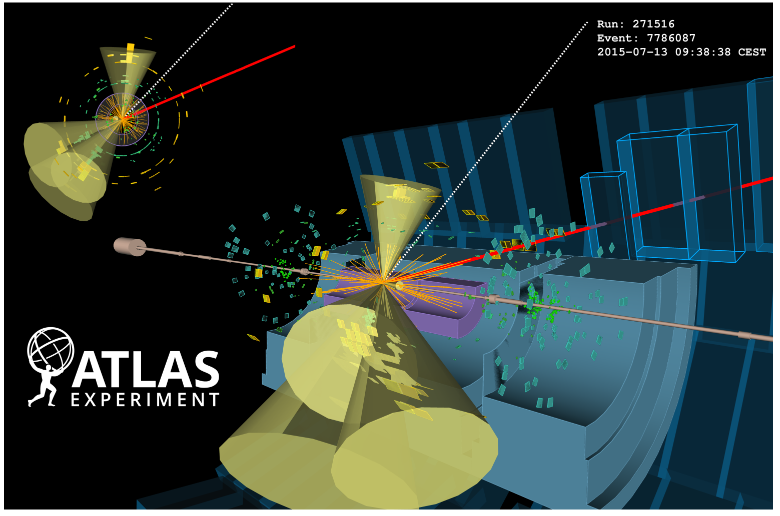
- ~40 millions of $t\bar{t}$ events produced at the ATLAS detector
- Era of precision measurements for top quark physics
- Measurements of top quark properties as tests of Standard Model
- Possibility of probing new observables and extending existing analysis approaches



Publications since last DIS

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1) Measurements of **top quark spin observables** in $t\bar{t}$ events using **dilepton** final states in 8 TeV *pp* collisions with the ATLAS detector: [JHEP 03 (2017) 113]
2) Measurements of the **charge asymmetry** in top-quark pair production in the **dilepton** final state at 8 TeV with the ATLAS detector: [Phys. Rev. D 94, 032006]
3) Measurements of **charge and CP asymmetries in *b*-hadron decays** using top-quark events collected by the ATLAS detector in *pp* collisions at 8 TeV: [JHEP02(2017)071]
4) Measurement of the ***W* boson polarisation** in $t\bar{t}$ events from pp collisions at 8 TeV in the **lepton+jets** channel with ATLAS: *submitted to EPJC* [arXiv:1612.02577]
5) Measurement of the **$t\bar{t}Z$ and $t\bar{t}W$ production cross sections** in multilepton final states using 3.2 fb^{-1} of *pp* collisions at 13 TeV at the LHC: [Eur. Phys. J. C (2017) 77: 40.]

Top Quark Spin Observables (1)

- 8 TeV, 20.2 fb^{-1}, dilepton channel of $t\bar{t}$ decays
- Top quark spin is correlated, strength quantified by quantisation axis and production process
- Spin information is transferred to decay products
  → use angular observables of decay products

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+^a \, d\cos\theta_-^b} = \frac{1}{4}(1 + B_+^a\cos\theta_+^a + B_-^b\cos\theta_-^b - C(a,b)\cos\theta_+^a\cos\theta_-^b)$$

$$B^a = 3 < \cos\theta^a >$$

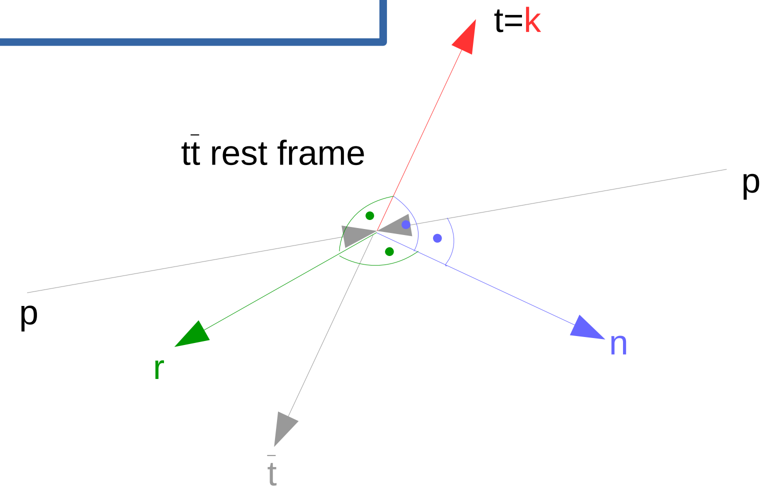
6 polarisation coefficients

$$C(a,b) = -9 < \cos\theta_+^a \cos\theta_-^b >$$

9 spin correlation coefficients

10 measured for the first time!

k: helicity axis
n: transverse axis
r: r-axis



Top Quark Spin Observables (2)

