TESTING THE STANDARD MODEL IN BOOSTED TOP QUARK PRODUCTION WITH THE ATLAS DETECTOR

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ATLAS EXPERIMENT

INTRODUCTION

- Three measurements involving $t\bar{t}$ production with large transverse momentum using the *ATLAS* detector with full 139 fb^{-1} Run-II dataset
  - Measurement of energy asymmetry in $t\bar{t}j$ (Covered by Nello Bruscino in his talk) Eur. Phys. J. C 82 (2022) 374
  - Measurements of $t\bar{t}$ differential cross-sections in the Lepton+Jets Channel JHEP 06 (2022) 063
  - Measurements of $t\bar{t}$ differential cross-sections in the All-Hadronic Channel CERN-EP-2022-026
- Test models of top-quark production, decay, parton-showering, and hadronization
- High invariant mass in their boosted event topologies well-suited for probing UV extensions to the standard model

INTERPRETATIONS USING STANDARD MODEL EFFECTIVE FIELD THEORY (SMEFT)

- SMEFT: For new physics appearing at scale Λ, modifications to low-energy interaction ($E \ll \Lambda$) can be introduced in terms of higher-dimensional operators

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{B_j}{\Lambda^4}\mathcal{O}_j^{(8)}$$

- Measurement strategy is to parameterize measured cross-sections in terms of Wilson coefficients of dim-6 operators

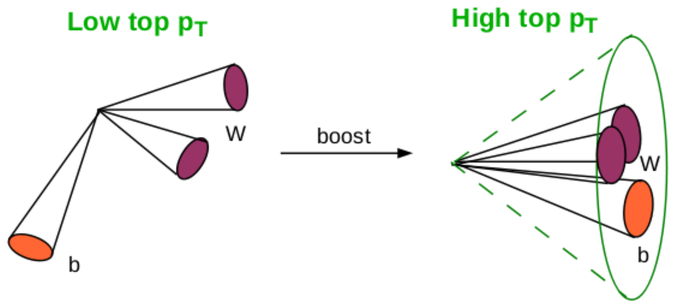
$$\begin{aligned}\sigma(C_i, B_j) &= \sigma_{\text{SM}} + \sigma_{\text{SM-EFT}} + \sigma_{\text{EFT-EFT}} \\ &= \sigma_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i \alpha_i C_i + \frac{1}{\Lambda^4}\sum_{i,j,i\leq j} \beta_{ij} C_i C_j + \frac{1}{\Lambda^4}\sum_i \kappa_i B_i + \mathcal{O}\left(\frac{1}{\Lambda^6}\right)\end{aligned}$$

- Fit Wilson coefficients to measured data under certain assumptions

ATL-PHYS-PUB-2020-017

MEASURING TOPS IN A BOOSTED TOPOLOGY

- In this boosted topology ($p_T \gtrsim 300$ GeV) constituents of a fully-hadronically decaying top become collimated into a single large-radius jet



- Exploiting their three-pronged internal structure, top-taggers built from deep neural nets (DNN) identify those jets originating from top quarks

- Use of DNN-based discriminants for the identification of jets originating from bottom quarks is also crucial for suppressing background processes

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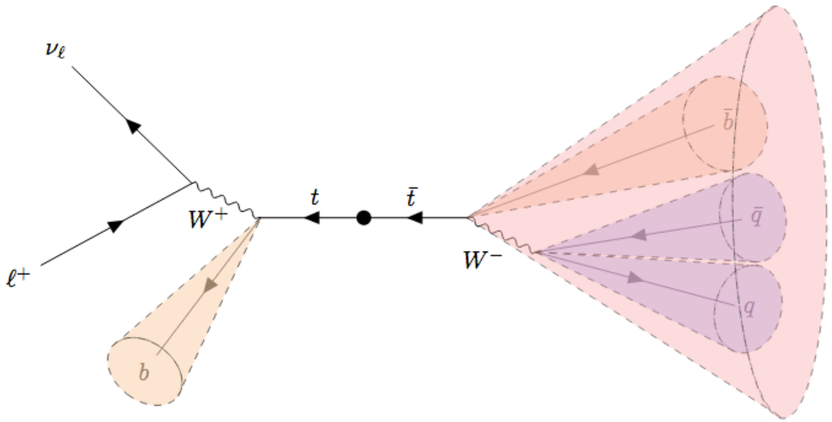
MEASUREMENTS OF $t\bar{t}$ DIFFERENTIAL CROSS-SECTIONS IN THE LEPTON+JETS CHANNEL

- Measure both single- and double-differential distribution of several kinematic observables
- Unfolding to particle-level phase-space

Leptonic Top:

