Measurements of top-quark cross sections and properties with the ATLAS detector at the LHC

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ATLAS EXPERIMENT

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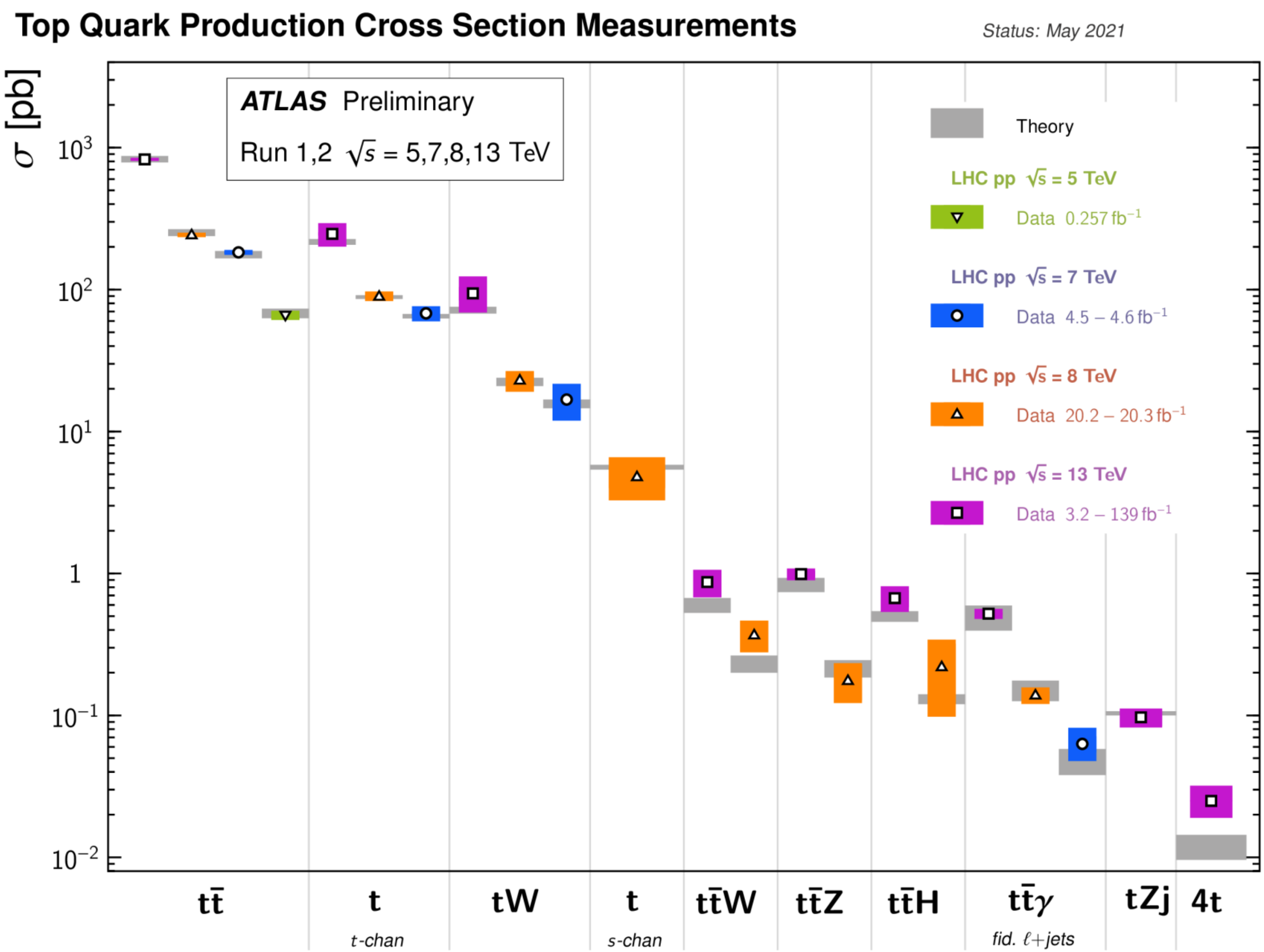
Top quark physics

- The top quark is the **heaviest** known fundamental particle. Could it play a special role in electroweak symmetry breaking?
- The top quark has a **very short lifetime**, and is the only quark that decays before forming **hadronic bound states**
- This leads to many **measureable properties** that we can test from its **decay products**, probing the **predictions of QCD**
- **Understanding $t\bar{t}$ production is crucial** for many searches for rare SM processes and **physics beyond the SM**
- **The LHC is a Top factory!**

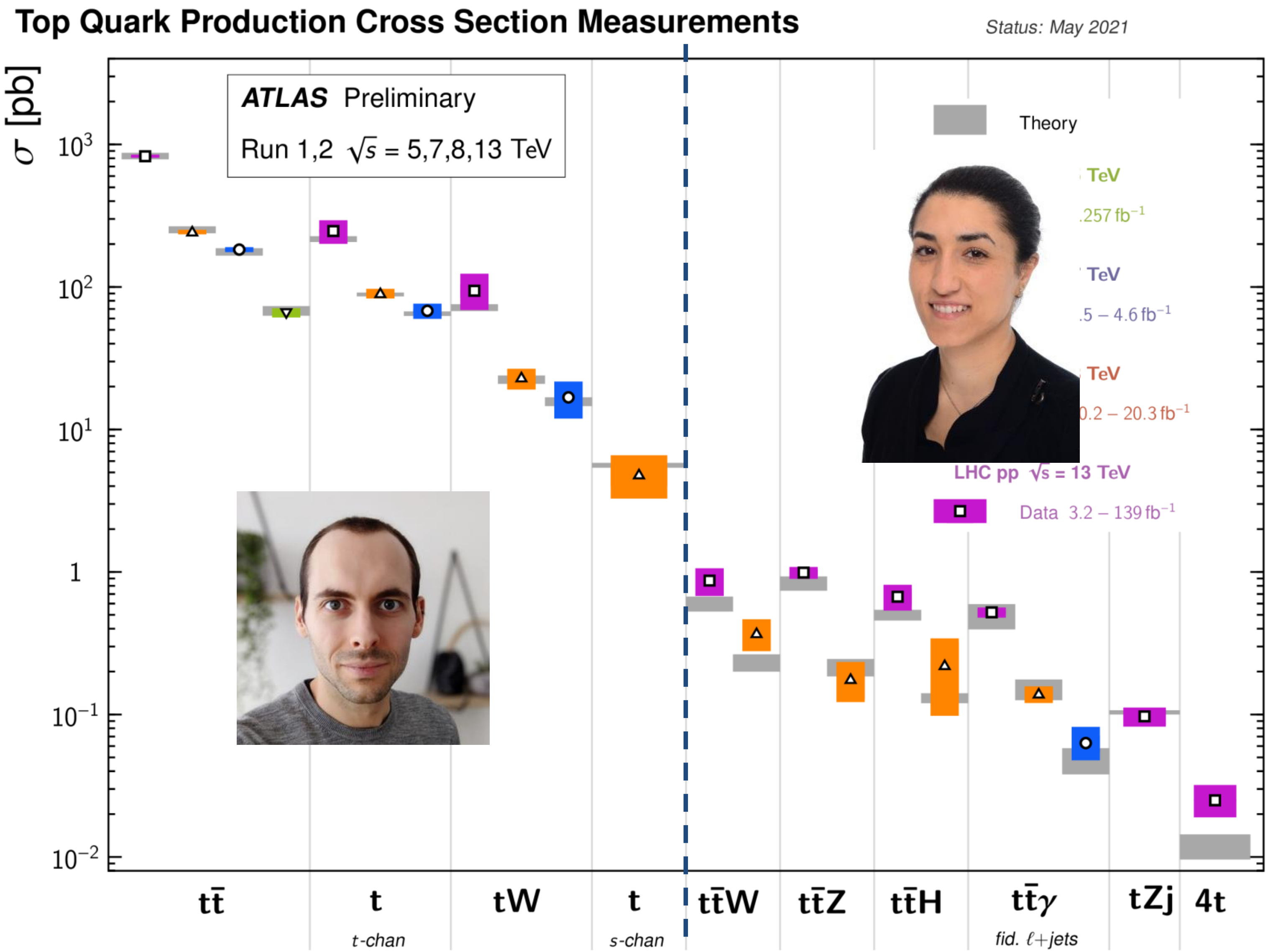
Top cross section

ATL-PHYS-PUB-2021-014



Top cross section

ATL-PHYS-PUB-2021-014



Top + X talk

This talk

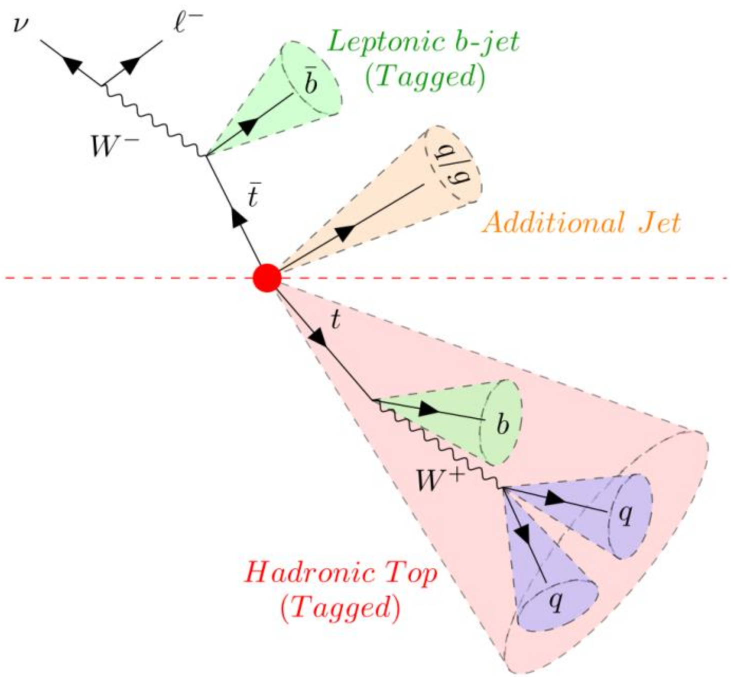
ATLAS $139\ \mathrm{fb}^{-1}$

- Boosted $t\bar{t}$ differential cross section
  - l+jets ATLAS-CONF-2021-031
  - All hadronic ATLAS-CONF-2021-050
- Charge Asymmetry ATLAS-CONF-2019-026
- Energy Asymmetry – Accepted by EPJC (arXiv)
- Top-quark Polarisation ATLAS-CONF-2021-027

Boosted differential cross section
$t\bar{t} \rightarrow l + \text{jets}$

CONF

Measurement of 1D, 2D differential cross sections of highly energy top quarks
- Comparison to various MC generators reweighted to match NNLO predictions at parton level
- Interpretation of measurements in EFT framework



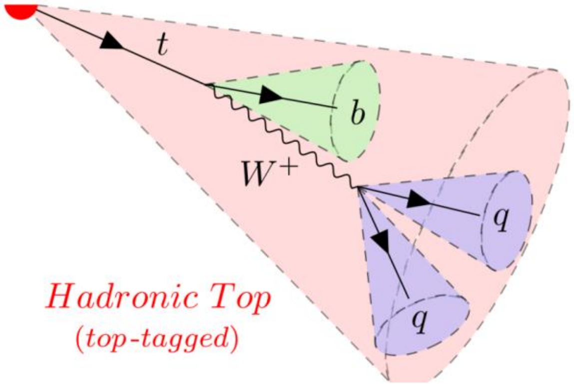
- One W bosons decay hadronically, one decays leptonically - one lepton in the final state
- Large-R jets are 'top-tagged' (deep neural network, DNN)

- Unfolding the differential cross sections to particle level in a fiducial phase space

Boosted differential cross section $t\bar{t} \rightarrow l + \text{jets}$

CONF

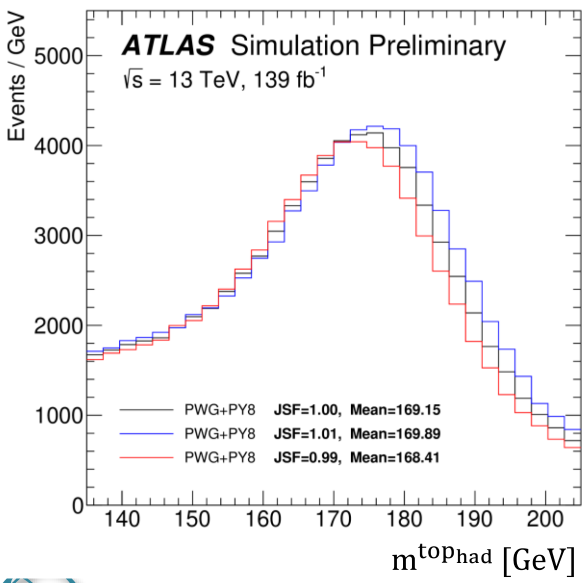
Jet Energy Scale (JES) can be a dominant uncertainty – special technique to deal with it using a **Jet Energy Scale Factor (JSF)**

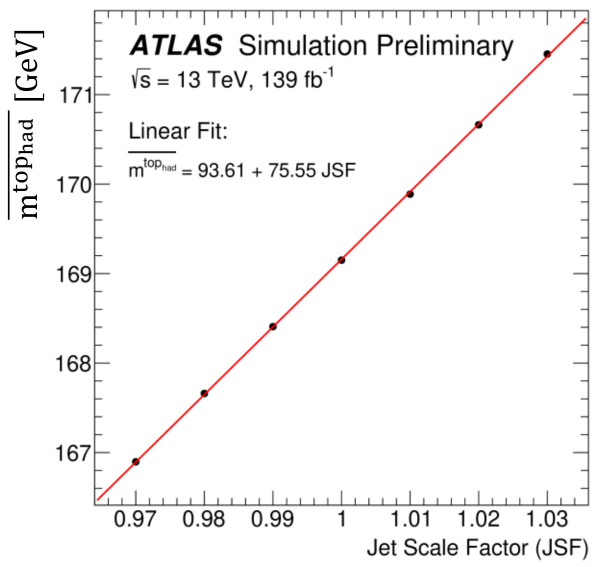


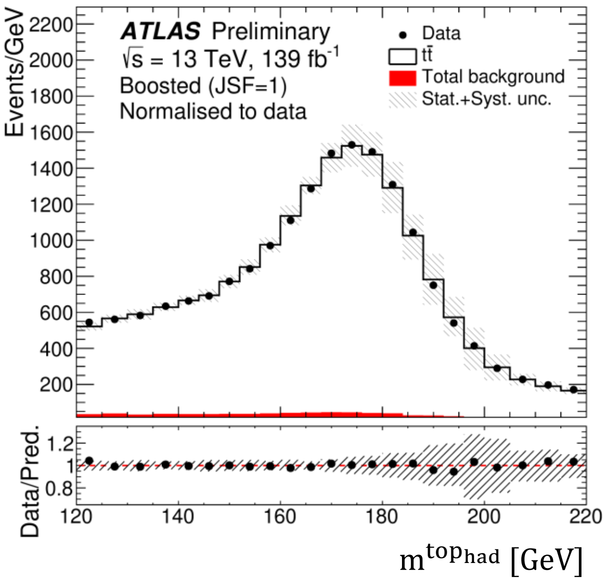
Mass of Large-R jet depends on energy scale of sub-jets

Data and MC are assumed to have an overall difference in JES that may be described by a JSF.

