

Top quark pair properties in the production and decays of $t\bar{t}$ events at ATLAS

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on behalf of the ATLAS collaboration



DESY, Hamburg

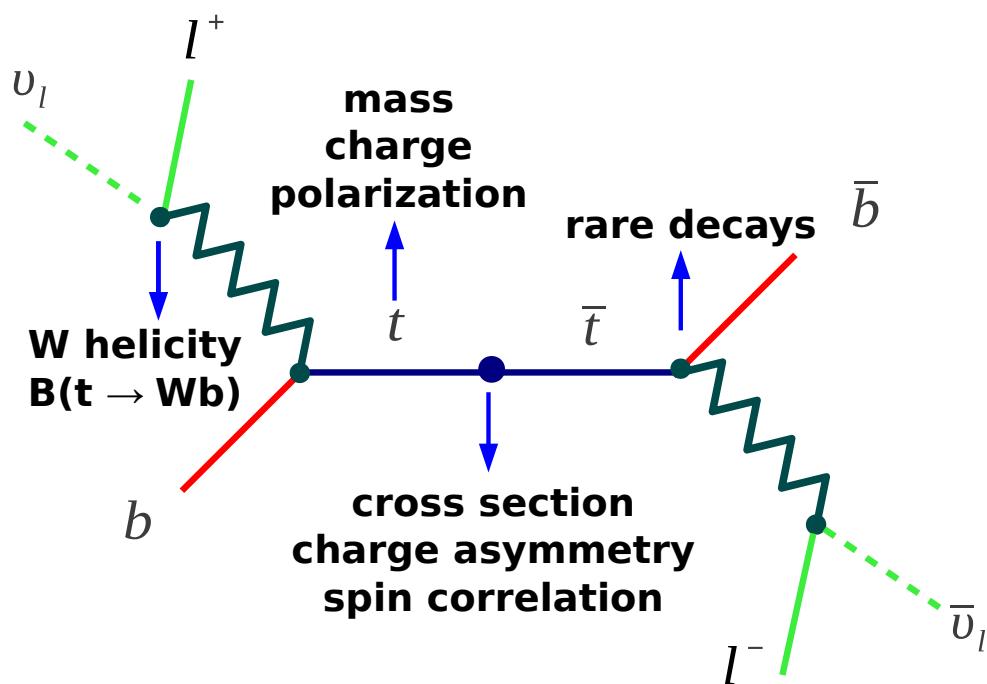


DIS2014 Warsaw, 29.04.14



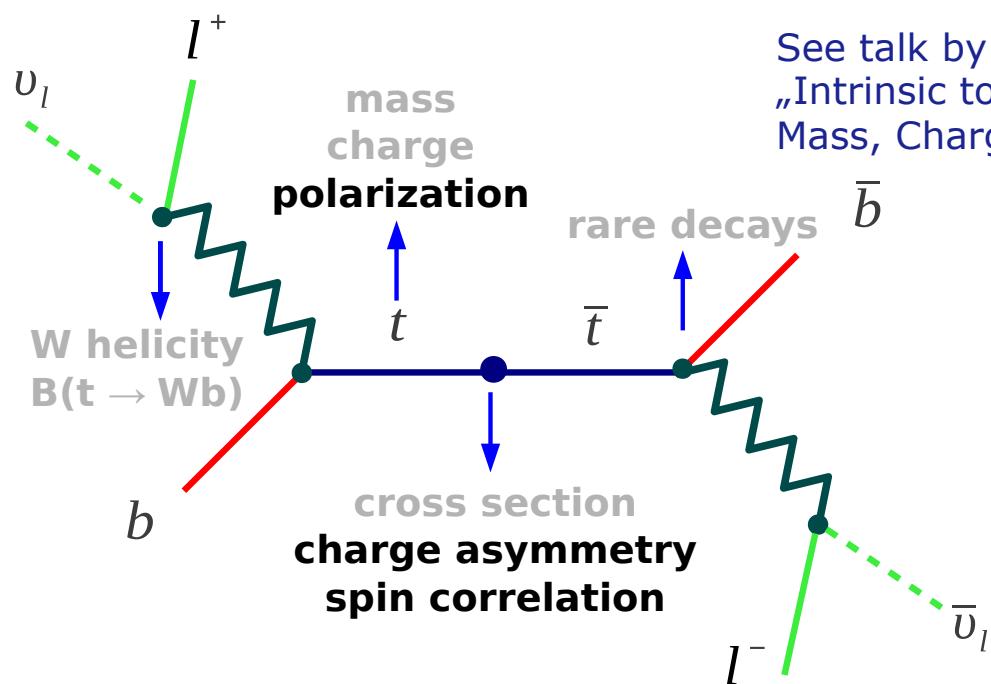
Top quark properties

- Why top quark properties?
 - Heaviest fundamental particle → large Higgs coupling (special role in EWSB?).
 - Short life time ($\sim 10^{-25}$ s) → decays before hadronization ($\sim 10^{-23}$ s).
Spin information carried to final state particles.
 - Possibility to study a bare quark.
 - Great tool to test the Standard Model.



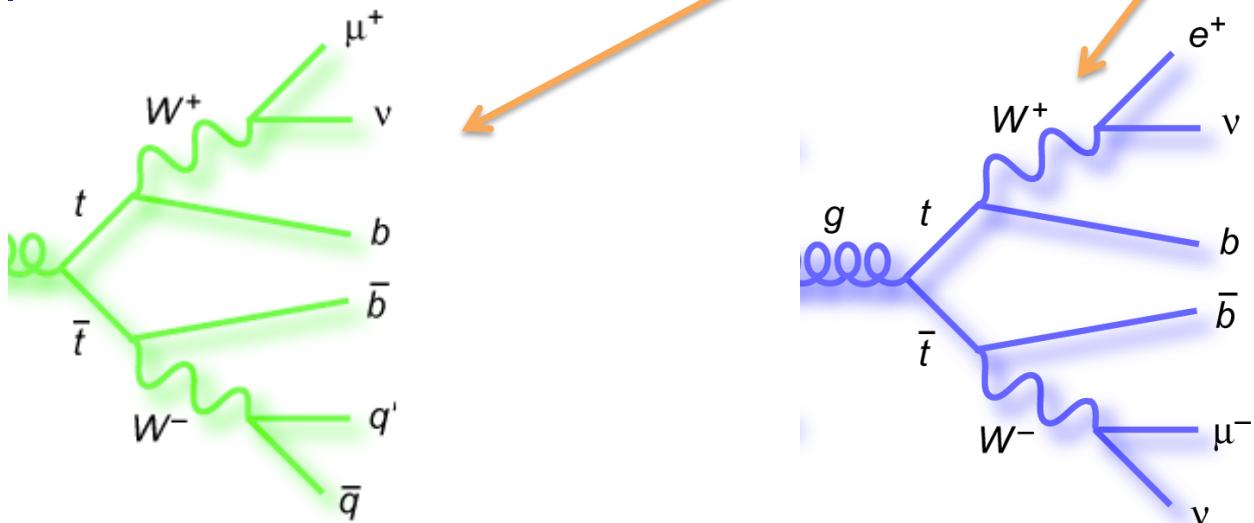
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Decay channels

- All measurements performed in the **I+jets** and/or **dilepton** channel



- 1 isolated high p_T lepton
- At least 4 jets with $p_T > 25$ GeV with 1 b-tagged jet
- $e+jets$:
 - missing $E_T > 30$ GeV
 - $M_T(W) > 30$ GeV
- $\mu+jets$:
 - missing $E_T > 20$ GeV
 - $M_T(W) + \text{missing } E_T > 60$ GeV
- 2 isolated high p_T leptons
- At least 2 jets with $p_T > 25$ GeV
- ee and $\mu\mu$:
 - missing $E_T > 60$ GeV
 - $|m_{||} - m_Z| > 10$ GeV; $m_{||} > 15$ GeV
- $e\mu$:
 - $H_T > 130$ GeV
 - H_T : Scalar sum of lepton and jet p_T