- e/μ w/ $p_T > 27$ GeV
- $E_T^{miss} \geq 20$ GeV
- b-tagged $R = 0.4$ anti-k_t jet w/ $p_T > 26$ GeV
- $M_T^W \geq 60$ GeV
- $m_{\ell b} < 180$ GeV



Hadronic Top:

- $R = 1.0$ anti-k_t jet w/ $p_T > 355$ GeV (reclustered using $R = 0.4$ anti-k_t jets)
- 120 GeV $< m_{jet} <$ 220 GeV
- Contain b-tagged $R = 0.4$ anti-k_t jet w/ $p_T > 26$ GeV

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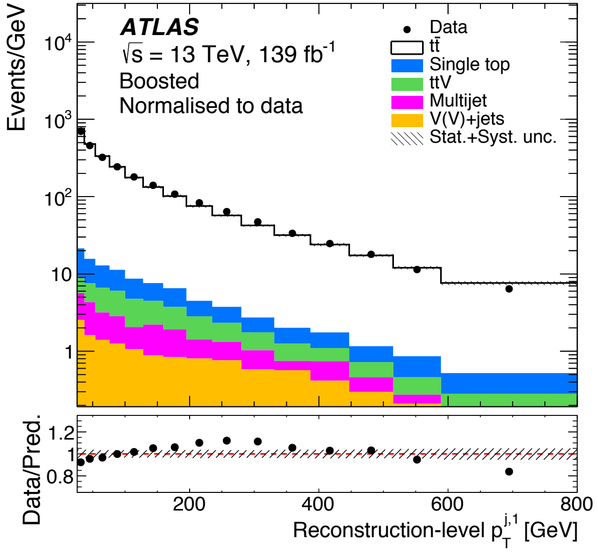
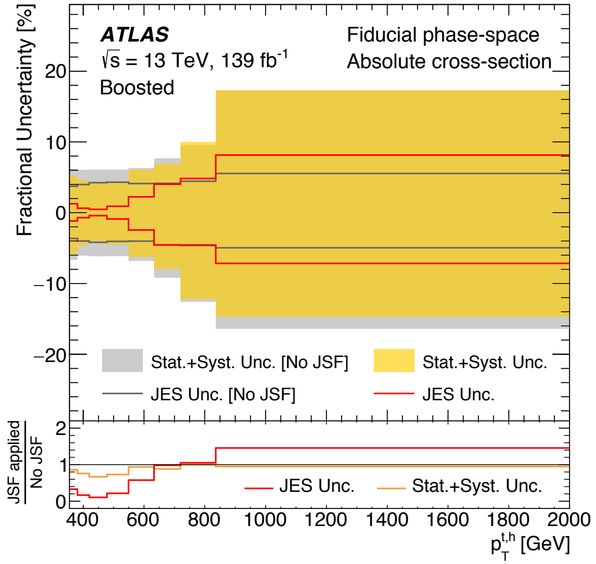
MEASUREMENTS OF $t\bar{t}$ DIFFERENTIAL CROSS-SECTIONS IN THE LEPTON+JETS CHANNEL

- Analysis selection results in high purity sample
  - >95% $t\bar{t}$, 2% single-top
- Results unfolded to fiducial (particle-level) phase space using Iterative Bayesian Unfolding





- **JSF correction:** Employ extra in-situ calibration to jet energy scale using the measured top mass
- Significantly reduces the leading uncertainty related to jet calibration over most bins

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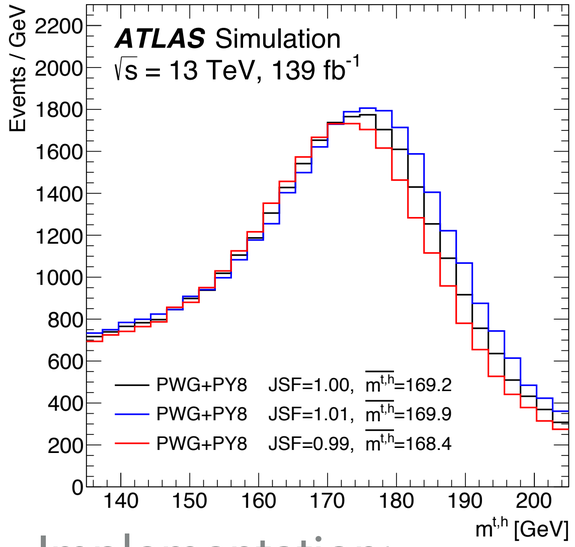
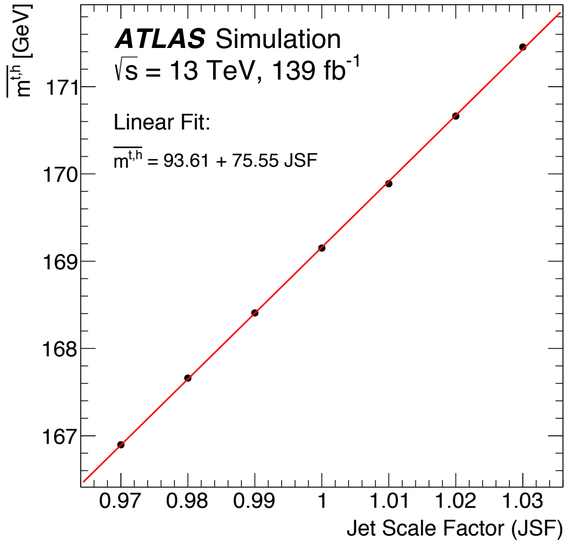
MEASUREMENTS OF $t\bar{t}$ DIFFERENTIAL CROSS-SECTIONS IN THE LEPTON+JETS CHANNEL