Applying different values of JSF to MC small-R jets linearly modifies $\overline{m_{\text{top-jet}}}$







Find value of JSF that matches the MC $\overline{m^{\text{top}_{\text{had}}}}$ distribution to data! Reduces overall jet uncertainties by a factor of 6

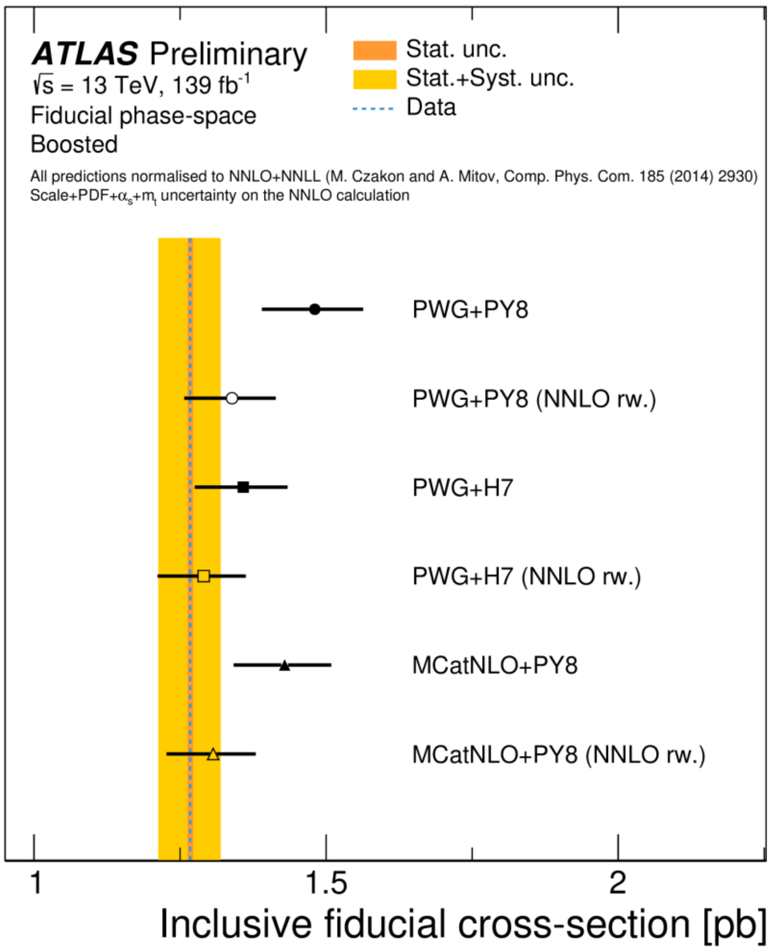
Boosted differential cross section
$t\bar{t} \rightarrow l + \text{jets}$

CONF

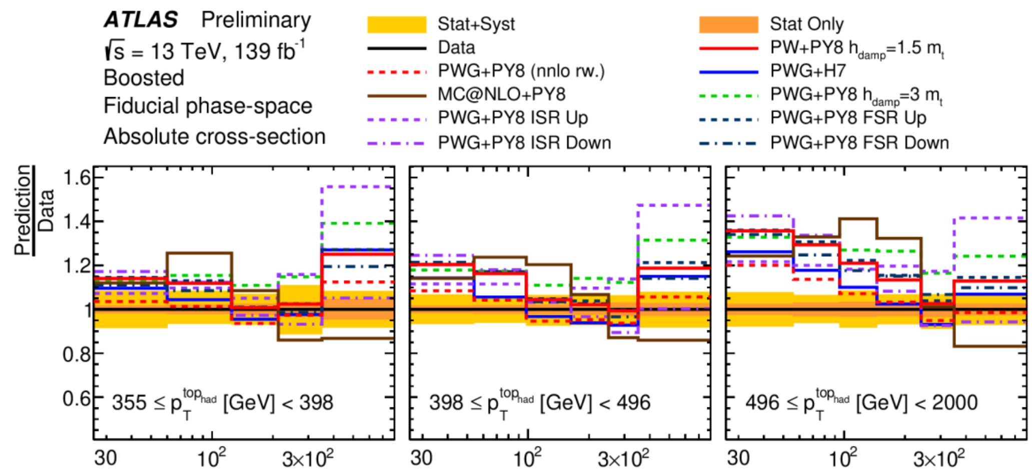
Dominant Systs: b-tagging, Hadronisation modelling, Luminosity

$$\sigma^{t\bar{t}}_{\text{particle,fiducial}} = 1.267 \pm 0.005(\text{stat.}) \pm 0.053(\text{syst.})\text{pb}$$

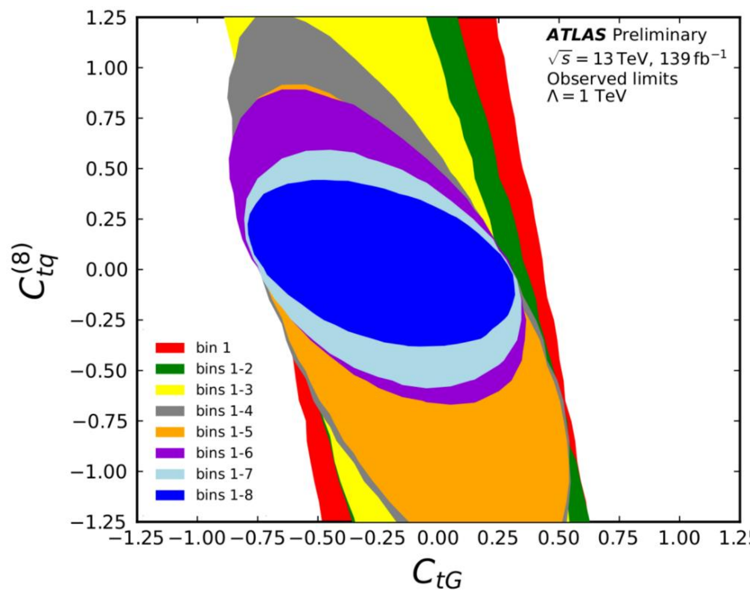
Data falls slightly below prediction but within uncertainties



Particle-level



Additionally radiated jet p_T



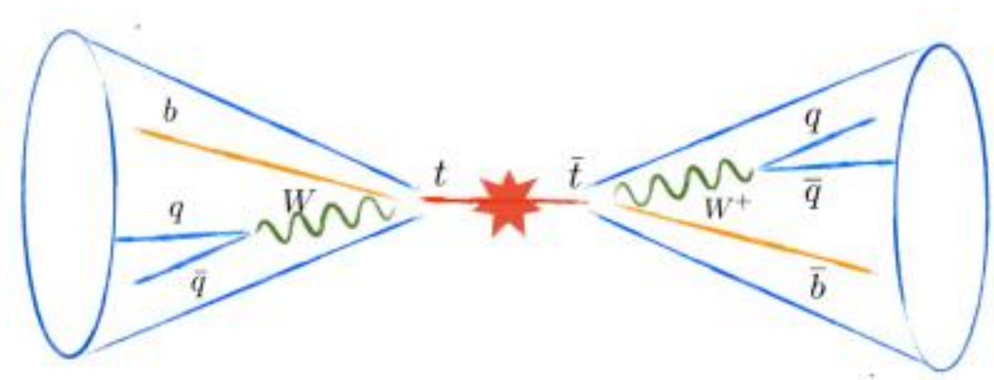
$C^{(8)}_{tq}$ limits comparable to global fits

Boosted differential cross section
$t\bar{t} \rightarrow$ All hadronic

CONF

Measurement of 1D, 2D and 3D differential cross sections of highly energy top quarks

- Comparison to NLO MC predictions and NNLO QCD fixed order predictions
- Interpretation of measurements in EFT framework



- Both W bosons decay hadronically – no leptons in final state
- Large-R jets are 'top-tagged' (deep neural network, DNN)
- Sub-jets are b-tagged

- Unfolding the differential cross sections to particle and parton level in fiducial phase spaces

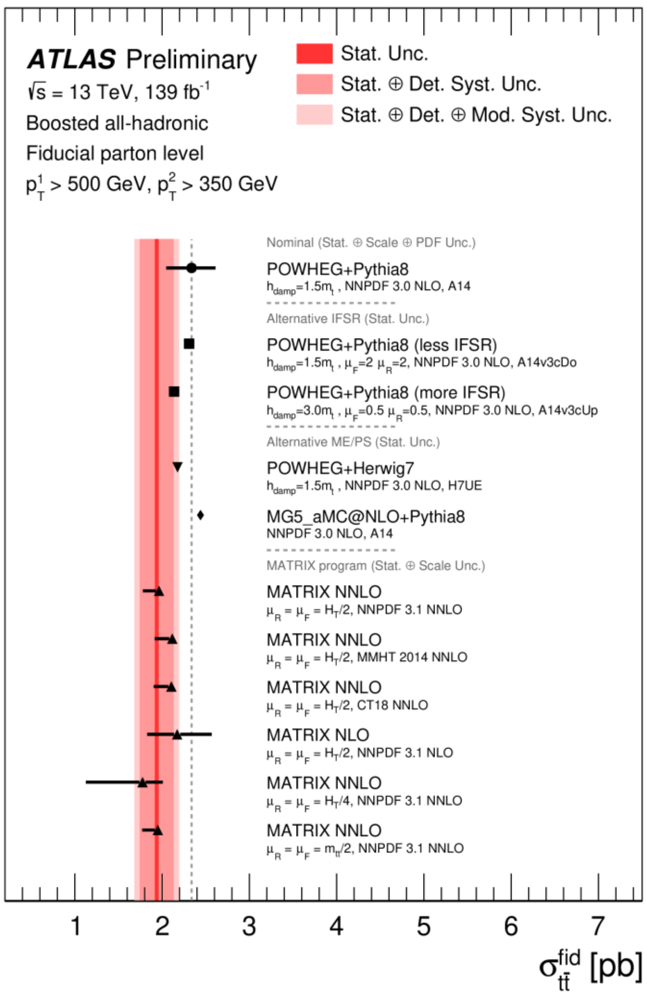
Boosted differential cross section $t\bar{t} \rightarrow$ All hadronic

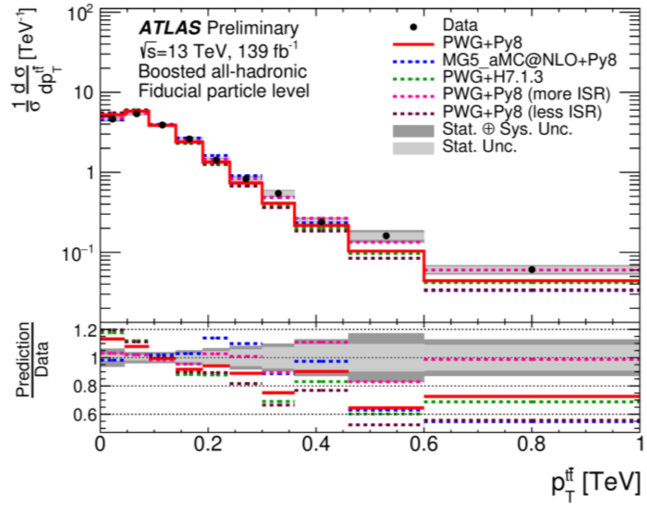
CONF

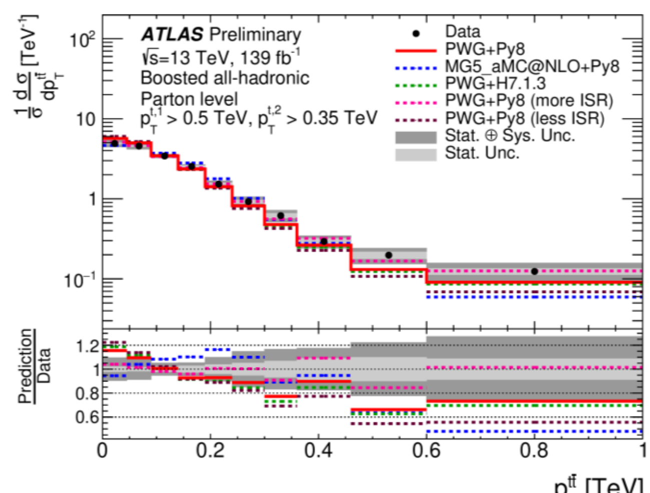
Dominant Systs: Top-tagging, Jet energy resolution, Radiation modelling

$$\sigma^{t\bar{t}}_{\text{particle,fiducial}} = 330 \pm 3(\text{stat.}) \pm 38(\text{syst.})\text{pb}$$
$$\sigma^{t\bar{t}}_{\text{parton,fiducial}} = 1.94 \pm 0.02(\text{stat.}) \pm 0.25(\text{syst.})\text{pb}$$

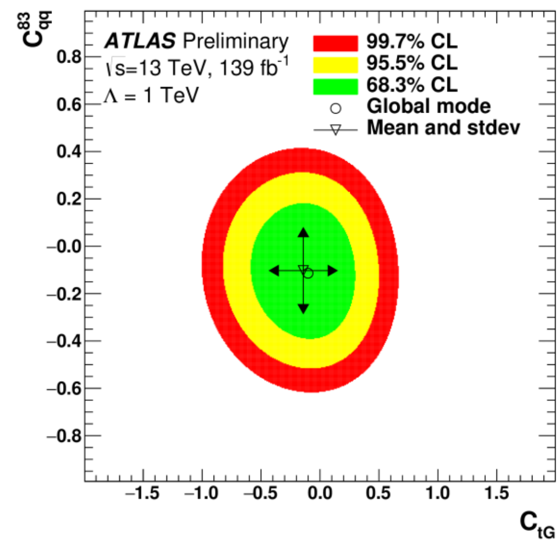
~20% lower than NLO+PS predictions normalised to NNLO total cross section







Most tension in radiation-sensitive distributions ($p_T^{t\bar{t}}$, $\Delta\varphi_{t\bar{t}}$) – deficit of radiation at particle level



Limits on 2-light-quark-2-heavy-quark operators

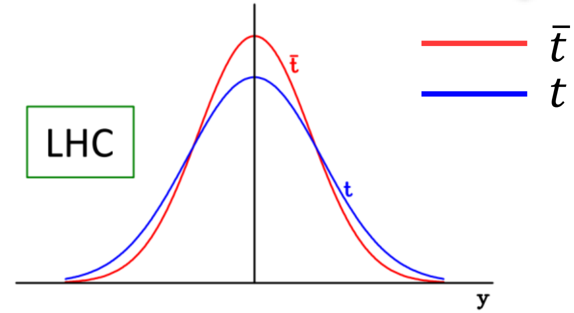
~35% improvement on existing bounds

Charge Asymmetry

CONF

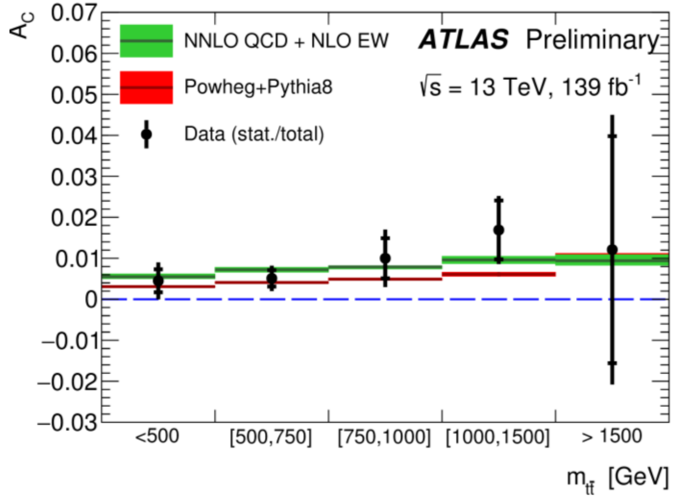
- Higher-order interferences between $q\bar{q}$ and qg create an asymmetric top production at the LHC
  - t is produced preferentially in direction of incoming q