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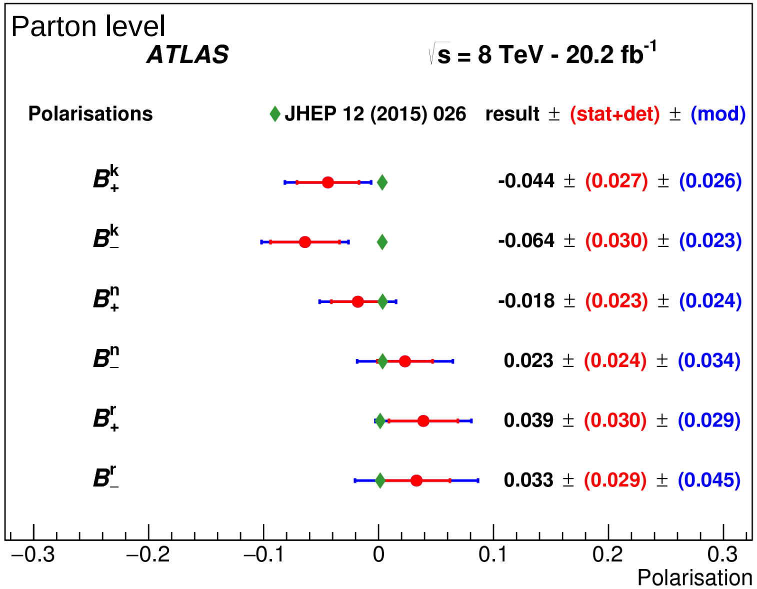
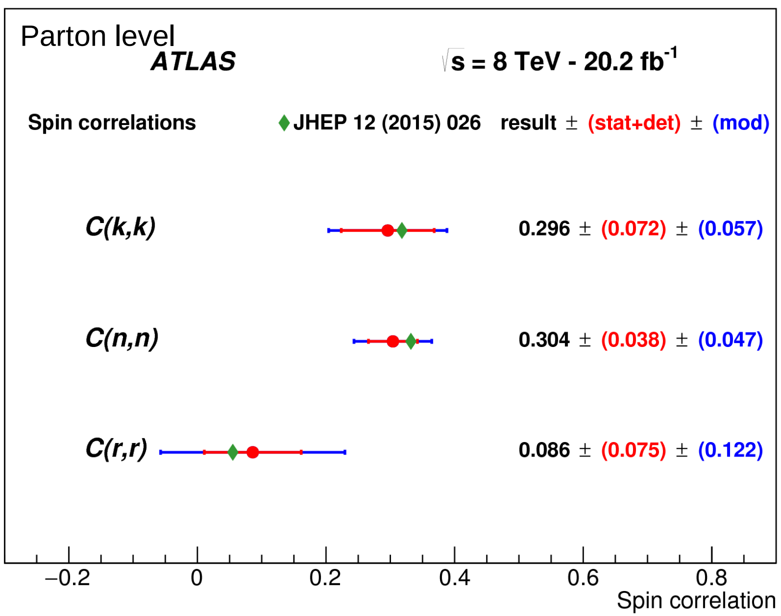
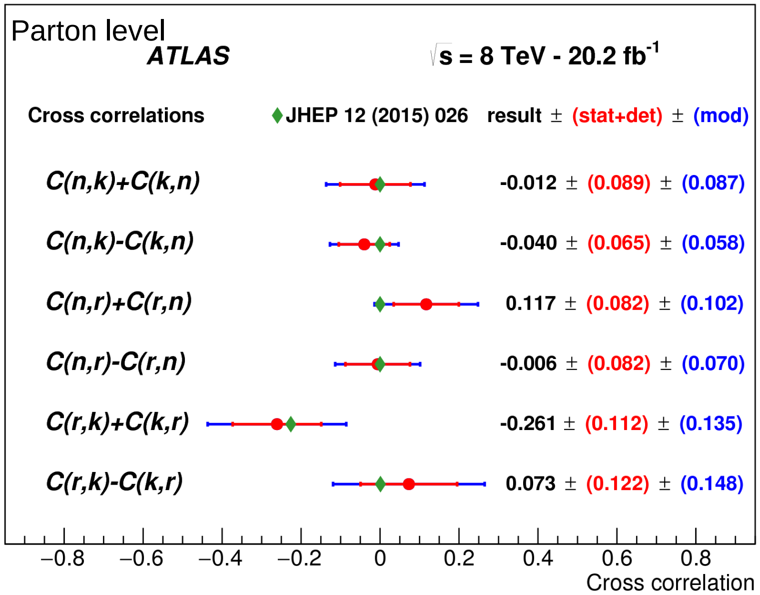
- 2 different analyses:
  - parton level (full phase space)
  - stable particle level (fiducial space)
- $t\bar{t}$ reconstruction using neutrino weighting technique
- Fully Bayesian unfolding to deal with distortions due to cuts and detector resolution
- No significant deviation from SM
- Observation of *C*(n,n) with 5.1σ







Charge Asymmetry in dilepton (1)

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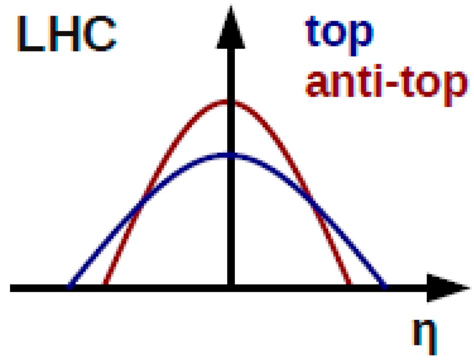

- 8 TeV, 20.3 fb^{-1}, dilepton channel of $t\bar{t}$ decays
- Asymmetries expected from valence quark – sea antiquark fusion
  → antitop more central than top

Leptonic asymmetries:

$$A_C^{\ell\ell} = \frac{N(\Delta|\eta| > 0) - N(\Delta|\eta| < 0)}{N(\Delta|\eta| > 0) + N(\Delta|\eta| < 0)}, \quad \Delta|\eta| = |\eta_{\ell^+}| - |\eta_{\ell^-}|$$