JSF Correction:

- Apply extra in-situ calibration to jets in data to ensure mean of the reconstructed top-quark mass agrees with simulation
- Method limited by uncertainty in the top-quark mass
  - Corresponding uncertainty small in this measurement
- Not all kinematic dependencies can be absorbed by the JSF

Implementation:

- In simulation, fit linear relationship between JSF and mean of hadronic top mass distribution, $\overline{m^{t,h}}$
- Use $\overline{m^{t,h}}$ in data to extract JSF from linear relationship (Measured JSF: 0.99965± 0.00087)
- Correct each jet in data by 1/JSF

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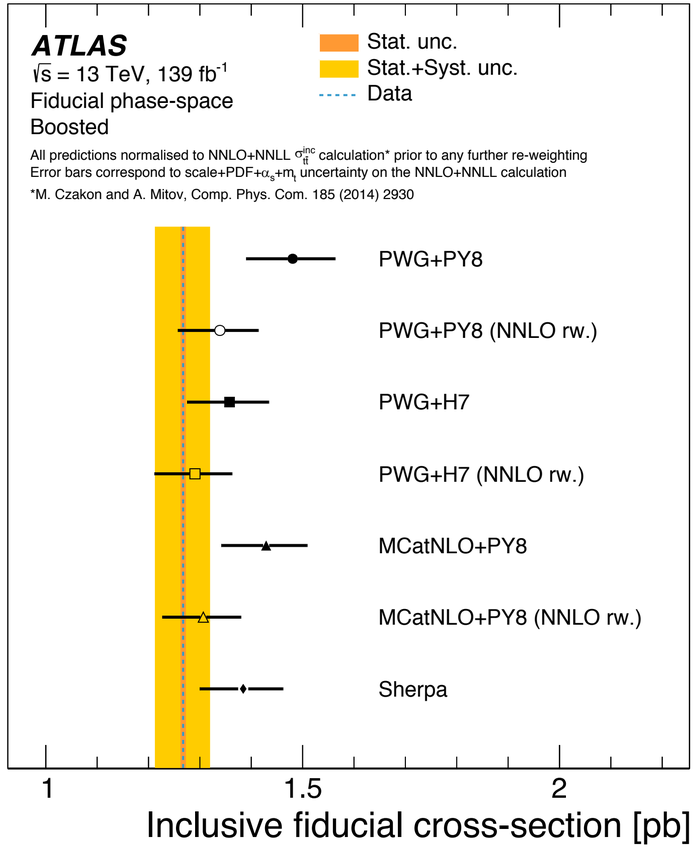
MEASUREMENTS OF $t\bar{t}$ DIFFERENTIAL CROSS-SECTIONS IN THE LEPTON+JETS CHANNEL



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

- Measured cross-section lower than theory predictions
- **Relative precision of measurement is 4.2%**
  - NNLO+NNLL prediction: 6.1% uncertainty
  - Inclusive $t\bar{t}$ measurement: 4.6% uncertainty
- Resulting precision significantly better than previous measurements:
  - Reduced jet energy scale uncertainties (JSF correction)
  - Reduced W+jets contamination ($m_{\ell b}$ cut, 2 b-tags)