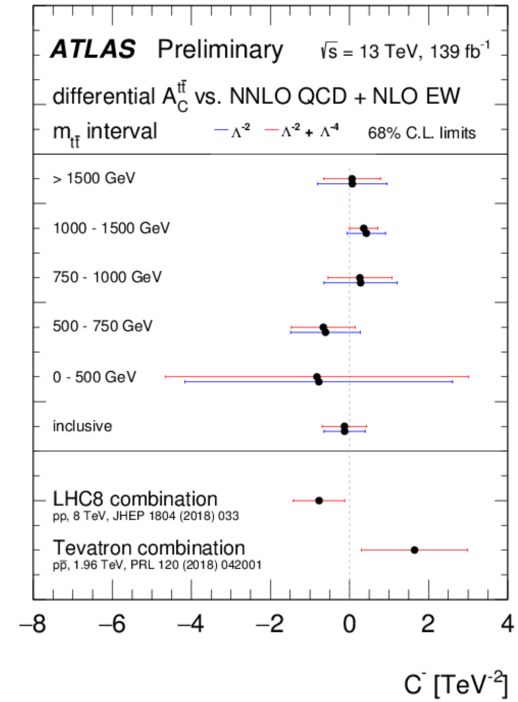
$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)} \qquad \Delta|y| = |y_t| - |y_{\bar{t}}|$$



- Charge symmetric gg production dilutes asymmetry

- Several BSM models predict alterations to A_C , especially with variation as a function of $m_{t\bar{t}}$ and $\beta_{z,t\bar{t}}$





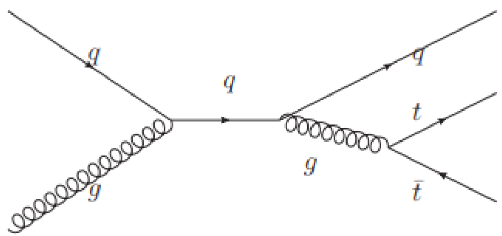
C^- / Λ^2 — C^- is linear combination of Wilson Coefficients. Λ is scale of new physics

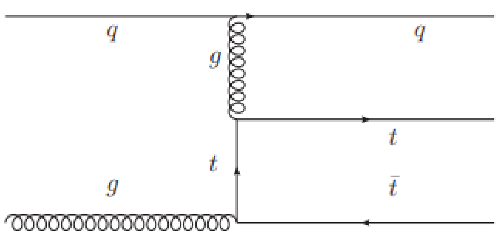
EFT coefficient useful for many models (axigluons, kaluza-klein, randall-sundrum)

$$A_C = 0.0060 \pm 0.0015 \text{ (stat+syst.)}$$

Energy Asymmetry

arXiv

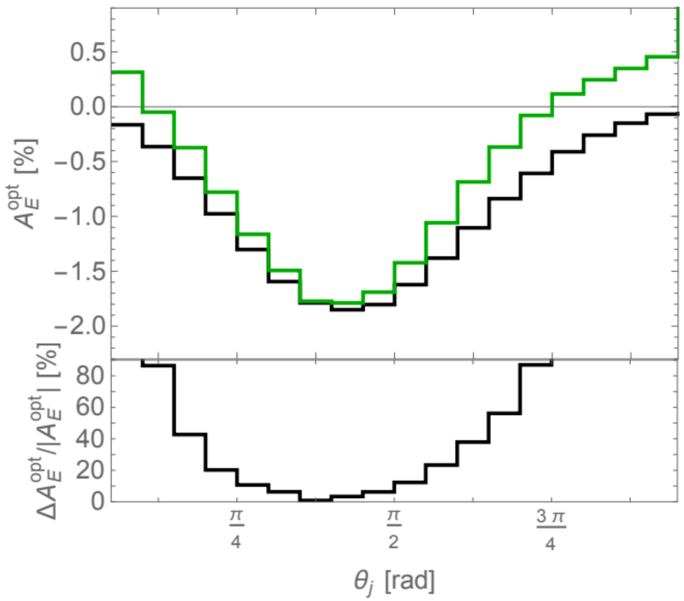




Asymmetry built in $t\bar{t}j$ production

- $\Delta E = E_t - E_{\bar{t}}$
- θ_j = Jet scattering angle w.r.t incoming parton
- ΔE , θ_j defined in $t\bar{t}j$ rest frame

$$A_E(\theta_j) \equiv \frac{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) - \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)}{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) + \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)} \equiv \frac{\sigma_A(\theta_j)}{\sigma_S(\theta_j)}$$



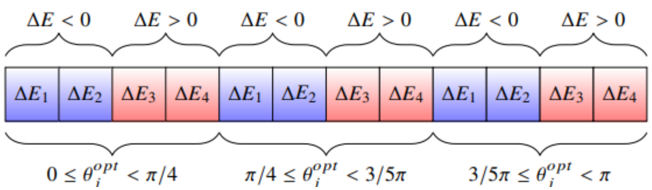
- Complementary measurement to charge (rapidity) asymmetry (CA) – probes new directions in SMEFT
- Potential for future combination with CA
- Many BSM models generate multiple four-quark operators simultaneously

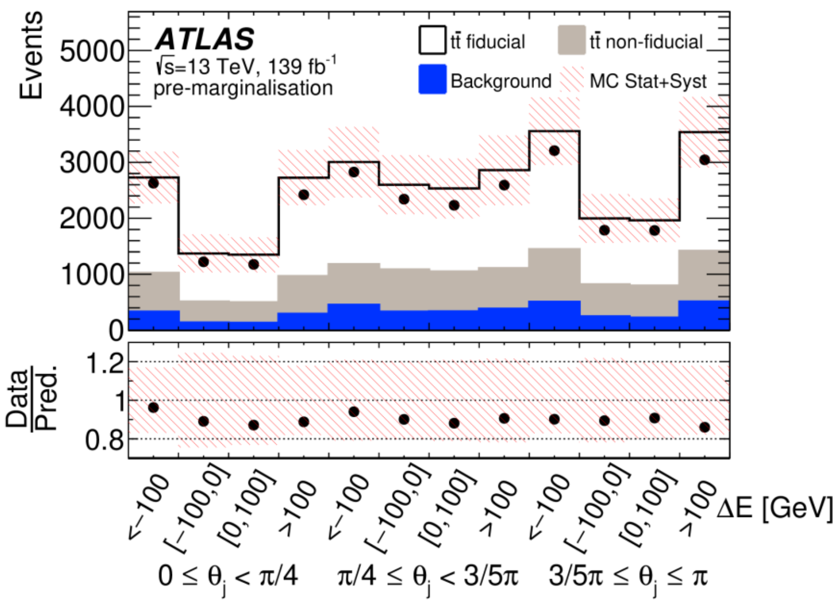
Observing the top energy asymmetry at the LHC, S. Berge and S. Westhoff, Phys. Rev. D 95 014035 (2017)

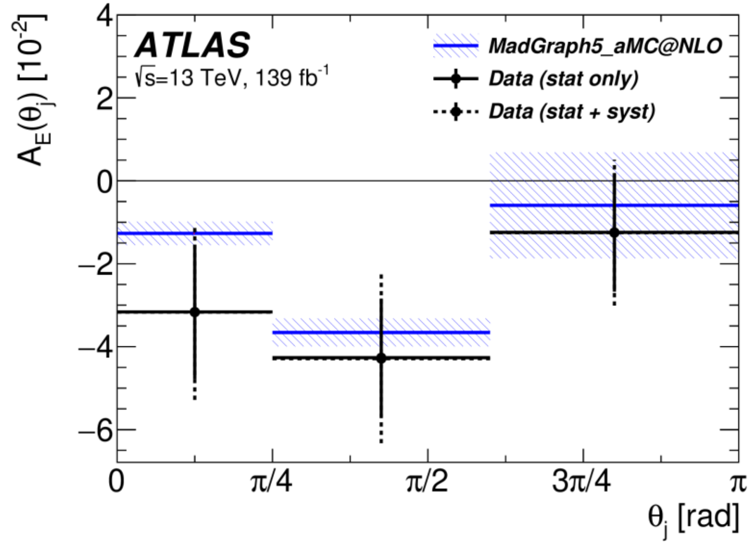
Energy Asymmetry

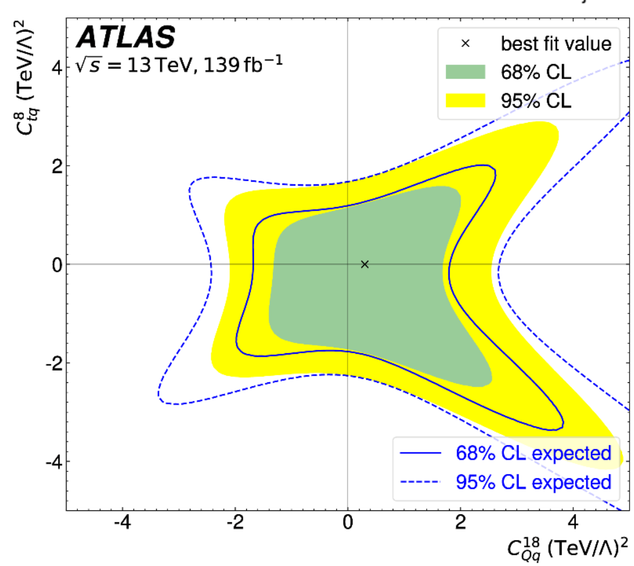
arXiv

- $t\bar{t}$ lepton+jets boosted topology
- Fully Bayesian Unfolding to particle level
- Binned in θ_j to increase sensitivity





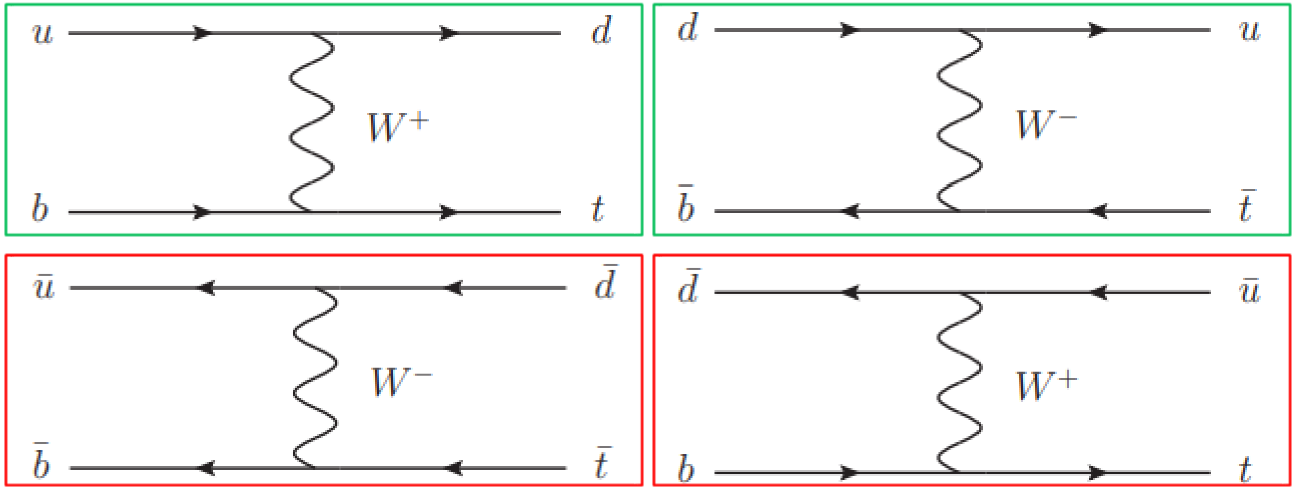


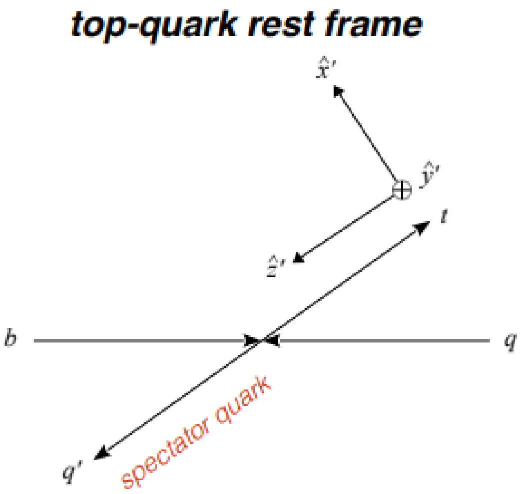


All asymmetry results agree with SM predictions (MG5_aMC@NLO+Pythia8, NLO QCD + PS)

Heavily dominated by statistical uncertainties

Spin Polarisation in single-top production





$t\bar{t}$ produces unpolarised tops (parity conservation in QCD)

t-channel is dominant process for single-top production at LHC

Single-top production (V-A coupling in Wtb vertex) leads to tops with their spin completely aligned along (or against) the direction of the down-type quark (the ‘spectator’ quark), depending on the dominant or subdominant process and the production of a t or $\bar{t}$

t = Aligned $\quad\bar{t}$ = Anti Aligned $\quad P_{z'}(t)\sim 0.90$

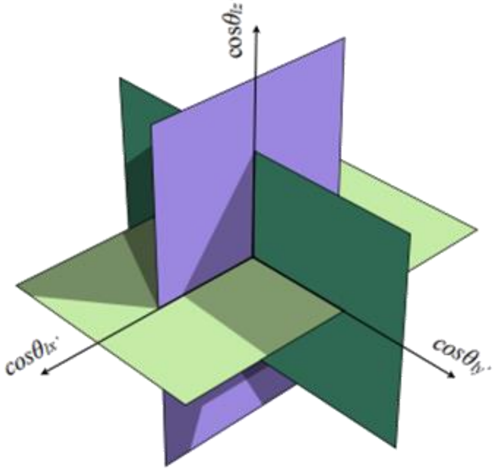
t = Anti Aligned $\quad\bar{t}$ = Aligned $\quad P_{z'}(\bar{t})\sim -0.86$

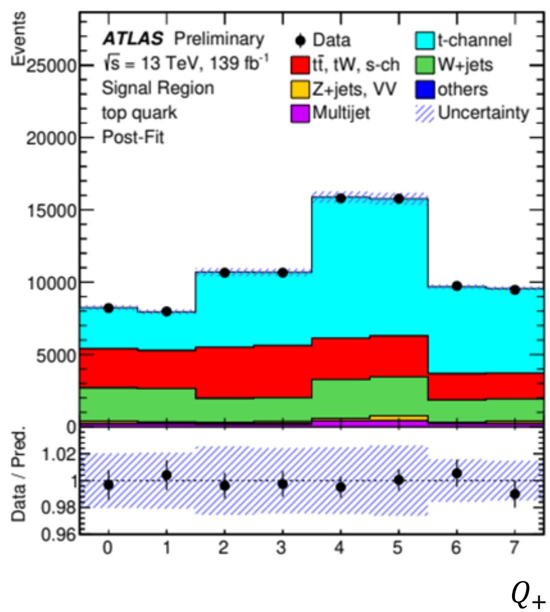
(Depend on $\sqrt{s}$, acceptance…)

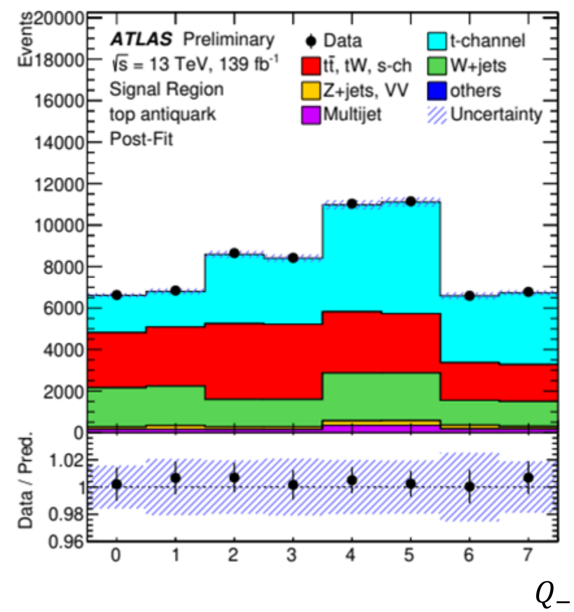
Spin Polarisation in single-top production

