Measurement of top-quark properties with the ATLAS detector at the LHC

Nello Bruscino - Sapienza Università di Roma & INFN Roma 1
on behalf of the ATLAS Collaboration

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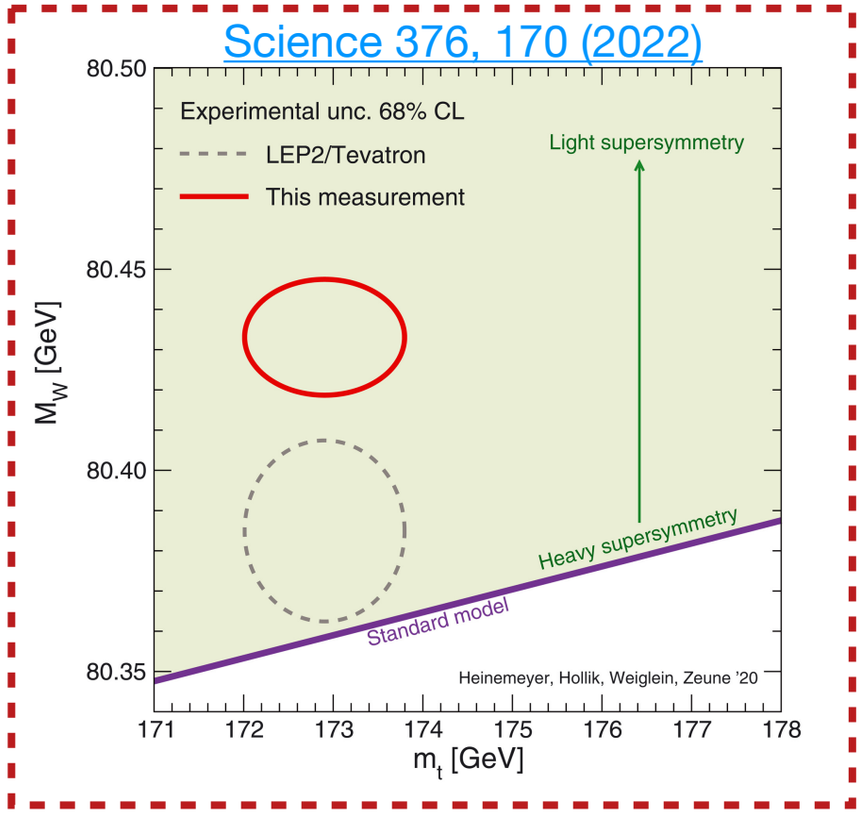
Top quark physics

Production time		Decay time		Hadronisation time		Spin-Decorr. time
$\frac{1}{m_t}$	<	$\frac{1}{\Gamma_t}$	<	$\frac{1}{\Lambda_{QCD}}$	<	$\frac{m_t}{\Lambda_{QCD}^2}$
~10^{-27} s		~10^{-25} s		~10^{-24} s		~10^{-21} s

Why top quarks?

- heaviest known particle, only "bare" quark
- high statistics allows precision tests and search for new physics (Effective Field Theory frameworks)



Copious production at the LHC (top-factory):

- ≈140/fb @13TeV collected in Run 2 by ATLAS…

$$\frac{dN}{dt} = \mathscr{L} \cdot \sigma_{t\bar{t}},$$

$$\sigma_{t\bar{t}} \approx 830\,\text{pb}, \implies$$

$$\mathscr{L} \approx 15 \cdot 10^{33}\,\text{cm}^2\,\text{s}^{-1}$$

Top recent results* (24)

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Top x-section

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Top x-section **Top + X**

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Top x-section **Top + X** **Top mass**

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Top x-section | **Top + X** | **Top mass** | **Top properties**

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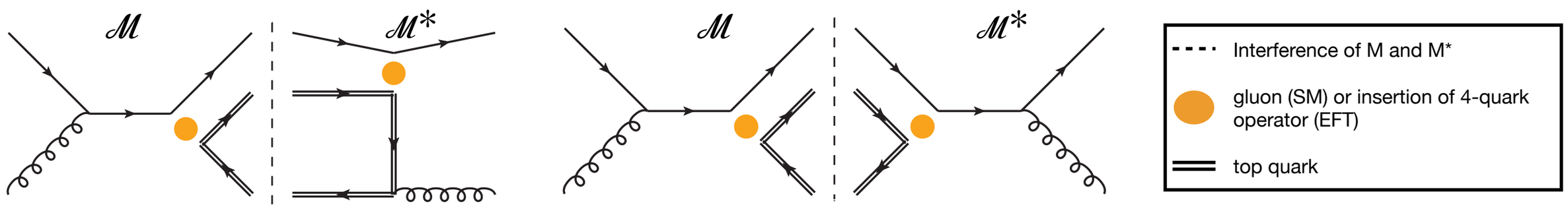
Energy asymmetry in $t\bar{t}$+j at 13 TeV and interpretation in the SMEFT framework

Energy Asymmetry: introduction

Eur. Phys. J. C 82 (2022) 374

$t\bar{t}$ energy asymmetry ($A_E^{t\bar{t}}$) happens at LO mainly through qg → $t\bar{t}$g

- different probability of t and $\bar{t}$ from to be emitted in a certain phase-space
- → t and $\bar{t}$ have different energy in $t\bar{t}$ + high p_T jet
- → measure asymmetry in top quark energy in $t\bar{t}$ + 1 jet boosted events and search for BSM



Observable defined for $t\bar{t}$+j production as $$A_E(\theta_j) = \frac{\sigma^{\mathbf{opt}}(\theta_j \,|\, \Delta E > 0) - \sigma^{\mathbf{opt}}(\theta_j \,|\, \Delta E < 0)}{\sigma^{\mathbf{opt}}(\theta_j \,|\, \Delta E > 0) + \sigma^{\mathbf{opt}}(\theta_j \,|\, \Delta E < 0)}$$

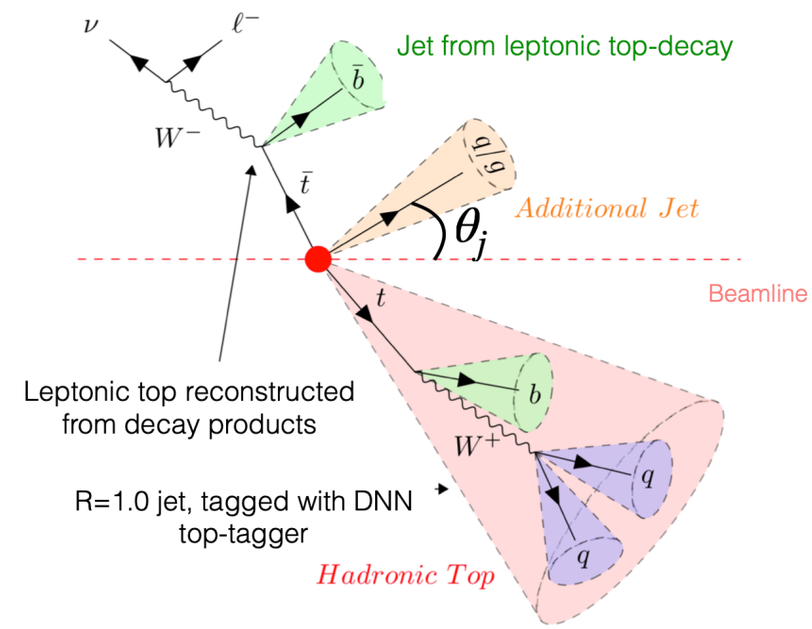
- where $\Delta E = E_t - E_{\bar{t}}$ and θ_j scattering angle of additional jet in tt+j rest frame
- QCD asymmetry is closely related to the charge asymmetry in inclusive $t\bar{t}$ production
- observable probes for possible new physics in tt+j events

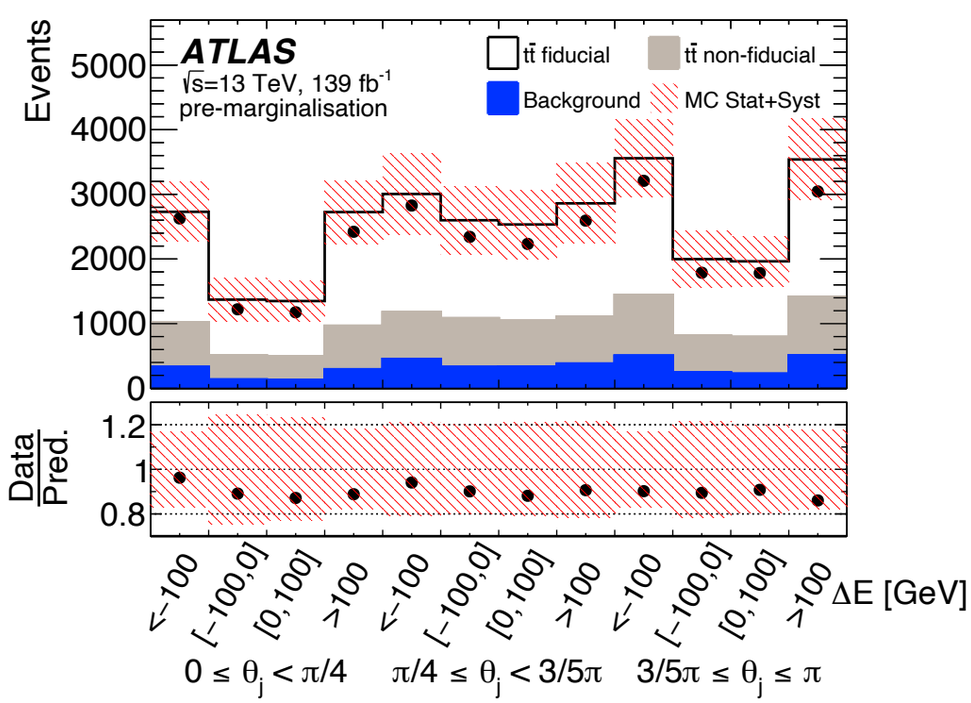
Energy Asymmetry: strategy

Eur. Phys. J. C 82 (2022) 374

Select l+jets boosted events:

- "leptonic" top (large m_T^W and E_T^{miss})
- high p_T hadronic top (p_T > 350 GeV) as R=1 jet tagged by substructure based Neural Network (NN)
- high p_T (> 350 GeV) additional jet