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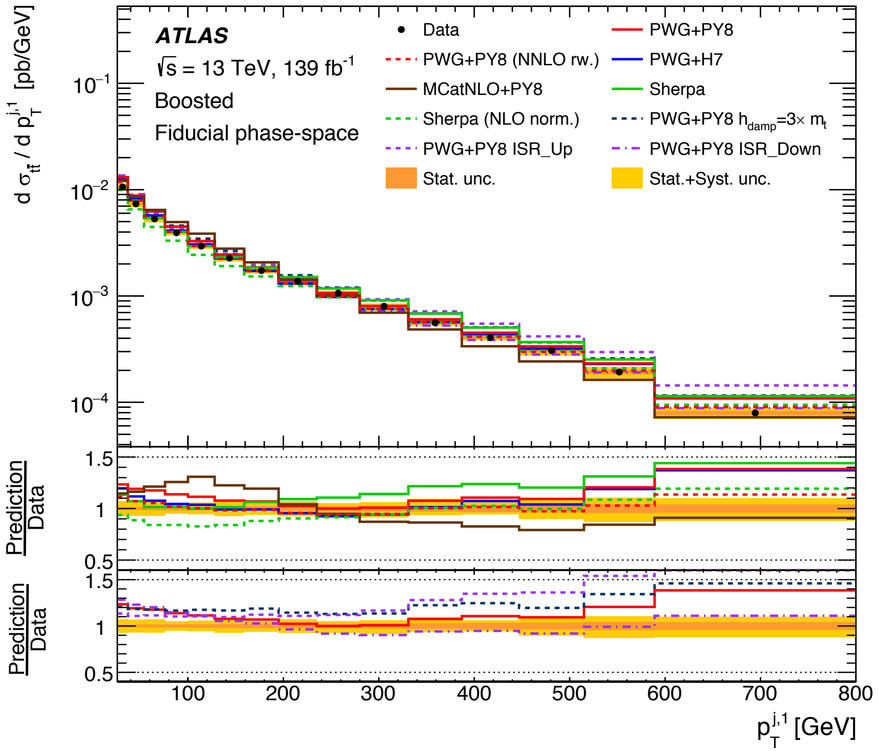

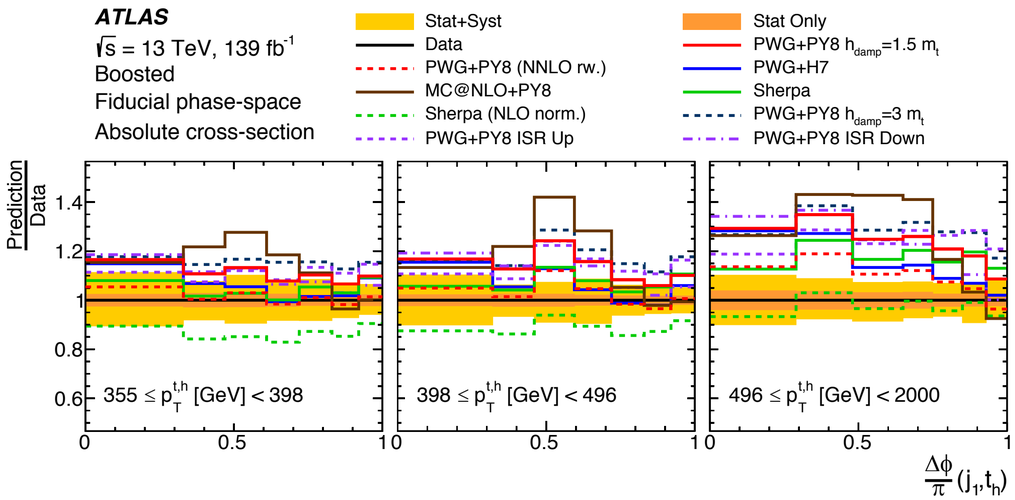

- No single model described all variables well
- Generally poor description of the emission of additional radiation (extra jets)

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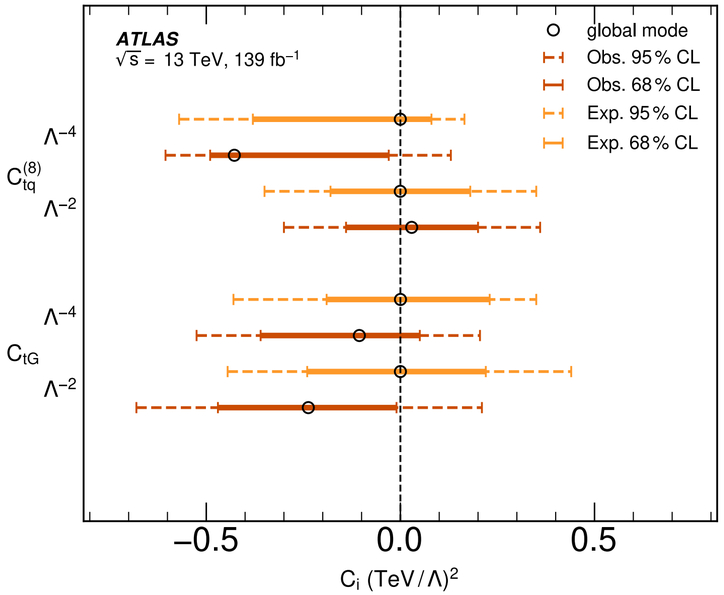
MEASUREMENTS OF $t\bar{t}$ DIFFERENTIAL CROSS-SECTIONS IN THE LEPTON+JETS CHANNEL

