Studies of top quark spin and polarisation in ATLAS

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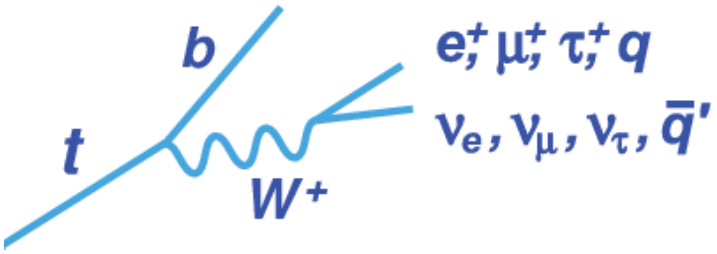
ATLAS EXPERIMENT

UNIVERSITY OF BIRMINGHAM

Introduction and overview

- Top quarks decay before hadronisation & lifetime is shorter than decorrelation time



- Spin information passed directly to decay products
- V-A structure of *Wtb* vertex defines W decay properties
- Extract spin and polarisation information from angular distributions in top quark decays

- In this talk:
  - Overview of $t\bar{t}$ spin/polarisation measurements
  - Single top quark polarisation in the t-channel at 13 TeV
  - Overview of W polarisation measurements
  - W boson polarisation in dilepton $t\bar{t}$ events at 13 TeV

New!

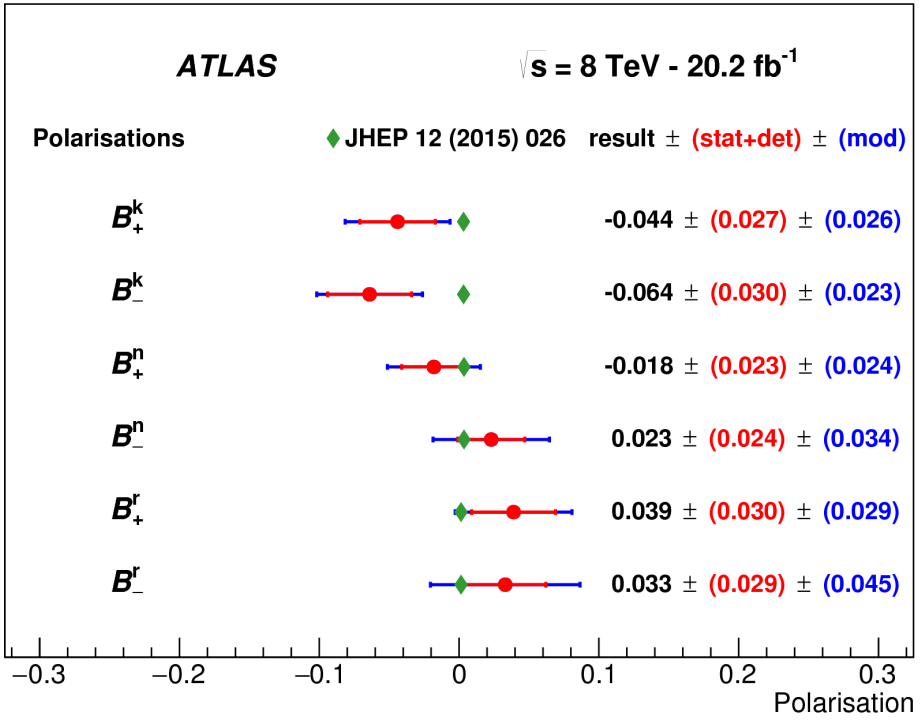
Spin polarisation and correlation in $t\bar{t}$ events

- Top quarks mainly produced as $t\bar{t}$ pairs at the LHC
- Strong interaction conserves parity
  - t and $\bar{t}$ quarks are essentially *unpolarised*

Polarisation observables from spin density matrix of $t\bar{t}$ production at 8 TeV