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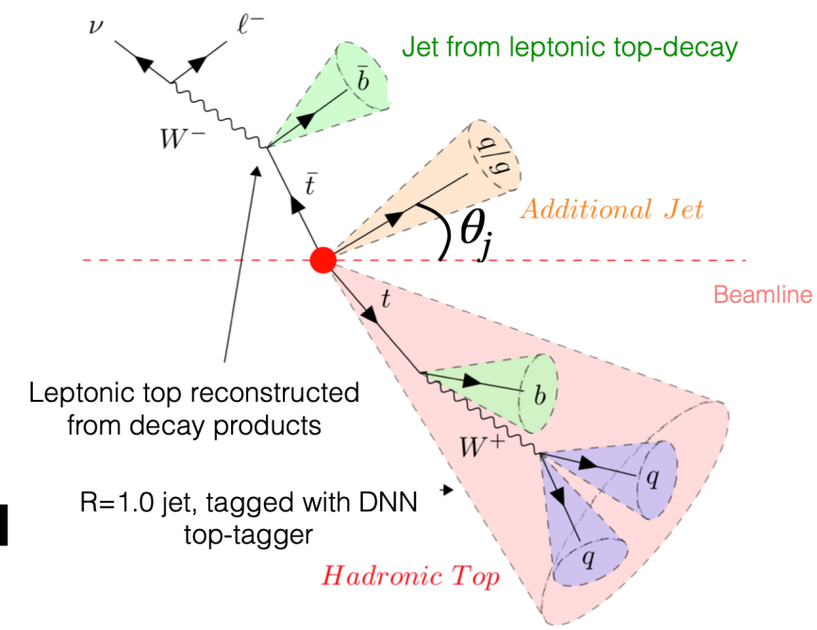
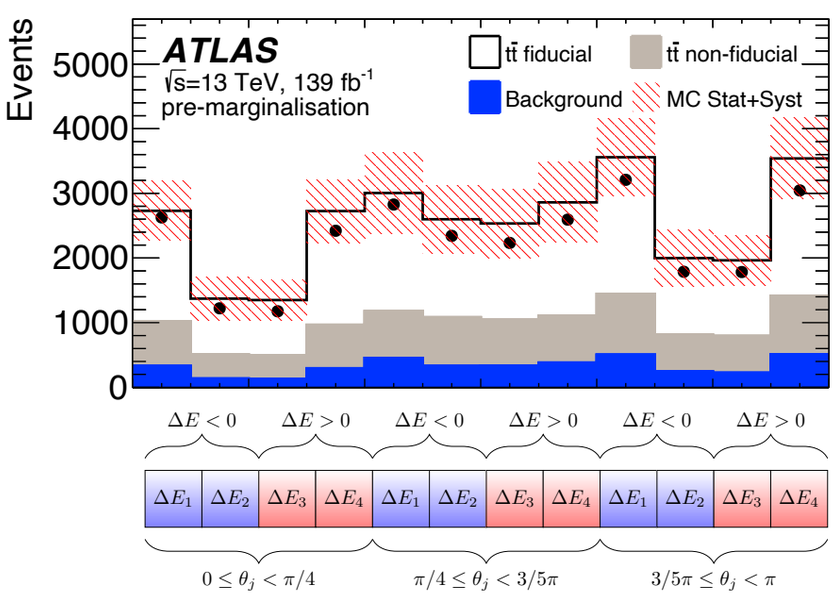


Count events with ΔE >0 or <0 in bins of θ_j and unfolded data with Fully Bayesian Unfolding technique (FBU)

- analysis currently limited by available data statistics and $t\bar{t}$ FSR modelling



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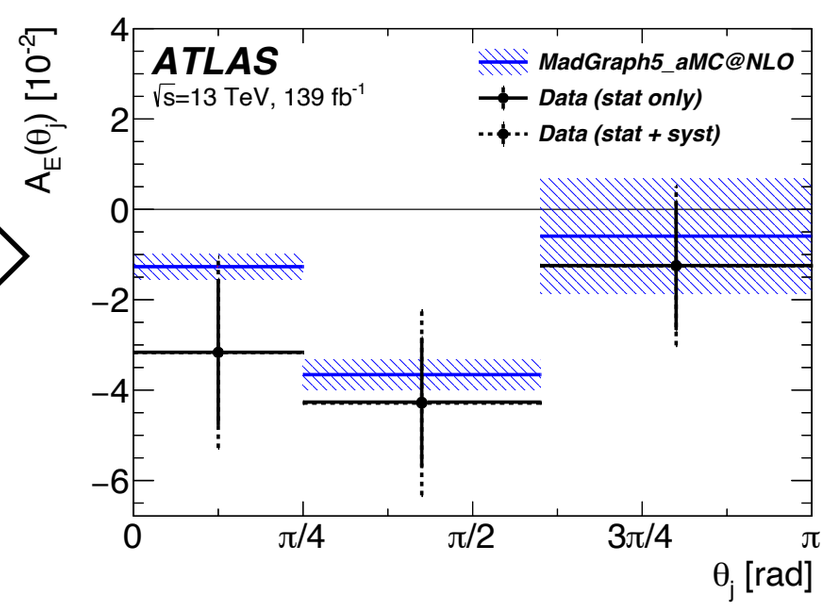

Consistent with NLO QCD prediction

2.1σ deviation from 0 asymmetry in the central bin

Energy Asymmetry: EFT

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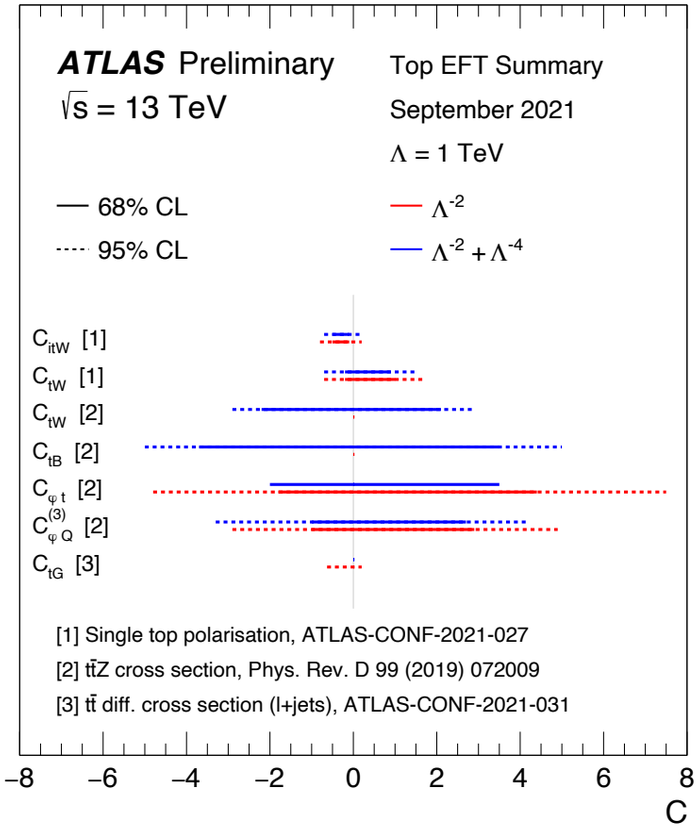
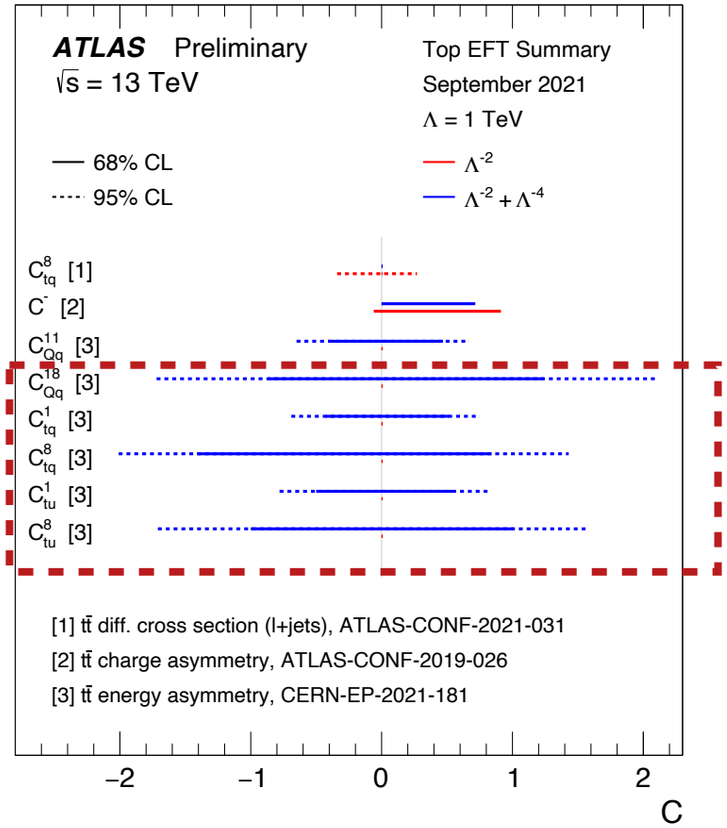
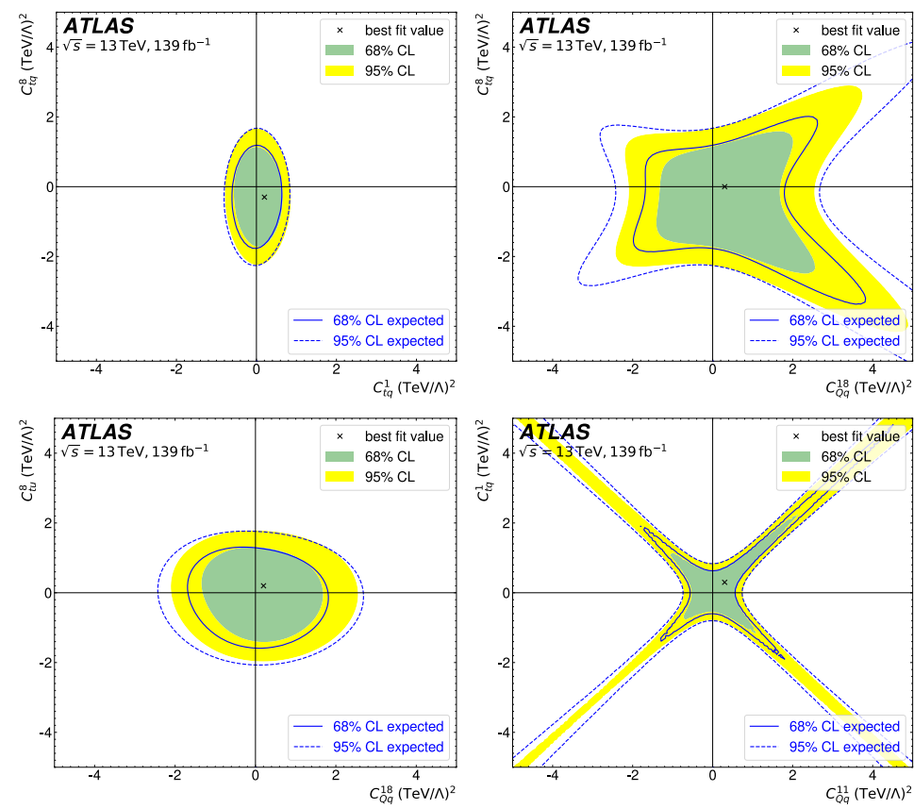
$A_E^{t\bar{t}}$ sensitive to top chirality in 4-quark operators

- → valuable new observable in global SMEFT fits
- it probes new directions in dim-6 parameter space (w.r.t. charge asymmetry, for instance)
- 2D limits on pairs of 6 corresponding Wilson coefficients breaking degeneracy