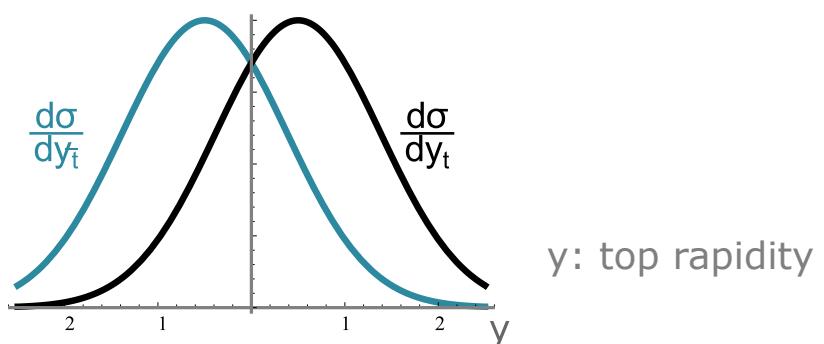
$$M_T^2(W) = m_l^2 + m_\nu^2 + 2(E_T^l E_T^\nu - \vec{p}_T^l \vec{p}_T^\nu)$$

Charge asymmetry

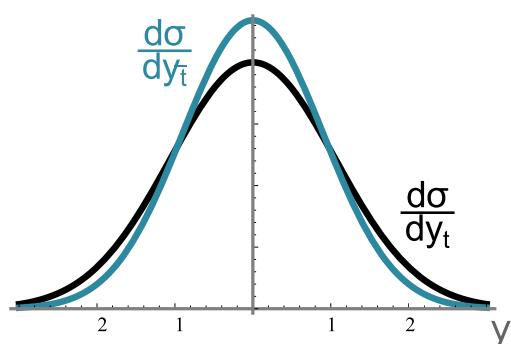
- Tension between prediction and measurement of $t\bar{t}$ production asymmetry seen at Tevatron → Test similar effect at LHC



- (Anti)top quarks produced preferentially in direction of (anti) quark (NLO effect predicted by SM)
 - Effect only coming from $q\bar{q}$ and qg fusion → bigger effect at Tevatron
 - At LHC, \bar{q} only coming from sea quarks → lower momentum fraction



Tevatron: Forward-Backward asymmetry A_{FB}



LHC: Charge asymmetry A_C

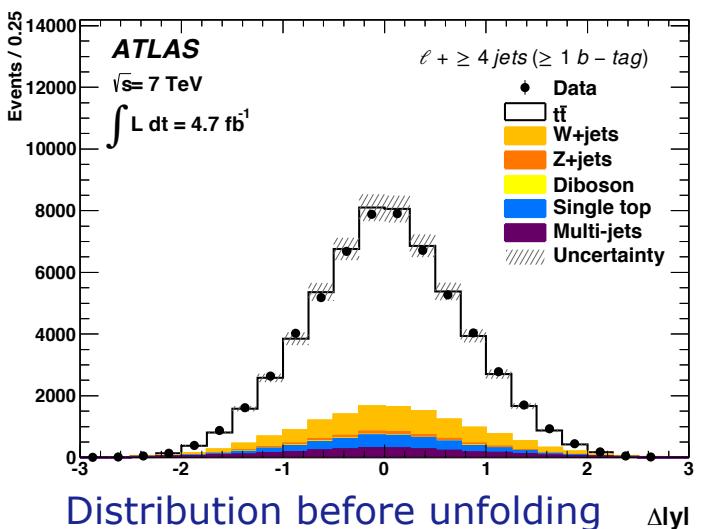
Charge asymmetry at ATLAS

- Measure absolute difference of top quark rapidities.

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

$$\Delta|y| \equiv |y_t| - |\bar{y}_t|$$

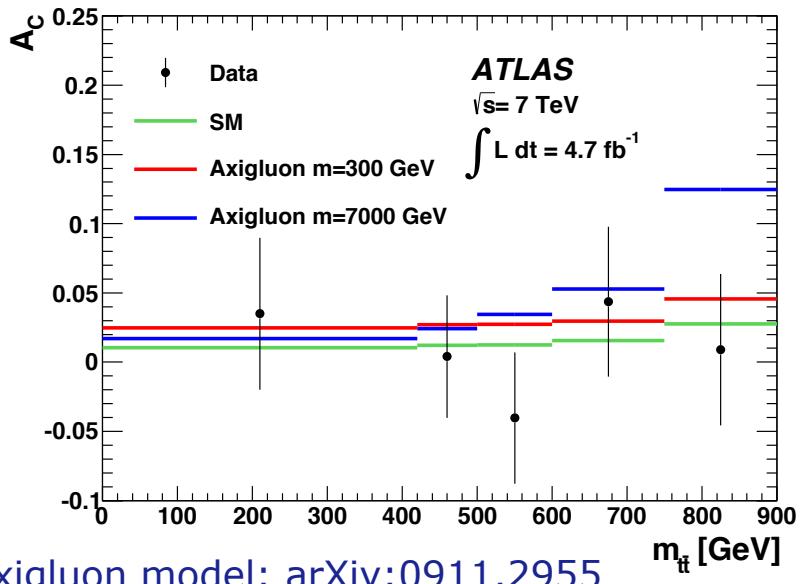
- Small effect at LHC compared to Tevatron.
- Performed measurement in l+jets channel using 4.7 fb^{-1} of 7 TeV data.
- Reconstruction of the full $t\bar{t}$ system via kinematic likelihood fit.



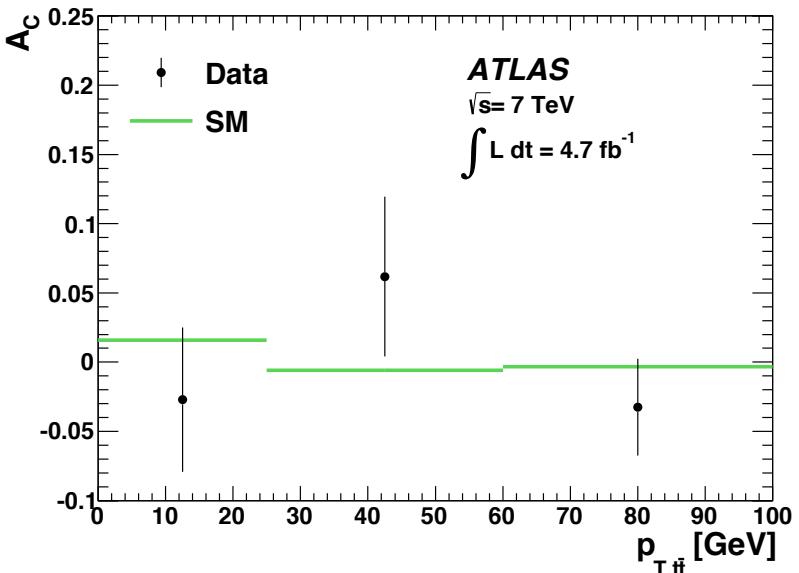
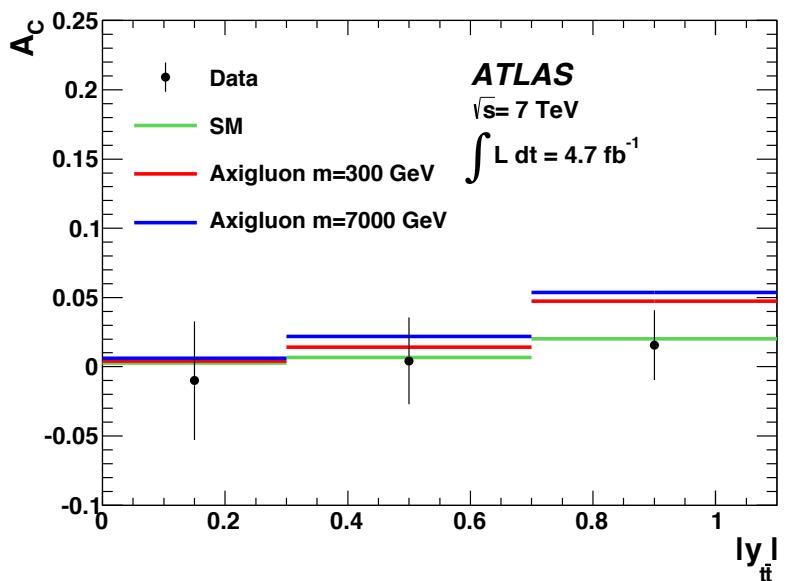
- Result **unfolded** to parton level distribution.
- SM prediction: $1.23 \pm 0.05 \%$
 $\text{PRD86 (2012) 034026}$
- Unfolded result: $A_C = 0.6 \pm 1.0 \%$
 (stat+syst)