- Set 68% and 95% credibility intervals for fits at order Λ^{-2} and Λ^{-4}
- More stringent limits on $C_{tg}^{(8)}$ than set by recent global fit: JHEP 11 (2021) 089
- Measured Wilson coefficients consistent with standard model



Model	C_i $(\Lambda/\text{TeV})^2$	Marginalised 95% intervals Expected	Marginalised 95% intervals Observed	Individual 95% intervals Expected	Individual 95% intervals Observed	Global fit 95% limits
Λ^{-4}	C_{tG}	[−0.44, 0.35]	[−0.53, 0.21]	[−0.44, 0.28]	[−0.52, 0.15]	[0.006, 0.107]
	$C_{tq}^{(8)}$	[−0.57, 0.17]	[−0.60, 0.13]	[−0.57, 0.18]	[−0.64, 0.12]	[−0.48, 0.39]
Λ^{-2}	C_{tG}	[−0.44, 0.44]	[−0.68, 0.21]	[−0.41, 0.42]	[−0.63, 0.20]	[0.007, 0.111]
	$C_{tq}^{(8)}$	[−0.35, 0.35]	[−0.30, 0.36]	[−0.35, 0.36]	[−0.34, 0.27]	[−0.40, 0.61]

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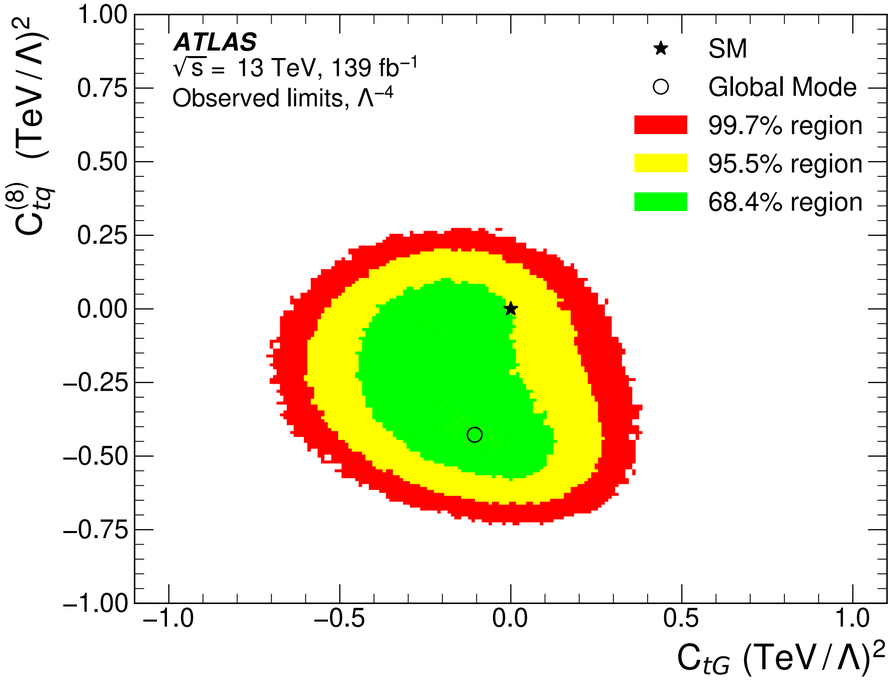

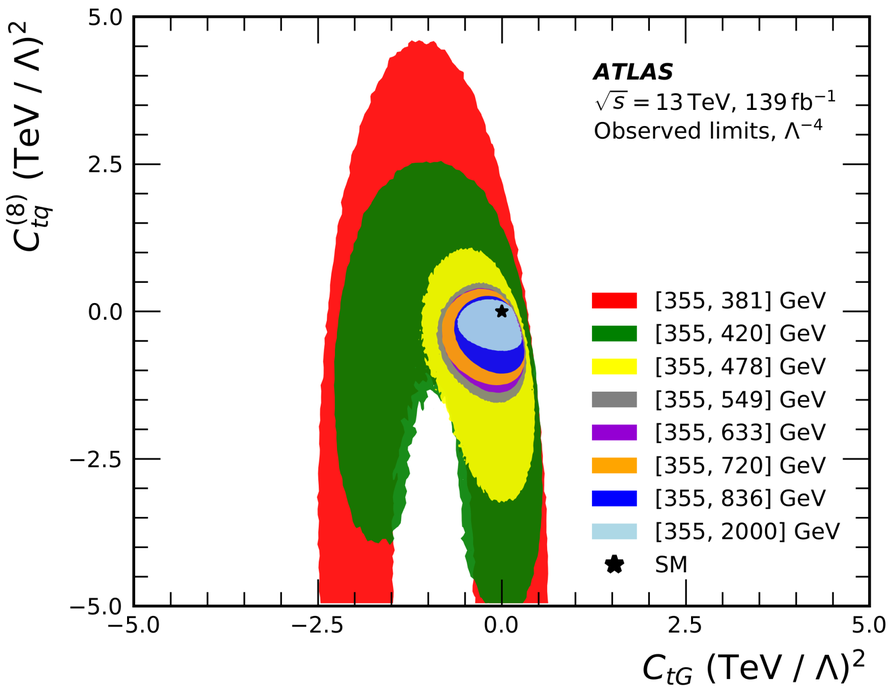

- Incorporating higher-p_T bins into fit provides significantly stronger constraints on C_{tG} and $C_{tg}^{(8)}$
- Asymmetric credibility intervals in Λ^{-4} fit due to quadratic terms in σ^{p_T} parameterization