ATL-PHYS-PUB-2021-043



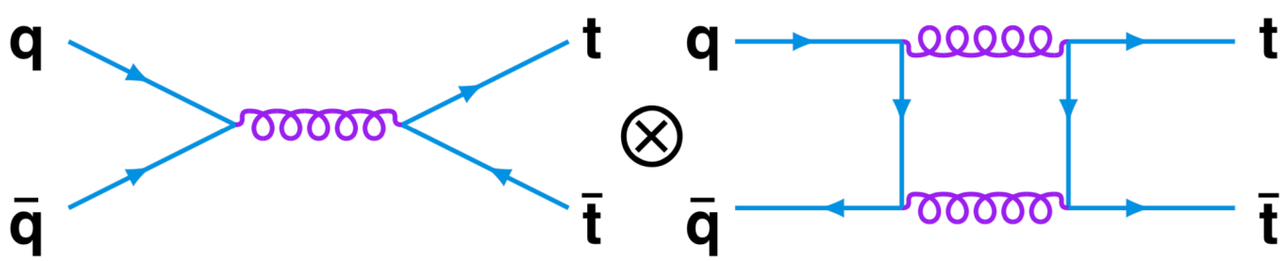


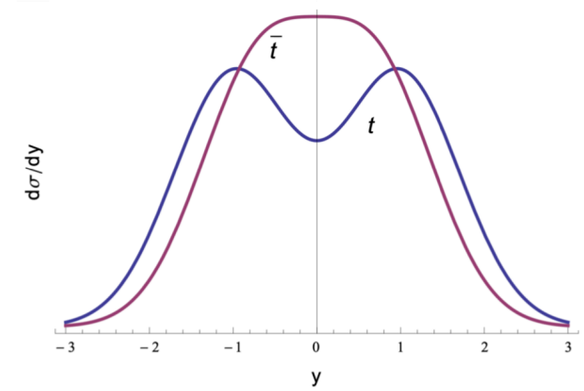


Charge asymmetry in $t\bar{t}+\gamma$ events at 13 TeV

Charge Asymmetry: introduction

ATLAS-CONF-2022-049





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

$t\bar{t}$ charge asymmetry ($A_C^{t\bar{t}}$) happens only at NLO

- gg initiated process (~90% @13 TeV) remains charge symmetric to all orders
  - → challenging to measure $A_C^{t\bar{t}}$ at LHC
- higher orders interference in qg and $q\bar{q}$, and EW contributions lead to asymmetries
  - also BSM physics can lead to enhancements
- evidence by ATLAS in Run II [ATLAS-CONF-2019-026] in agreement with NNLO QCD + NLO EW predictions

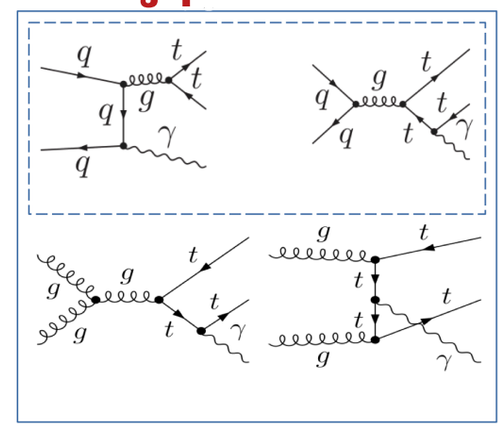
$t\bar{t}+\gamma$ has enhanced $q\bar{q}$ initiated production → perfect playground for tests of $A_C^{t\bar{t}}$

- enhancement only for events where the photon is radiated by initial state partons (a.k.a. "$t\bar{t}+\gamma$ production")

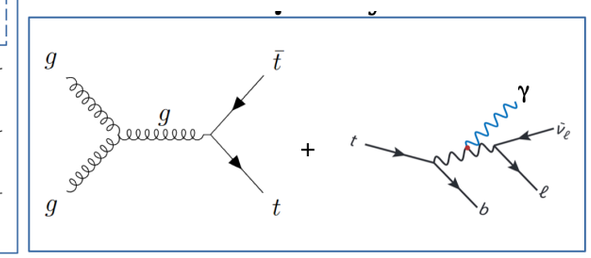
Charge Asymmetry: strategy

ATLAS-CONF-2022-049

$t\bar{t}+\gamma$ production



$t\bar{t}+\gamma$ decay

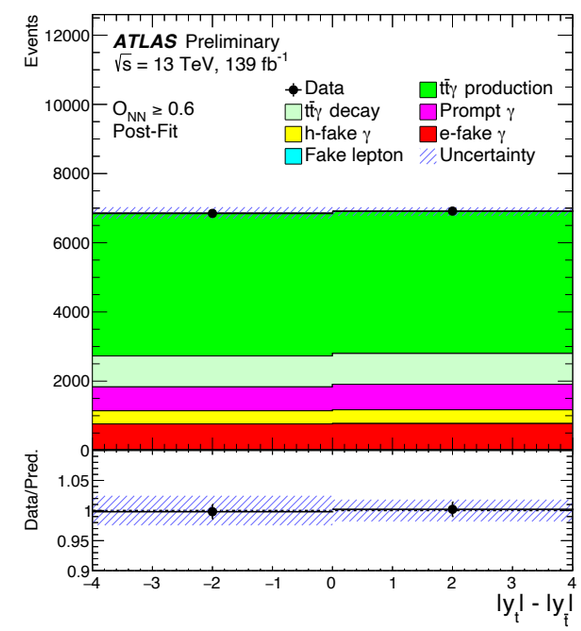


l+γ+jets selection with Run II data:

- e/μ trigger-matched with p_T>27 GeV
- isolated photon p_T>20 GeV and ΔR(l,γ)>0.4
- m(e,γ) outside Z-mass window (m_Z ± 5 GeV)
- ≥4 jets of which ≥1 b-tagged
- kinematic likelihood fit (KLFitter) to reconstruct $t\bar{t}$ system
- Neural Network (NN) to separate signal ($t\bar{t}+\gamma$ production) vs. backgrounds
  - "$t\bar{t}+\gamma$ decay" as irreducible background
  - 21 input variables, 3 hidden layers, 5-fold cross validation
  - two regions NN<0.6 and NN>0.6

Main backgrounds: prompt γ, jet- and e-faking γ

- $t\bar{t}+\gamma$ decay (30%) and prompt-γ (15%) estimated with MC
  - validated in Zγ and Wγ dedicated regions
- data-driven e-faking γ (16%) using tag-and-probe Z→ee/eγ events
- data-driven jet-faking γ (7%) using ABCD method (γ-iso and γ-ID)



$A_C^{t\bar{t}}$ extraction by Profile Likelihood Unfolding (PLU)

- $A_C^{t\bar{t}}$ = -0.006 ± 0.030 = -0.006 ± 0.024(stat) ± 0.018(syst)
- precision is limited by the statistical uncertainty

Consistent with SM prediction $A_C^{t\bar{t}}$ = -0.014±0.001 (MadGraph NLO)

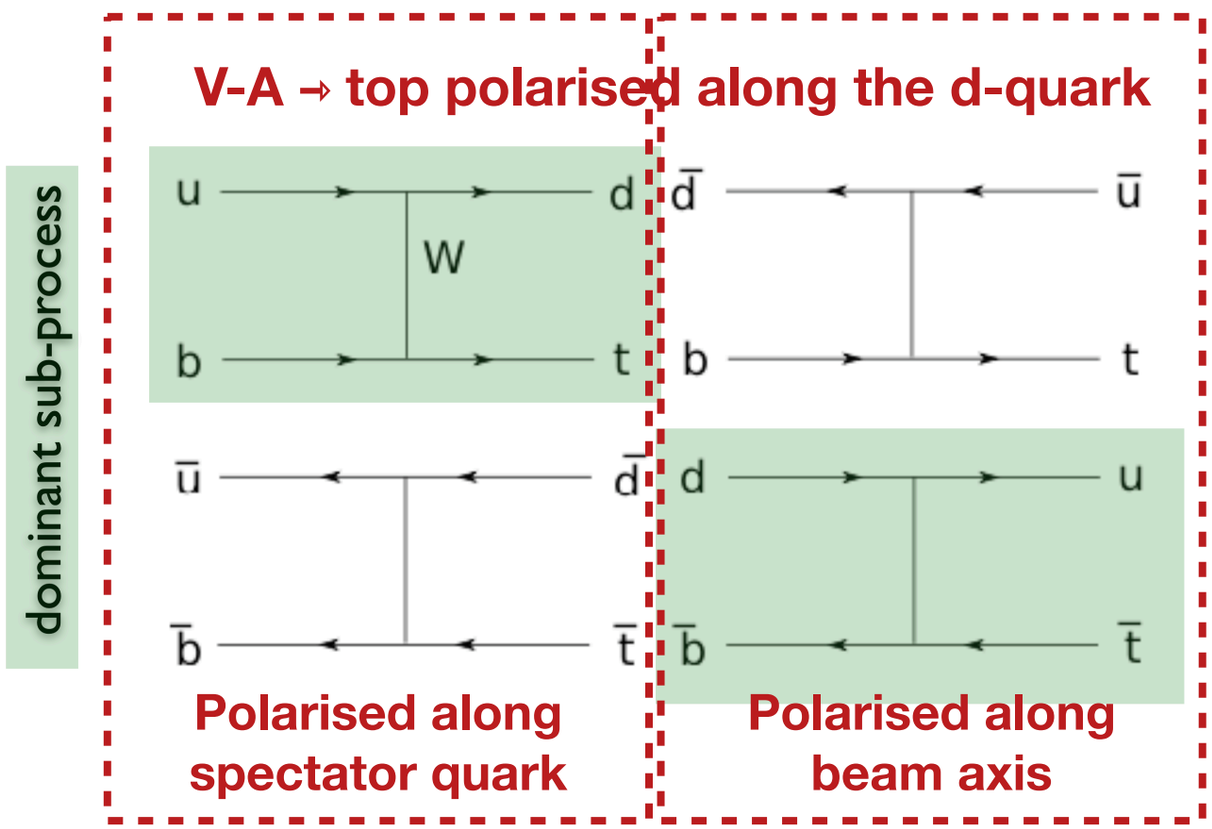
Top polarisation at 13 TeV in single-top t-channel and bounds on tWb dipole operator

Top Polarisation: introduction

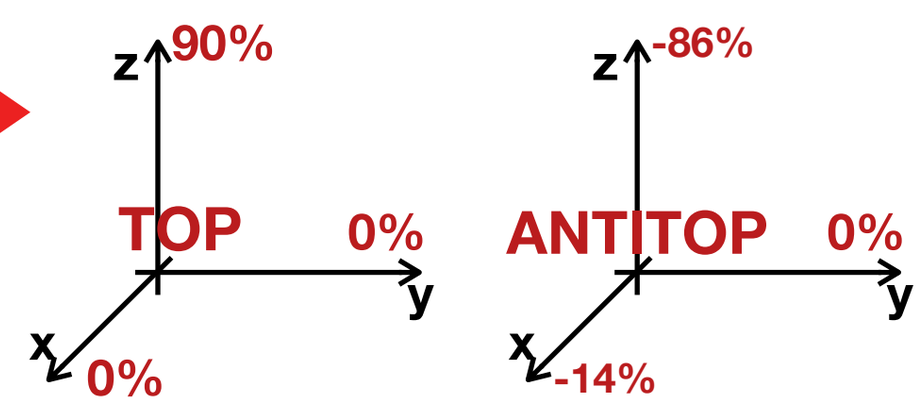
Submitted to JHEP

At the LHC (pp collisions)...