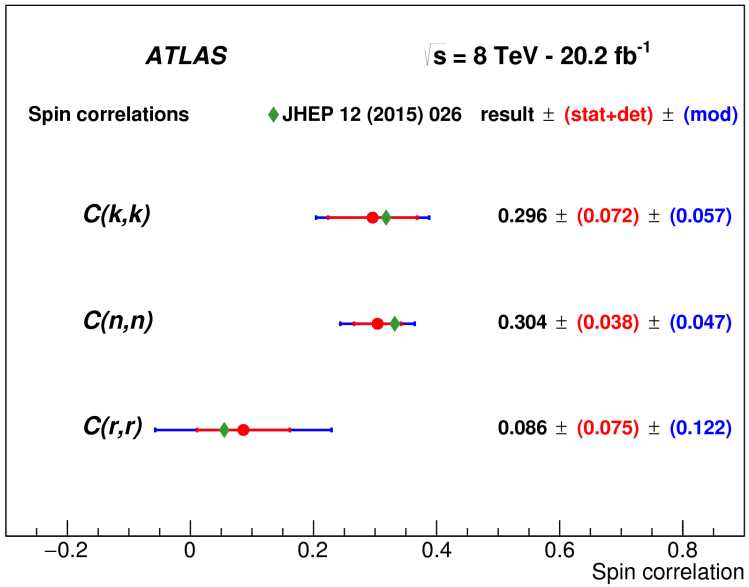
JHEP 03 (2017) 113

Consistent with NLO QCD and ~0 polarisation



Spin polarisation and correlation in $t\bar{t}$ events

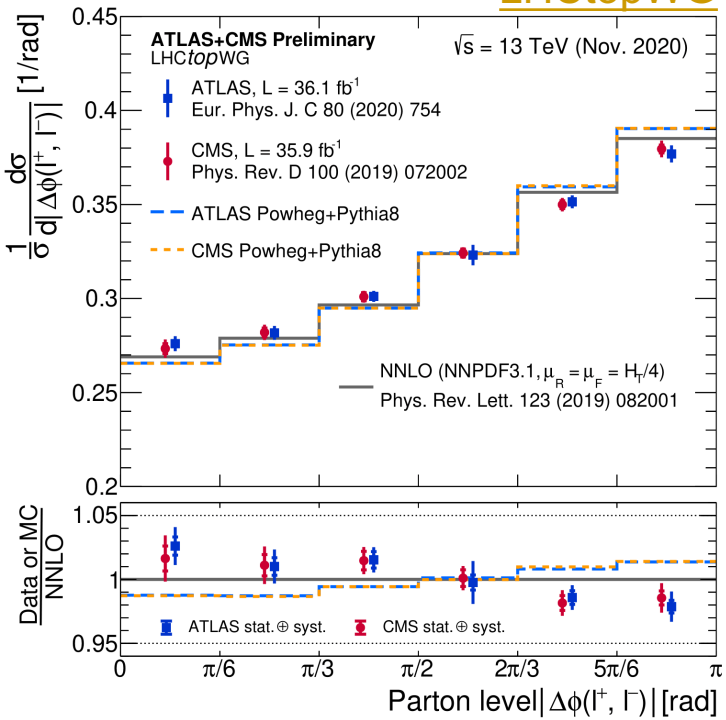
- Top quarks mainly produced as $t\bar{t}$ pairs at the LHC
- Strong interaction conserves parity
  - t and $\bar{t}$ quarks are essentially *unpolarised*
  - However, the *spins* of the t and $\bar{t}$ are *correlated*



Correlation observables from spin density matrix of $t\bar{t}$ production at 8 TeV

JHEP 03 (2017) 113

LHCtopWG



Lab frame azimuthal angle between leptons in $t\bar{t}$ dilepton events, 13 TeV

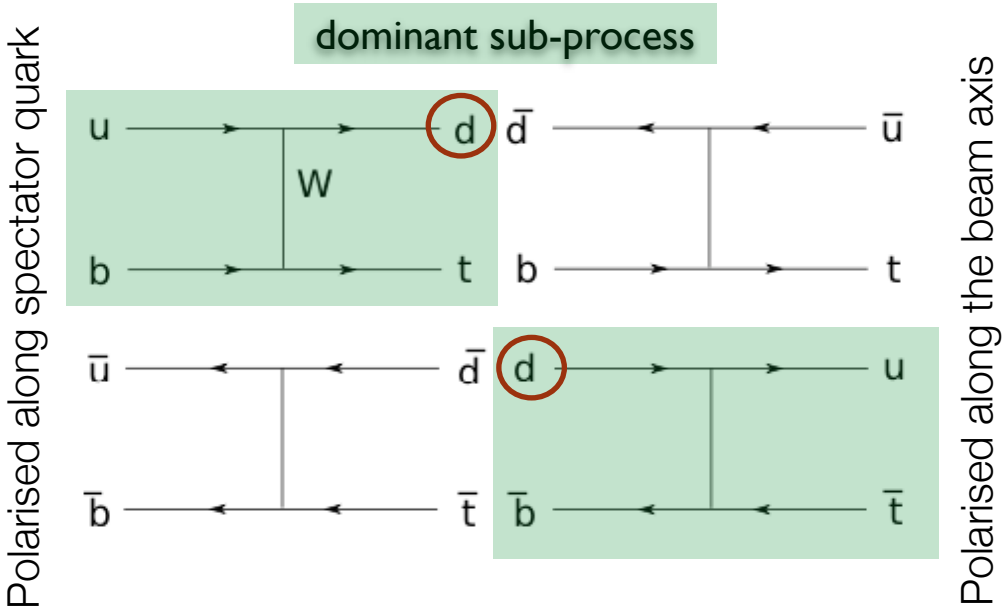
ATLAS: *Eur. Phys. J. C 80 (2020) 754*

Polarisation in single top processes

arXiv:2202.11382
Sub. to JHEP

- t-channel is dominant process for Electroweak single-top production at the LHC
- Top quarks in t-channel are strongly polarised
- Spins aligned with the direction of down-type quarks (V-A coupling in Wtb vertex)

- Dominant polarisation directions:
  - *t* quark: *along* 'spectator' quark direction
  - $\bar{t}$ quark: *opposite* incoming quark direction

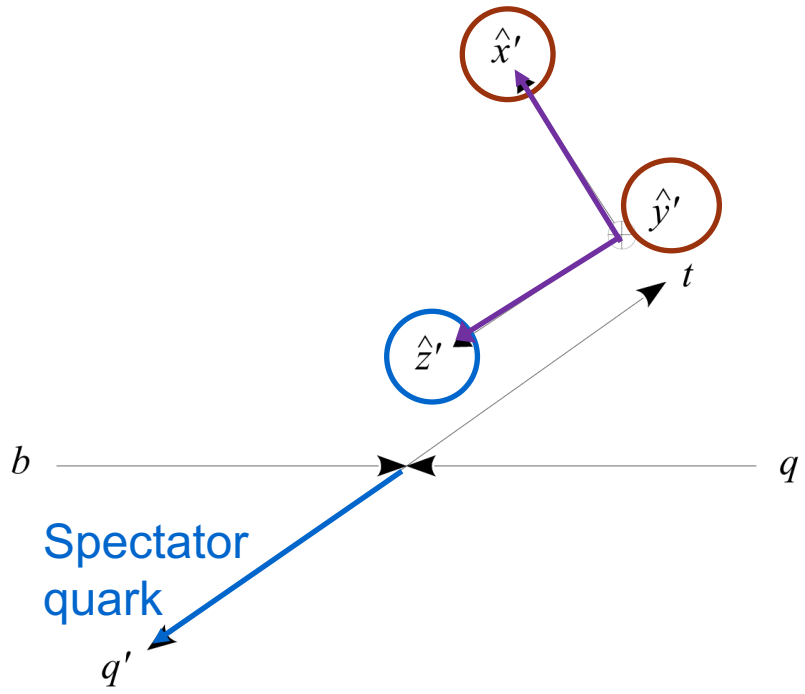


Data selection in t-channel

arXiv:2202.11382

- Single-top selection with 139 fb^{-1} at 13 TeV
- Uses $t \rightarrow W^+b \rightarrow bl^+\nu$ (and charge conjugates)
- 1 charged lepton (e/μ), passing trigger $p_T > 30$ GeV
- 2 jets, of which 1 b-tagged $p_T > 30$ GeV (35 GeV forward)
- m_T, E_T^{miss} and other kinematic cuts
- QCD background estimated using data-driven methods