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CERN-EP-2022-026

MEASUREMENTS OF $t\bar{t}$ DIFFERENTIAL CROSS-SECTIONS IN THE ALL-HADRONIC CHANNEL

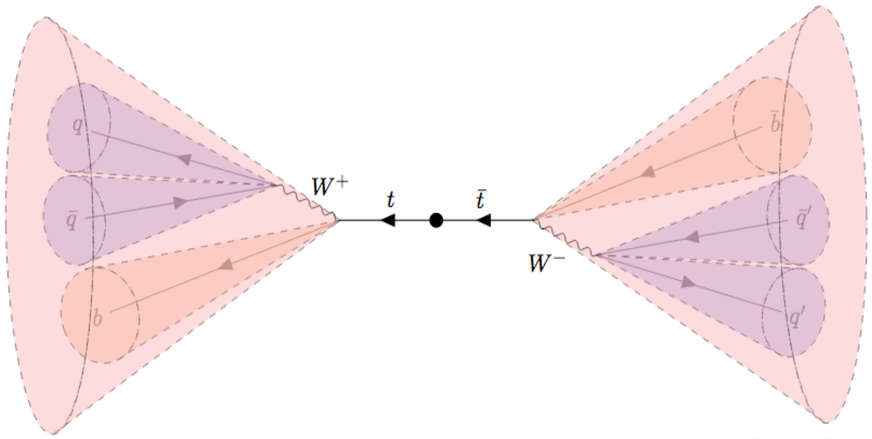
- Measure single-, double-, and triple-differential distribution of several kinematic observables
- Unfolding to both particle- and parton-level phase-spaces

Lepton Veto:

- 0 e/μ w/ p_T > 25 GeV

Hadronic Tops:

- 1 R = 1.0 anti-k_t jet w/ p_T > 500 GeV
- 2 R = 1.0 anti-k_t jet w/ p_T > 350 GeV
- 122.5 GeV < m_{jet} < 222.5 GeV
- Both jets top-tagged
- Both jets contain a b-tagged variable-radius anti-k_t track jet w/ p_T > 10 GeV



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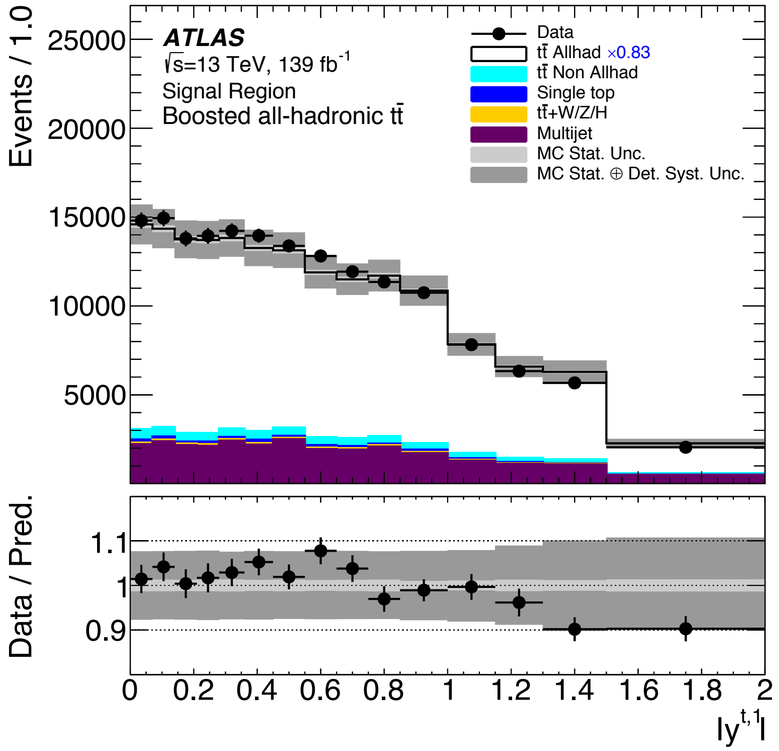
MEASUREMENTS OF $t\bar{t}$ DIFFERENTIAL CROSS-SECTIONS IN THE ALL-HADRONIC CHANNEL