CONF

- Top quark spin affects angular distributions of decay products
- MC Templates may be built between samples to represent any combination of valid polarisations $\{P_{x'}, P_{y'}, P_{z'}\}$
- Build angular distributions for the charged lepton with respect to each axis θ_{li}







- *Octant Variable Q* defines all signal regions, broken by sign of $\cos\theta_{l\hat{\imath}}$ and q_l
- CRs are introduced for $t\bar{t}$, W+jets backgrounds

Profile likelihood fit over all regions simultaneously:

- 6 PoIs (polarisations split by top charge)
- Normalisation Factors for CRs
- Nuisance parameters associated to systematic uncertainties

Spin Polarisation in single-top production

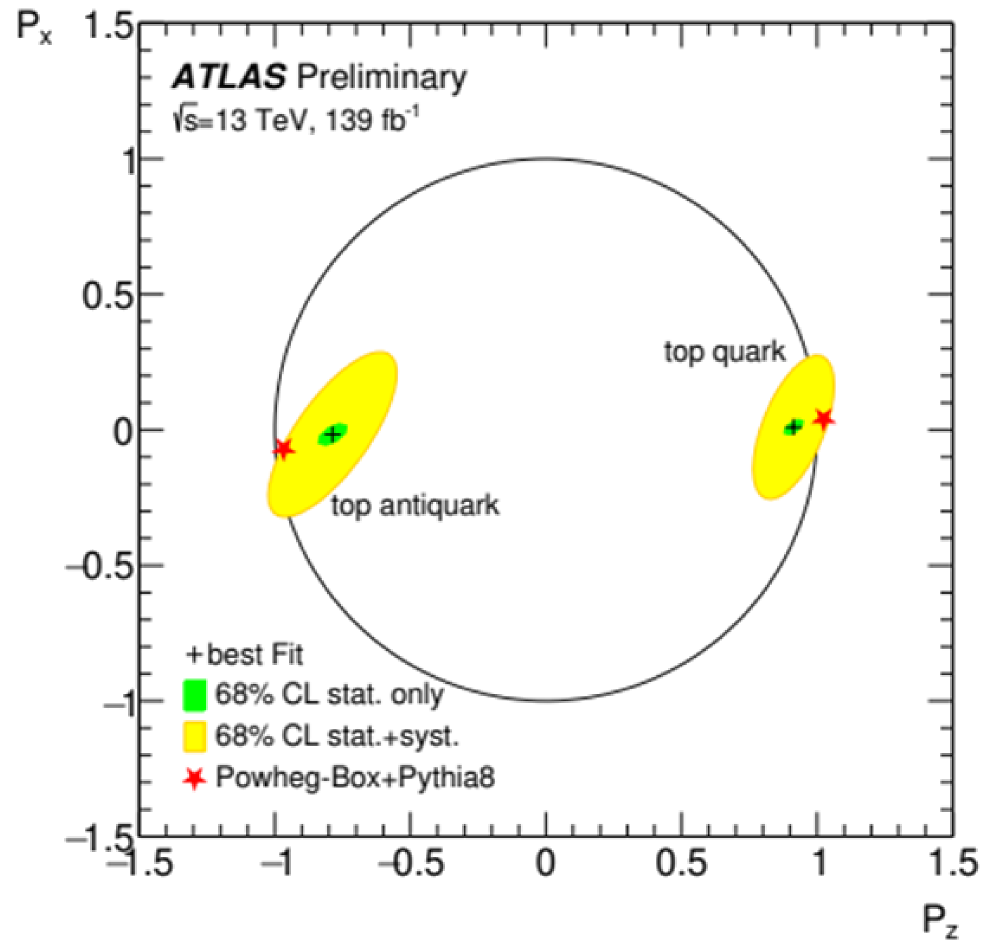
CONF

Polarisations in agreement with SM predictions to 1σ

(Powheg+Pythia8)

Uncertainties dominated by Jet Energy Resolution (JER)

- Polarisation depends on kinematic angles determined in top-quark rest frame
- JER is key to reconstruction of this frame



Spin Polarisation in single-top production

CONF

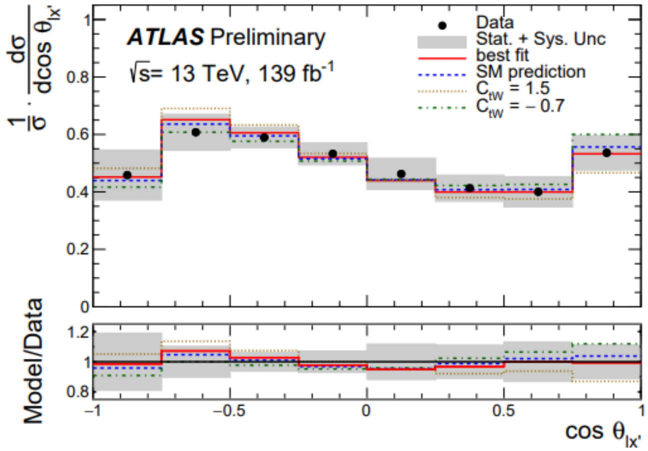
First order dim6 EFT operators that contribute to t-channel production:

- O_{tW} - Operator to focus on

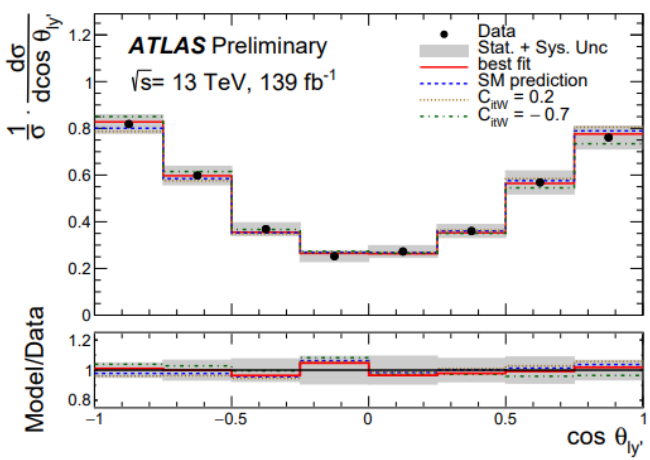
C_{tW} most affects $P_{x'}$

C_{itW} most affects $P_{y'}$

(Non-zero value could imply **CPV**)

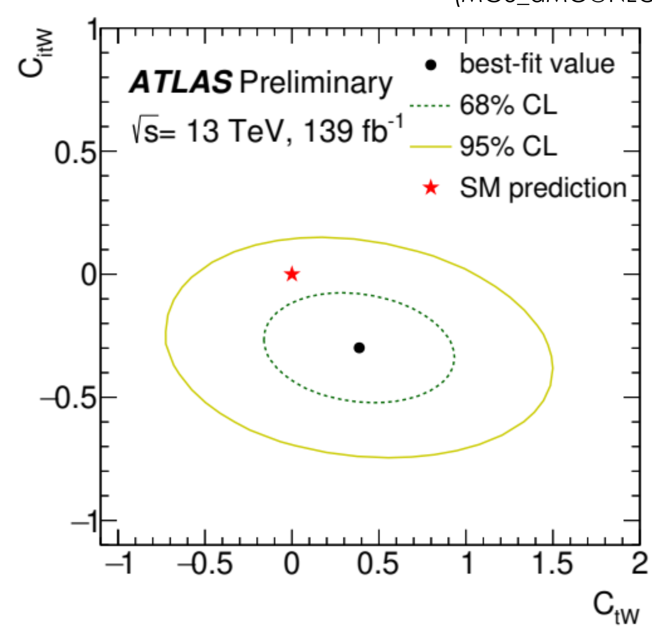


- Morphing technique used to interpolate between different Wilson Coefficient values
- Both coefficients fitted simultaneously (does not assume other is zero)



Result compatible with SM within 2σ

(MG5_aMC@NLO+Pythia8)



Summary

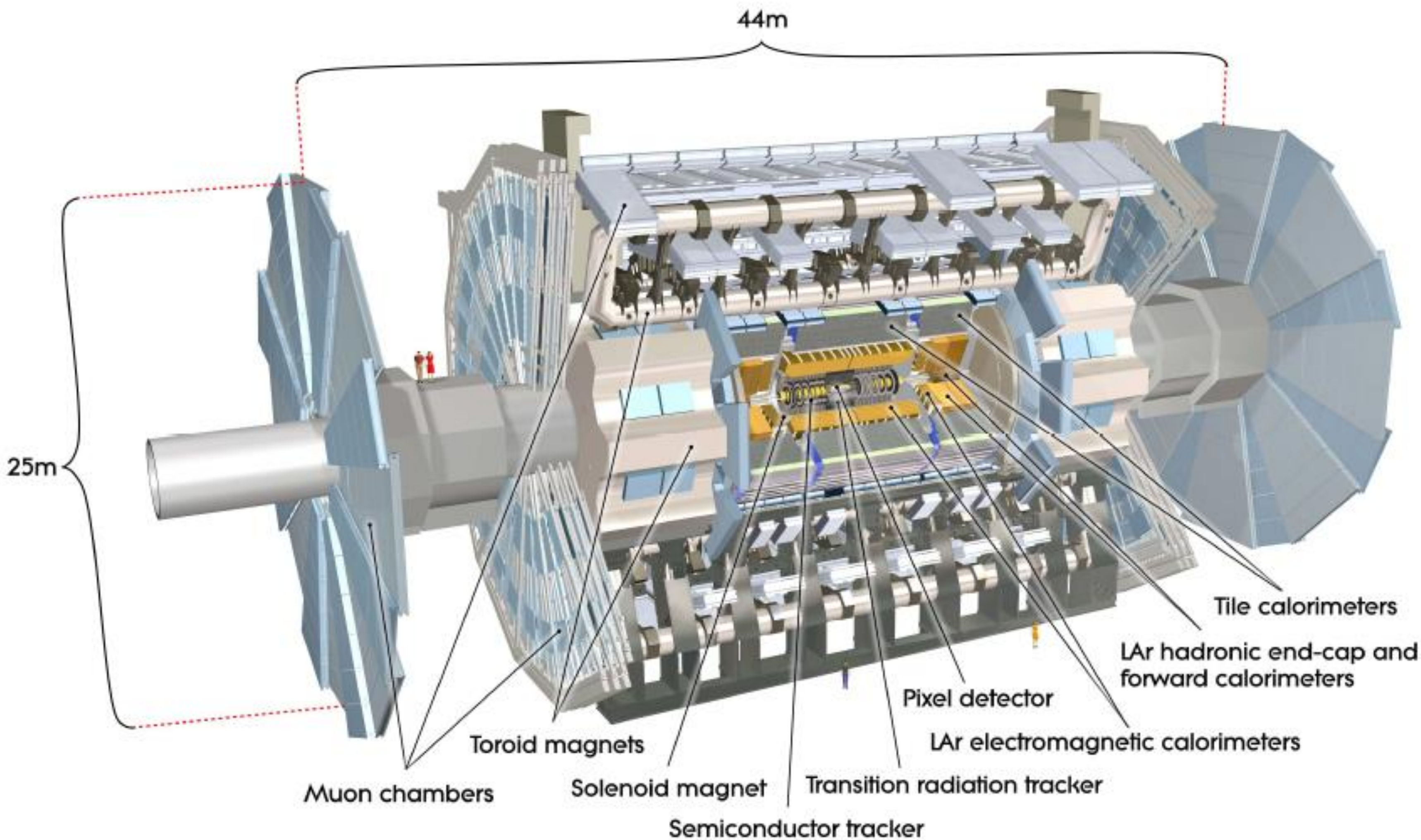
- There is a lot of very interesting physics being studied with respect to the properties of the top quark!

- Novel analysis techniques are being created to probe new and interesting properties at increasing precision – aiming to answer fundamental universal questions
  - Boosted top cross sections at this precisions are difficult to perform
    - Top pair inclusive cross sections fall lower than NLO QCD MC predictions but are consistent within uncertainties
    - Differential tensions greatest in distributions sensitive to radiation
  - Charge asymmetry finds strong evidence for SM effect, even with the large dilution from gluonic production
  - Energy Asymmetry in agreement with SM and useful for constraining blind directions in other fits
  - Top Polarisation in agreement with SM
    - Competitive EFT bounds on imaginary part of EFT operator

ATLAS Top Public Results
LHC Top Working Group


$\bar{t}$
t

BACKUP


44m
25m
Tile calorimeters
LAr hadronic end-cap and
forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

Top EFT

arXiv:1008.4484

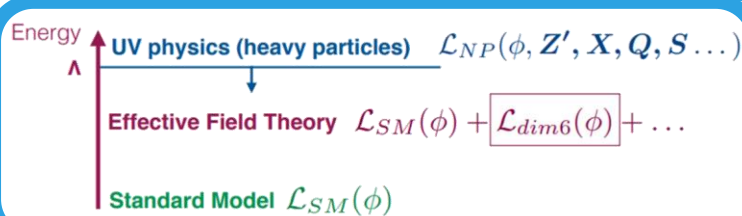
Effective Field Theories parameterise the effect of new physics via higher-dimension operators:

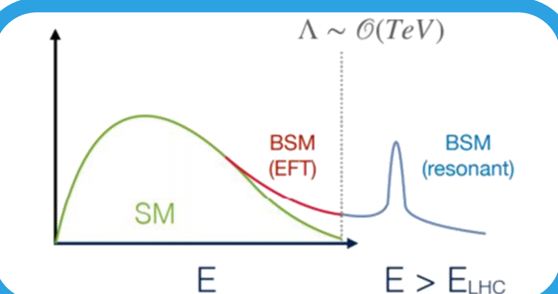
$$\mathcal{L}_{SM} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

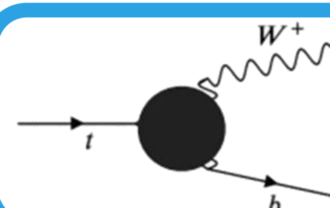
Wilson coefficients: Couplings of SM fields to NP

Gauge invariant operators

Higher terms supressed by increasing powers of Λ







- May induce corrections to the SM couplings.

Boosted differential cross sections

Why boosted and why differential?