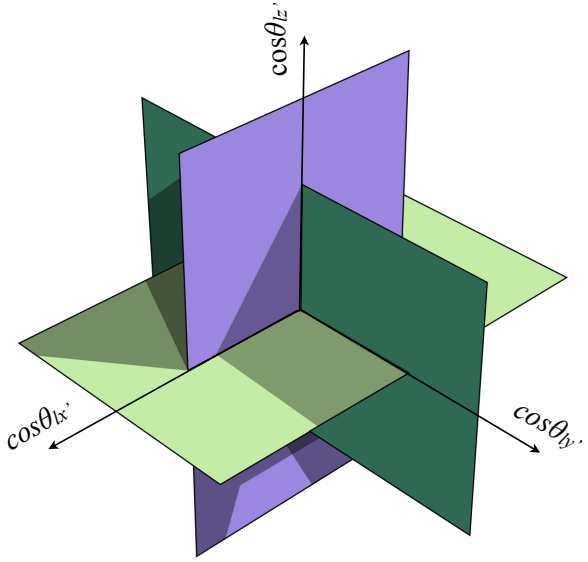
- Non-b-jet is "spectator" jet:
  - Expect strong polarisation in this direction
  - Define 3 axes in top quark reference frame



Extraction of polarisation

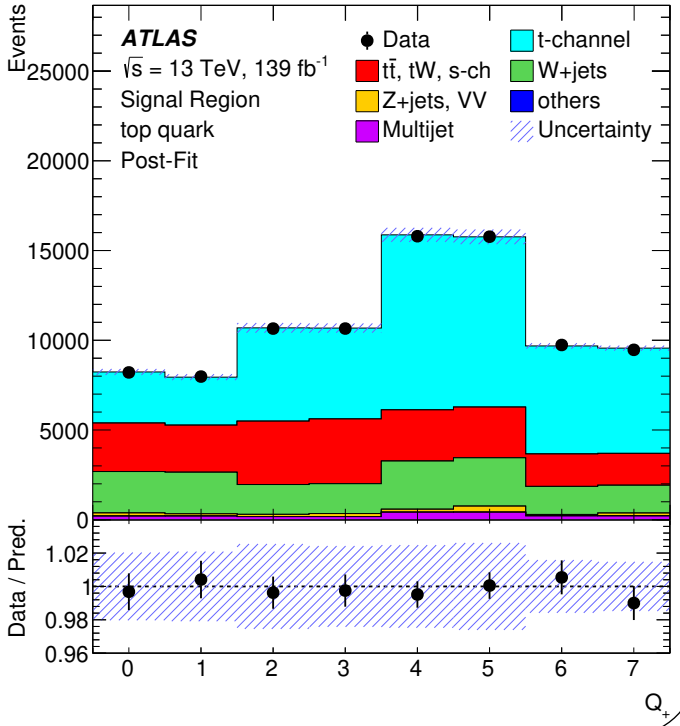
arXiv:2202.11382

- Build angular distributions of unit vector for charged lepton with respect to each axis θ_{li}
  $i = \{x', y', z'\}$



- *Octant Variable Q* defines all signal regions, divided by sign of $\cos\theta_{li}$ and lepton charge

$$Q = 4 \cdot \Theta(\cos\theta_{\ell z'}) + 2 \cdot \Theta(\cos\theta_{\ell x'}) + \Theta(\cos\theta_{\ell y'})$$



- Fit Q_+, Q_- to extract polarisation $\vec{P} = \{P_{x'}, P_{y'}, P_{z'}\}$ for t and $\bar{t}$

Template fit for top quark polarisation

arXiv:2202.11382

- Binned profile-likelihood fit
- Simulated Protos+Pythia8 templates with fully polarised states used in the fit
- Control regions for $t\bar{t}$, W+jets
- 3 normalisations (t−channel signal, $t\bar{t}$ and W+jets)
- Sensitive to *jet energy resolution*

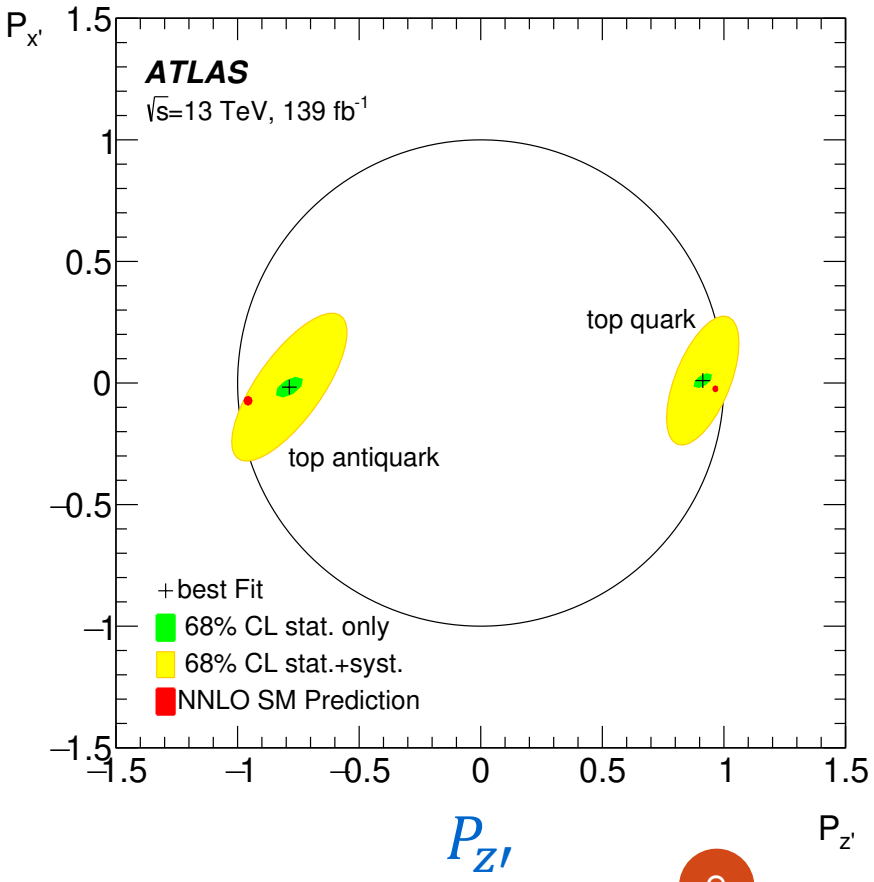
Parameter	Extracted value	(stat.)
t-channel norm.	$+1.045 \pm 0.022$	(± 0.006)
W+ jets norm.	$+1.148 \pm 0.027$	(± 0.005)
$t\bar{t}$ norm.	$+1.005 \pm 0.016$	(± 0.004)
$P^{t}_{x'}$	$+0.01 \pm 0.18$	(± 0.02)
$P^{\bar{t}}_{x'}$	-0.02 ± 0.20	(± 0.03)
$P^{t}_{y'}$	-0.029 ± 0.027	(± 0.011)
$P^{\bar{t}}_{y'}$	-0.007 ± 0.051	(± 0.017)
$P^{t}_{z'}$	$+0.91 \pm 0.10$	(± 0.02)
$P^{\bar{t}}_{z'}$	-0.79 ± 0.16	(± 0.03)