JHEP02(2014)107

Differential charge asymmetry



axigluon model: arXiv:0911.2955



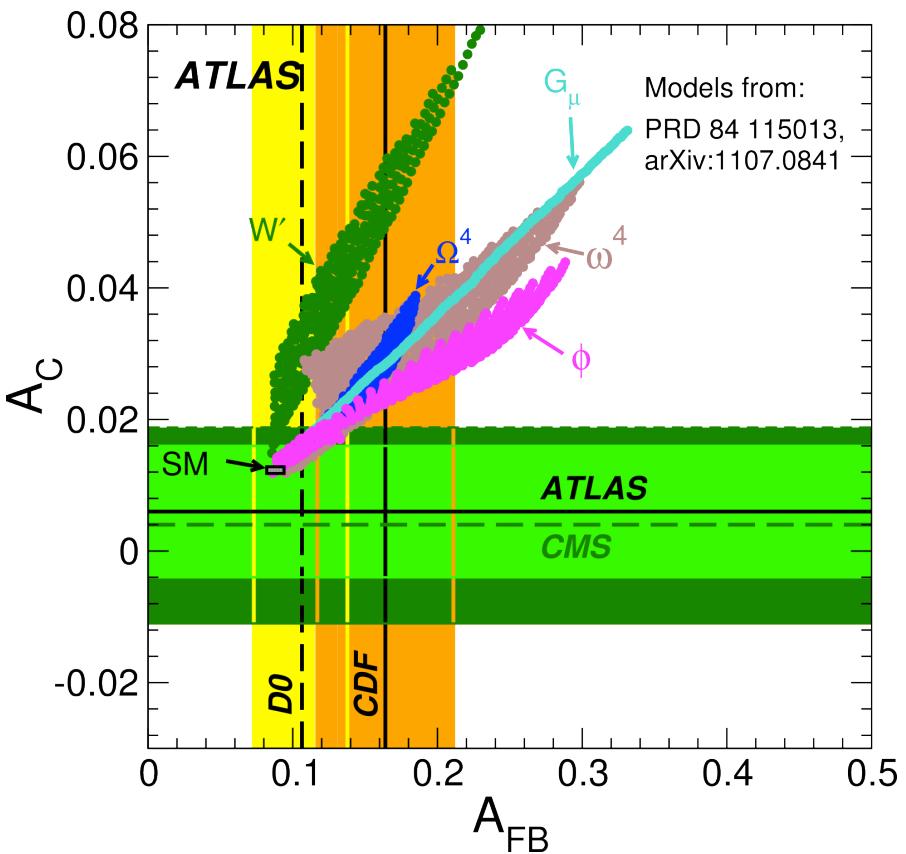
A_C	Data	Theory
Unfolded	0.006 ± 0.010	0.0123 ± 0.0005
Unfolded with $m_{t\bar{t}} > 600 \text{ GeV}$	0.018 ± 0.022	$0.0175^{+0.0005}_{-0.0004}$
Unfolded with $\beta_{z,t\bar{t}} > 0.6$	0.011 ± 0.018	$0.020^{+0.006}_{-0.007}$

Good agreement with SM
 over whole phase space.
 Statistical uncertainty still
 dominant.

JHEP02(2014)107

Charge asymmetry interpretation

- Test new physics models with results from Tevatron and LHC
- Models taken from PRD (84) 115013.
- Charge asymmetry measurement at LHC disfavours large parameter space for some of those models.



Top quark spin I

- Top quark pairs produced almost **unpolarized** in the Standard Model, but spins **correlated**.
- Both polarization and spin correlation sensitive to BSM physics
- Double differential cross section for $t\bar{t}$ production:

$$\frac{1}{\sigma} \frac{d^2\sigma}{d \cos \theta_1 d \cos \theta_2} = \frac{1}{4} (1 + \alpha_1 P_1 \cos \theta_1 + \alpha_2 P_2 \cos \theta_2 - \alpha_1 \alpha_2 A \cos \theta_1 \cos \theta_2)$$

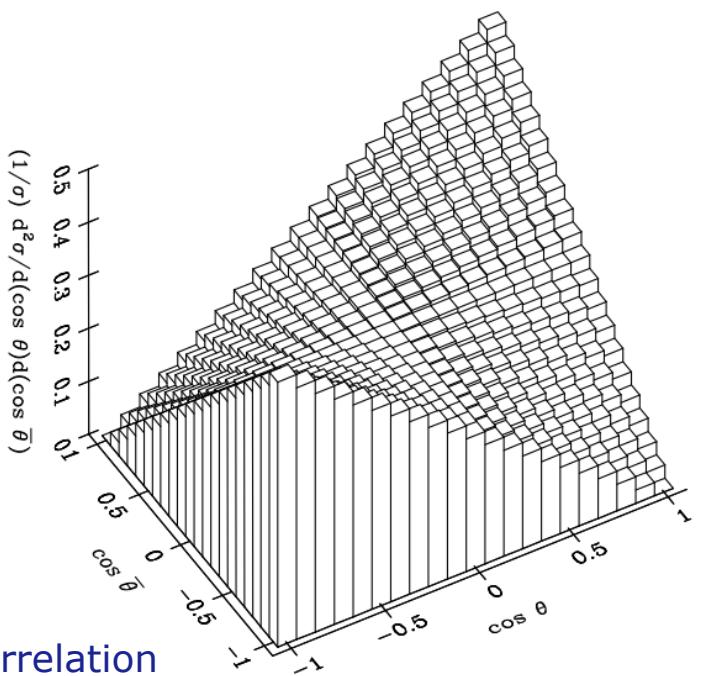
α : spin analysing power

P : polarisation

A : spin correlation strength

$\cos \theta$: angle between final state particle
and spin quantization axis

SM Monte Carlo spin correlation



Top quark spin II

- Top quark pairs produced almost **unpolarized** in the Standard Model, but spins correlated.
- Double differential cross section for $t\bar{t}$ production:

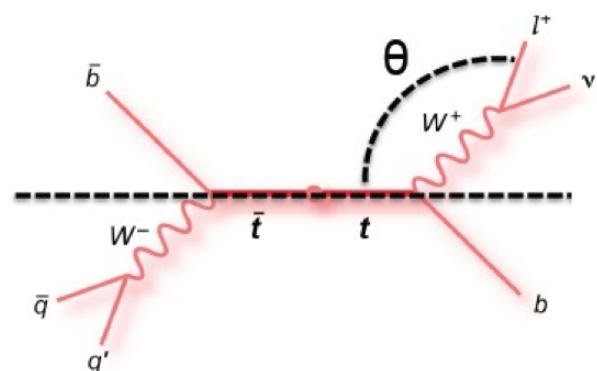
$$\frac{1}{\sigma} \frac{d^2\sigma}{d \cos \theta_1 d \cos \theta_2} = \frac{1}{4} (1 + \alpha_1 \boxed{P_1} \cos \theta_1 + \alpha_2 \boxed{P_2} \cos \theta_2 - \alpha_1 \alpha_2 \boxed{A} \cos \theta_1 \cos \theta_2)$$

α : spin analysing power

$\cos \theta$: angle between final state particle

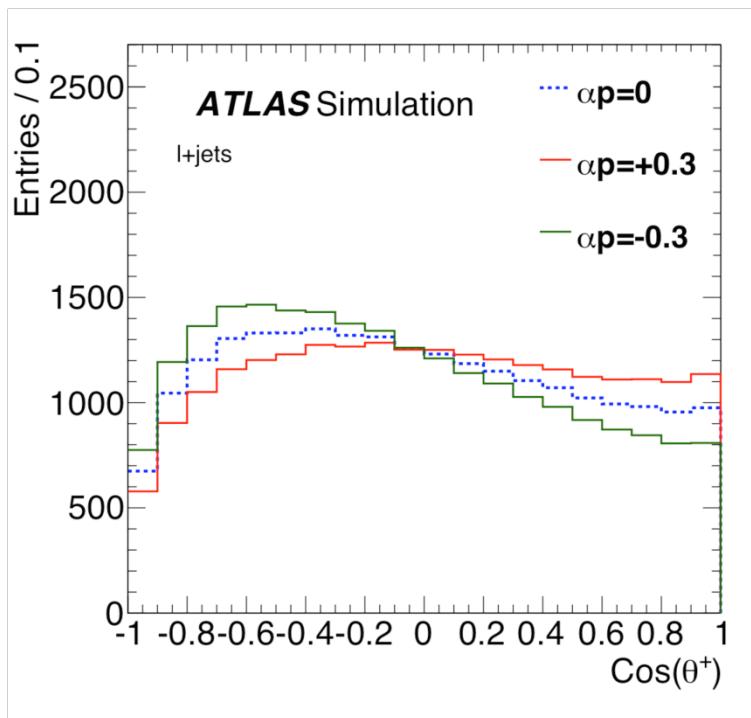
and spin quantization axis

- Charged Leptons have $\alpha \approx 1$ at NLO → Take leptons for building $\cos \theta$
- Several spin quantization axes to measure
 - Top helicity basis well defined
- $\cos \theta$ needs full $t\bar{t}$ system reconstruction