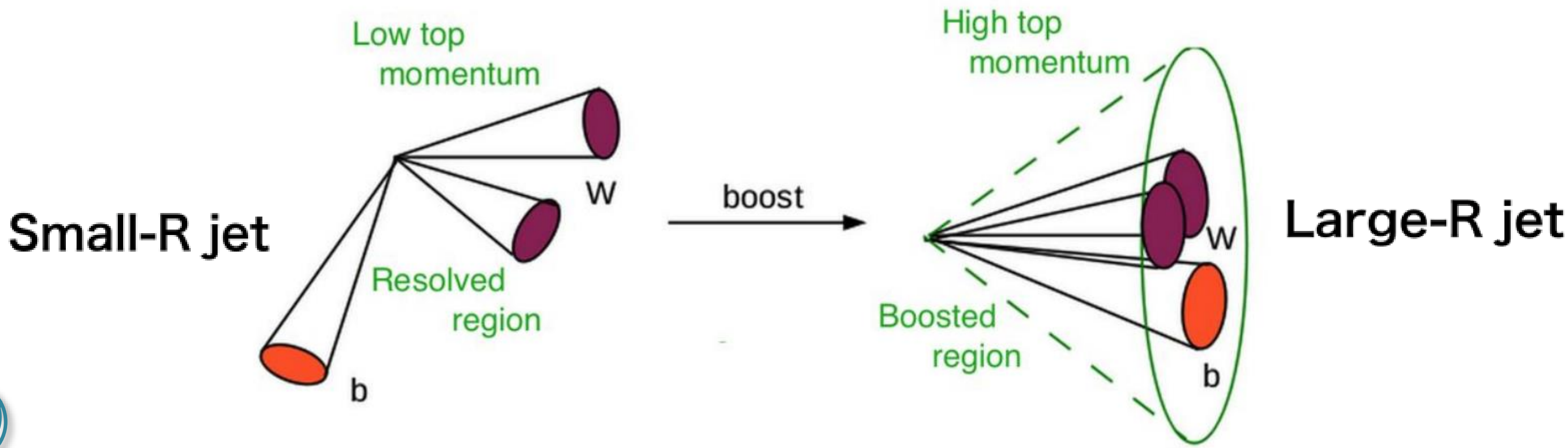
Probing the QCD $t\bar{t}$ production processes in the TeV scale range – testing existing models

Theoretical Standard Model (SM) calculations present large uncertainties in the boosted regime – especially for top quark pair invariant mass $m_{t\bar{t}} > 2$ TeV

Non-resonant deviations from the SM often appear at high top quark transverse momentum p_T and high $m_{t\bar{t}}$

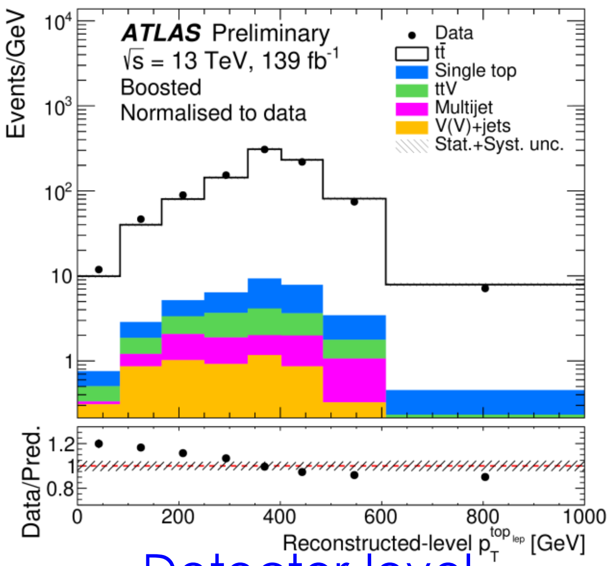
- New physics may be parameterised in a model-independent way through Effective Field Theory (EFT)

Interesting experimental techniques!

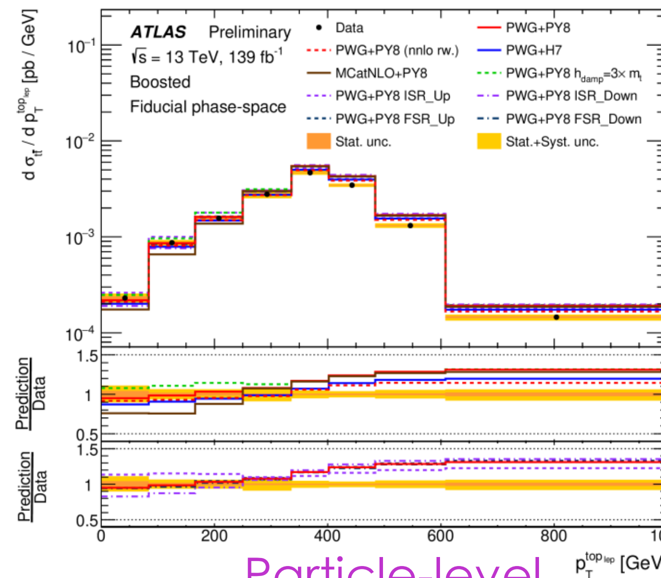


Boosted differential cross section
$t\bar{t} \rightarrow l + \text{jets}$

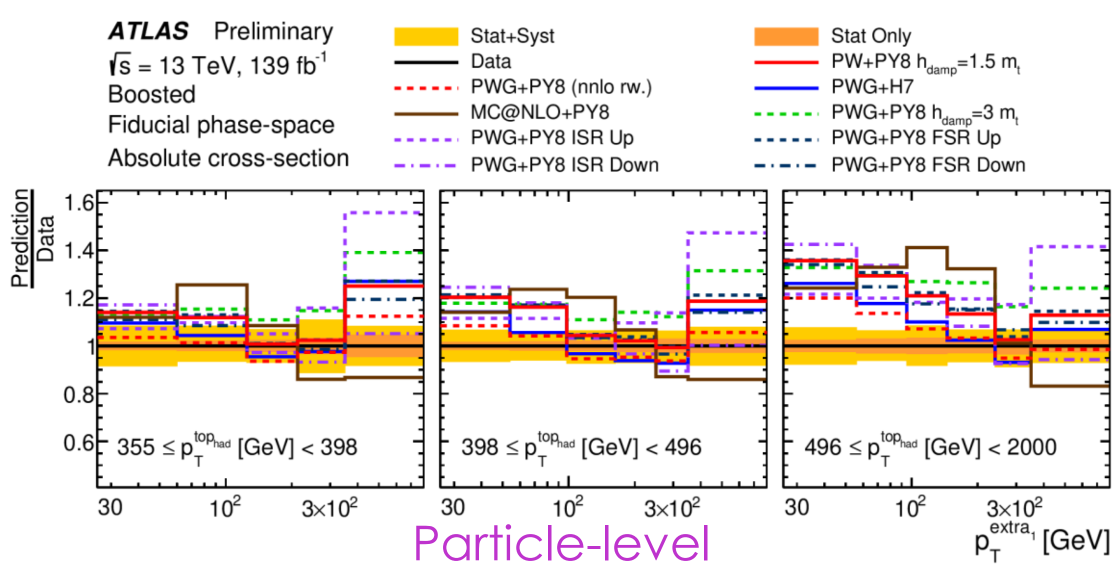
CONF



Detector-level



Particle-level

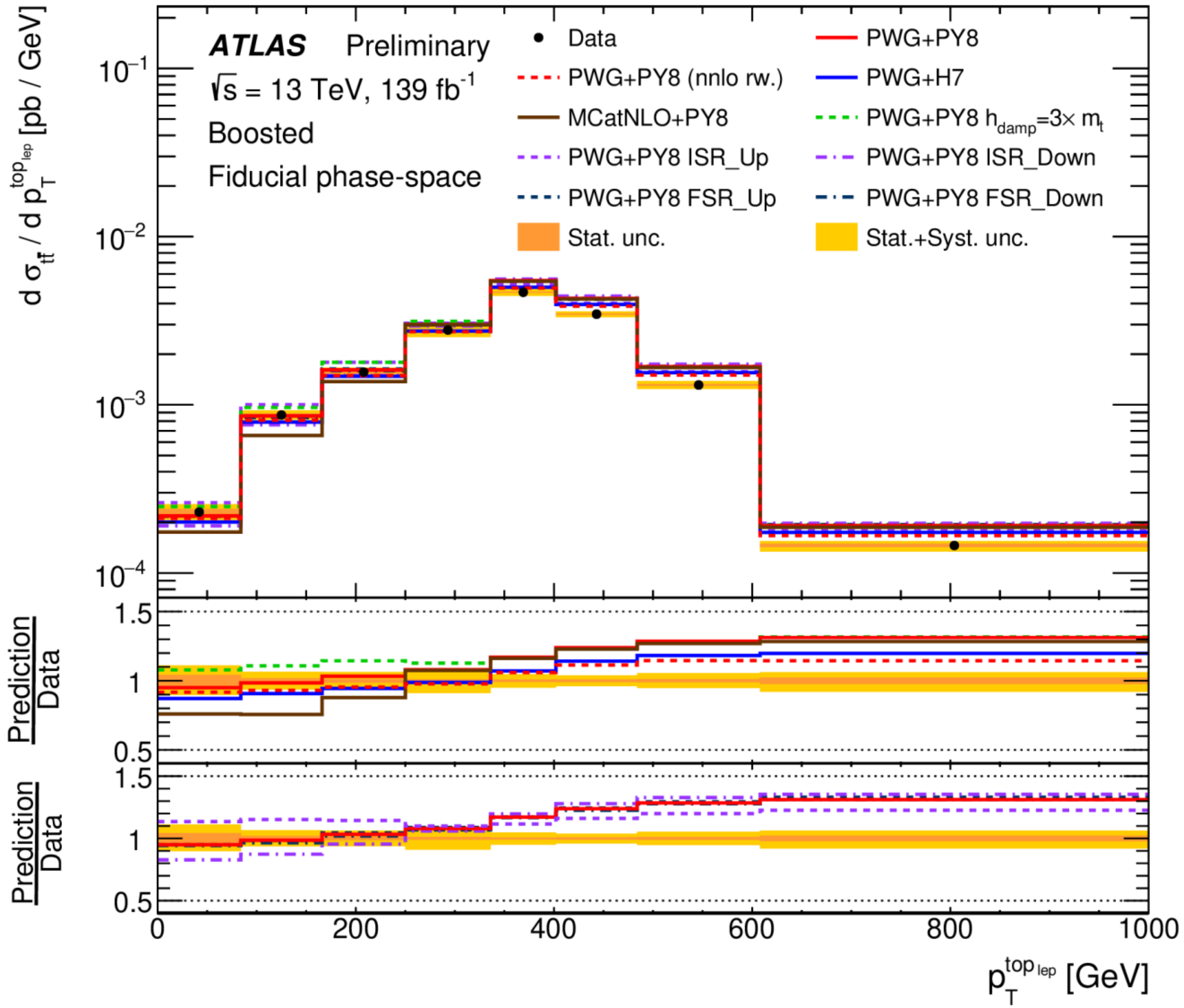


Particle-level

Momentum of additionally radiated jet

Boosted differential cross section
$t\bar{t} \rightarrow l + \text{jets}$

CONF

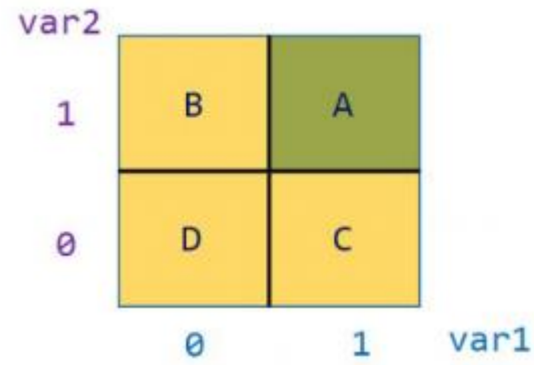


$t\bar{t} \rightarrow$ All hadronic

CONF

Largest background is 'multijet' (QCD)
- Estimated using 'ABCD' method

$$\frac{N_B^{\text{bkg}}}{N_D^{\text{bkg}}} = \frac{N_A^{\text{bkg}}}{N_C^{\text{bkg}}}$$



- Top-tagging (t) and b-tagging (b) status of two Large-R jets used as separating axes

- 16 regions defined
  - Validation regions > 20% $t\bar{t}$ signal yield (KLMN).

2nd large-R jet				
1t1b	J (7.0%)	K (25%)	L (39%)	S
0t1b	B (1.2%)	D (5.0%)	H (9.0%)	N (47%)
1t0b	E (0.5%)	F (2.3%)	G (4.9%)	M (31%)
0t0b	A (0.09%)	C (0.5%)	I (1.1%)	O (9.0%)
	0t0b	1t0b	0t1b	1t1b

Leading large-R jet

Usually then use regions JASO, such that $S = \frac{J \times O}{A}$

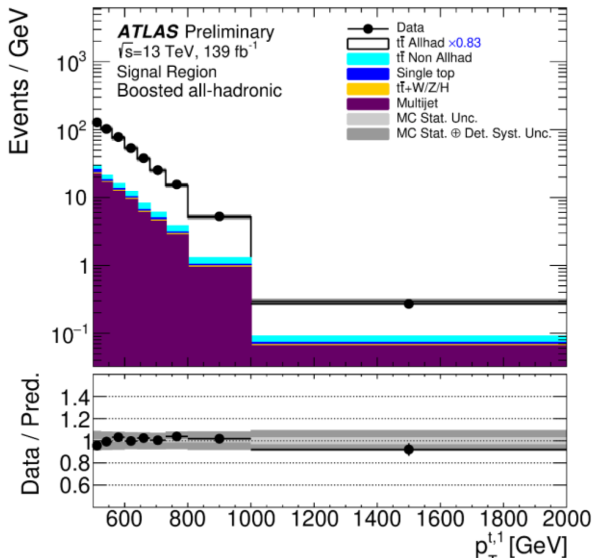
Top-mistag rate of the Large-R jets are actually correlated, which makes traditional ABCD invalid – hence other regions are used to account for this

$$S = \frac{J\times O}{A} \cdot \frac{D\times A}{B\times C} \cdot \frac{G\times A}{E\times I} \cdot \frac{F\times A}{E\times C} \cdot \frac{H\times A}{B\times I}$$

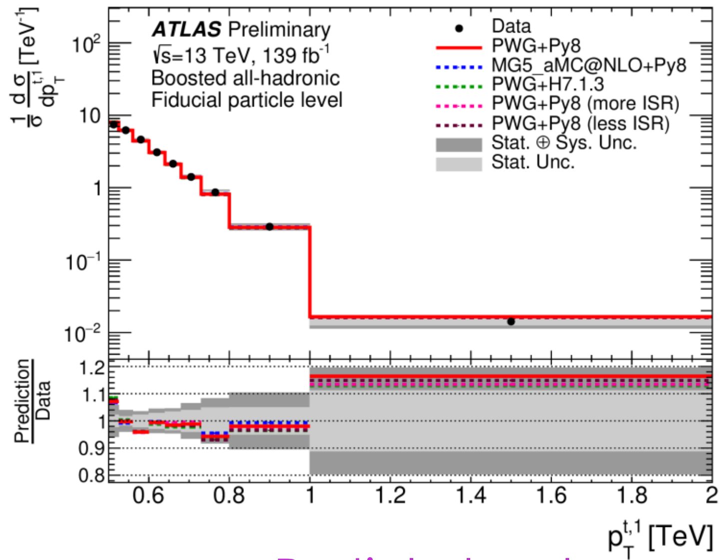
(affects yield predictions by ~15%)