$t\bar{t}$ asymmetries:

$$A_C^{t\bar{t}} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}, \quad \Delta|y| = |y_t| - |y_{\bar{t}}|$$

3 different measurements of both observables:

- inclusive measurements on parton level in the full pase space
- inclusive measurements on particle level in the fiducial region
- differential measurements:
  inv. mass ($m_{t\bar{t}}$), $p_{T,t\bar{t}}$, and longitudinal boost ($\beta_{z,t\bar{t}}$) of $t\bar{t}$ system
  in the fiducial regions and the full phase space

Charge Asymmetry in dilepton (2)

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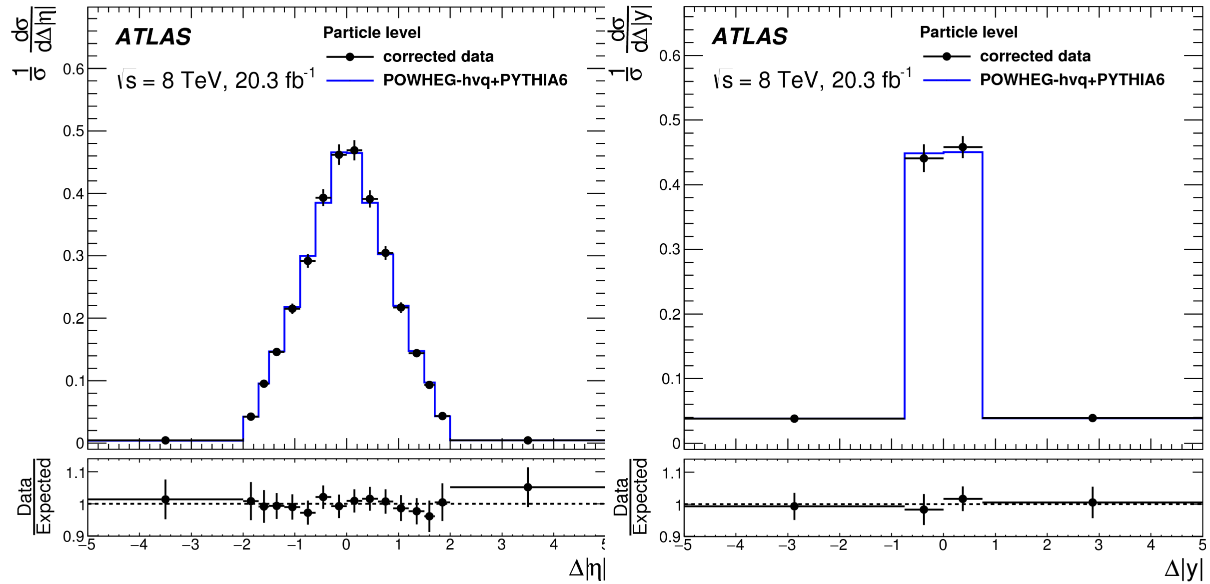
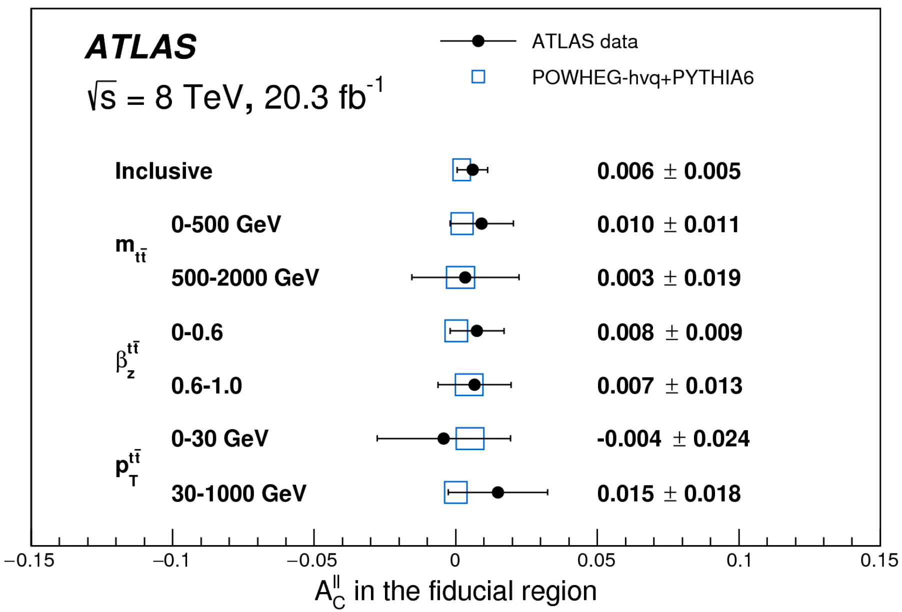
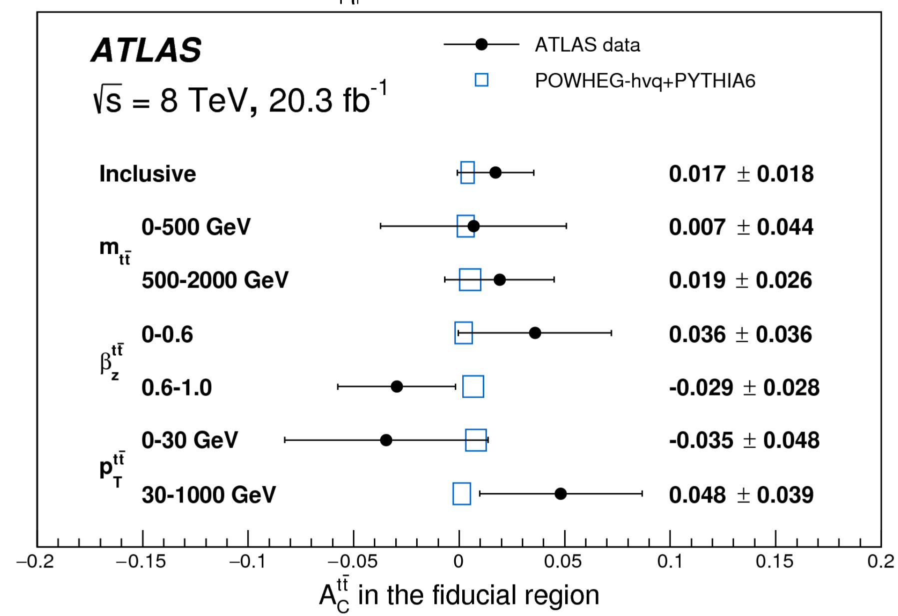
- Kinematic reconstruction of $t\bar{t}$ system
- Fully Bayesean unfolding
- Result: $A_C^{\ell\ell} = 0.008 \pm 0.006$, $A_C^{t\bar{t}} = 0.021 \pm 0.016$
- SM prediction: $A_C^{\ell\ell} = 0.0064 \pm 0.0003$, $A_C^{t\bar{t}} = 0.0111 \pm 0.0004$