- *EW production:* highly polarised top quarks due to V-A nature
  - Top-quark polarisation (***P***) can only be measured in single top-quark t-channel events*
    - * In $t\bar{t}$ production, top quarks are produced unpolarised because of parity conservation in QCD
- *detectable:* accessible via angular distributions (in top rest frame)
- *spin polarisation:* depends upon specific top-/antitop- sample and chosen basis
  - valence *u*-quark density ~2x valence *d*-quark density (pp collisions)
  - $P_i = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}, \quad \uparrow / \downarrow$ w.r.t. i



z axis: along the top-quark boost in c.m. of colliding partons (= along dir. of spectator jet)
x axis: in the plane of production
y axis: perpendicular to the plane of production (CP violating axis)

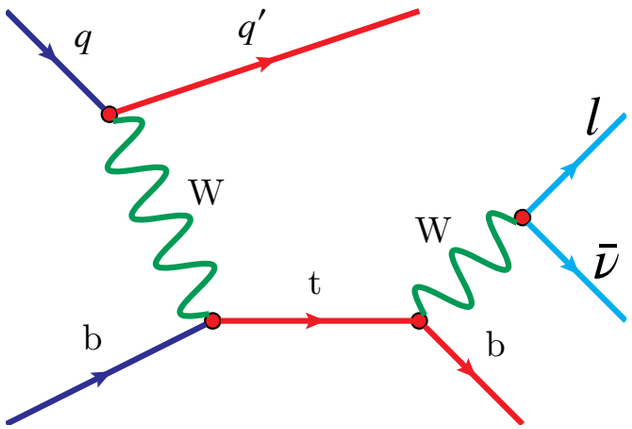


Top Polarisation: strategy

Submitted to JHEP

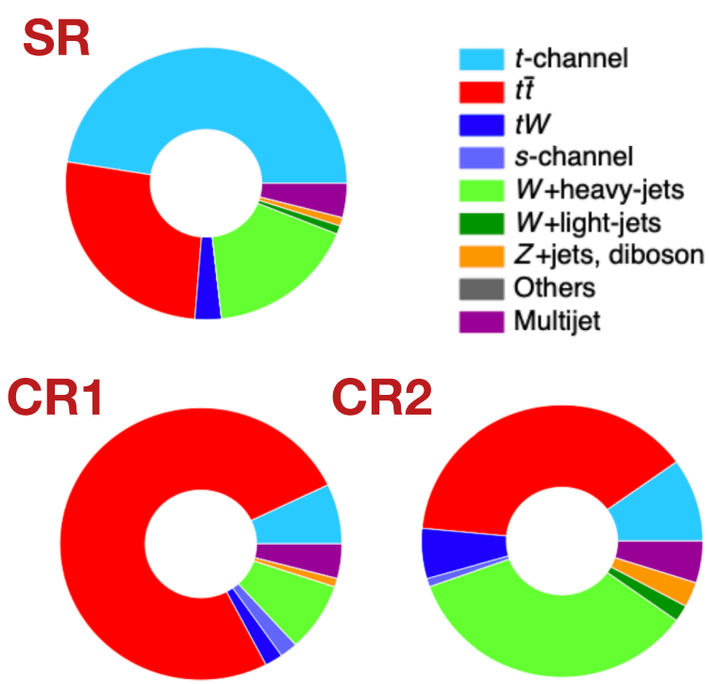
Fiducial measurement of top polarisation in t-channel with full Run II dataset (139 /fb)

- *template fit:* measurement of top quark and anti-quark polarisations (P_x,P_y,P_z) in the t-channel events, at reco. level within a fiducial region
- *unfolding:* normalised differential measurements ($\cos\theta_{x/y/z}$) unfolded at particle level within the same fiducial region
- *EFT interpretation* of the unfolded results



Cut-based analysis in 1L final state:

- exactly 1 triggering lepton (e/μ),
- exactly 2 jets, of which 1 b-quark tagged,
- m_T^W and E_T^{miss} cuts to reject QCD background
- QCD background estimated via data-driven methods
  - *jet-electron* (e-channel) and *anti-muon* (μ-channel)
- further split into 1 signal region and 2 control regions

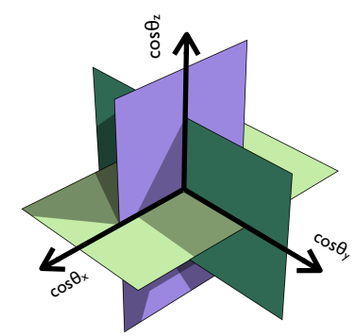


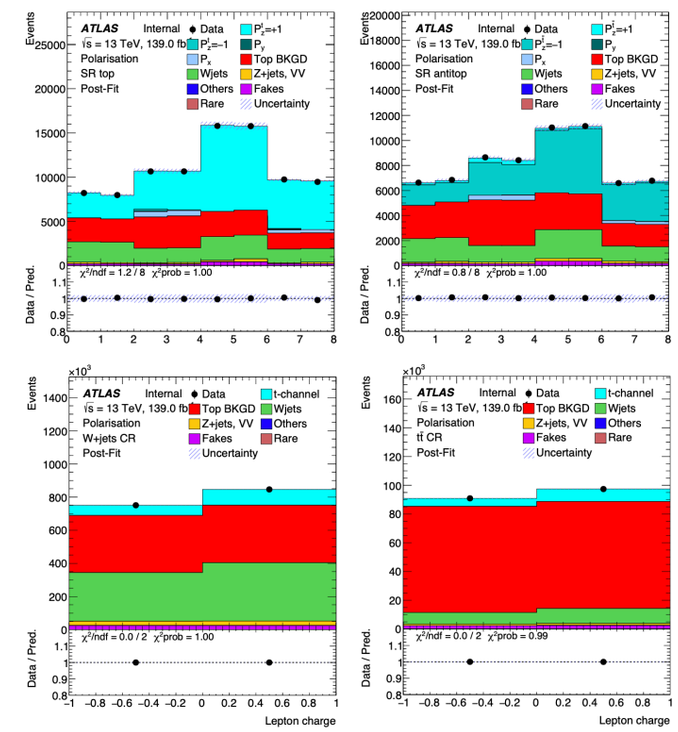
Top Polarisation: template fit

Submitted to JHEP

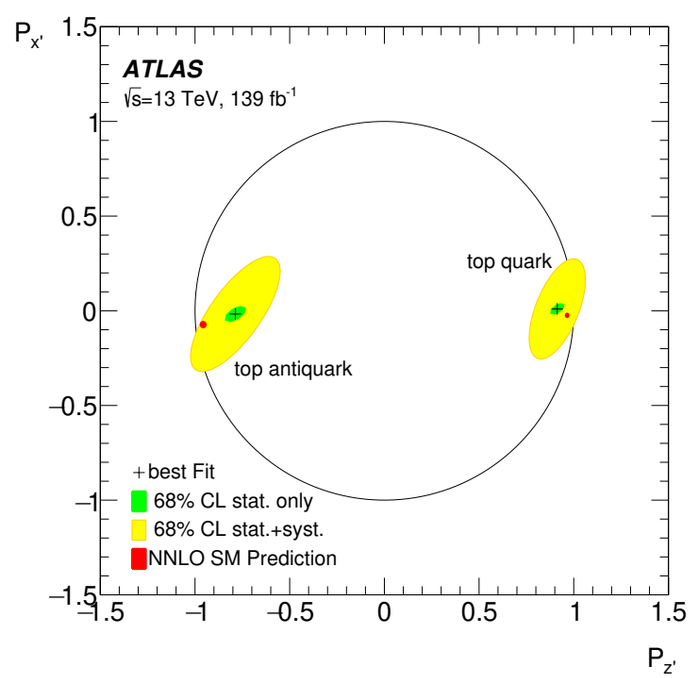
Simultaneous profile likelihood fit of top and antitop polarisations:

- $\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega d\Omega^*} = \frac{1+P_z}{2}\mathcal{F}_{z+} + \frac{1-P_z}{2}\mathcal{F}_{z-} + \frac{P_x}{2}\mathcal{F}_x + \frac{P_y}{2i}\mathcal{F}_y$
- *4 regions:* 2 SRs (top, anti-top) + 2 CRs (W+jets, $t\bar{t}$)
- *6 polarisation parameters* $P(t)=\{P_x^t, P_y^t, P_z^t\}$ and $P(\bar{t})=\{P_x^{\bar{t}}, P_y^{\bar{t}}, P_z^{\bar{t}}\}$
- *3 normalisations* $N_{t\text{-ch}}$, $N_{t\bar{t}}$ and $N_{W+\text{jets}}$
- *Octant distribution "Q"* to fit in SR (split the phase space into 8 regions in terms of signs of **$\cos\theta_x$** / **$\cos\theta_y$** / **$\cos\theta_z$**)
- "lepton charge" distribution in CRs





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)



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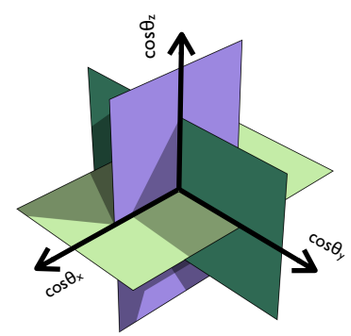

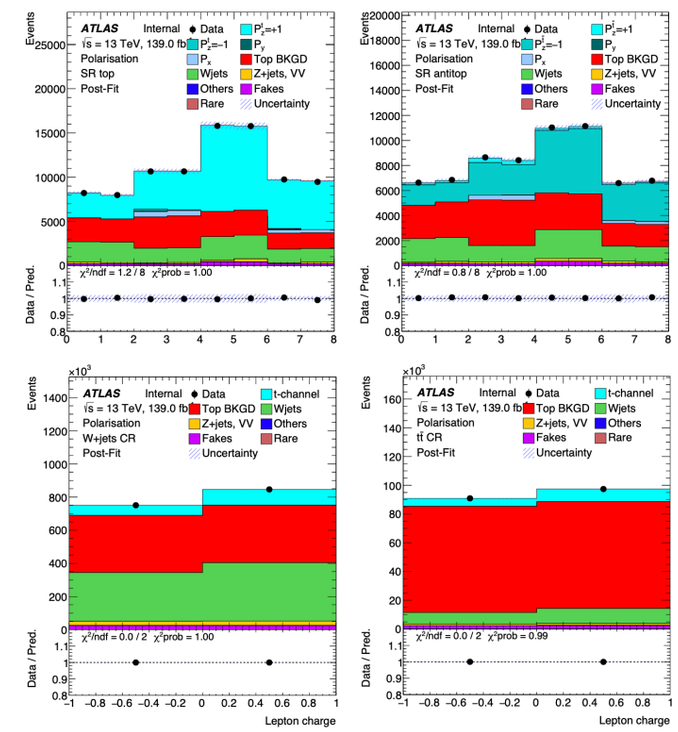

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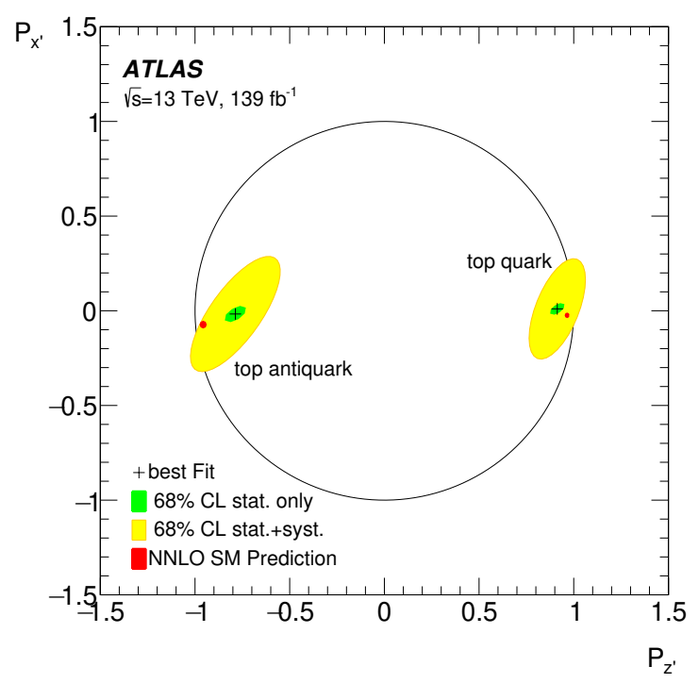


Very good agreement with NLO SM prediction

Py ≈ 0 → no CP violation

Largest uncertainty from jet-energy resolution (JER)