Boosted differential cross section
$t\bar{t} \rightarrow$ All hadronic

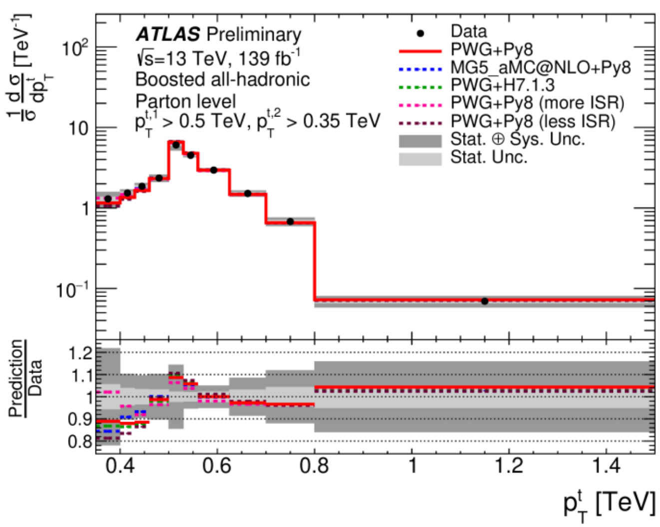
CONF



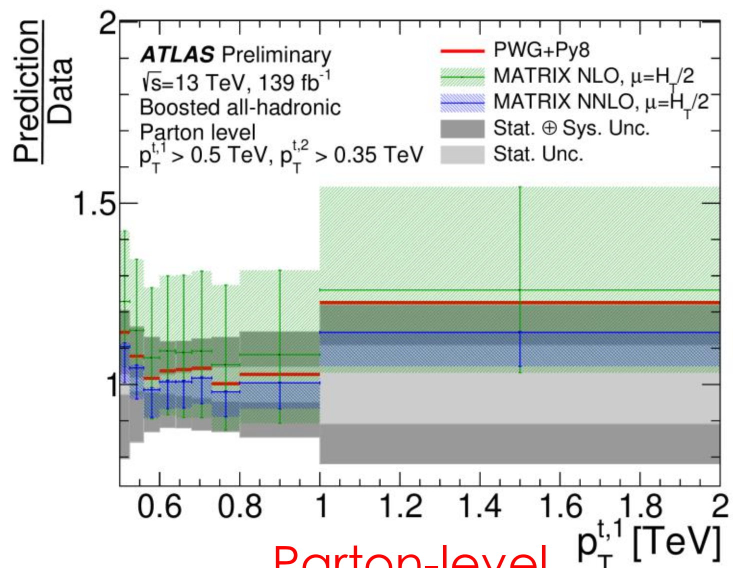
Detector-level



Particle-level



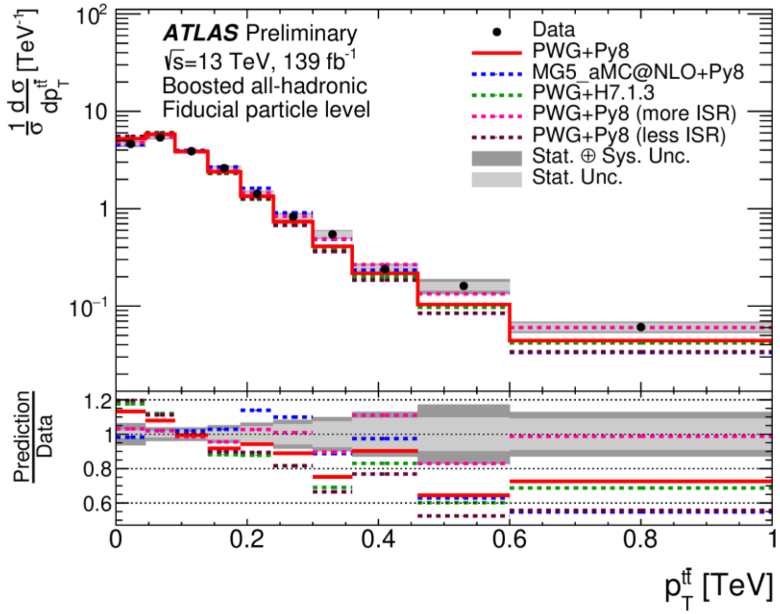
Parton-level

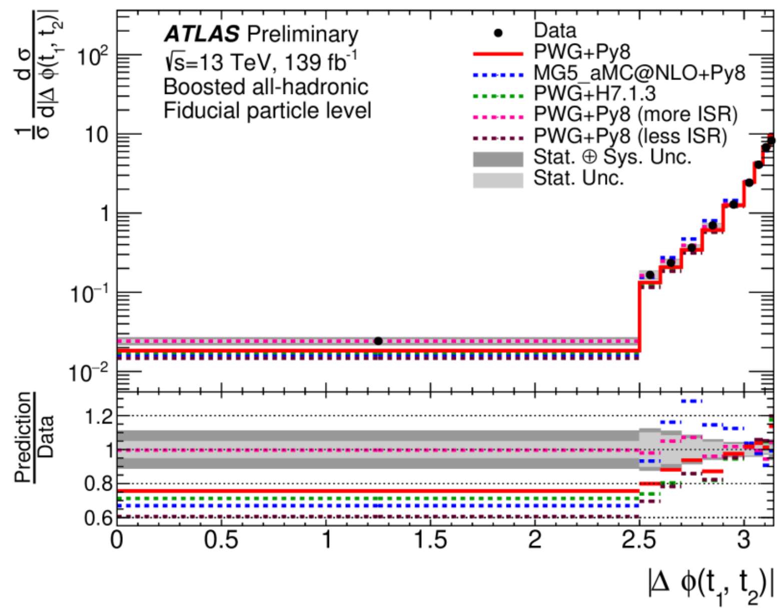


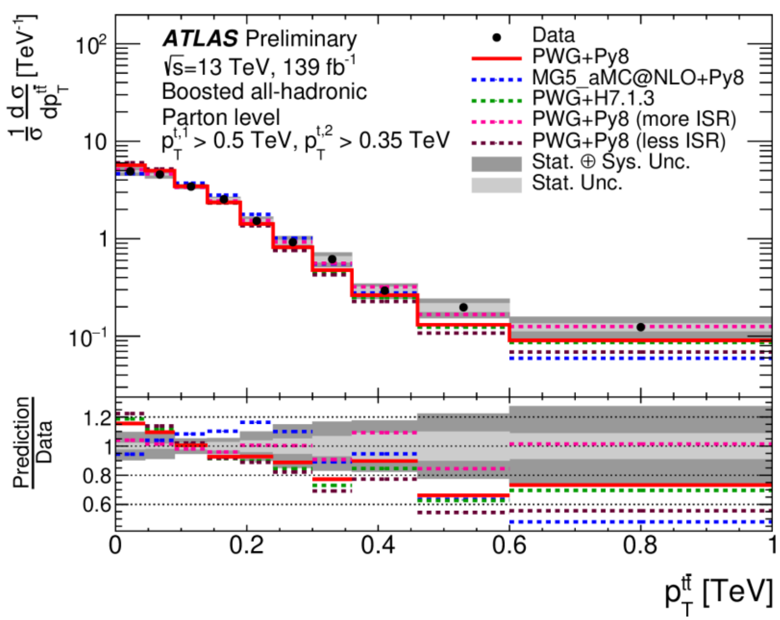
Parton-level

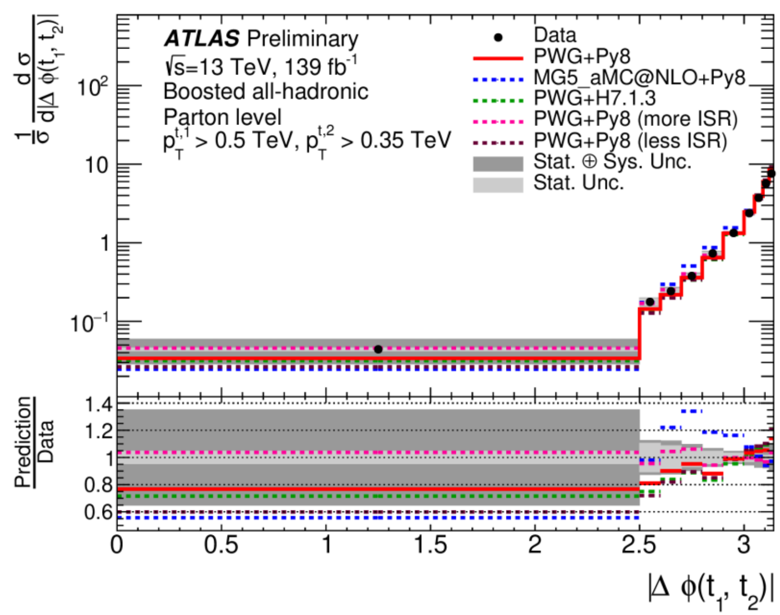
Boosted differential cross section
$t\bar{t} \rightarrow$ All hadronic

CONF









Boosted differential cross section
$t\bar{t} \rightarrow$ All hadronic

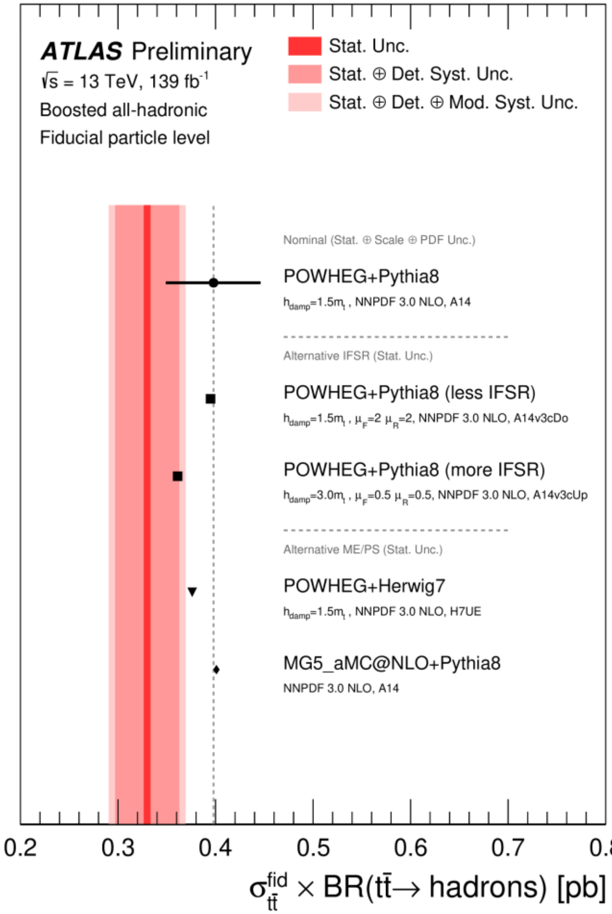
CONF

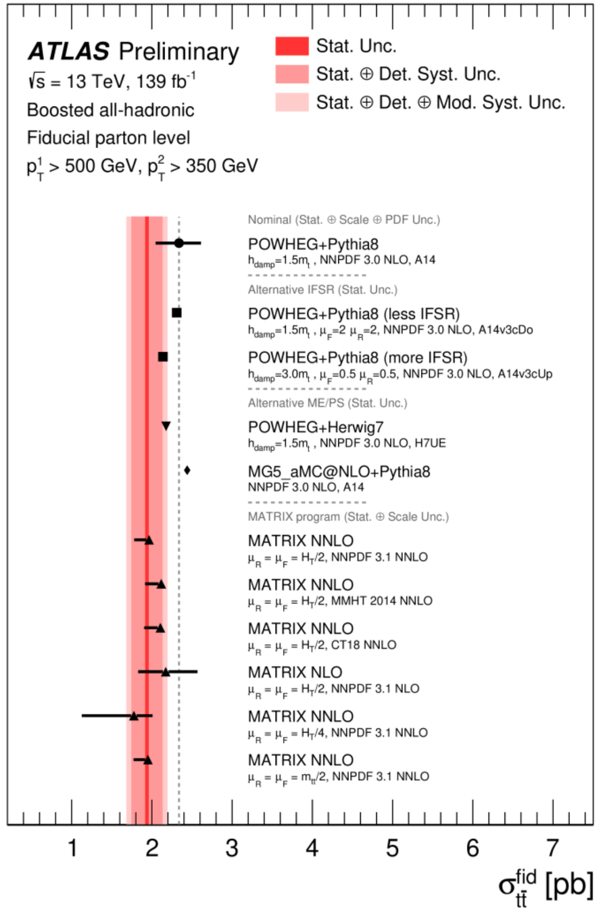
$$\sigma^{t\bar{t}}_{\text{particle,fiducial}} = 330 \pm 3(\text{stat.}) \pm 38(\text{syst.})\text{pb}$$

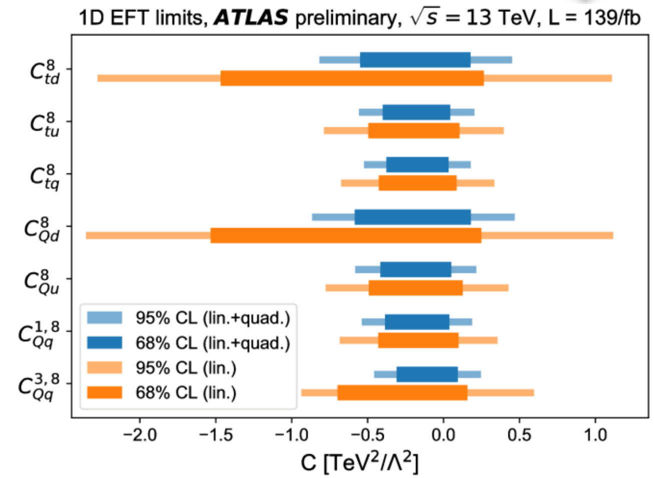
Systs: Top-tagging
Jet energy resolution
Radiation modelling

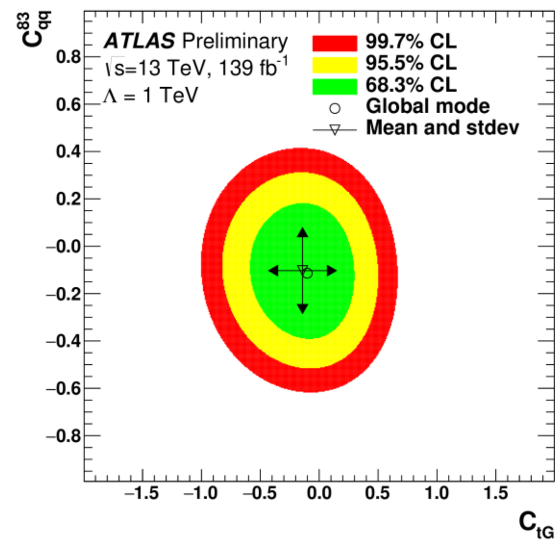
$$\sigma^{t\bar{t}}_{\text{parton,fiducial}} = 1.94 \pm 0.02(\text{stat.}) \pm 0.25(\text{syst.})\text{pb}$$