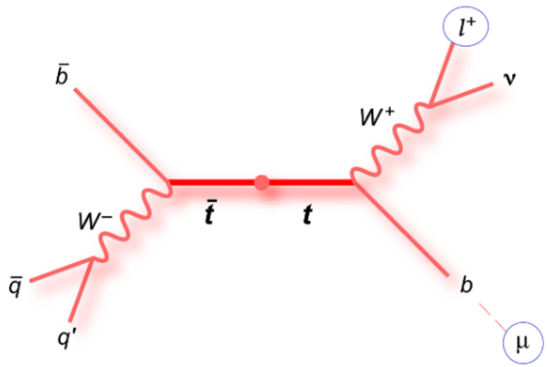


Unfolded distributions in fiducial volume

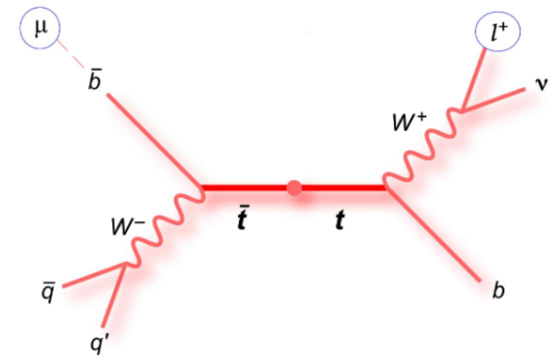




Charge and CP asymmetries in b-decay (1)



(a) Same-top SMT muon



(b) Different-top SMT muon

- 8 TeV, ℓ+jets, *b* decaying semileptonically to a soft muon
- 5 CP asymmetries, 2 charge asymmetries
- charge of lepton from *W* determines the charge of the produced *b*-quark
- charge of soft lepton determines the charge of *b*-quark at decay

Charge asymmetries

$$A^{\mathrm{ss}} = \frac{P\left(b \to \ell^+\right) - P\left(\bar{b} \to \ell^-\right)}{P\left(b \to \ell^+\right) + P\left(\bar{b} \to \ell^-\right)}$$

$$A^{\mathrm{os}} = \frac{P\left(b \to \ell^-\right) - P\left(\bar{b} \to \ell^+\right)}{P\left(b \to \ell^-\right) + P\left(\bar{b} \to \ell^+\right)}$$

CP asymmetries: B_q-$\bar{B}_q$ mixing

$$A^{b\ell}_{\mathrm{mix}} = \frac{\Gamma\left(b \to \bar{b} \to \ell^+ X\right) - \Gamma\left(\bar{b} \to b \to \ell^- X\right)}{\Gamma\left(b \to \bar{b} \to \ell^+ X\right) + \Gamma\left(\bar{b} \to b \to \ell^- X\right)}$$

$$A^{bc}_{\mathrm{mix}} = \frac{\Gamma\left(b \to \bar{b} \to \bar{c} X\right) - \Gamma\left(\bar{b} \to b \to c X\right)}{\Gamma\left(b \to \bar{b} \to \bar{c} X\right) + \Gamma\left(\bar{b} \to b \to c X\right)}$$

CP asymmetries: direct CP violation

$$A^{b\ell}_{\mathrm{dir}} = \frac{\Gamma\left(b \to \ell^- X\right) - \Gamma\left(\bar{b} \to \ell^+ X\right)}{\Gamma\left(b \to \ell^- X\right) + \Gamma\left(\bar{b} \to \ell^+ X\right)}$$

$$A^{bc}_{\mathrm{dir}} = \frac{\Gamma\left(b \to c X_L\right) - \Gamma\left(\bar{b} \to \bar{c} X_L\right)}{\Gamma\left(b \to c X_L\right) + \Gamma\left(\bar{b} \to \bar{c} X_L\right)}$$

$$A^{c\ell}_{\mathrm{dir}} = \frac{\Gamma\left(\bar{c} \to \ell^- X_L\right) - \Gamma\left(c \to \ell^+ X_L\right)}{\Gamma\left(\bar{c} \to \ell^- X_L\right) + \Gamma\left(c \to \ell^+ X_L\right)}$$