Top Polarisation: unfolding

Submitted to JHEP

Three normalised angular observables ($\cos\theta_x$, $\cos\theta_z$, $\cos\theta_z$) unfolded to particle level

- Iterative Bayesian Unfolding (IBU) employed for deconvolution
- comparisons with different MC predictions at particle level in fiducial region
- results (including covariance matrix) to be published in HepData

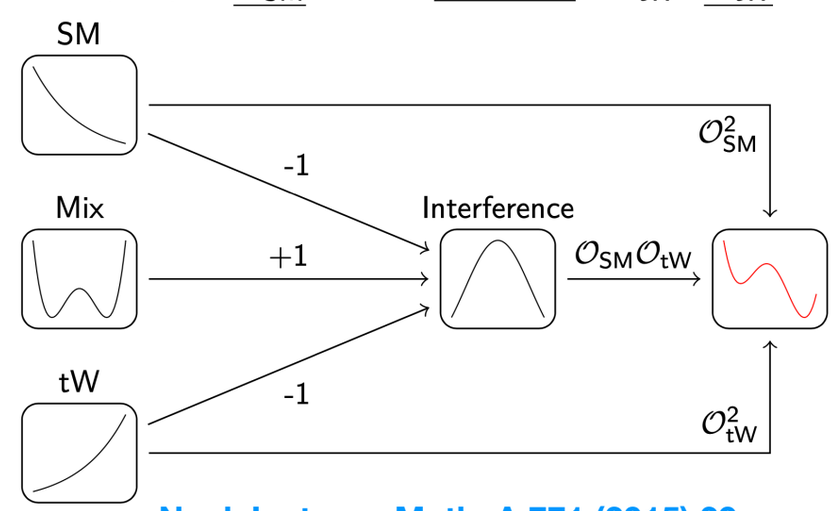
EFT interpretation of normalised $\cos\theta_{x/y}$ with morphing technique

- parametric description for EFT operators using minimal number of templates
- focus on O_{tW} (variables not sensitive to $O_{\phi Q}$, O_{qQ})
  - **Re[C_{tW}] ∈ [0.4±1.1]**
  - **Im[C_{tW}] ∈ [-0.3±0.4]**

	C_{tW}		C_{itW}	
	68% CL	95% CL	68% CL	95% CL
All terms	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^4$	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^2$	[-0.2, 1.0]	[-0.7, 1.7]	[-0.5, -0.1]	[-0.8, 0.2]

Sketch of a morphing example

$$\sigma(c_{tW}) = \underline{\mathcal{O}^2_{SM}} + c_{tW} \cdot \underline{\mathcal{O}_{SM}\mathcal{O}_{tW}} + c^2_{tW} \cdot \underline{\mathcal{O}^2_{tW}}$$



Nucl. Instrum. Meth. A 771 (2015) 39

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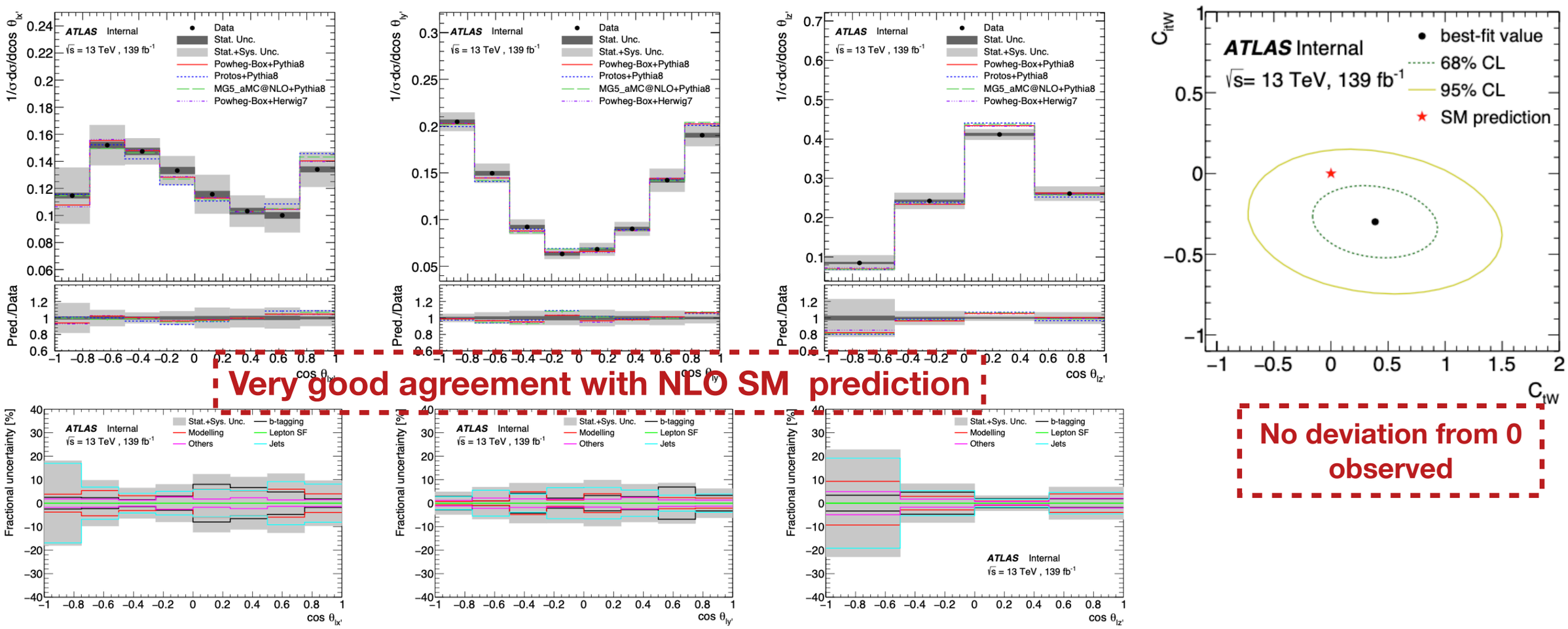


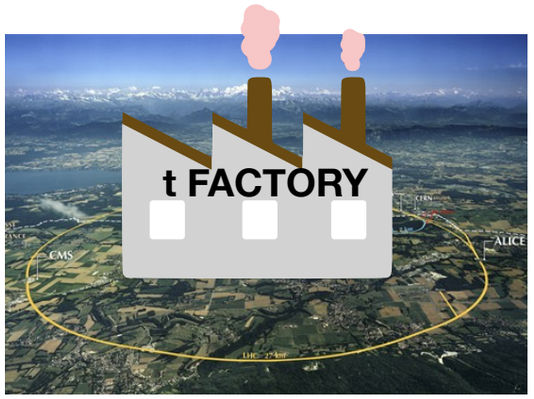
Conclusion

The top quark has come a long way since 1995 (discovery)

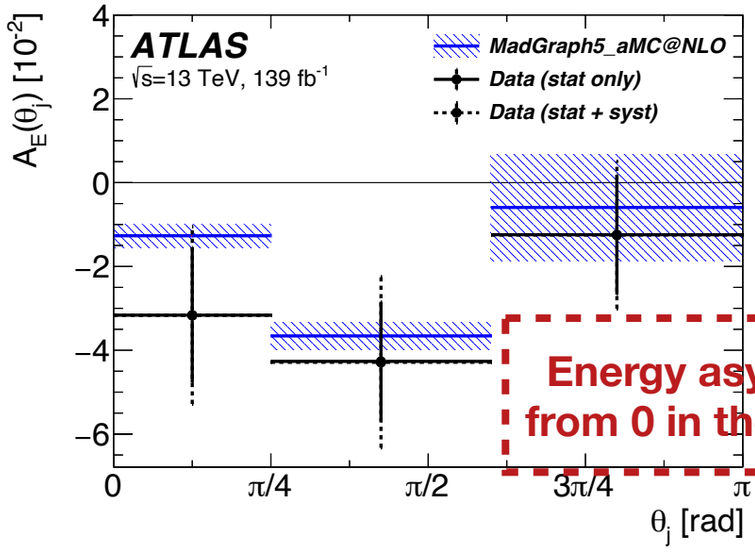
- back then: missing quark, similar to other quarks
- today: know that top quark is special

In precision era, top quark is key to an abundance of different research areas

- many different properties of top quarks measured by ATLAS
- so far, Standard Model describes data extremely well
- more results with the Run 2 dataset in the pipeline
- Run 3 (and beyond) promise even larger datasets

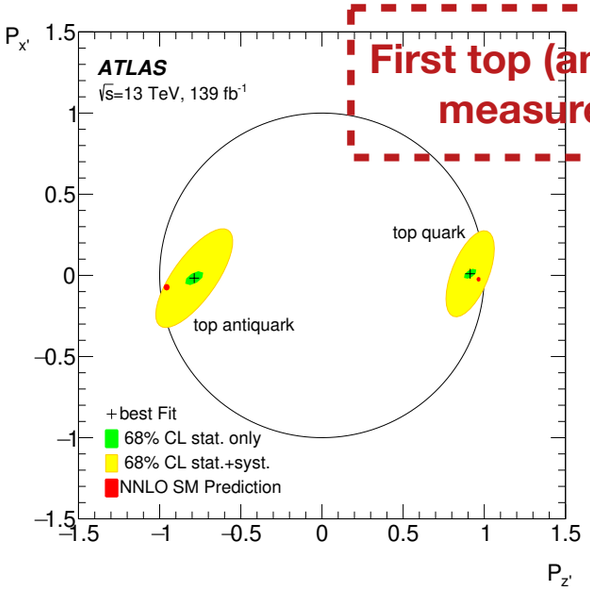


Many more exciting top physics results still to come!



First charge asymmetry measurement in $t\bar{t}+\gamma$ events
$A_C^{t\bar{t}} = -0.006 \pm 0.030$