~20% lower than NLO+PS predictions normalised to NNLO total cross section







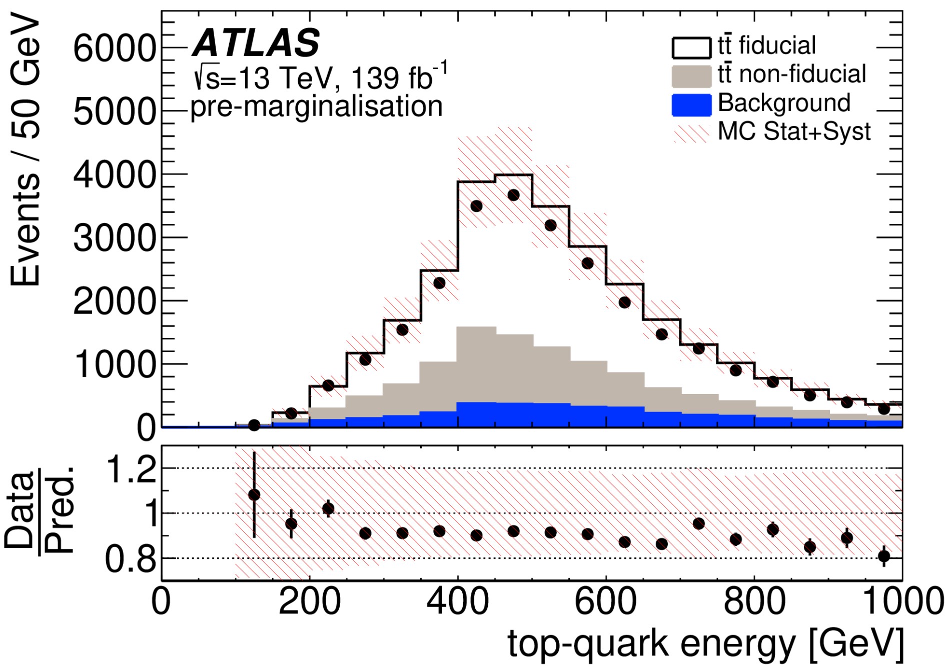


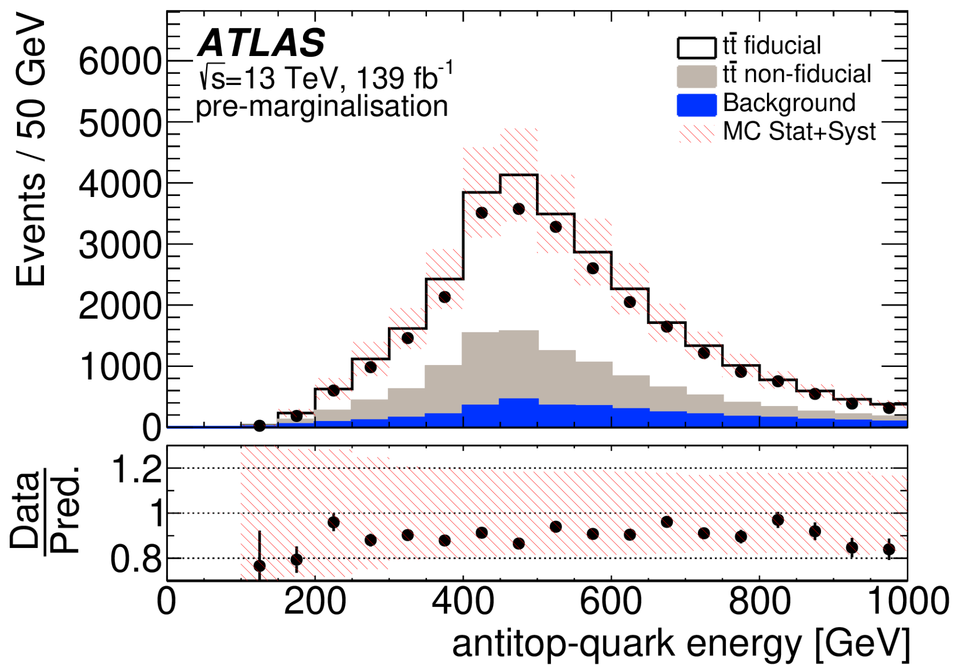
Limits on 4-light-quark-heavy-quark operators

Most tension in radiation-sensitive distributions ($p_T^{t\bar{t}}$, $\Delta\varphi_{t\bar{t}}$)

Energy Asymmetry

arXiv





Top Polarisation

Top polarisation is sensitive to NP that affects the tWb vertex

First order dim6 EFT operators that contribute to t-channel production:

- $O_{\phi q}$ - Affects cross-section only
- $O_{\phi q}$ - Four-fermion operator, negligible effect on angular distributions
- O_{tW} - Operator to focus on

C_{tW} most affects $P_{x'}$

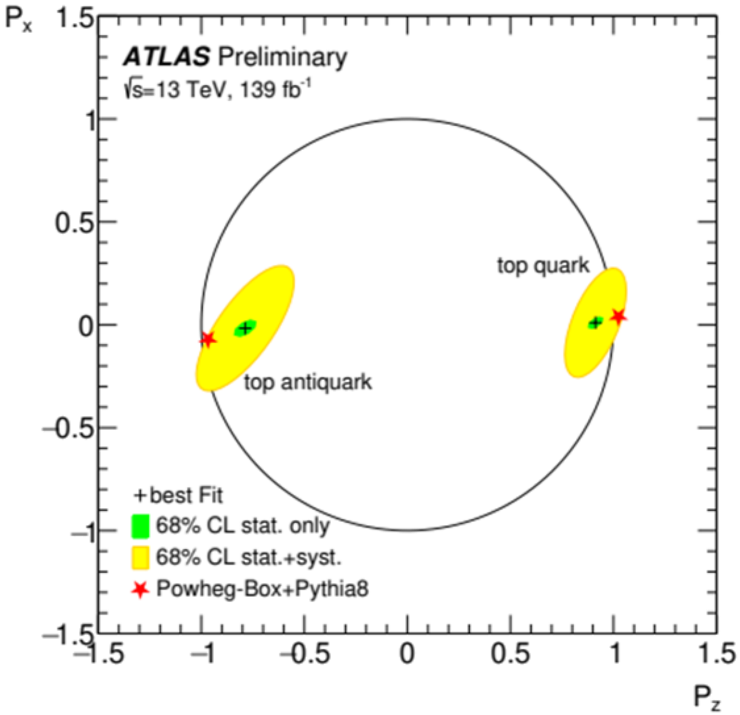
$P_{z'}$ less sensitive as ~1

C_{itW} most affects $P_{y'}$
(Non-zero value could imply **CPV**)

Top Polarisation

ATLAS-CONF-2021-027
139 fb^{-1}

Polarisations in agreement with SM predictions to 1σ (Powheg+Pythia8)



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)

Uncertainties dominated by Jet Energy Resolution (JER)

- Polarisation depends on kinematic angles determined in top-quark rest frame
- JER is key to reconstruction of this frame

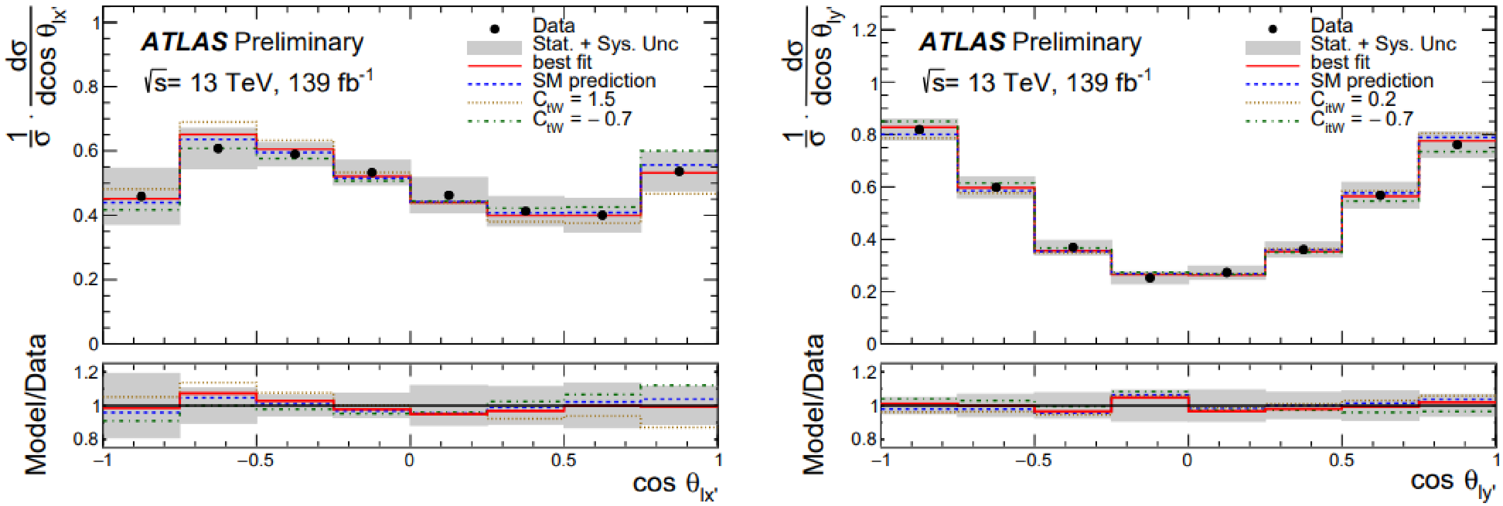
First order dim6 EFT operators that contribute to t-channel production:

- O_{tW} - Operator to focus on → C_{tW} most affects $P_{x'}$; → C_{itW} most affects $P_{y'}$ (Non-zero value could imply **CPV**)

Top Polarisation

ATLAS-CONF-2021-027

139 fb^{-1}



Unfolded to particle level fiducial region

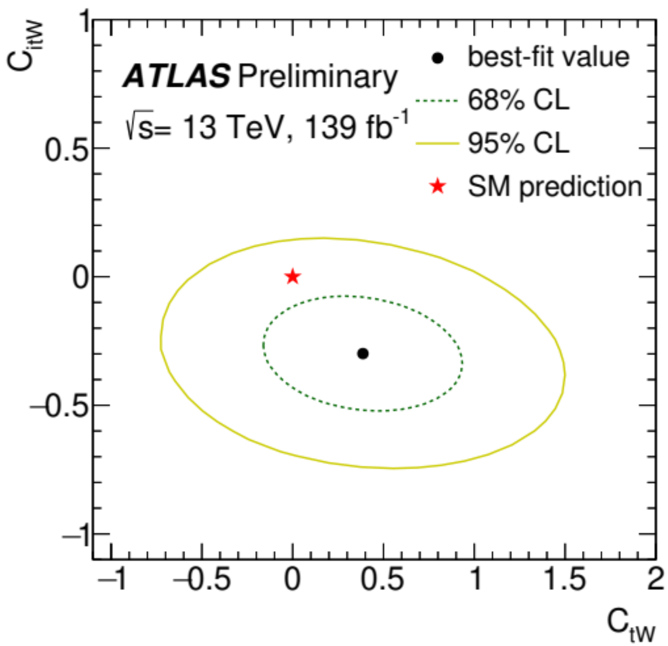
$$\sigma(C_{tW}, C_{itW}) \propto \left| O_{SM} + \frac{C_{tW}}{\Lambda^2} \cdot O_{tW} + \frac{C_{itW}}{\Lambda^2} \cdot O_{itW} \right|^2_{\text{production}} \cdot \left| O_{SM} + \frac{C_{tW}}{\Lambda^2} \cdot O_{tW} + \frac{C_{itW}}{\Lambda^2} \cdot O_{itW} \right|^2_{\text{decay}}$$

Morphing technique used to interpolate between MC templates using difference Wilson Coefficient values

Both coefficients fitted simultaneously (does not assume other is zero)

Result compatible with SM within 2σ

(MG5_aMC@NLO+Pythia8)

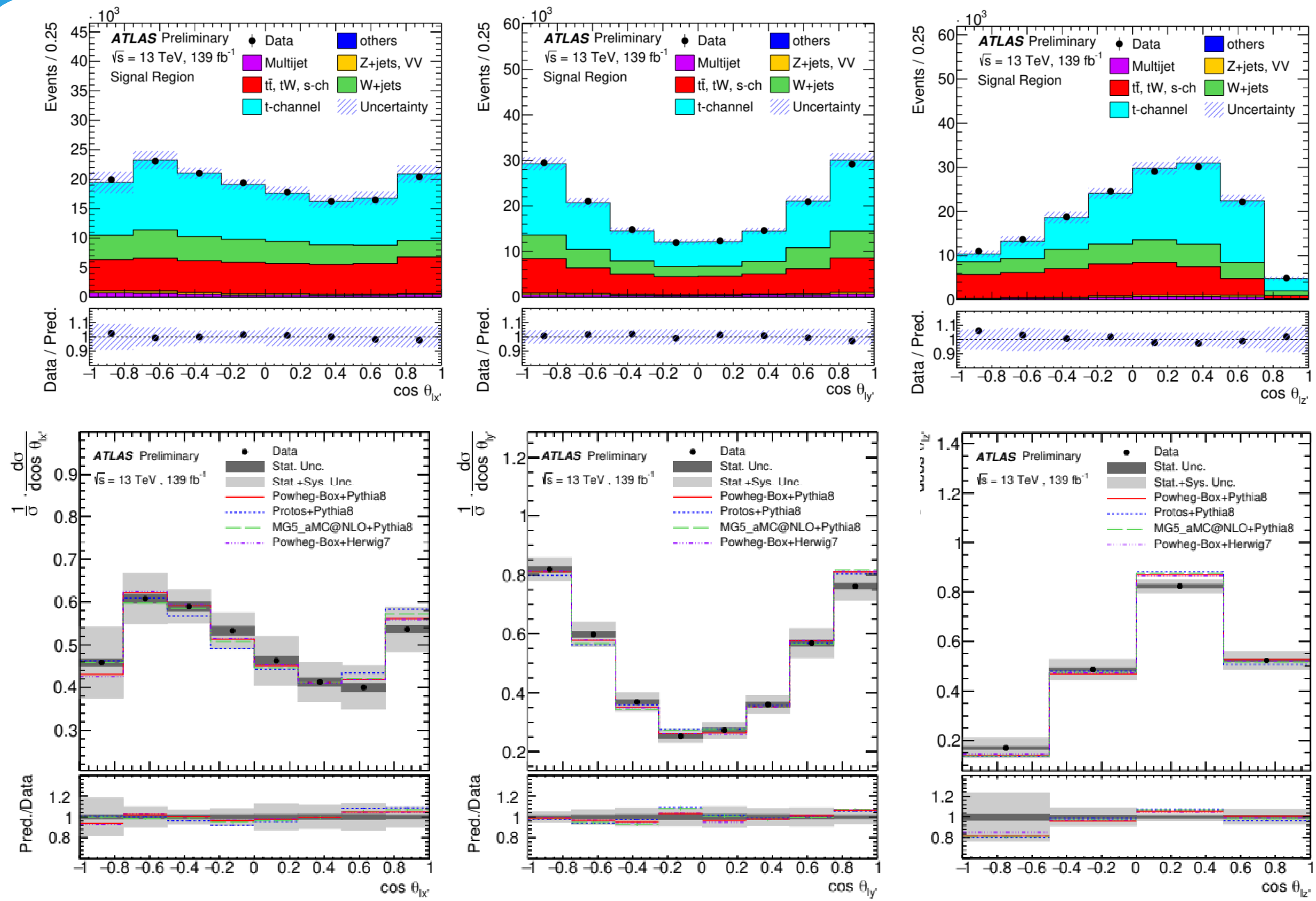


Measurement of Top Polarisation

ATLAS-CONF-2021-027

$\sqrt{s} = 13$ TeV, 139 fb^{-1}

June 2021



Charge Asymmetry

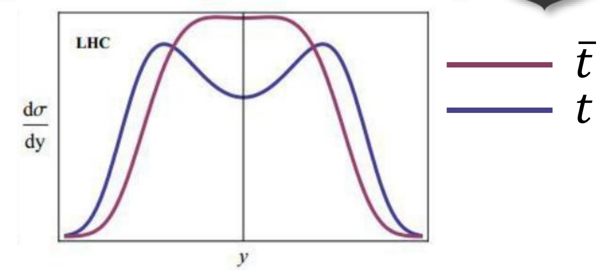
CONF

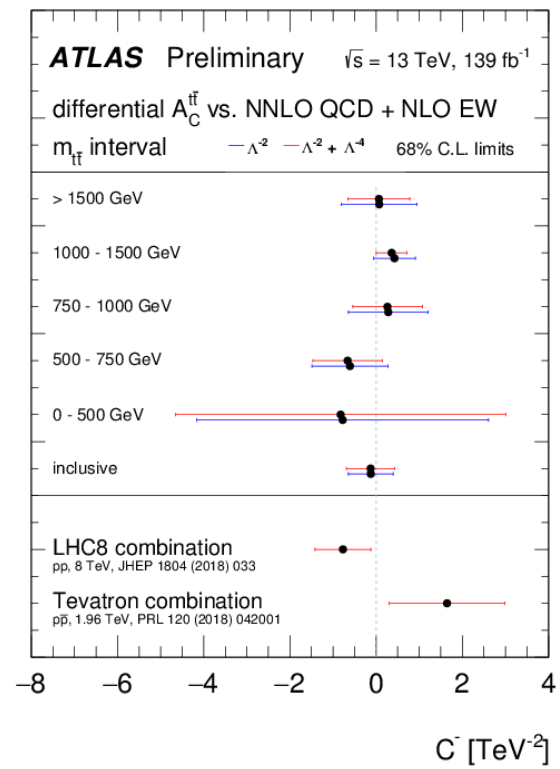
- LO $t\bar{t}$ production is symmetric
- Higher-order interferences between $q\bar{q}$ and qg create an asymmetric production
  - t is produced preferentially in direction of incoming q