- Boosted topology helps identify $t\bar{t}$ production in background-heavy all-hadronic channel
  - 81% $t\bar{t}$, 15% multijet
- QCD multijet estimated using a data-driven ABCD method
- Results unfolded to fiducial phase space (both at particle- and parton-level) using Iterative Bayesian Unfolding



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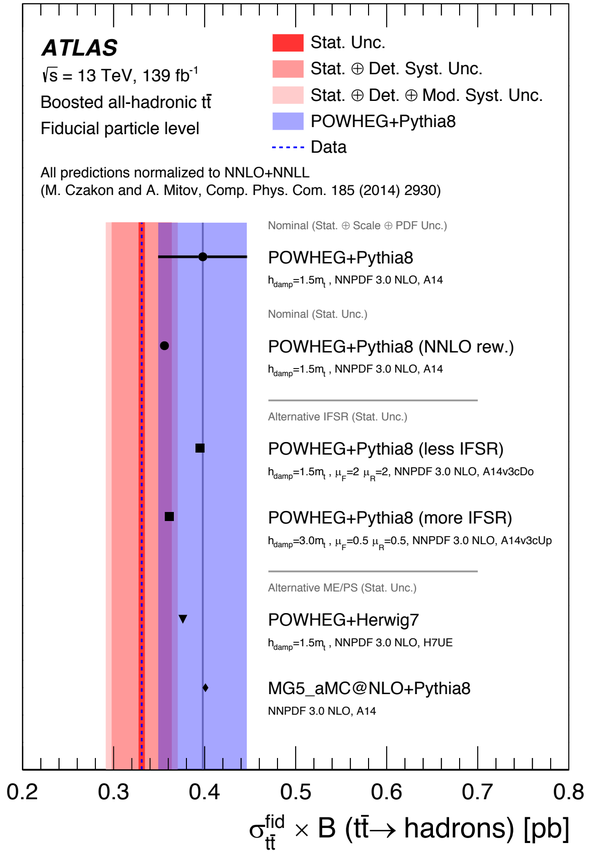

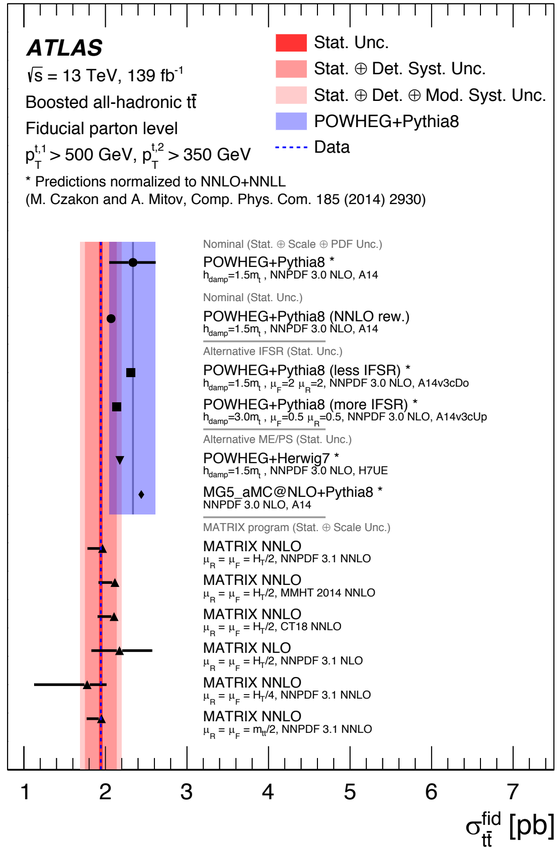

$$\sigma^{t\bar{t},fid}_{\text{particle}} \times B(t\bar{t} \to \text{hadrons}) = 333 \pm 3(\text{stat.}) \pm 39(\text{syst.})\ \text{fb}$$

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

- Better agreement at parton-level with NNLO prediction than with NLO+PS
- **Relative precision of measurement is 11.7%**
- Uncertainty reduced by a factor of 2 relative to previous *ATLAS* measurement: Phys. Rev. D 98, 012003 (2018)
- Major reductions in signal modelling and top/flavour tagging systematics