Energy asymmetry 2.1σ away from 0 in the most sensitive bin



First top (anti-top) polarisation measurement at 13 TeV

Conclusion

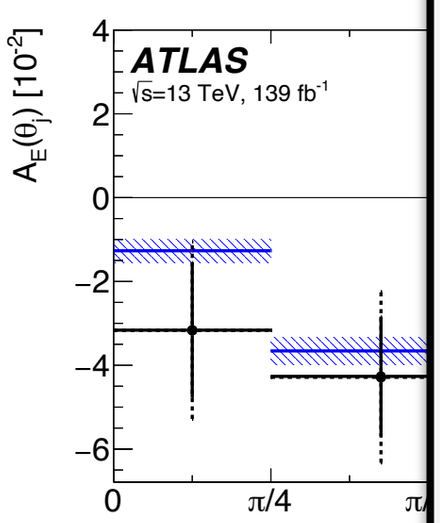
The top quark

- back then: n
- today: know

In precision era

- many differe
- so far, Stanc
- more results
- Run 3 (and b

Many more exc



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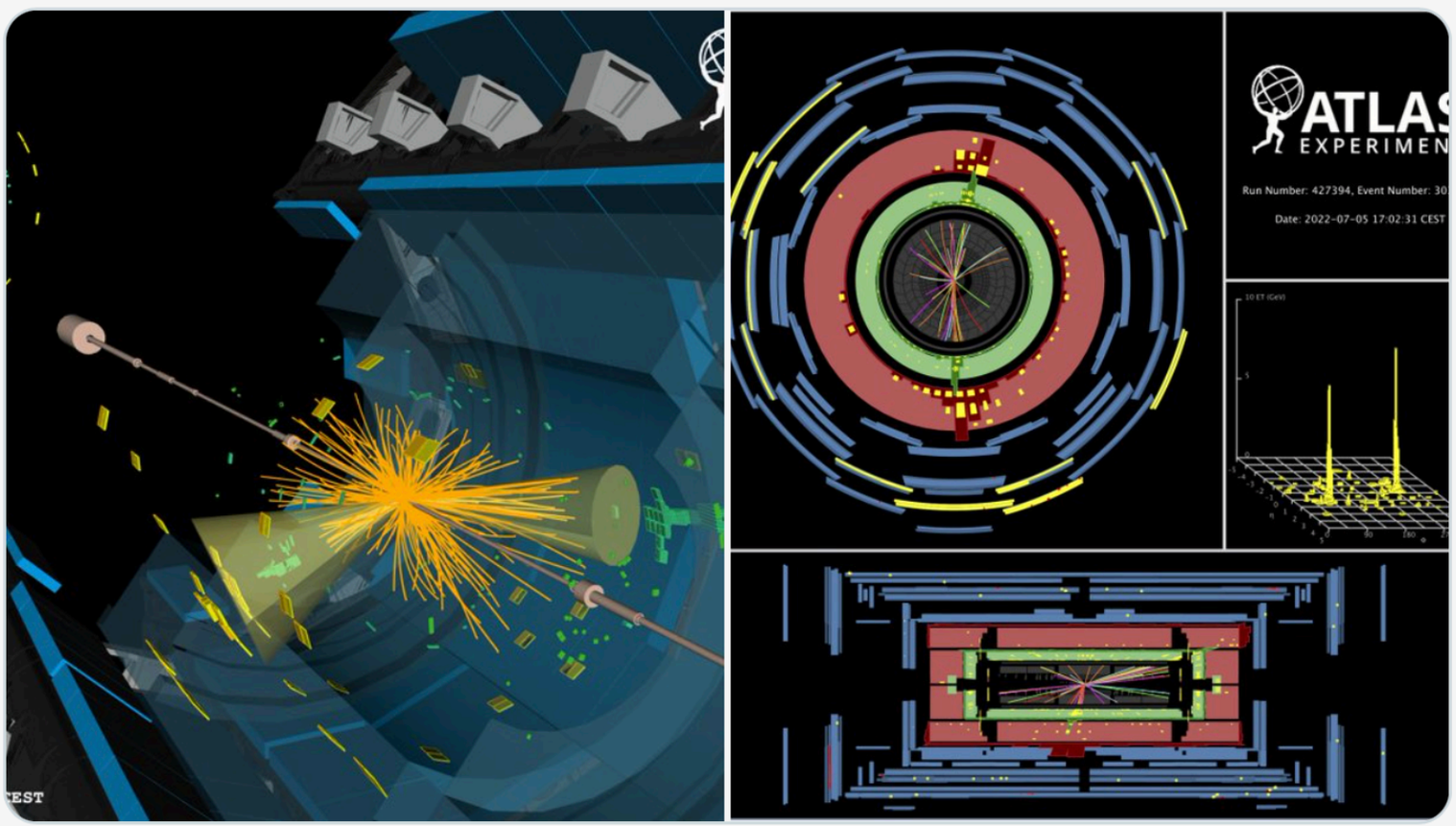
The higher beam energy and intensity of #LHCRun3 will allow ATLAS to push the very limits of its physics research. Learn about today's exciting LHC restart: cern.ch/go/6vxq



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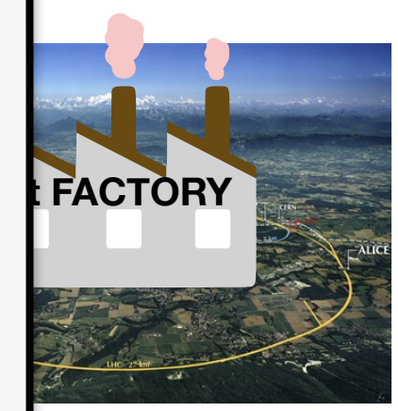
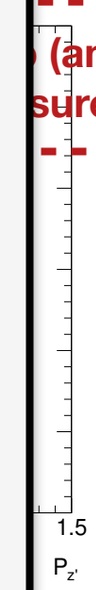


(anti-top) polarisation
surement at 13 TeV

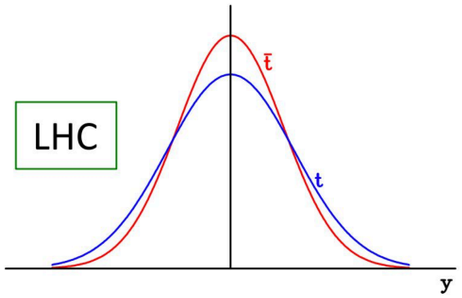


Backup

$A_C^{t\bar{t}}$ vs. $A_E^{t\bar{t}}$

$t\bar{t}$ charge asymmetry ($A_C^{t\bar{t}}$) strongly diluted @LHC (gg-fusion (≈90%))

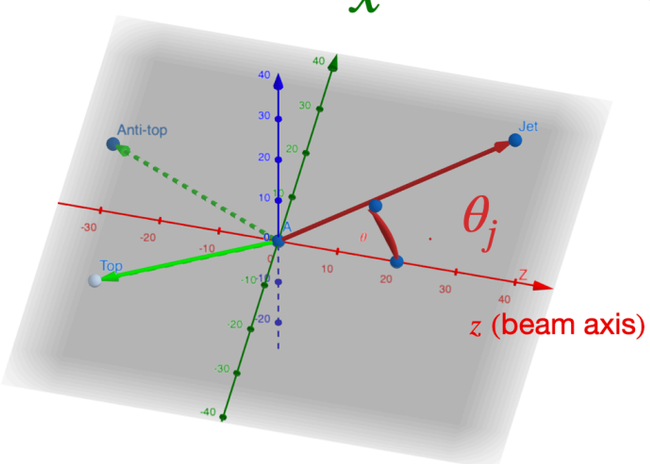
- $gg \to t\bar{t}$ (LO): charge symmetric to all orders
- $q\bar{q} \to t\bar{t}$ (NLO): top (anti-top) produced preferentially along q ($\bar{q}$)
- @LHC (*p-p*): momentum imbalance of initial-state q and $\bar{q}$
  - → tops more longitudinally boosted than anti-tops



$t\bar{t}$+1j energy asymmetry ($A_E^{t\bar{t}}$) happens at any order thanks to the additional jet

- → gateway for $A_C^{t\bar{t}}$ in a different phase-space
- → complementary SMEFT tests

$t\bar{t}j$ – Rest frame

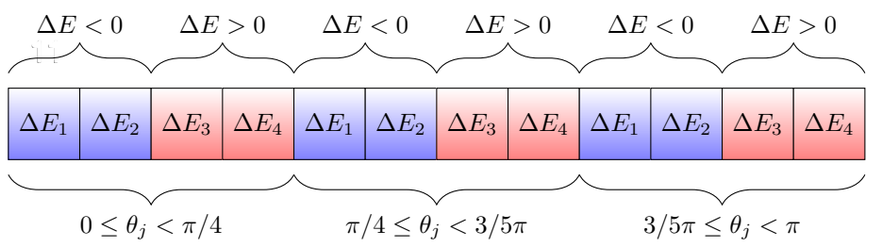


(a) (b)

$$\sigma^{\text{opt}}(\theta_j) = \sigma(\theta_j | y_{t\bar{t}j} > 0) + \sigma(\pi - \theta_j | y_{t\bar{t}j} < 0)\,, \qquad \theta_j \in [0, \pi]$$

- $\Delta E = E_t - E_{\bar{t}}$

$$A_E(\theta_j) \equiv \frac{\sigma^{\text{opt}}(\theta_j|\Delta E > 0) - \sigma^{\text{opt}}(\theta_j|\Delta E < 0)}{\sigma^{\text{opt}}(\theta_j|\Delta E > 0) + \sigma^{\text{opt}}(\theta_j|\Delta E < 0)}\,,$$



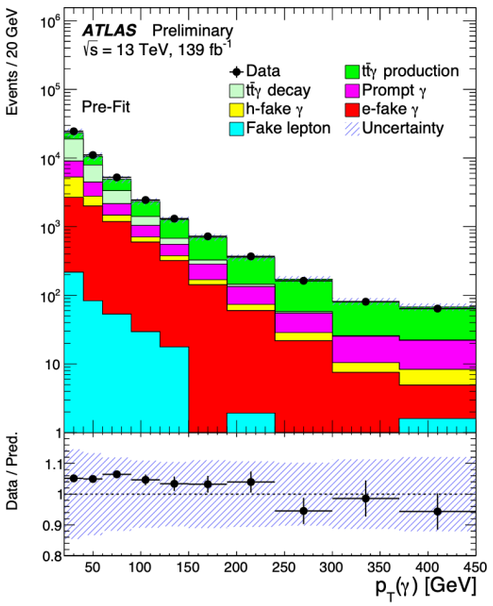
Energy Asymmetry

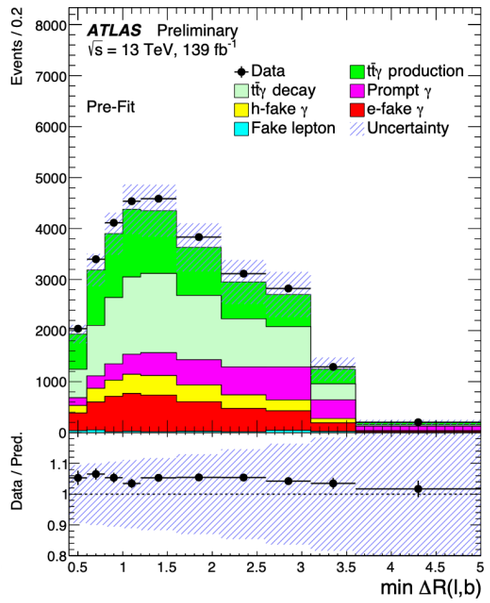
Scenario	ΔA_E $[10^{-2}]$ $0 \leq \theta_j < \frac{\pi}{4}$	$\frac{\pi}{4} < \theta_j \leq \frac{3\pi}{5}$	$\frac{3\pi}{5} \leq \theta_j \leq \pi$
Data statistical uncertainty	1.60	1.40	1.40
$t\bar{t}$ modelling	0.08	0.87	0.34
$t\bar{t}$ response MC statistics	0.51	0.42	0.42
W+jets modelling and PDF	0.29	0.49	0.42
Single-top modelling	0.28	0.60	0.29
$t\bar{t}$ and single-top PDF	0.08	0.10	0.07
Multijet	0.53	0.54	0.51
Jet energy resolution	0.98	0.40	0.36
Other detector uncertainties	0.42	0.43	0.30
Total	2.10	2.00	1.80

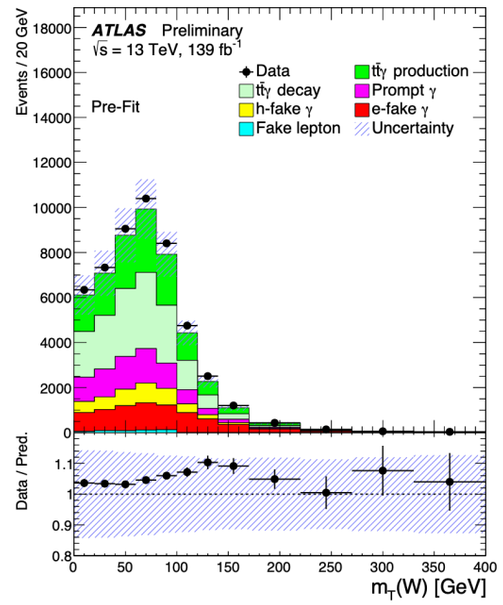
Scenario	$A_E \pm \Delta A_E$ $[10^{-2}]$ $0 \leq \theta_j \leq \frac{\pi}{4}$	$\frac{\pi}{4} \leq \theta_j \leq \frac{3\pi}{5}$	$\frac{3\pi}{5} \leq \theta_j \leq \pi$
Data	-3.2 ± 2.1	-4.3 ± 2.0	-1.3 ± 1.8
SM prediction (MadGraph5_aMC@NLO)	-1.3 ± 0.3	-3.7 ± 0.3	-0.6 ± 1.3
SM expectation	-1.3 ± 2.1	-3.7 ± 2.0	-0.6 ± 1.6