- Strongly polarized along z'
- P_y, consistent with zero

Polarisation values in 2D

arXiv:2202.11382

- Good agreement with SM prediction to NNLO
- Top quark strongly polarised along spectator quark direction z'
- Top antiquark polarised in opposite direction



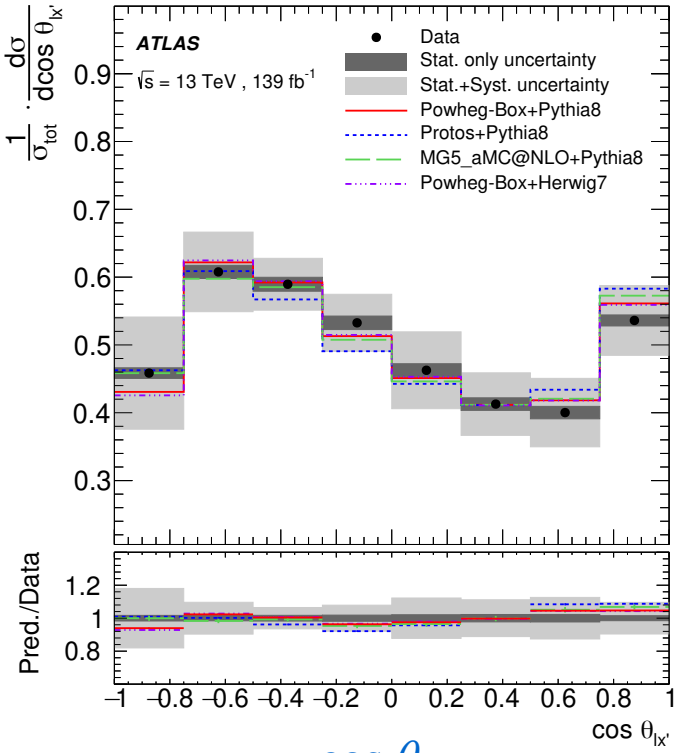
$P_{x'}$

$P_{z'}$

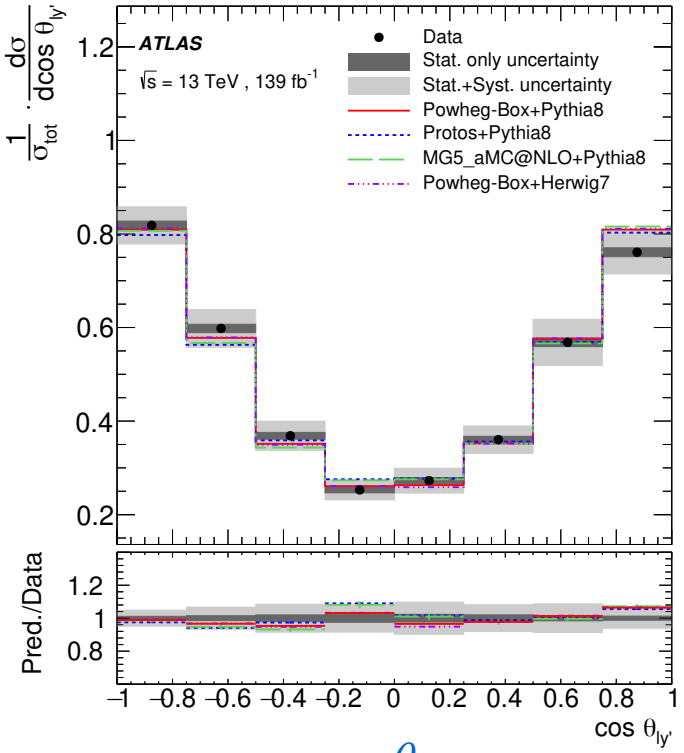
Unfolded distributions

arXiv:2202.11382

- Unfold angular distribution w.r.t. each axis to remove detector and event selection distortions
- Iterative Bayesian unfolding to fiducial particle level
- Differential cross-sections measured for 3 angles for t, $\bar{t}$ and *both combined*