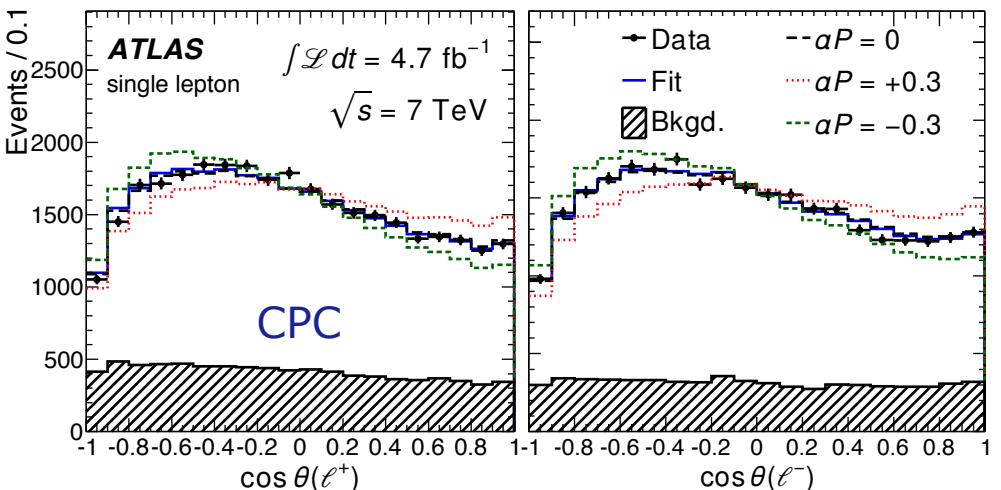
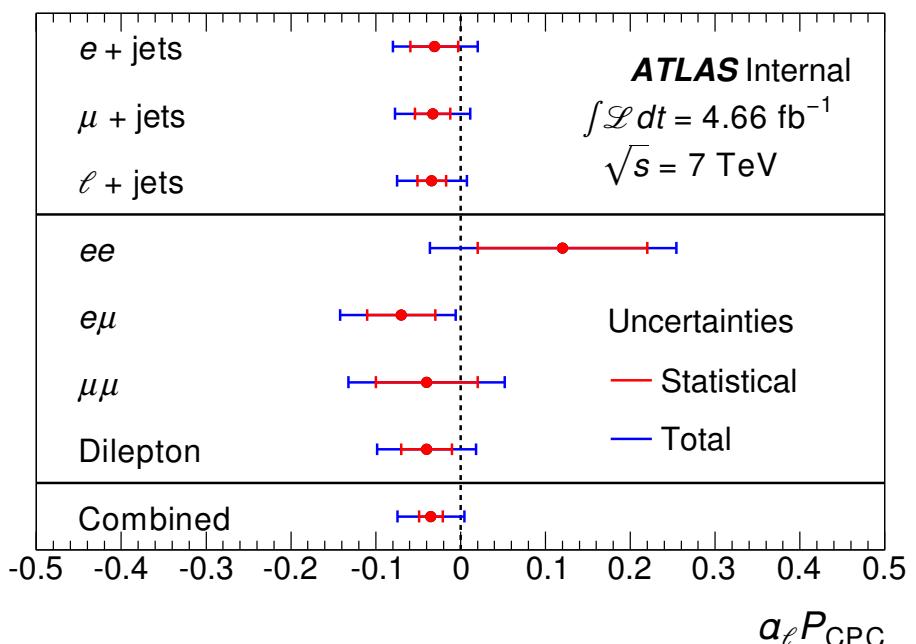
Top quark polarization

- Analyze 4.7 fb^{-1} of 7 TeV data in the l+jets and dilep. channels.
- $t\bar{t}$ reconstruction:
 - The kinematic likelihood fit in l+jets channel
 - The neutrino weighting method in dilepton channel
- Create templates of fixed injected polarization ($\alpha p = \pm 0.3$).
- Consider two different production mechanisms:
 - CP conserving (Standard Model like)
 - maximally CP violating (opposite polarization for top and antitop)



Top quark polarization meas. procedure

- Perform binned likelihood template fit to extract amount of polarization.
- Combine all channels by multiplying likelihoods.



$$\alpha_l P_{CPC} = -0.035 \pm 0.014(\text{stat}) \pm 0.037(\text{syst})$$

$$\alpha_l P_{CPV} = 0.020 \pm 0.016(\text{stat})^{+0.013}_{-0.017}(\text{syst})$$

All results in agreement with Standard Model.
 Systematics dominated, main systematics come from jet reconstruction uncertainties.

Phys. Rev. Lett 111, 232002 (2013)

Spin correlation

- Spin correlation already observed at ATLAS

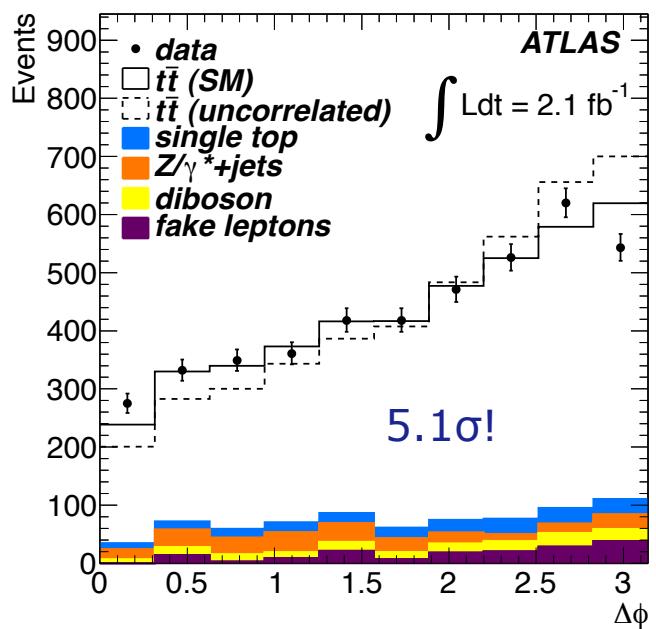
Phys. Rev. Lett. 108, 212001 (2012)

- Look at both top quarks at the same time,
not independently

$$\frac{1}{\sigma} \frac{d^2\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4} (1 + \alpha_1 P \cos\theta_1 + \alpha_2 P \cos\theta_2 - \alpha_1 \alpha_2 A \cos\theta_1 \cos\theta_2)$$