$C\,(\mathrm{TeV}/\Lambda)^2$	A_E (Λ^{-4}) 68% CL	95% CL	A_E (Λ^{-2}) 68% CL	95% CL
C_{Qq}^{11}	$[-0.41, 0.47]$	$[-0.65, 0.67]$	$[-0.68, 4.06]$	$[-3.36, 6.16]$
C_{Qq}^{18}	$[-0.87, 1.24]$	$[-1.72, 2.10]$	$[-1.26, 4.76]$	$[-3.24, 9.64]$
C_{tq}^{1}	$[-0.43, 0.52]$	$[-0.69, 0.75]$	$[-0.60, 5.76]$	$[-3.42, 9.36]$
C_{tq}^{8}	$[-1.41, 0.84]$	$[-2.01, 1.43]$	$[-1.86, 1.70]$	$[-3.30, 3.98]$
C_{tu}^{1}	$[-0.50, 0.56]$	$[-0.78, 0.81]$	$[-0.96, 5.82]$	$[-4.72, 8.88]$
C_{tu}^{8}	$[-1.00, 1.01]$	$[-1.71, 1.56]$	$[-1.30, 2.52]$	$[-3.02, 4.66]$

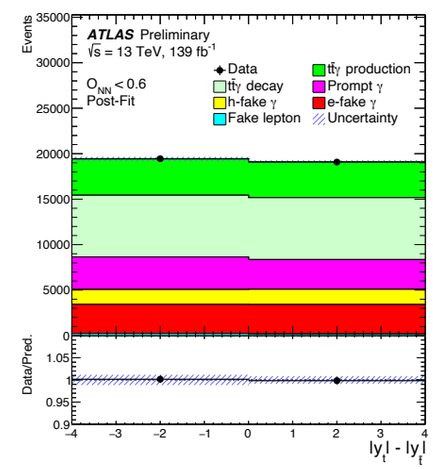
Charge Asymmetry

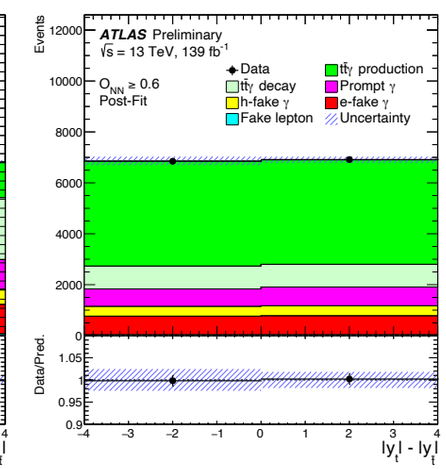


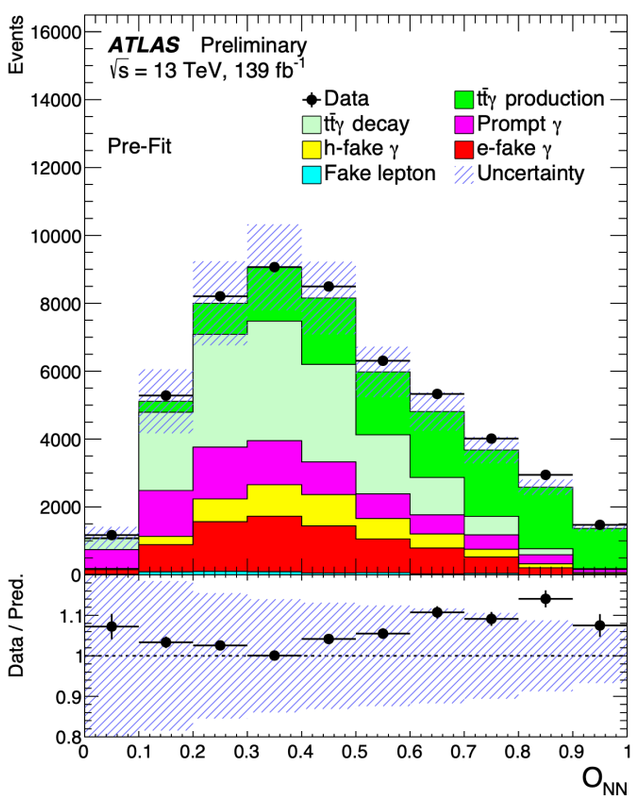




	$O_{\mathrm{NN}} < 0.6$	$O_{\mathrm{NN}} \geq 0.6$
$t\bar{t}\gamma$ prod (signal)	6660 ± 350	6910 ± 340
$t\bar{t}\gamma$ decay	14 100 ± 3100	1900 ± 560
h-fake γ	3400 ± 1400	790 ± 360
e-fake γ	6420 ± 860	1480 ± 260
prompt γ	6400 ± 2000	1300 ± 400
lepton fake	410 ± 110	57 ± 35
Total	37 400 ± 4500	12 400 ± 1100
Data	38527	13763



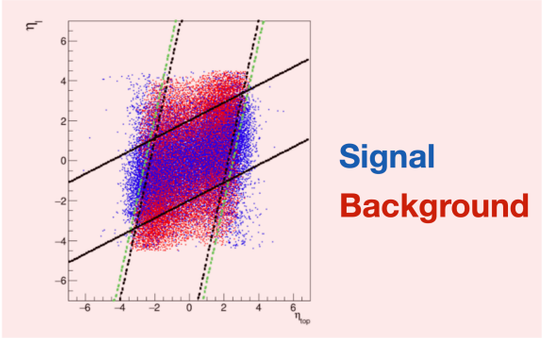


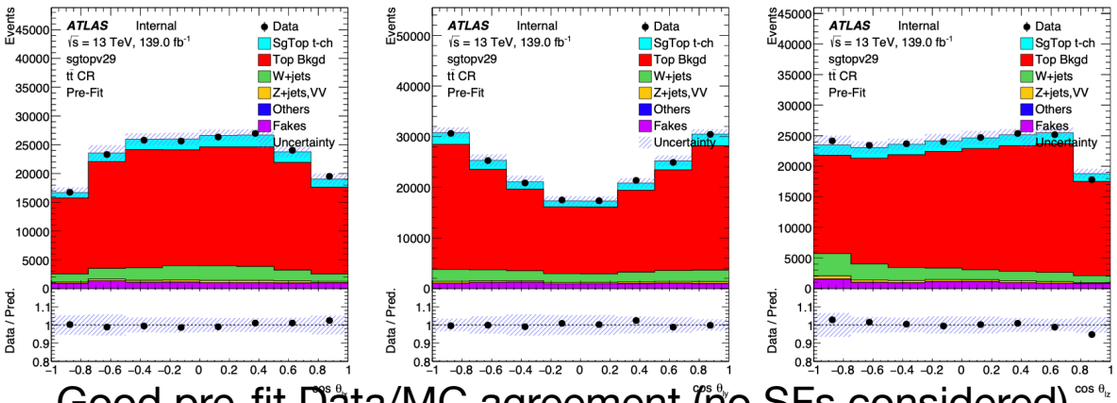


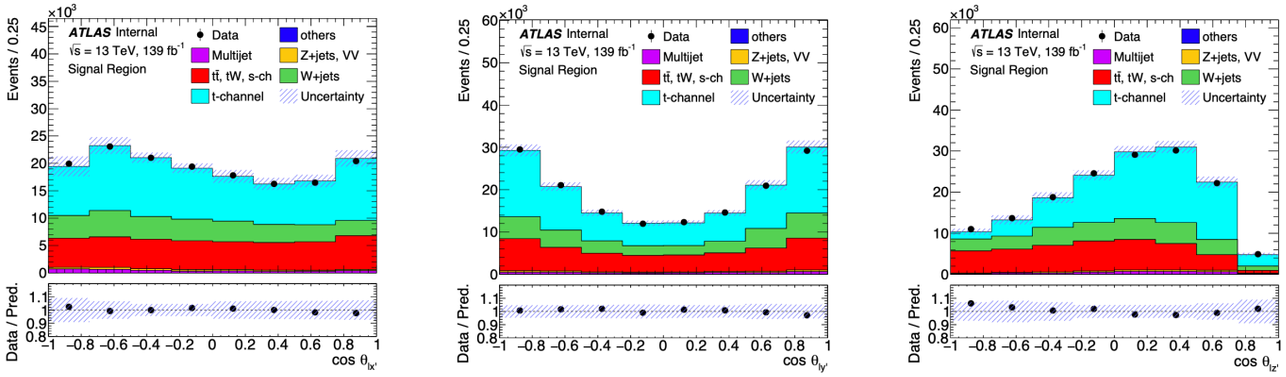
Total uncertainty	0.030
Statistical uncertainty	0.024
MC statistical uncertainties	
$t\bar{t}\gamma$ production	0.004
Background processes	0.008
Modelling uncertainties	
$t\bar{t}\gamma$ production modelling	0.003
Background modelling	0.002
Prompt background normalisation	0.003
Experimental uncertainties	
Jet and b-tagging	0.010
Fake lepton background estimate	0.005
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.009
Fake photon background estimates	0.004
Photon	0.003
Other experimental	0.004

Top polarisation

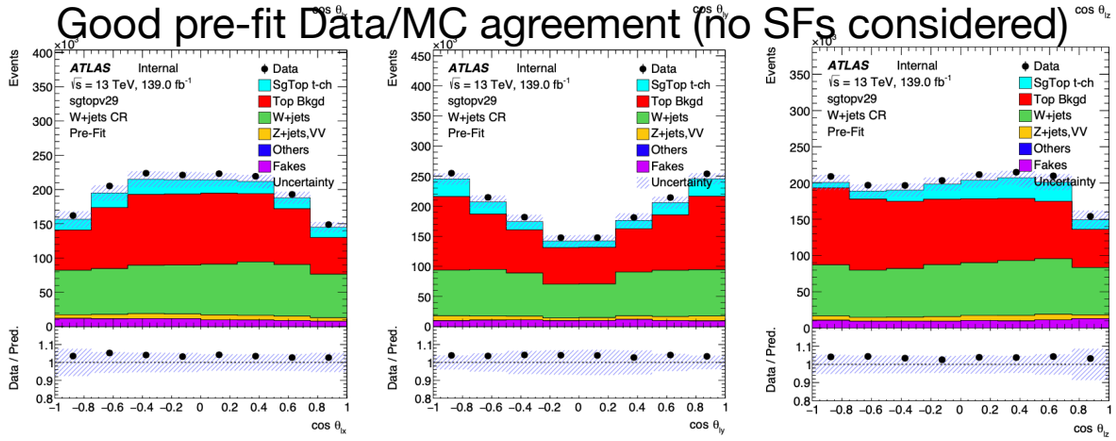
Preselection region	Signal region	$t\bar{t}$ control region	W+jets control region
=1 charged tight lepton ($p_T > 30$ GeV and $\|\eta\| < 2.5$)			
Veto secondary low-p_T charged loose leptons ($p_T > 10$ GeV and $\|\eta\| < 2.5$)			
=2 jets ($p_T > 30$ GeV and $\|\eta\| < 4.5$; $p_T > 35$ GeV within $2.7 < \|\eta\| < 3.5$)			
$E_T^{miss} > 35$ GeV			
$m_T(\ell E_T^{miss}) > 60$ GeV			
$p_T(\ell) > 50\left(1 - \frac{\pi - \|\Delta\phi(j_1,\ell)\|}{\pi - 1}\right)$ GeV			
=1 b-jet ($\|\eta\| < 2.5$; 60%WP)		=2 b-jet ($\|\eta\| < 2.5$; 60%WP)	=1 b-jet ($\|\eta\| < 2.5$; 60%WP)
	$m_{\ell b} < 153$ GeV $m_{\ell E_T^{miss} b} \in [120.6, 234.6]$ GeV trapez. requirement $m_{j\ell E_T^{miss} b} > 320$ GeV $H_T > 190$ GeV		$m_{\ell b} > 153$ GeV $m_{\ell E_T^{miss} b} \notin [120.6, 234.6]$ GeV veto trapez. requirement $m_{j\ell E_T^{miss} b} < 320$ GeV $H_T < 190$ GeV