Charge and CP asymmetries in b-decay (2)

- Soft muon heavy flavour tagging (SMT muons)
- Data is unfolded to well defined fiducial space
- CP result cannot disprove DØ deviation in dimuon asymmetry
  → result both compatible with SM and DØ results

	Data (10^{-2})		MC (10^{-2})		Existing limits (2σ) (10^{-2})		SM prediction (10^{-2})	
A^{ss}	-0.7	$\pm\ 0.8$	0.05	$\pm\ 0.23$	-		$< 10^{-2}$	[19]
A^{os}	0.4	$\pm\ 0.5$	-0.03	$\pm\ 0.13$	-		$< 10^{-2}$	[19]
A^{b}_{mix}	-2.5	$\pm\ 2.8$	0.2	$\pm\ 0.7$	< 0.1	[95]	$< 10^{-3}$	[96] [95]
$A^{b\ell}_{dir}$	0.5	$\pm\ 0.5$	-0.03	$\pm\ 0.14$	< 1.2	[94]	$< 10^{-5}$	[19] [94]
$A^{c\ell}_{dir}$	1.0	$\pm\ 1.0$	-0.06	$\pm\ 0.25$	< 6.0	[94]	$< 10^{-9}$	[19] [94]
A^{bc}_{dir}	-1.0	$\pm\ 1.1$	0.07	$\pm\ 0.29$	-		$< 10^{-7}$	[97]

First direct measurements of direct CP violation in this context,
improve existing limits of indirect measurements

W boson polarisation (1)

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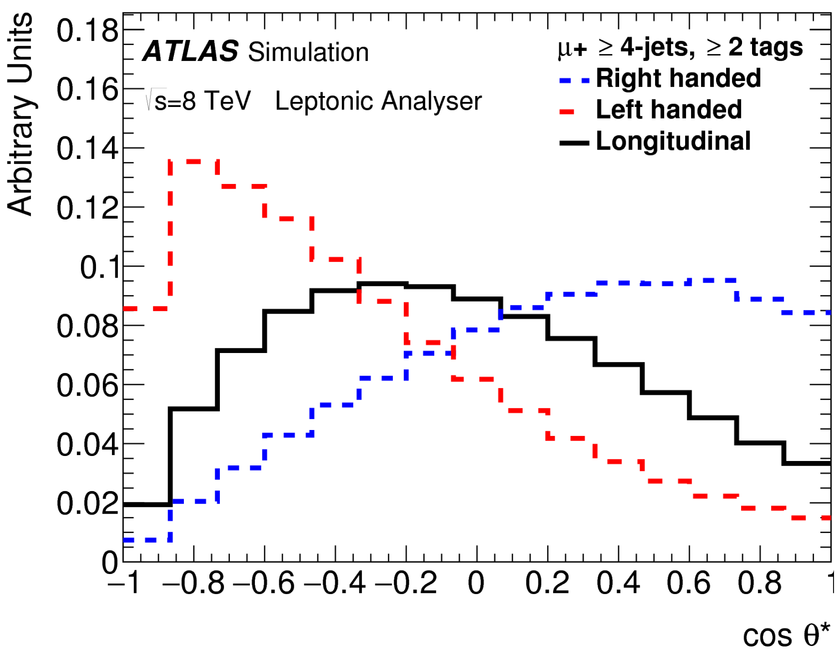
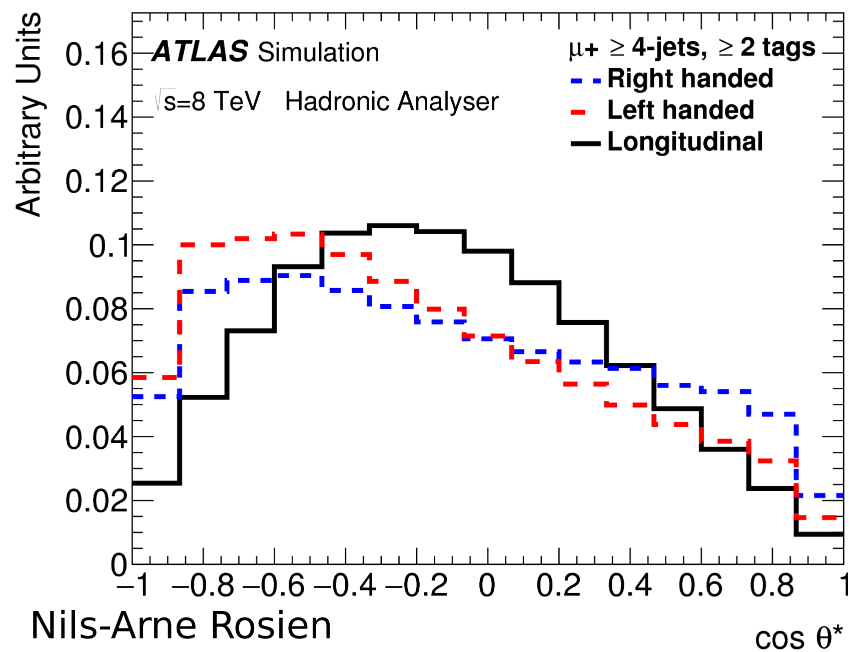
- 8 TeV, lepton+jets channel, 20.2 fb^{-1}
- Most precise *W* boson polarisation measurement to date
- Use orientation of analyser wrt. the b quark (inv. direction) in the *W* rest frame of top decay