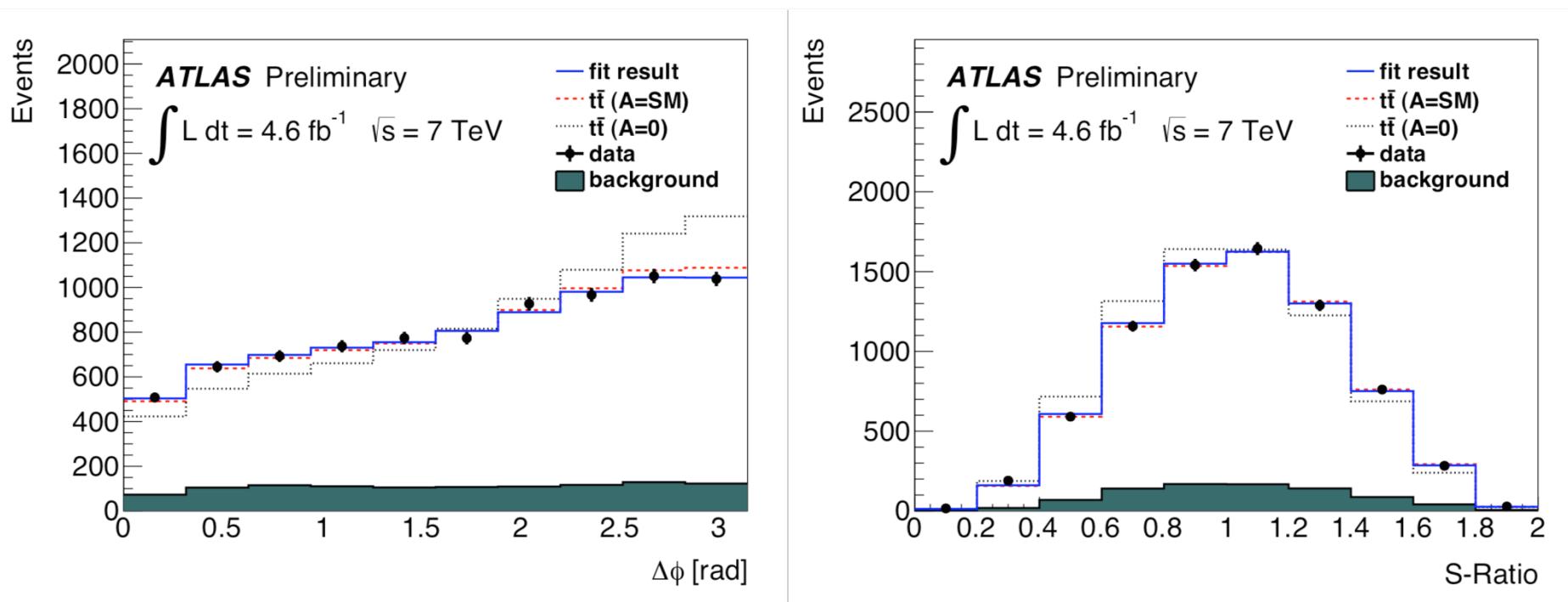
$$A = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}$$

- Correlation strength A consists of difference between like-helicity and unlike-helicity top quarks



Spin correlation observables I

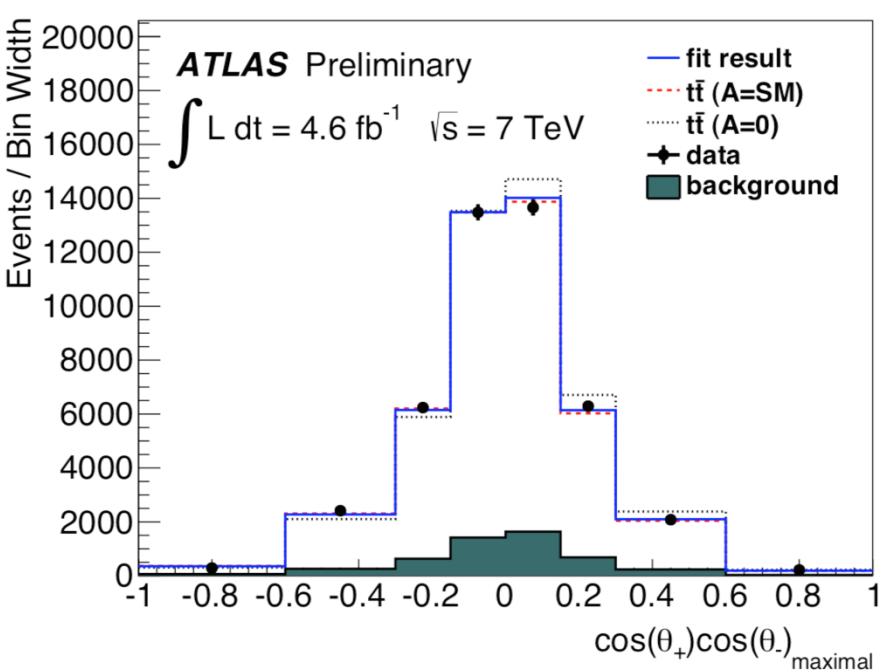
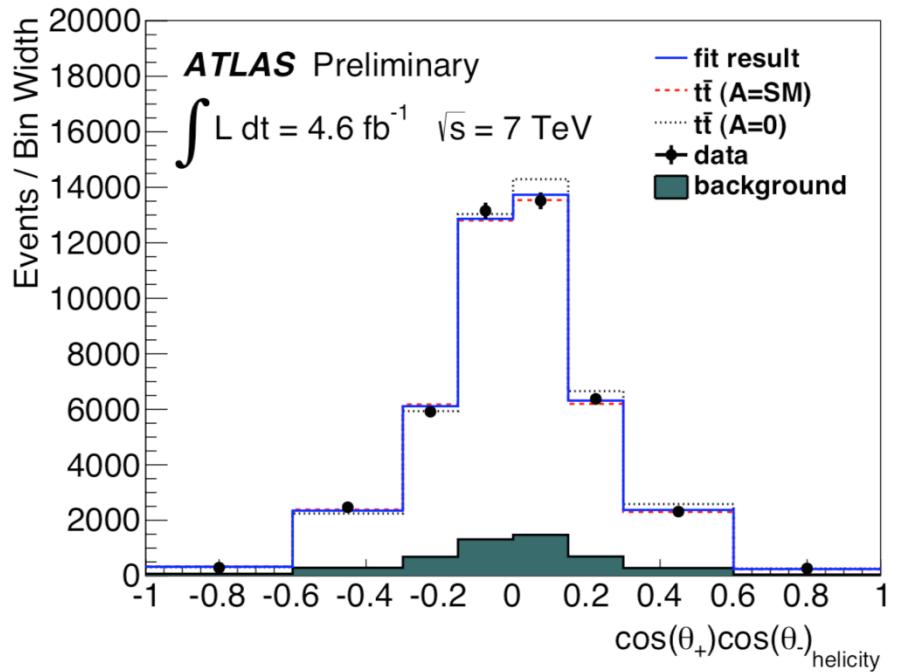
- New measurement performed in dilepton channel at 7 TeV.
- Four different **observables** to extract spin correlation.
- Templates used to perform binned likelihood fit



- Azimuthal difference $\Delta\Phi$ between reconstructed leptons.
- Easy to measure and very sensitive to top spin correlation.
- Ratio of matrix elements from fusion of like-helicity gluons with and without spin correlation.

$$S = \frac{(|\mathcal{M}|_{RR}^2 + \mathcal{M}|_{LL}^2)_{\text{corr}}}{(|\mathcal{M}|_{RR}^2 + \mathcal{M}|_{LL}^2)_{\text{uncorr}}}$$