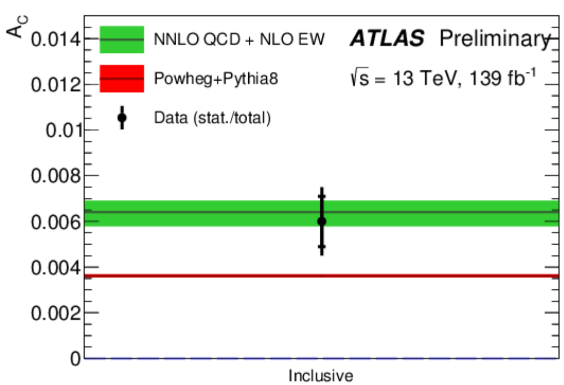
$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

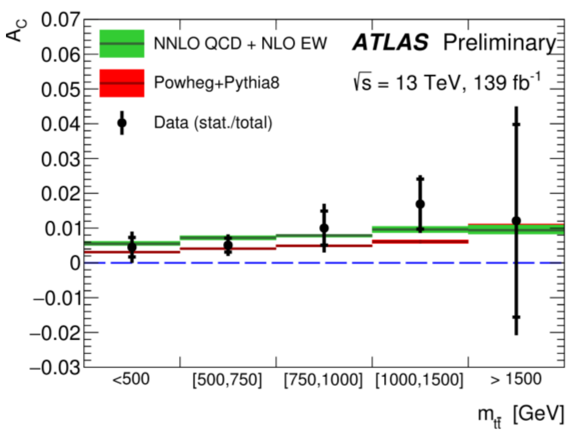
$\Delta|y| = |y_t| - |y_{\bar{t}}|$

- Charge symmetric gg production dilutes asymmetry
- Several BSM models predict alterations to A_C , especially with variation as a function of $m_{t\bar{t}}$ and $\beta_{z,t\bar{t}}$
  - Anomalous vector/axial couplings (e.g. axigluons)
  - Heavy Z' bosons









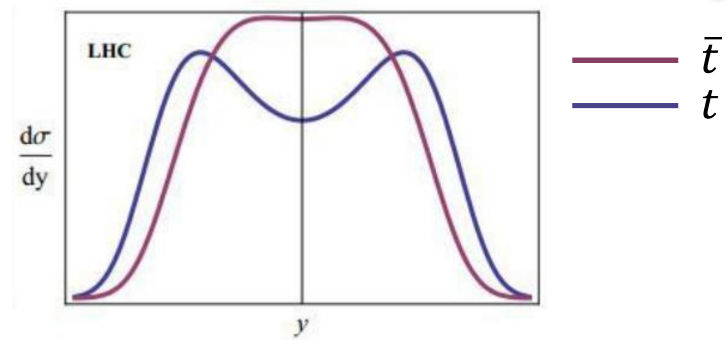
C^- / Λ^2 — C^- is linear combination of Wilson Coefficients. Λ is scale of new physics

EFT coefficient useful for many models (axigluons, kaluza-klein, randall-sundrum)

$A_C = 0.0060 \pm 0.0015$ (stat+syst.)

Charge Asymmetry

- LO $t\bar{t}$ production is symmetric
- Higher-order interferences between $q\bar{q}$ and qg create an asymmetric production
  - t is produced preferentially in the direction of the incoming q

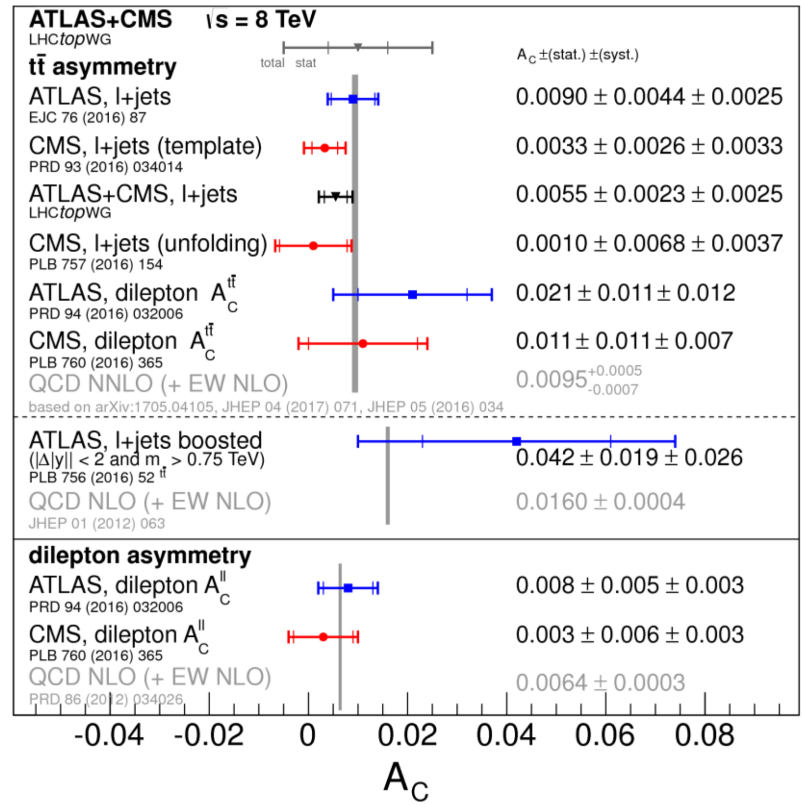


- At the LHC, this produces a central-forward charge asymmetry:

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

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

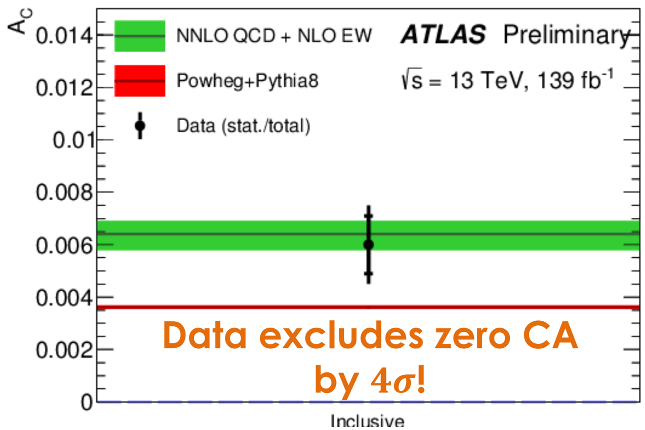
- Charge symmetric gg production dilutes measurable asymmetry
- Several BSM models predict alterations to A_C especially with variation as a function of $m_{t\bar{t}}$ and $\beta_{z,t\bar{t}}$
  - Anomalous vector/axial couplings (e.g. axigluons)
  - Heavy Z' bosons

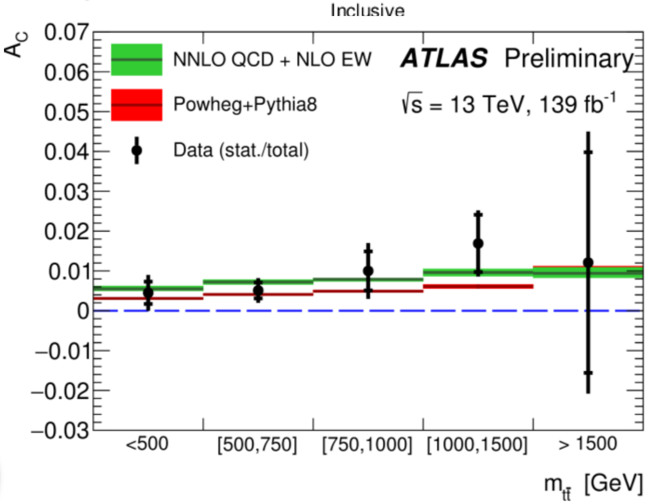


Possible to do an EFT interpretation to test many models!

$A_C = 0.0060 \pm 0.0015$ **(stat+syst.)**

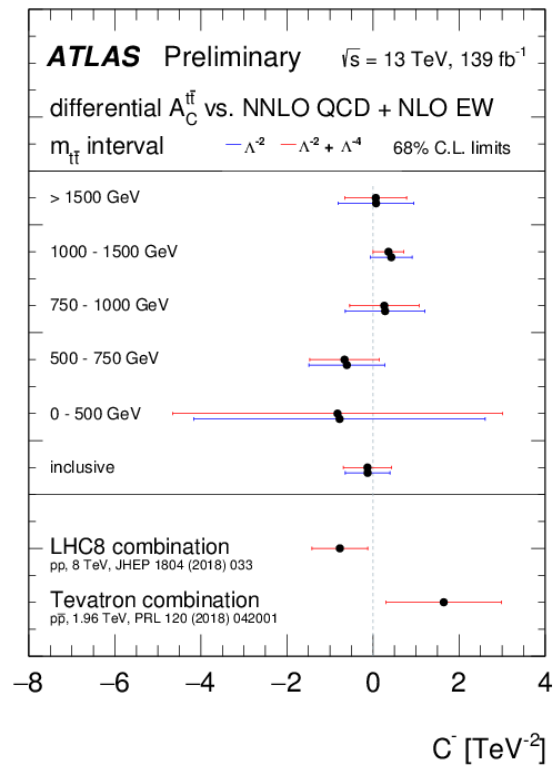
Both **inclusive and differential** measurements are found to be **compatible with SM** predictions, at NNLO in perturbation theory with NLO electroweak corrections





EFT interpretation probes single important parameter in the Warsaw basis (see CONF note!): C^-/Λ^2

C^- is linear combination of Wilson Coefficients
Λ is scale of new physics

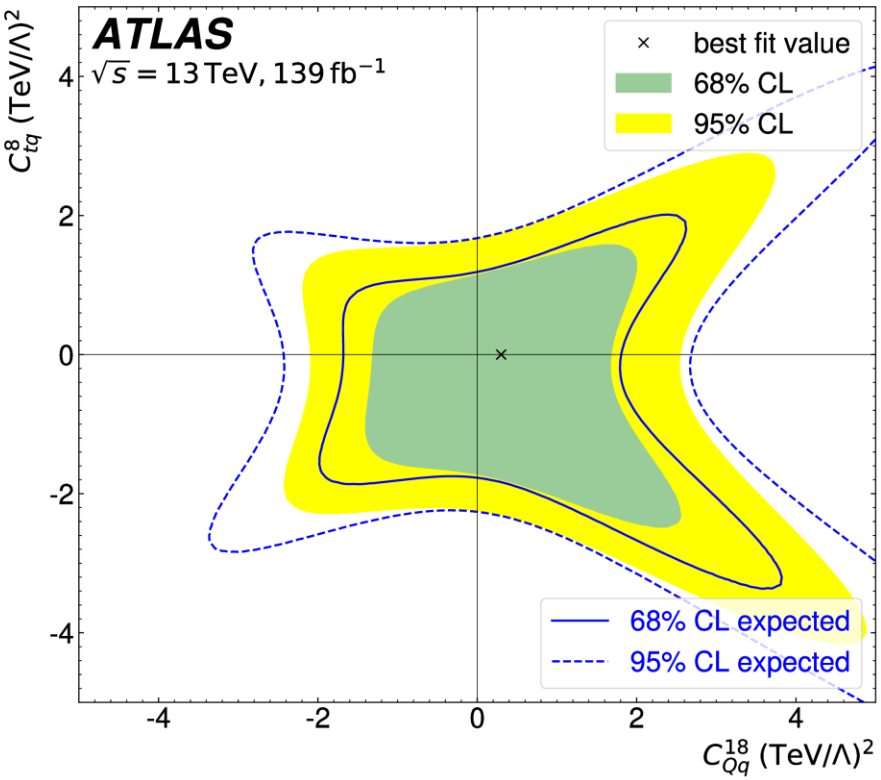


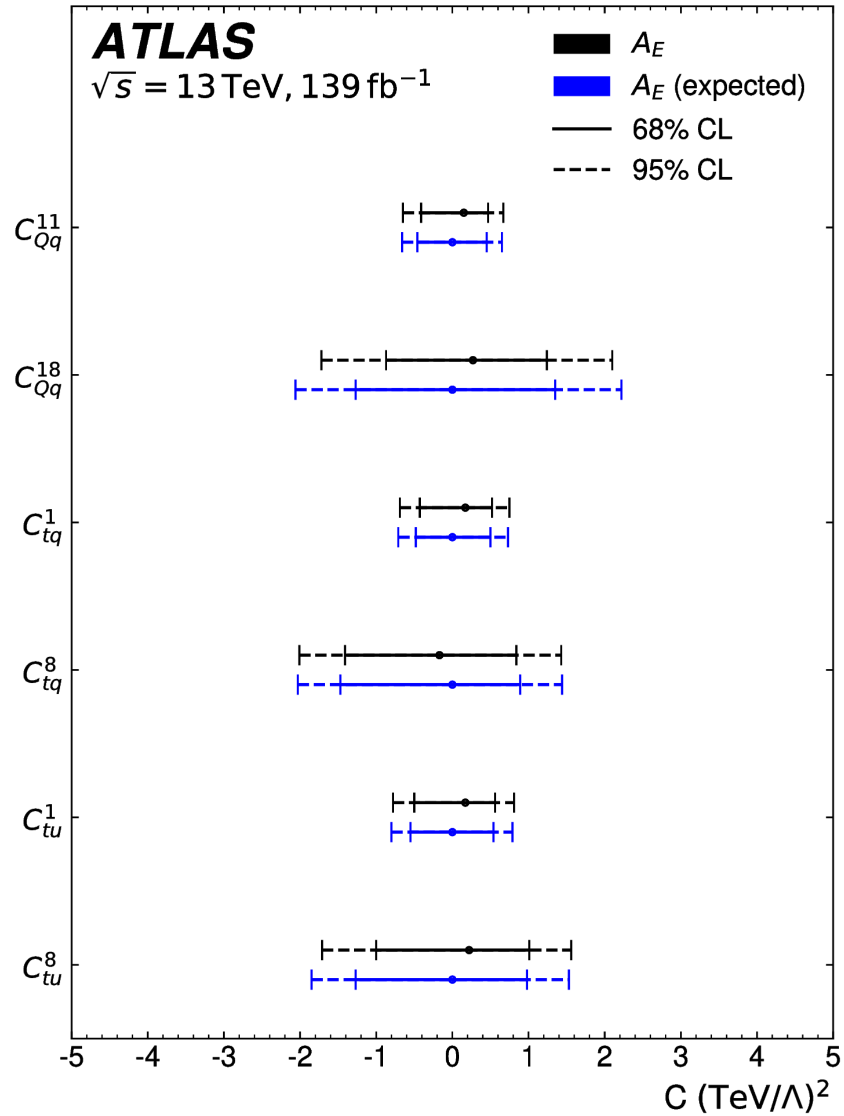
This is valid for many models (axigluons, kaluza-klein, randall-sundrum), for example:

$$C^-/\Lambda^2 = -4g_s^2/m_A^2$$

Tighter bounds achieved than for previous LHC 8 TeV combination!

arXiv





All EFT fits are consistent with zero