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

- Take both charged lepton or down-type quark from *W* decay as analyser
- 3 reweighted $t\bar{t}$ samples for F_L, F_R, F_0 + bkg. samples





W boson polarisation (2)

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- KLFitter $t\bar{t}$ reconstruction [Nucl. Instrum. Meth. A 748 (2014) 18–25]
- Perform template fit
- Best fits (=smallest uncertainty):
  - two channel combination (ejets+mujets, ≥2b) for leptonic analyser
  - four channel combination (ejets+mujets, =1b and ≥2b) for hadronic analyser

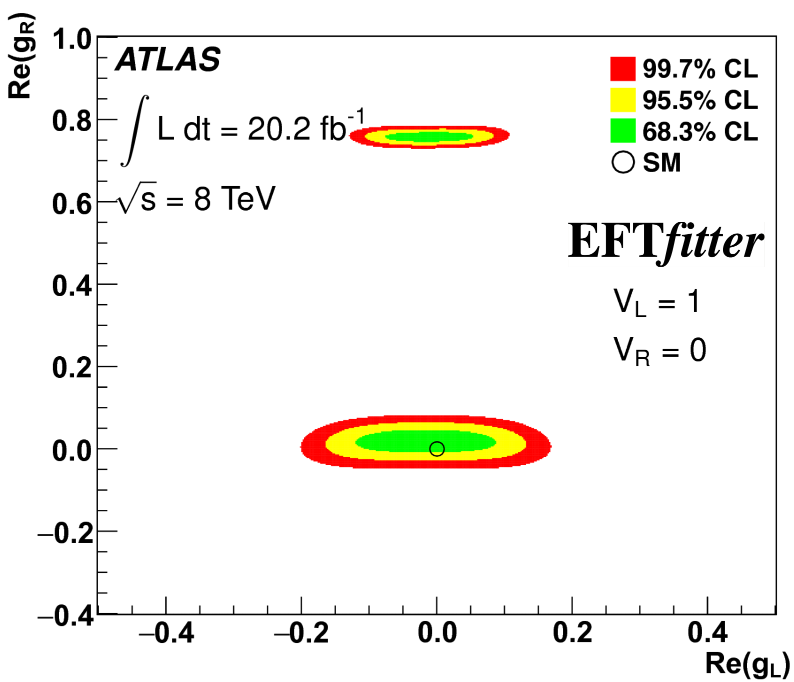
Leptonic analyser (≥2 *b*-tags)	Hadronic analyser (1 *b*-tag + ≥2 *b*-tags)
$F_0 = 0.709 \pm 0.012$ (stat.+bkg. norm.) $^{+0.015}_{-0.014}$ (syst.)	$F_0 = 0.659 \pm 0.010$ (stat.+bkg. norm.) $^{+0.052}_{-0.054}$ (syst.)
$F_L = 0.299 \pm 0.008$ (stat.+bkg. norm.) $^{+0.013}_{-0.012}$ (syst.)	$F_L = 0.281 \pm 0.021$ (stat.+bkg. norm.) $^{+0.063}_{-0.067}$ (syst.)
$F_R = -0.008 \pm 0.006$ (stat.+bkg. norm.) ± 0.012 (syst.	$F_R = 0.061 \pm 0.022$ (stat.+bkg. norm.) $^{+0.101}_{-0.108}$ (syst.)

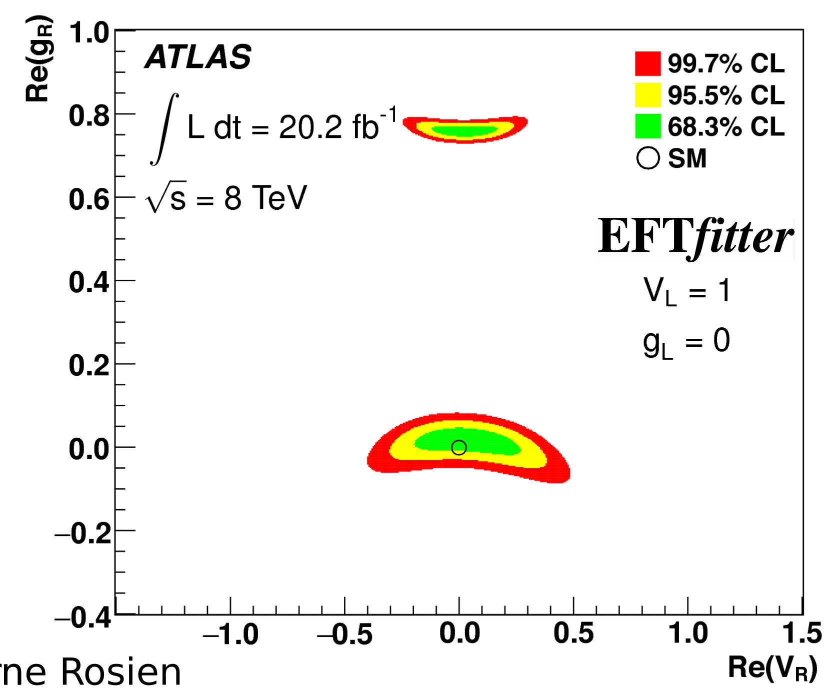
W boson polarisation (3)