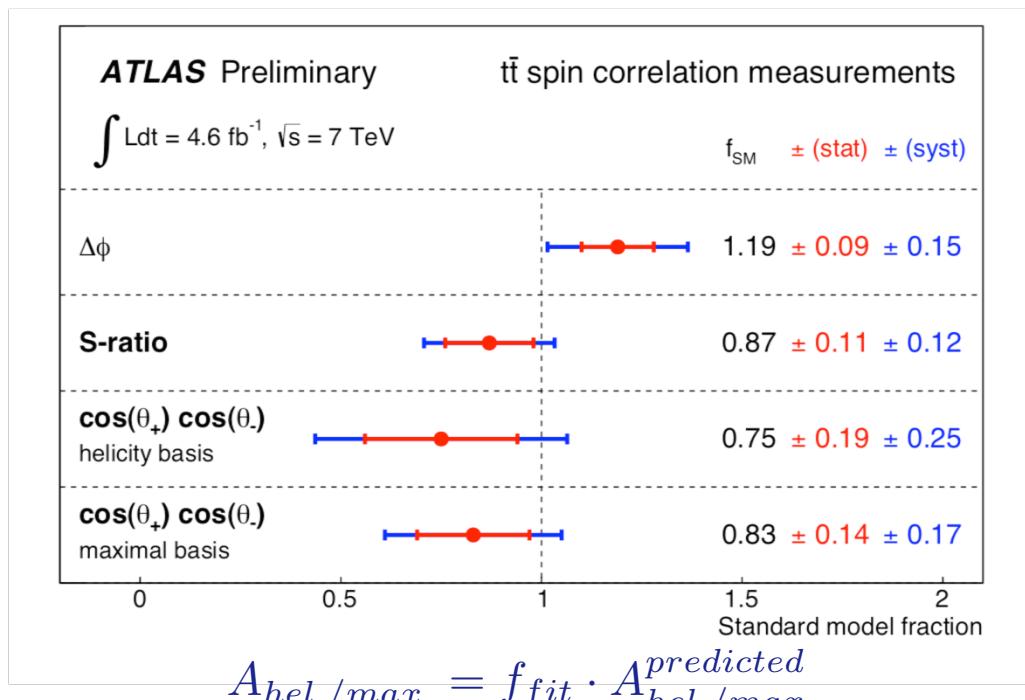
Spin correlation observables II



- Product of $\cos(\theta_+)$ and $\cos(\theta_-)$ in the **helicity** basis .
- Standard model prediction:
 $A_{hel} = 0.31$
- Product of $\cos(\theta_+)$ and $\cos(\theta_-)$ in the **maximal** basis .
- Standard model prediction:
 $A_{max} = 0.44$
- S-Ratio and $\cos(\theta)$ information require full reconstruction of the $t\bar{t}$ system; Neutrino weighting method used

Spin correlation results

- Extract parameter f ($f_{\text{SM}} = 1$; $f_{\text{uncorr}} = 0$) from template fit.



Basis	$\Delta\phi$	S-ratio	$\cos(\theta_+) \cos(\theta_-)_{\text{helicity}}$	$\cos(\theta_+) \cos(\theta_-)_{\text{maximal}}$
$A_{\text{helicity}}^{\text{measured}}$	$0.37 \pm 0.03 \pm 0.05$	$0.27 \pm 0.03 \pm 0.04$	$0.23 \pm 0.06 \pm 0.10$	—
$A_{\text{maximal}}^{\text{measured}}$	$0.52 \pm 0.04 \pm 0.07$	$0.38 \pm 0.05 \pm 0.06$	—	$0.36 \pm 0.06 \pm 0.09$

- Dominant systematic uncertainties come from signal modelling.

ATLAS-CONF-2013-101

Summary

- Many top quark properties measured at **ATLAS** testing the Standard Model using **7 TeV** data.
- Precision of measurements already often limited by systematics.
- No deviation from **SM** has been found so far.
- **8 TeV** measurements in **preparation** extending and improving existing analyses.

See you next year with new exciting results. ☺

Backup

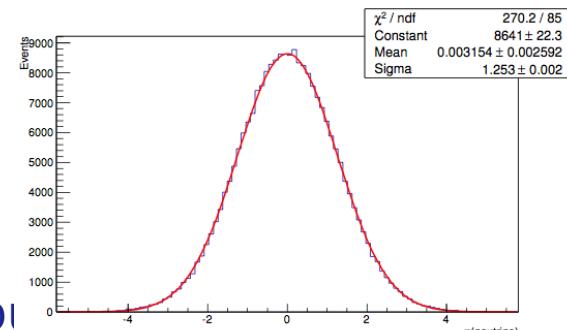
Kinematic likelihood fitter (KL Fitter)

- Likelihood-based reconstruction for l+jets channel (arxiv: 1312.5595)
- Missing E_T gives estimate on neutrino p_T
- Likelihood fit performed to get whole neutrino information and correct lepton-jet assignment
- Consists of double gaussian transfer functions for object energies, gaussian resolution for missing E_T and separate Breit-Wigner PDFs for W bosons and top quarks
- Solution with highest probability taken for event reconstruction

Neutrino Weighting Method (dilepton)

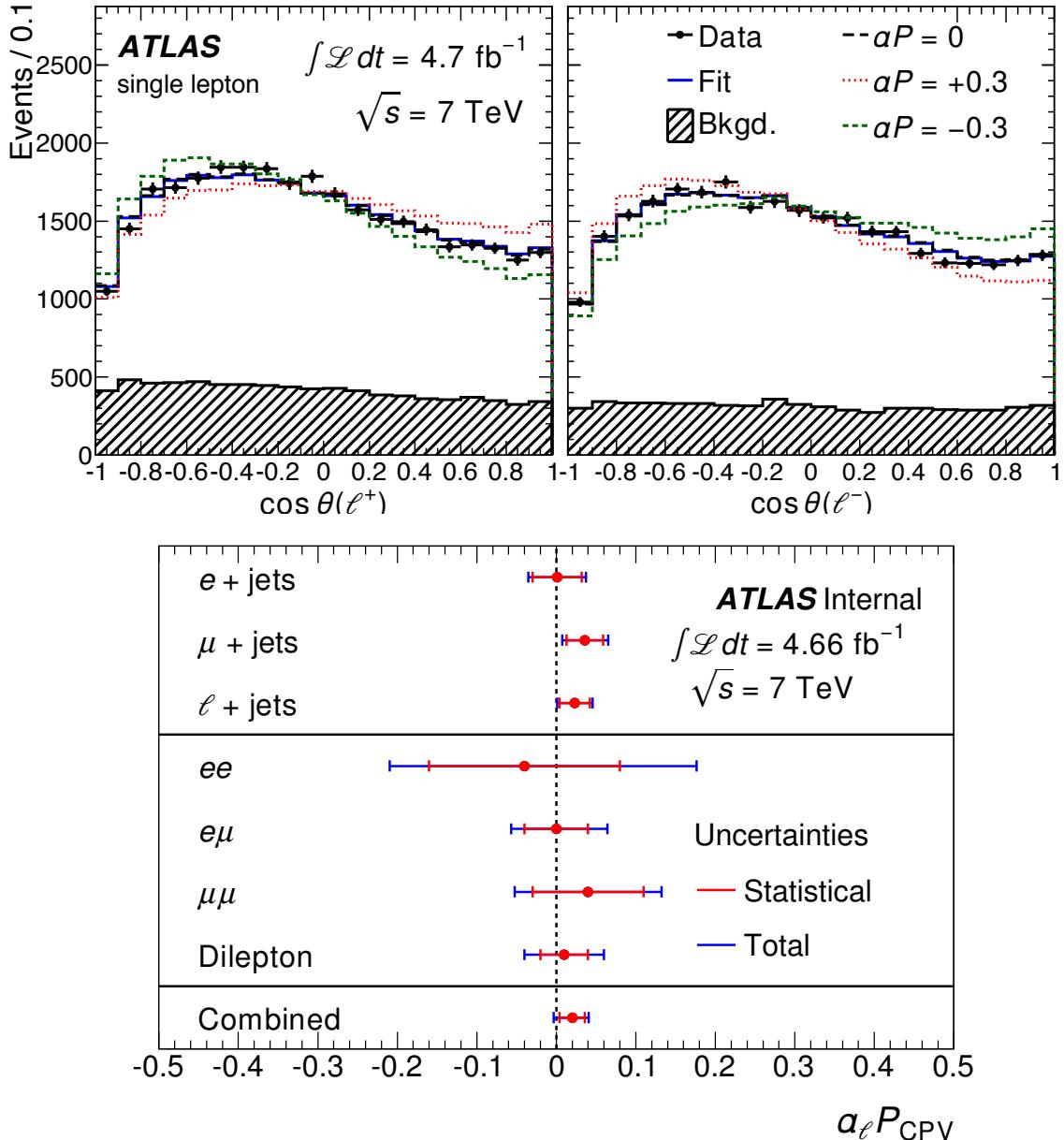
- Hard to reconstruct due to two neutrinos
- Neutrino weighting method used before at D0 to reconstruct the $t\bar{t}$ system
 - Make an independent hypothesis on neutrino and antineutrino eta according to Gaussian distribution taken from MC (100 guesses)
 - Solve equations for longitudinal neutrino momentum; 2 solutions for each neutrino
 - Redo this procedure for every lepton-jet combination and additionally smear the jets 50 times
 - For all these combinations, a weight w is computed comparing neutrino momenta to the measured E_T^{miss}

$$w = \prod_{i=x,y} \exp \left(-\frac{(E_i^{\text{miss}} - p_{i,\nu 1} - p_{i,\nu 2})^2}{2\sigma_{E_T^{\text{miss}}}^2} \right)$$



- Take either solution with the highest weight (polarization) or weighted average (spin correlation) as best guess for our reconstructed system