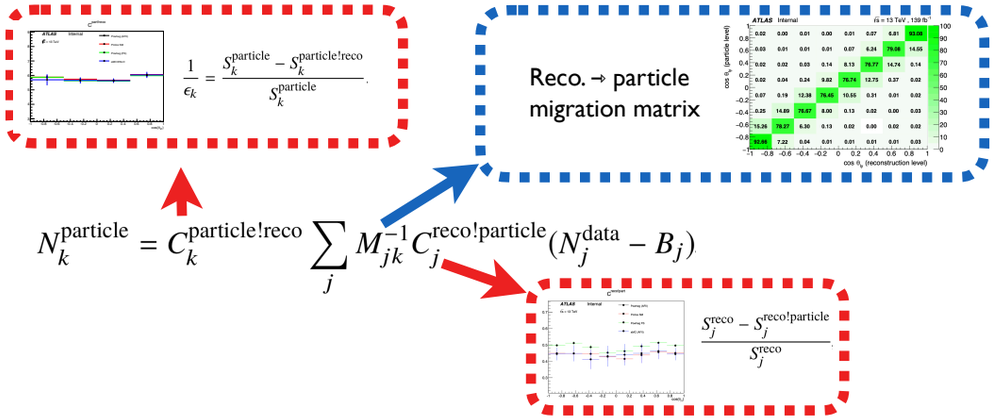
Good pre-fit Data/MC agreement (no SFs considered)

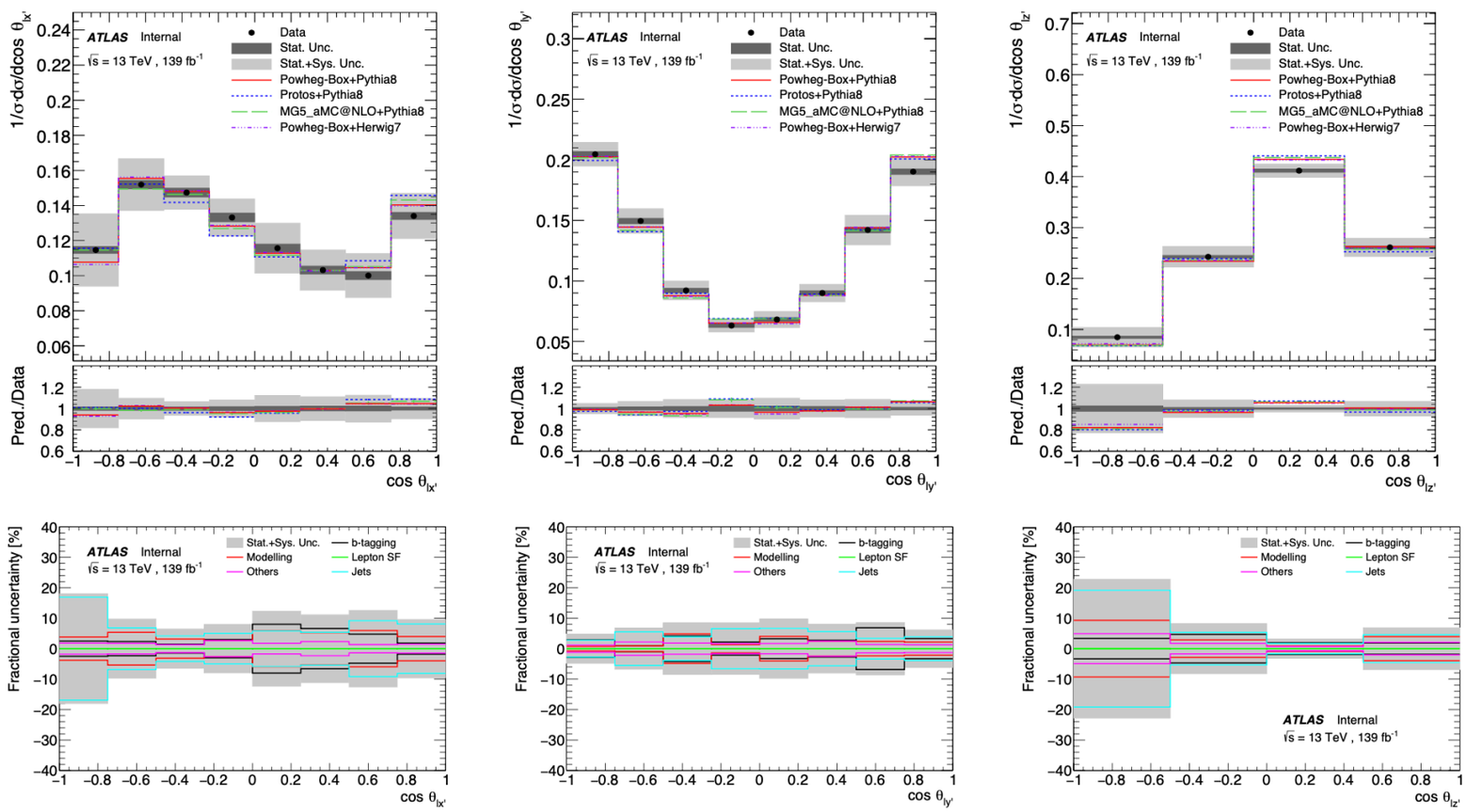


SF (top-quark bkg.): 0.996 ± 0.005 (stat.)
SF (W+jets bkg.): 1.153 ± 0.009 (stat.)
SF (t-channel): 1.073 ± 0.012 (stat.)

Top polarisation

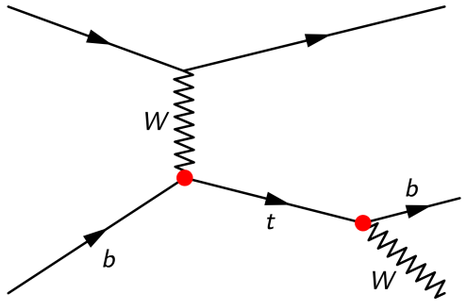
Uncertainty source	$\Delta P^{t}_{x'}$	$\Delta P^{\bar{t}}_{x'}$	$\Delta P^{t}_{y'}$	$\Delta P^{\bar{t}}_{y'}$	$\Delta P^{t}_{z'}$	$\Delta P^{\bar{t}}_{z'}$
Modelling						
Modelling (t-channel)	±0.037	±0.051	±0.010	±0.015	±0.061	±0.061
Modelling ($t\bar{t}$)	±0.016	±0.021	±0.004	±0.016	±0.003	±0.016
Modelling (other)	±0.013	±0.031	±0.003	±0.006	±0.026	±0.043
Experimental						
Jet energy scale	±0.045	±0.048	±0.005	±0.007	±0.033	±0.025
Jet energy resolution	±0.166	±0.185	±0.021	±0.040	±0.070	±0.130
Jet flavour tagging	±0.004	±0.002	<0.001	±0.001	±0.007	±0.009
Other experimental uncertainties	±0.015	±0.029	±0.002	±0.007	±0.014	±0.026
Multijet estimation	±0.008	±0.021	<0.001	±0.001	±0.008	±0.013
Luminosity	±0.001	±0.001	<0.001	<0.001	<0.001	<0.001
Simulation statistics	±0.020	±0.024	±0.008	±0.015	±0.017	±0.031
Total systematic uncertainty	±0.174	±0.199	±0.025	±0.048	±0.096	±0.153
Total statistical uncertainty	±0.017	±0.025	±0.011	±0.017	±0.022	±0.034





Top polarisation

$$\sigma\left(\frac{c}{\Lambda^2}\right) = \underbrace{O_{\mathrm{SM}}^2}_{\text{Pure SM}} + \frac{c}{\Lambda^2} \cdot \underbrace{O_{\mathrm{SM}} O_{\mathrm{dim6}}}_{\text{Interference term}} + \frac{c^2}{\Lambda^4} \cdot \underbrace{O_{\mathrm{dim6}}^2}_{\text{Pure BSM}}$$



EFT operator can contribute to production and/or decay vertex

3 operators that interfere with SM: $O_{\phi Q}$, O_{tW} *and* O_{qQ}

- four couplings: $C_{\phi Q}$, C_{tW} , C_{itW} and O_{qQ}
- $C_{tW}^* \neq C_{tW} \rightarrow$ CP Violation
- prediction @NLO available: arXiv:1807.03576

Interpretation of normalized $\cos\theta_{X/Y}$ focuses on C_{tW} and C_{itW}

- $O_{\phi Q}$ affects only normalisation
- $\cos\theta_{X/Y}$ not sensitive to O_{qQ}

Morphing reference: ATL-PHYS-PUB-2015-047

- Morphing works with any choice of templates
- Uncertainty does depend on this choice

	C_{tW}		C_{itW}	
	68% CL	95% CL	68% CL	95% CL
All terms	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^4$	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^2$	[-0.2, 1.0]	[-0.7, 1.7]	[-0.5, -0.1]	[-0.8, 0.2]

IBU vs. FBU vs. SVD vs. PLU

Reference: arxiv.org/1201.4612

FBU differs from *D'Agostini's iterative unfolding (IBU)* despite both using Bayes' theorem.

- In FBU the answer is not an estimator and its covariance matrix, but a posterior probability density defined in the space of possible spectra.
- FBU does not involve iterations, thus does not depend on a convergence criterion, nor on the first point of an iterative procedure, which in IBU is named "prior".
  - If more than one answers are equally likely, as can happen when the reconstructed spectrum has fewer bins than the inferred one, then FBU reveals all of them, while IBU converges towards some of the possible solutions.
- Regularization is not done by interrupting iterations, but by choosing a prior which favours certain characteristics, such as smoothness.
  - Thus, FBU offers intuition and full control of the regularizing condition, which makes the answer easy to interpret.

FBU differs significantly also from *SVD unfolding*.

- In FBU the migrations matrix is not distorted by singular value decomposition (SVD), therefore FBU assumes the intended migrations model.
- The answer of FBU is not an estimator plus covariance matrix, but a probability density function which does not have to be Gaussian, which is important especially in bins with small Poisson event counts.
- FBU does not involve matrix inversion and computation of eigenvalues, which makes it more stable numerically.
- SVD imposes curvature regularization, while FBU offers the freedom to use different regularization choices. This freedom becomes necessary when the correct answer actually has large curvature, or when the answer has only two bins, thus curvature is not even defined.

PLU is similar to *FBU* in terms of prior for regularisation, but it involves a Profile Likelihood fit too.