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

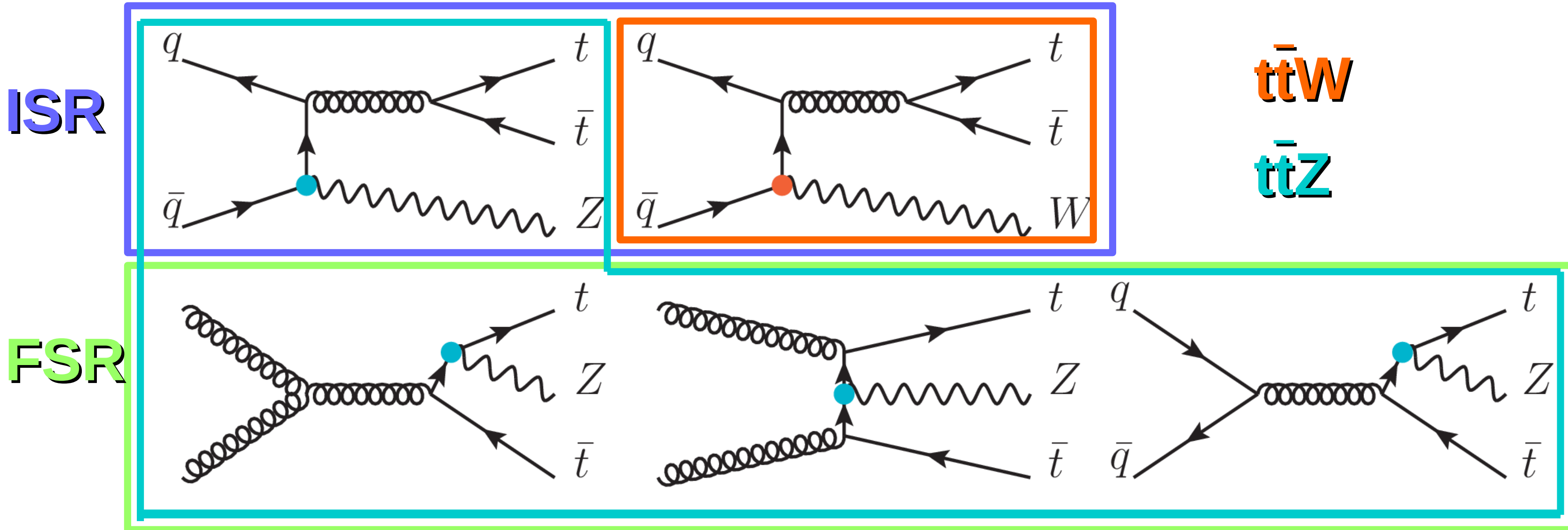
- F_L,F_R,F_0 can constrain anomalous *Wtb* couplings
- Anomalous couplings are constrained using EFTfitter [Eur. Phys. J. C (2016) 76: 432]

Coupling	95 % CL interval
V_{R}	$[-0.24, 0.31]$
g_{L}	$[-0.14, 0.11]$
g_{R}	$[-0.02, 0.06], [0.74, 0.78]$





$t\bar{t}Z$ and $t\bar{t}W$ cross sections (1)



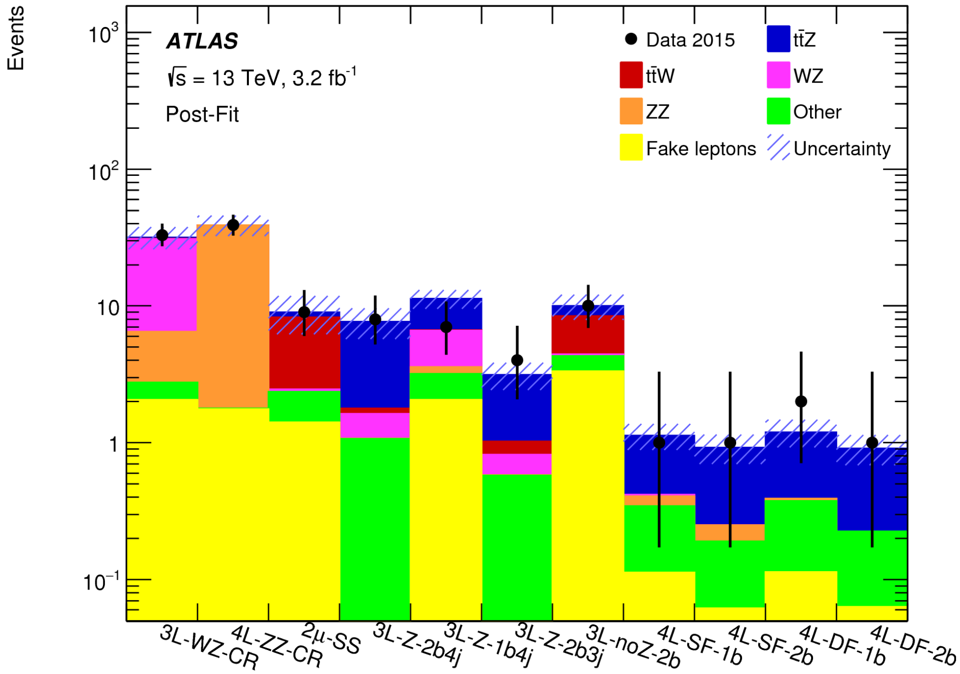
$$\mathcal{L}_{t\bar{t}Z} \propto \bar{t}\gamma^{\mu}(c_V^t - c_A^t\gamma^5)tZ_{\mu}$$

$$c_V^t = T_t^3 - 2Q_t \sin^2\theta_W$$
$$c_A^t = T_t^3$$

- Access to the the third component of the **weak isospin of the top quark** (FSR)
- Access to **anomalous $t\bar{t}Z$ Couplings**
- Learn about **electroweak symmetry breaking** via interactions of *W* and *Z*
- **Indicator** for strongly coupled Higgs sector, technicolour, heavy top partners
- Important **background process** for $t\bar{t}H$ (multilepton channel), SUSY (multilepton, stop pairs) and others
- Possibility to test **PDFs** via $t\bar{t}W$ because of ISR