Polarization CPV results



Polarization systematic uncertainties

Source	$\Delta\alpha_\ell P_{\text{CPC}}$		$\Delta\alpha_\ell P_{\text{CPV}}$	
Jet reconstruction	+0.031	-0.031	+0.009	-0.005
Lepton reconstruction	+0.006	-0.007	+0.002	-0.001
E_T^{miss} reconstruction	+0.008	-0.007	+0.004	-0.001
$t\bar{t}$ modeling	+0.015	-0.016	+0.005	-0.013
Background modeling	+0.011	-0.010	+0.005	-0.007
Template statistics	+0.005	-0.005	+0.006	-0.006
Total systematic uncertainty	+0.037	-0.037	+0.013	-0.017

Spin correlation observables

- S-Ratio definition:

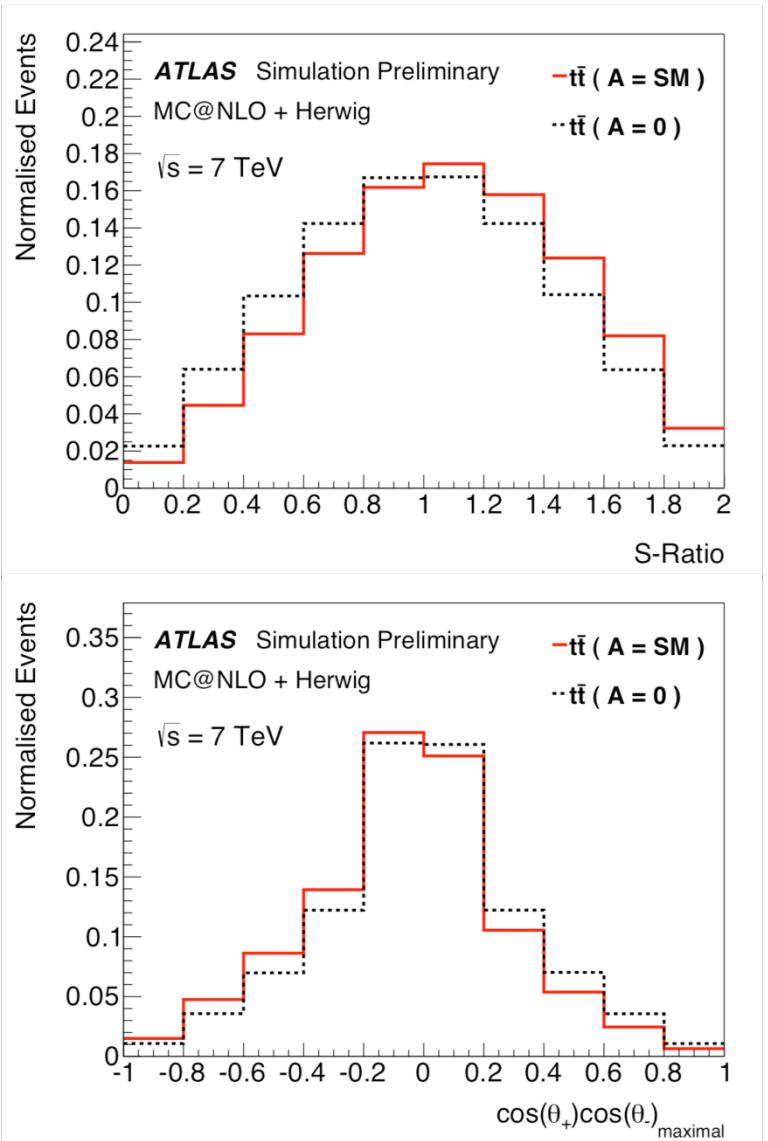
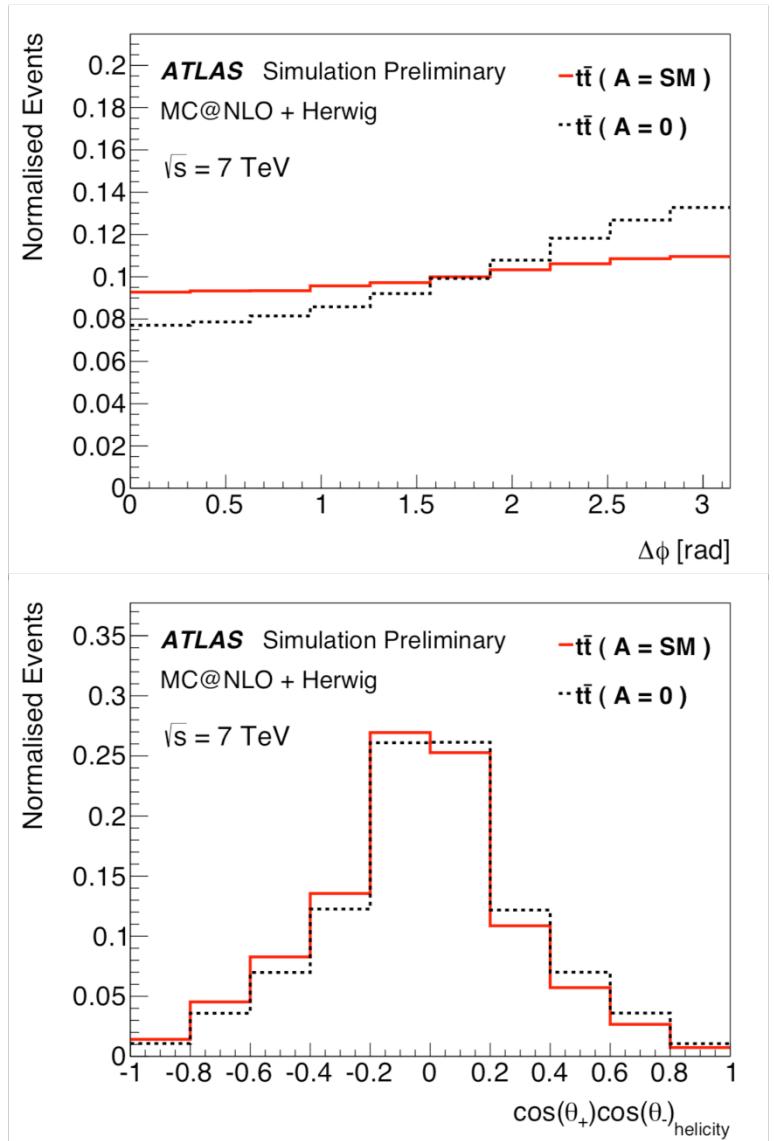
$$\begin{aligned}
 S &= \frac{(|\mathcal{M}|_{RR}^2 + |\mathcal{M}|_{LL}^2)_{\text{corr}}}{(|\mathcal{M}|_{RR}^2 + |\mathcal{M}|_{LL}^2)_{\text{uncorr}}} \\
 &= \frac{m_t^2 \{(t \cdot l^+)(t \cdot l^-) + (\bar{t} \cdot l^+)(\bar{t} \cdot l^-) - m_t^2(l^+ \cdot l^-)\}}{(t \cdot l^+)(\bar{t} \cdot l^-)(t \cdot \bar{t})}
 \end{aligned}$$

with t and l being the four-vectors of top quark and lepton.