$\cos\theta_{lx'}$



$\cos\theta_{ly'}$

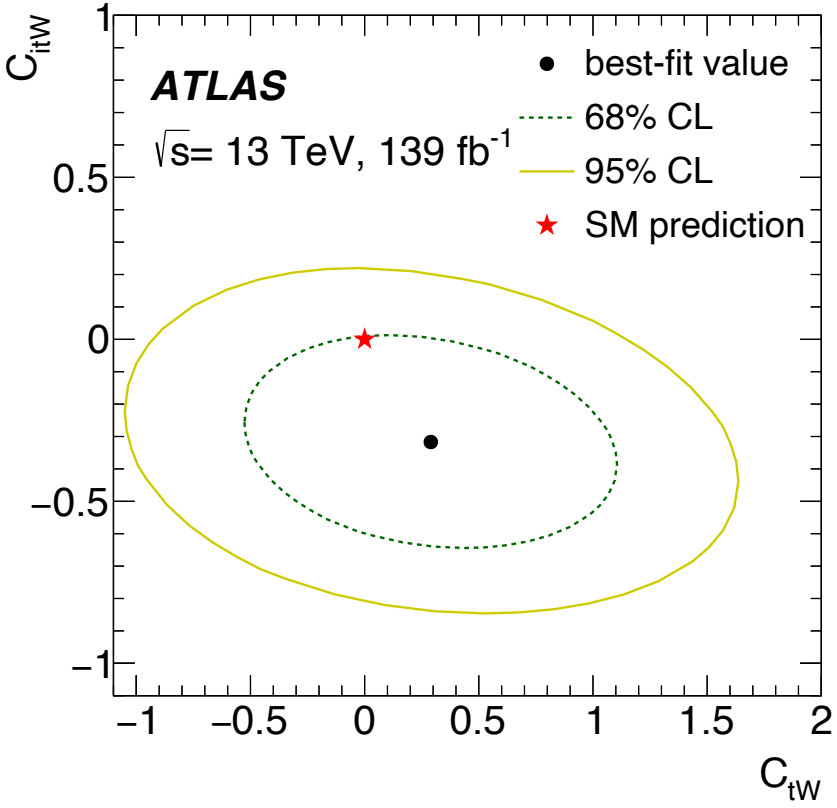
Bounds on EFT coefficients

arXiv:2202.11382

- Measurement is sensitive to BSM phenomena affecting *tWb* vertex
- Unfolded, normalised distributions give bounds on complex Wilson coefficient of dimension-6 operator $\mathcal{O}_{tW}$

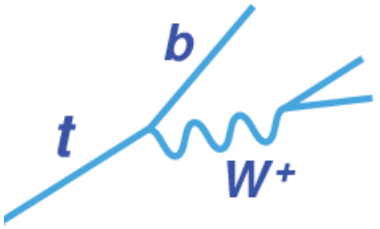
- Real C_{tW} mostly affects $P_{x'}$
- Imaginary C_{itW} mostly affects $P_{y'}$

- Simultaneous fit to $\cos\theta_{lx'}$ and $\cos\theta_{ly'}$
- Results are compatible with the SM predictions

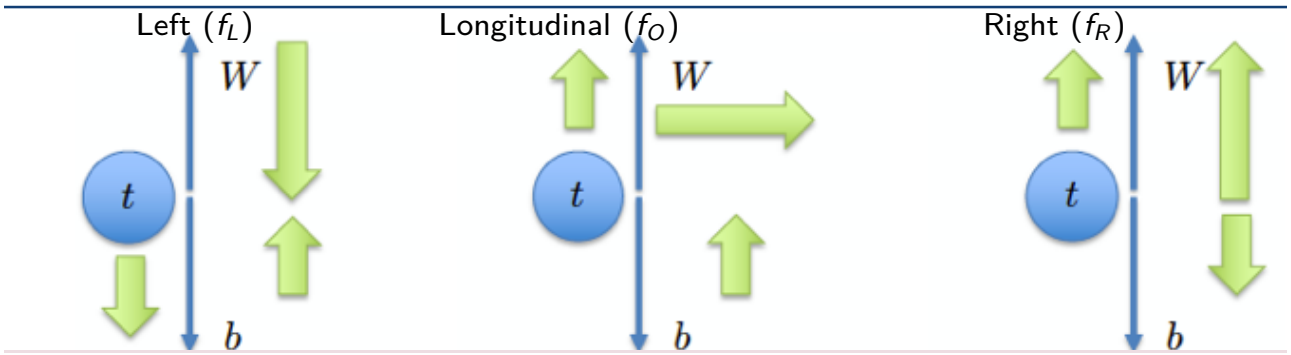


Measurements of W boson polarisation

- *Wtb* vertex structure + particle masses define decay properties of W boson from top decay
- W boson spin density matrix determines the angular distribution of the products of the W decay



- Extract W boson "helicity fractions" f_L, f_0, f_R from angular distributions of decay products:
  - Fractions of longitudinal (f_0), left-handed (f_L), and right-handed (f_R) polarisations



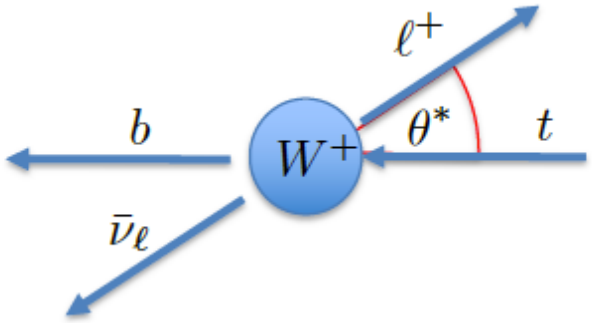
Measurements of W boson polarisation

- Consider products of the *W* leptonic decay $W \to \ell\,\nu$, with ℓ = e, μ

- Observable $\cos\theta^*$ sensitive to helicity fractions:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}(1-\cos^2\theta^*)f_0 + \frac{3}{8}(1-\cos\theta^*)^2 f_{\mathrm{L}} + \frac{3}{8}(1+\cos\theta^*)^2 f_{\mathrm{R}}$$

- θ^* is angle between charged lepton and reversed b-quark direction in W rest frame