$t\bar{t}Z$ and $t\bar{t}W$ cross sections (2)

- Separation into 3 different regions:
  2 same sign muons (2μSS) → sensitive to $t\bar{t}W$, dominant bkg: fake leptons
  3ℓ → sensitive to $t\bar{t}W$ and $t\bar{t}Z$, dominant bkg: WZ and fake leptons
  4ℓ → sensitive to $t\bar{t}Z$, dominant bkg: ZZ and fake leptons
- 2μSS and the 3ℓ channel: fakes are estimated using fully data driven matrix method
- 4ℓ channel: fake estimation using FF method using shapes from MC



$t\bar{t}Z$ and $t\bar{t}W$ cross sections (3)

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- Statistically limited
- First observation (>5σ) of this process for ATLAS (parallel to CMS at 8 TeV)

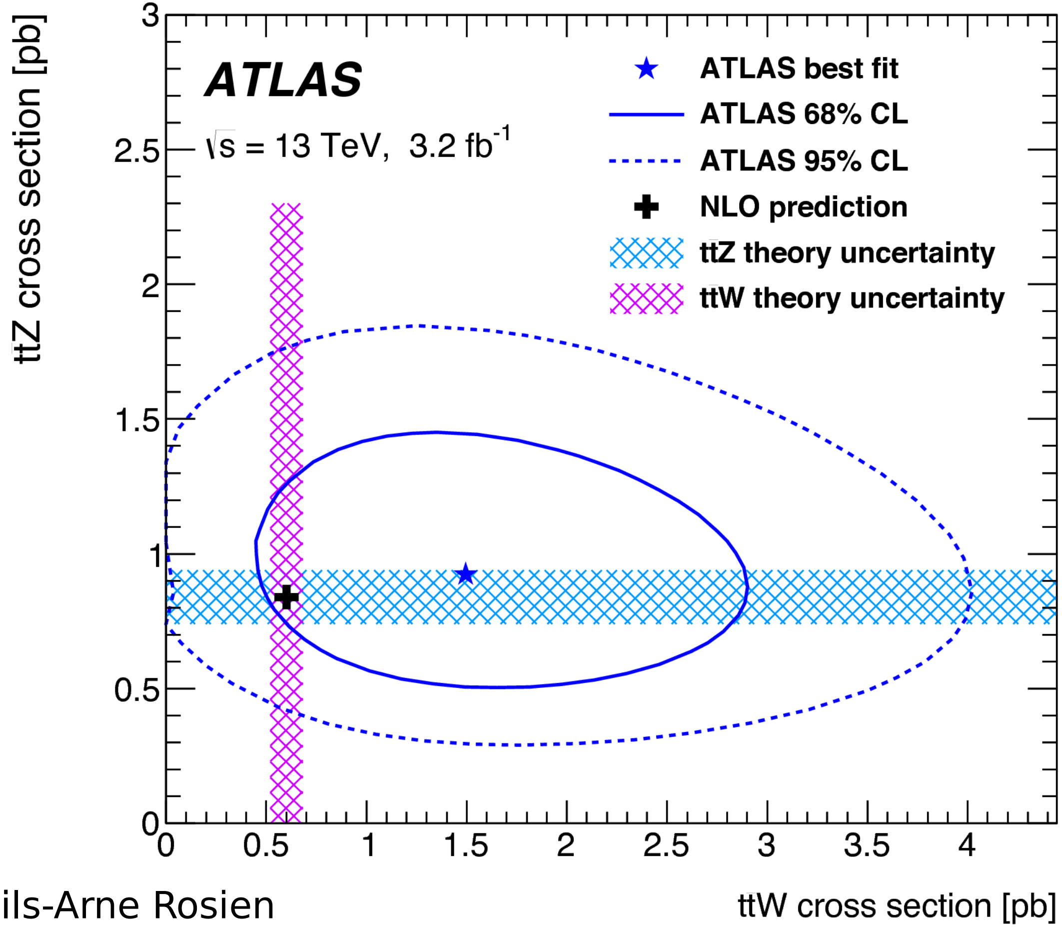
1D fit result

$$\sigma_{t\bar{t}W} = 1.5 \pm 0.8 \text{ pb}$$
$$\sigma_{t\bar{t}Z} = 0.9 \pm 0.3 \text{ pb}$$

NLO QCD

$$\sigma_{t\bar{t}W} = 0.60 \pm 0.08 \text{ pb}$$
$$\sigma_{t\bar{t}Z} = 0.84 \pm 0.09 \text{ pb}$$

2D fit result



Conclusion

- Top quark properties measurements at ATLAS in spin observables, charge and CP asymmetries, *W* boson polarisation and $t\bar{t}V$ cross section
- Some spin observables measured for the first time
- $t\bar{t}V$ observed for the first time at 8 TeV (parallel to CMS)
- No disagreements with the SM
- More measurements using 13 TeV data are right around the corner

Thank you very much for your attention!