- Helicity basis: Take parent top quark momentum direction in $t\bar{t}$ rest frame as quantization axis
- Maximal basis: Compute axis for which correlation of top quark spins is maximal for gg fusion

Spin correlation observable plots

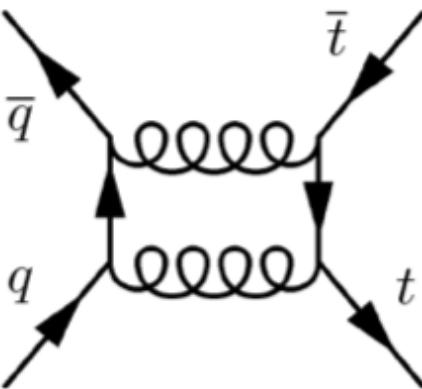
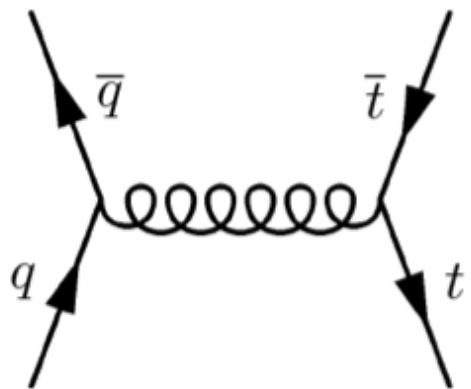
- Plots of observables on truth level



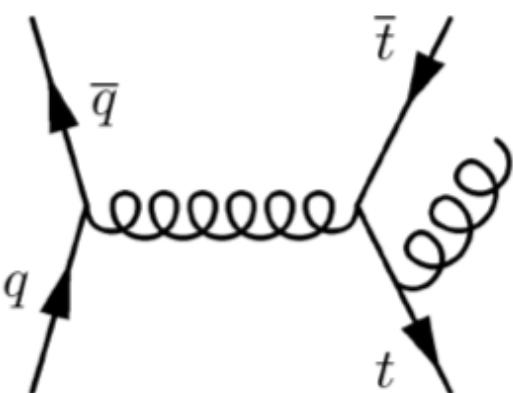
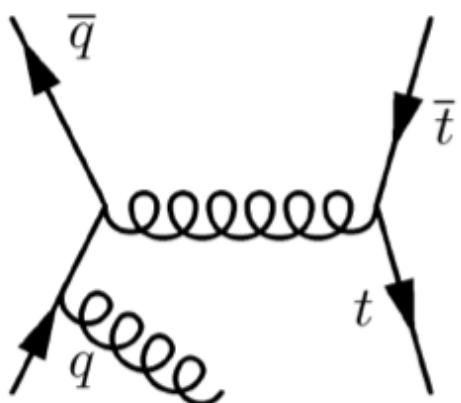
Spin correlation systematic uncertainties

Source of uncertainty	$\Delta\phi$	S -ratio	$(\cos \theta_+ \cos \theta_-)_{\text{helicity}}$	$(\cos \theta_+ \cos \theta_-)_{\text{maximal}}$
Detector Modeling				
Lepton reconstruction	± 0.01	± 0.02	± 0.05	± 0.03
Jet energy scale	± 0.02	± 0.04	± 0.12	± 0.08
Jet reconstruction	< 0.01	± 0.03	± 0.08	± 0.01
E_T^{miss}	± 0.01	± 0.01	± 0.03	± 0.02
Fake leptons	± 0.03	± 0.03	± 0.06	± 0.04
Signal and Background Modeling				
Renormalization/Factorization scale*	± 0.09	± 0.08	± 0.08	± 0.07
Parton Shower and Fragmentation*	< 0.01	< 0.01	± 0.13	± 0.08
ISR/FSR*	± 0.09	± 0.02	± 0.01	± 0.01
Underlying Event*	± 0.04	± 0.06	± 0.01	< 0.01
Color Reconnection*	± 0.01	± 0.02	± 0.07	± 0.07
PDF Uncertainty	± 0.02	± 0.01	± 0.04	± 0.03
Top Mass	< 0.01	± 0.02	± 0.02	± 0.02
Background	± 0.04	± 0.01	± 0.02	± 0.02
MC Statistics	± 0.03	± 0.03	± 0.08	± 0.04
Total Systematics	± 0.15	± 0.12	± 0.25	± 0.17
Data Statistics	± 0.09	± 0.11	± 0.19	± 0.14

Charge asymmetry



Positive asymmetry



Negative asymmetry

Charge asymmetry unfolding

- Use Fully Bayesian Unfolding (FBU;arXiv:1201.4612)
- Take FBU to calculate posterior distribution p

$$p(T|D, \mathcal{M}) \propto \mathcal{L}(D|T, \mathcal{M}) \cdot \pi(T)$$

$p(T|D, \mathcal{M})$: posterior prob. of true spectrum T given data D and mig. mat. \mathcal{M}

$\mathcal{L}(D|T, \mathcal{M})$: conditional likelihood for data D assuming true T and mig. mat. \mathcal{M}

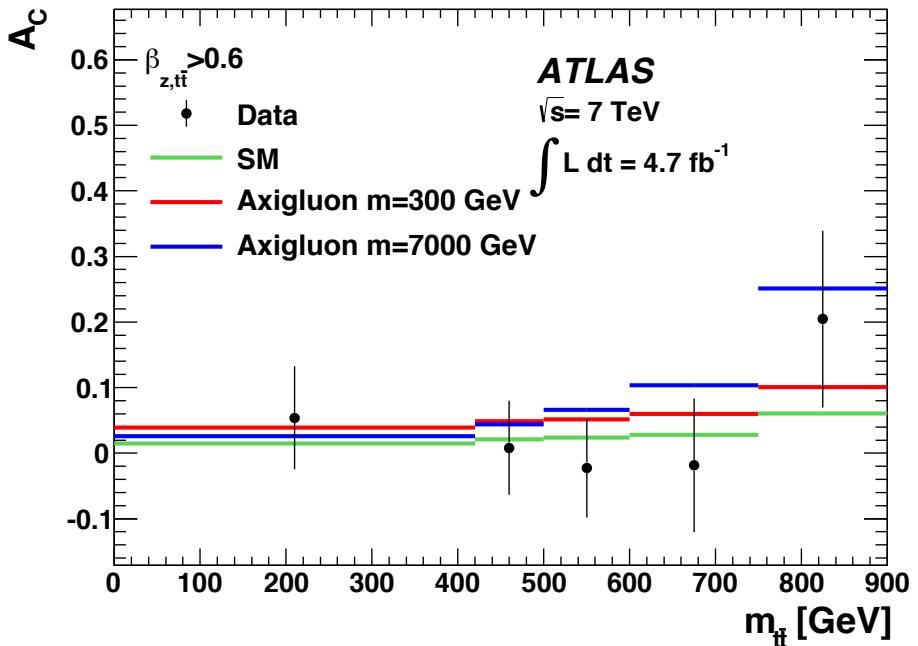
$\pi(T)$: prior probability for true T

- Two different priors taken depending on differential distribution
 - Flat for A_c as function of $m_{t\bar{t}}$ and $|y_{t\bar{t}}|$
 - Curvature prior based on exponential function with a regularisation parameter and a regularisation function based on the curvature of true and estimated $\Delta|y|$ distribution
- Systematic uncertainties are estimated using a marginalisation procedure
 - Assume Gaussian prior for all systematic uncertainties
 - Take weighted sum of central and $\pm 1\sigma$ posteriors
 - Final posterior taken to estimate systematic uncertainty

Charge asymmetry systematic uncertainties

Source of systematic uncertainty	δA_C	
	Inclusive	$m_{t\bar{t}} > 600 \text{ GeV}$
Lepton reconstruction/identification	< 0.001	0.001
Lepton energy scale and resolution	0.003	0.003
Jet energy scale and resolution	0.003	0.003
Missing transverse momentum and pile-up modelling	0.002	0.002
Multijet background normalisation	< 0.001	0.001
b -tagging/mis-tag efficiency	< 0.001	0.001
Signal modelling	< 0.001	< 0.001
Parton shower/hadronisation	< 0.001	< 0.001
Monte Carlo statistics	0.002	< 0.001
PDF	0.001	< 0.001
$W+jets$ normalisation and shape	0.002	< 0.001
Statistical uncertainty	0.010	0.021

Charge asymmetry boosted regime



Source of systematic uncertainty	δA_C		
	Inclusive	$m_{t\bar{t}} > 600 \text{ GeV}$	$\beta_{z,t\bar{t}} > 0.6$
Lepton reconstruction/identification	< 0.001	0.001	< 0.001
Lepton energy scale and resolution	0.003	0.003	0.003
Jet energy scale and resolution	0.003	0.003	0.005
Missing transverse momentum and pile-up modelling	0.002	0.002	0.004
Multi-jets background normalisation	< 0.001	0.001	0.001
b -tagging/mis-tag efficiency	< 0.001	0.001	0.001
Signal modelling	< 0.001	< 0.001	< 0.001
Parton shower/hadronisation	< 0.001	< 0.001	< 0.001
Monte Carlo statistics	0.002	< 0.001	< 0.001
PDF	0.001	< 0.001	< 0.001
$W+\text{jets}$ normalisation and shape	0.002	< 0.001	< 0.001
Statistical uncertainty	0.010	0.021	0.017