Polarisation of W bosons at 8 TeV

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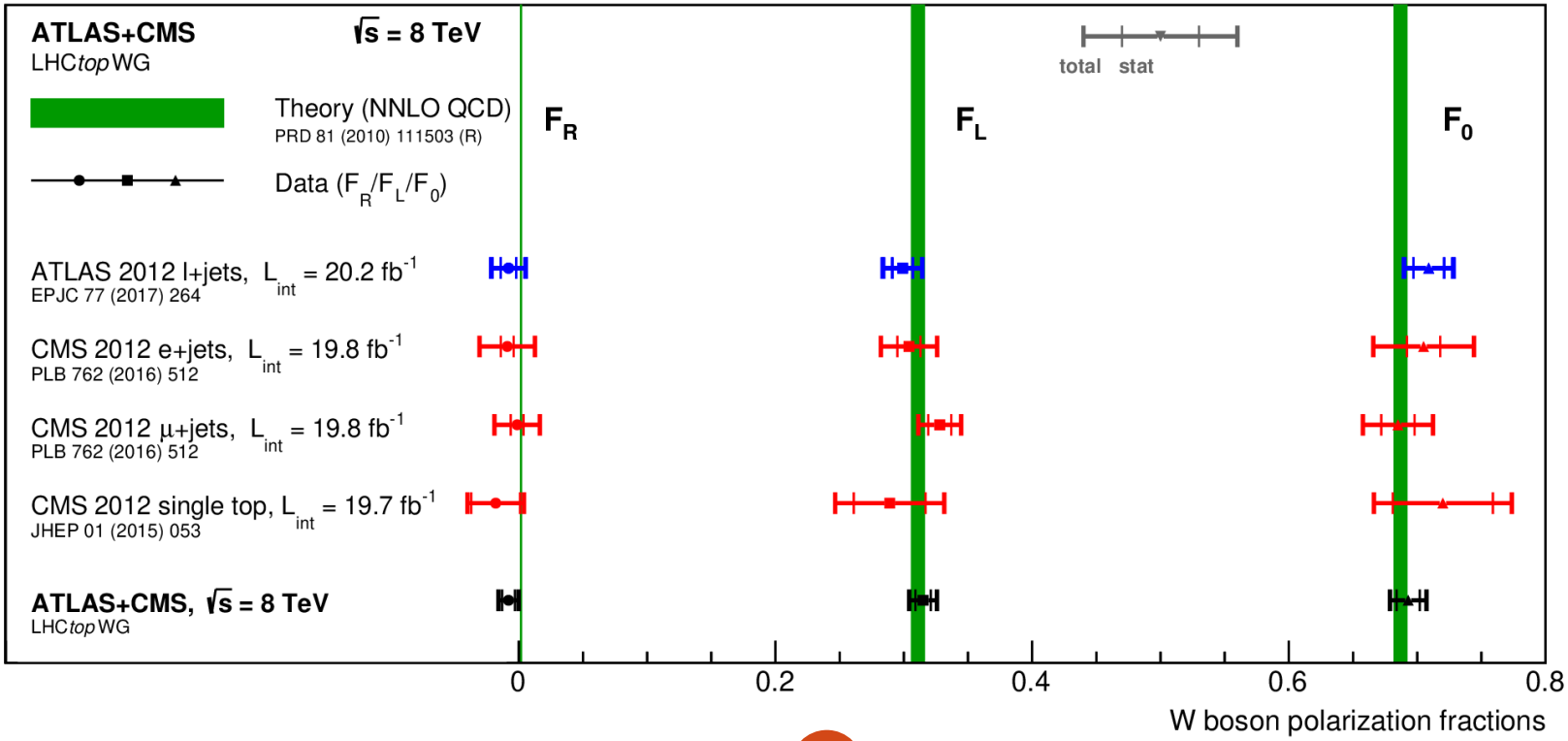
- ATLAS and CMS *$t\bar{t}$ lepton+jets* events at $\sqrt{s}$ = 8 TeV (~20 fb^{-1})
- CMS *single top t-channel* events
- Combined result (from W decays to e, μ)
- Consistent with SM predictions to NNLO in perturbative QCD

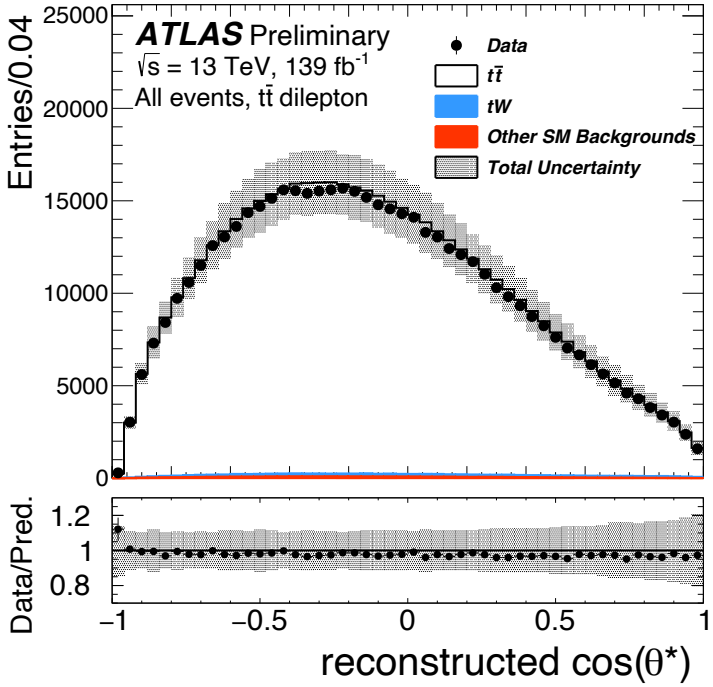


Polarisation of W bosons at 13 TeV

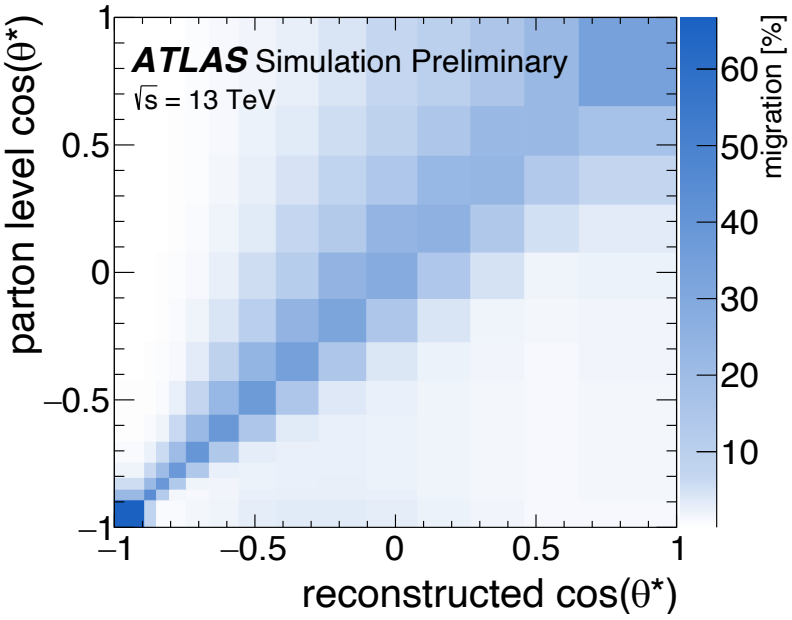
ATLAS-CONF-2022-063

New!

- ATLAS $t\bar{t}$ *dileptonic* events at $\sqrt{s}$ = 13 TeV, Run 2 (139 fb^{-1})
- ≥ 2 jets and ≥ 2 b-tagged jets p_T > 25 GeV
- 2 opposite-charge leptons p_T > 25 (27) GeV for 2015 (2016-18)
- Z veto and E_T^{miss} cuts on ee, μμ channels
- Neutrino Weighting algorithm used to reconstruct dileptonic $t\bar{t}$



Iterative Bayesian algorithm to unfold data to parton level



Differential cross-sections

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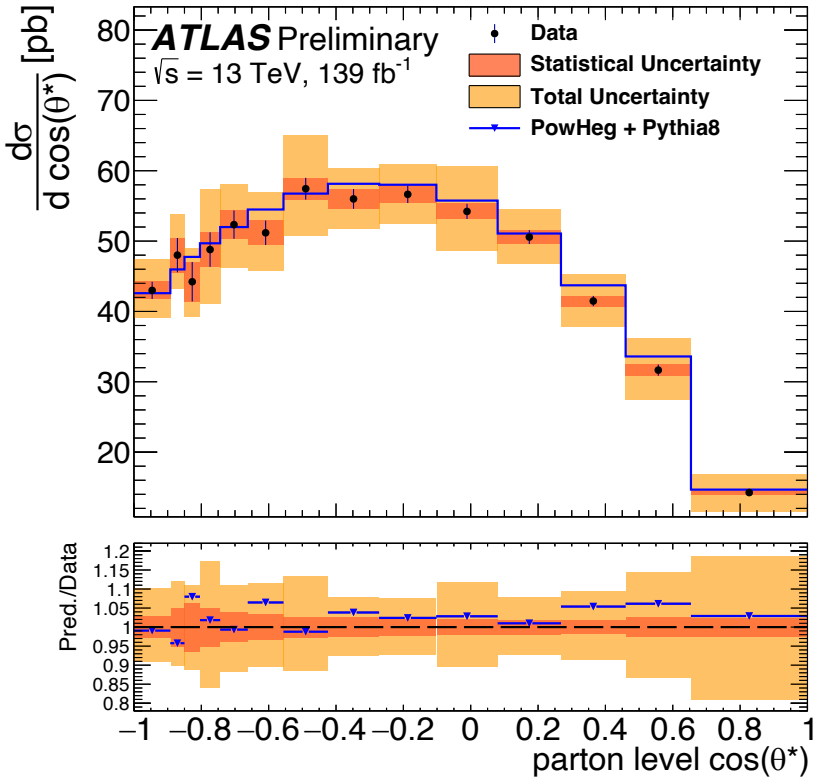
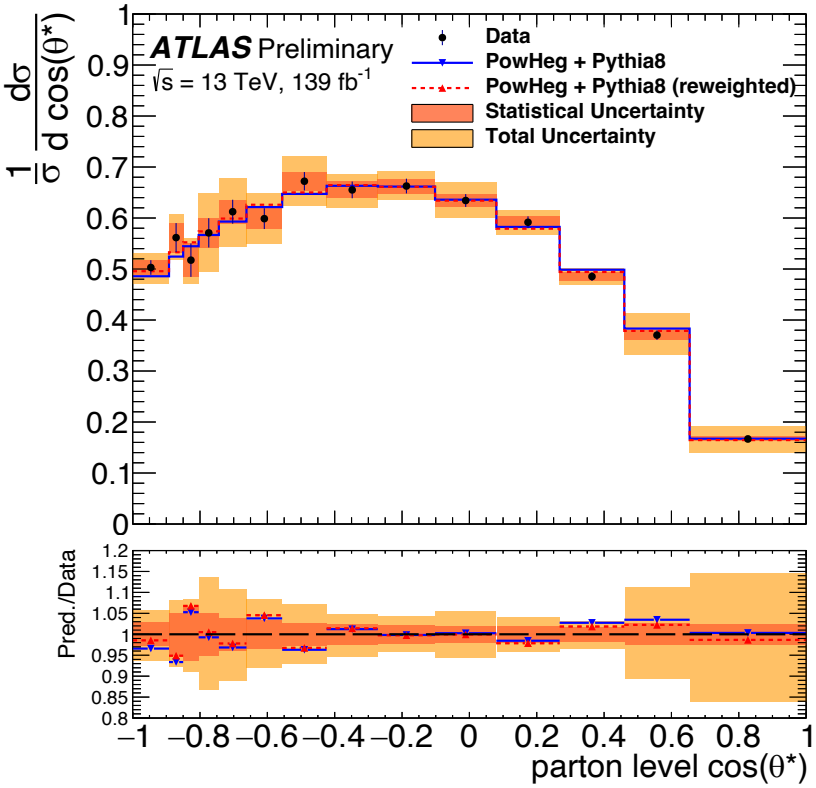
- Absolute and normalised differential distributions in $\cos\theta^*$
- Systematic uncertainties from detector and modelling effects
- Good agreement with the NLO prediction from Powheg+Pythia8



Absolute



Normalised

Extraction of the helicity fractions

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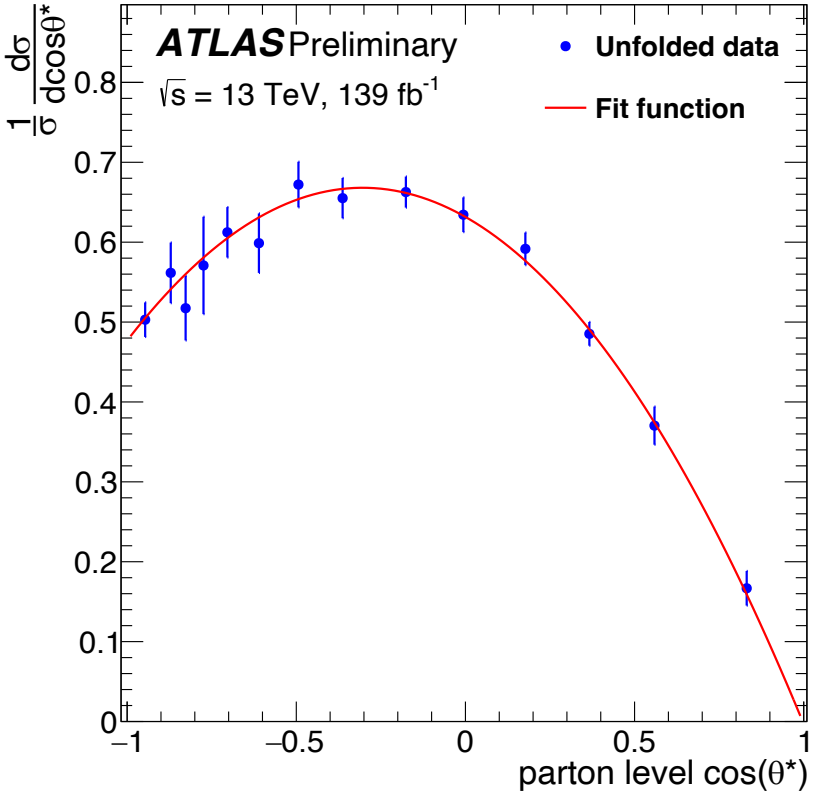
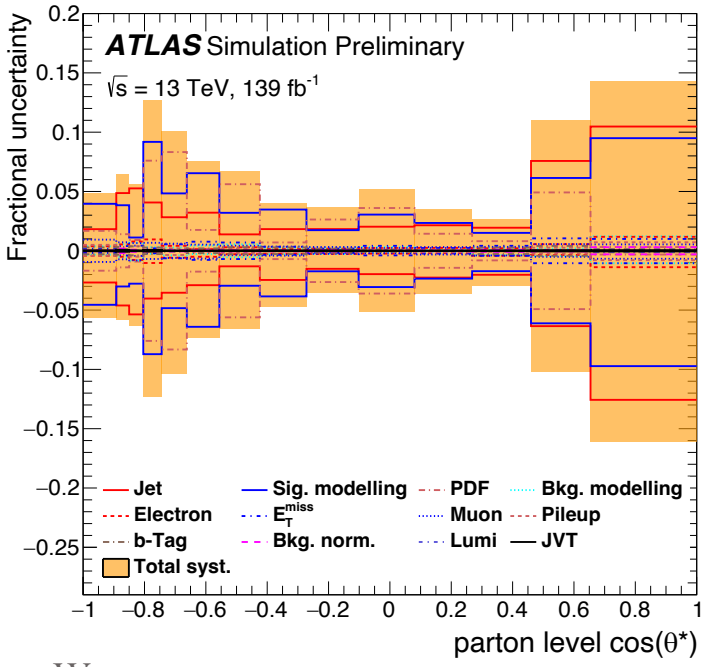
- Fit normalised differential cross-section, minimum χ^2 method.
- Include full covariance between bins
- Fit with $f_0 = 1 - f_L - f_R$
- Alternative unitarity constraint: Lagrange Multipliers





- Systematic uncertainty dominates, particularly $t\bar{t}$ modelling and jet reconstruction

Extraction of the helicity fractions

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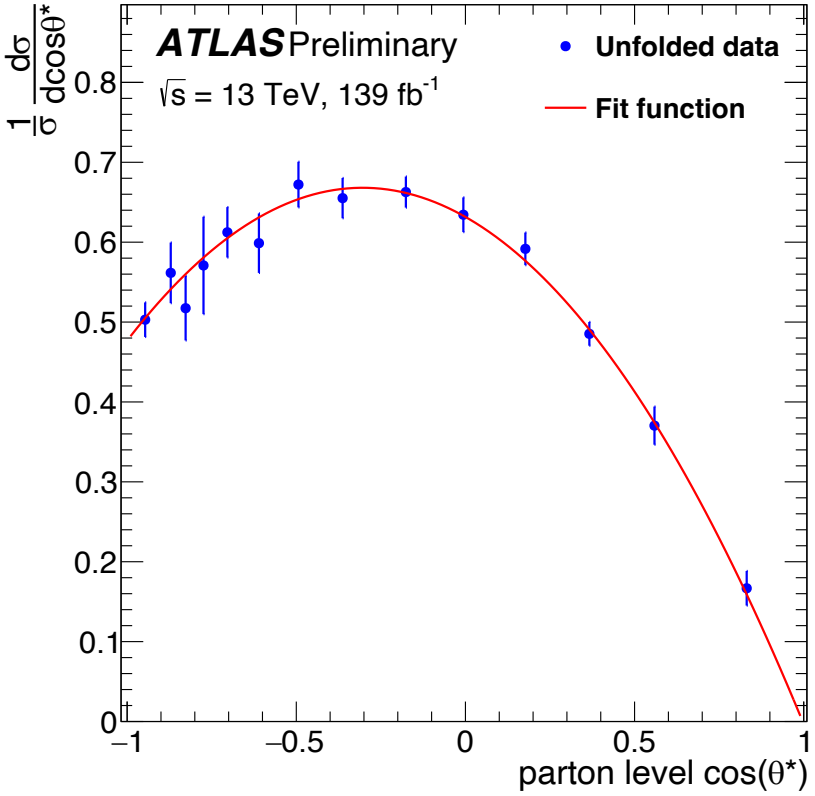

$$f_0 = 0.684 \pm 0.015\ (\text{stat.} + \text{syst.})$$
$$f_L = 0.318 \pm 0.008\ (\text{stat.} + \text{syst.})$$
$$f_R = -0.002 \pm 0.015\ (\text{stat.} + \text{syst.})$$

- Good agreement with SM prediction to NNLO QCD

f_0 = 0.687 ± 0.005

f_L = 0.311 ± 0.005

f_R = 0.0017 ± 0.0001

Summary

- Angular distributions of the decay products in top decays give access to detailed information on spin and polarisation

- Precise measurements in single-top t-channel decays:
  - Components of polarisation for top and antitop quarks
  - Differential cross-sections
  - Bounds on EFT operators

- Measurement of W boson helicity in dilepton $t\bar{t}$ events:
  - Extraction of 3 helicity fractions
  - Absolute and normalised differential cross-sections

- Complementary top quark spin and polarisation measurements in $t\bar{t}$ decays