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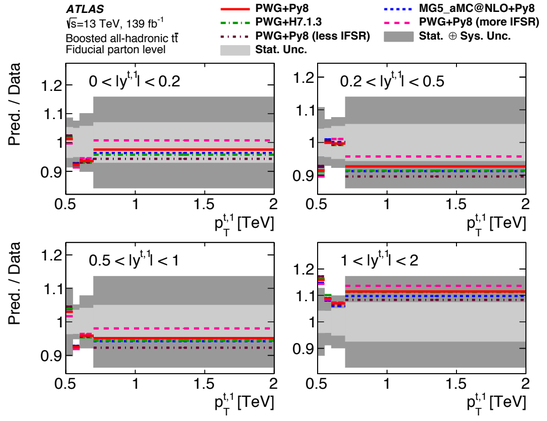
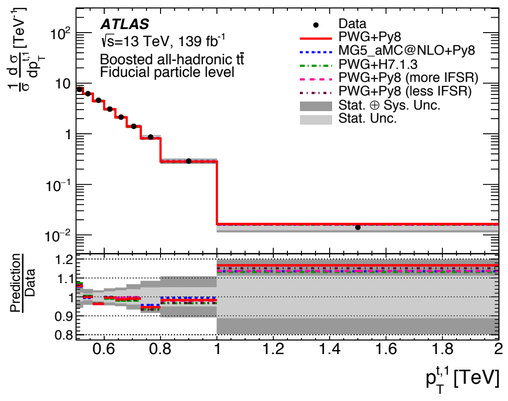
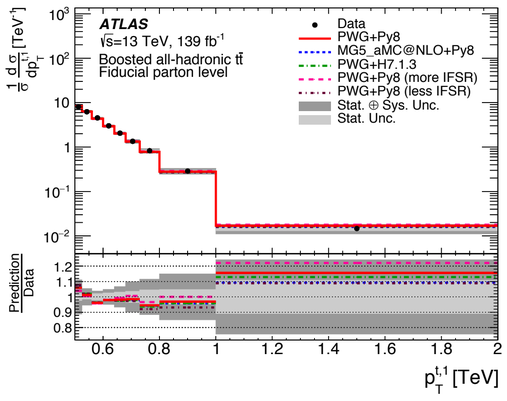
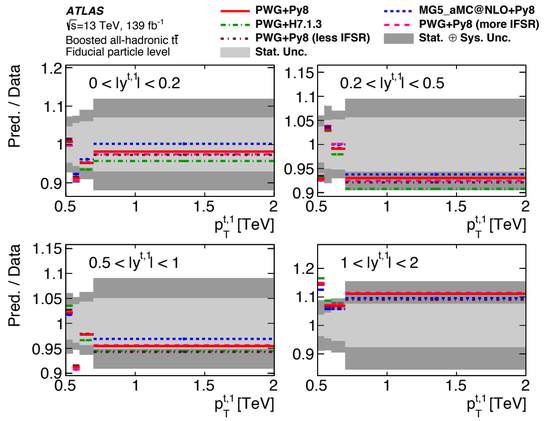
MEASUREMENTS OF $t\bar{t}$ DIFFERENTIAL CROSS-SECTIONS IN THE ALL-HADRONIC CHANNEL

- Good agreement for **normalized** differential cross-sections between NLO+PS predictions and data for most measured observables
- Gluon radiation generally not well described by NLO+PS models









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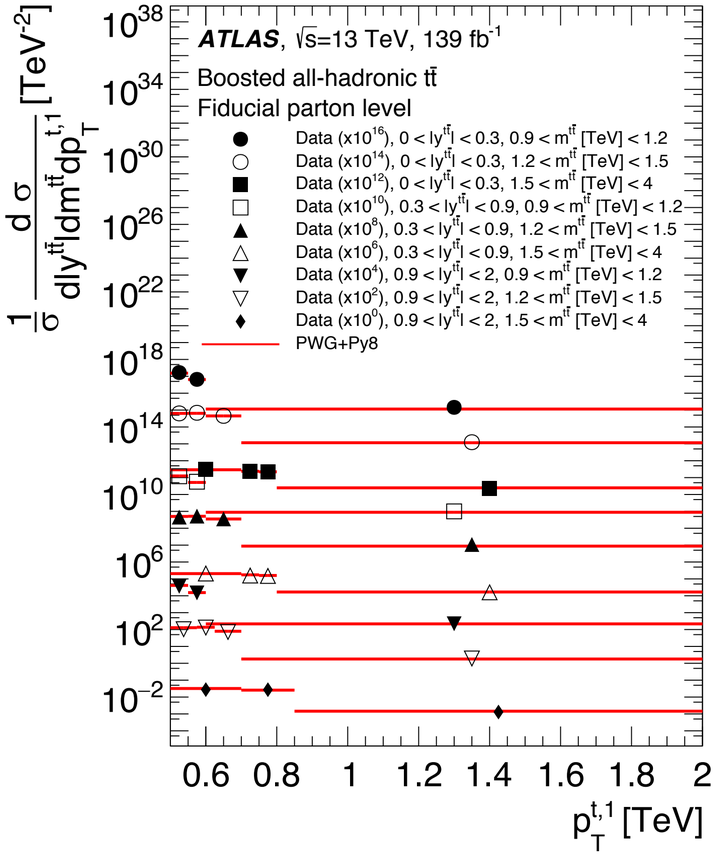

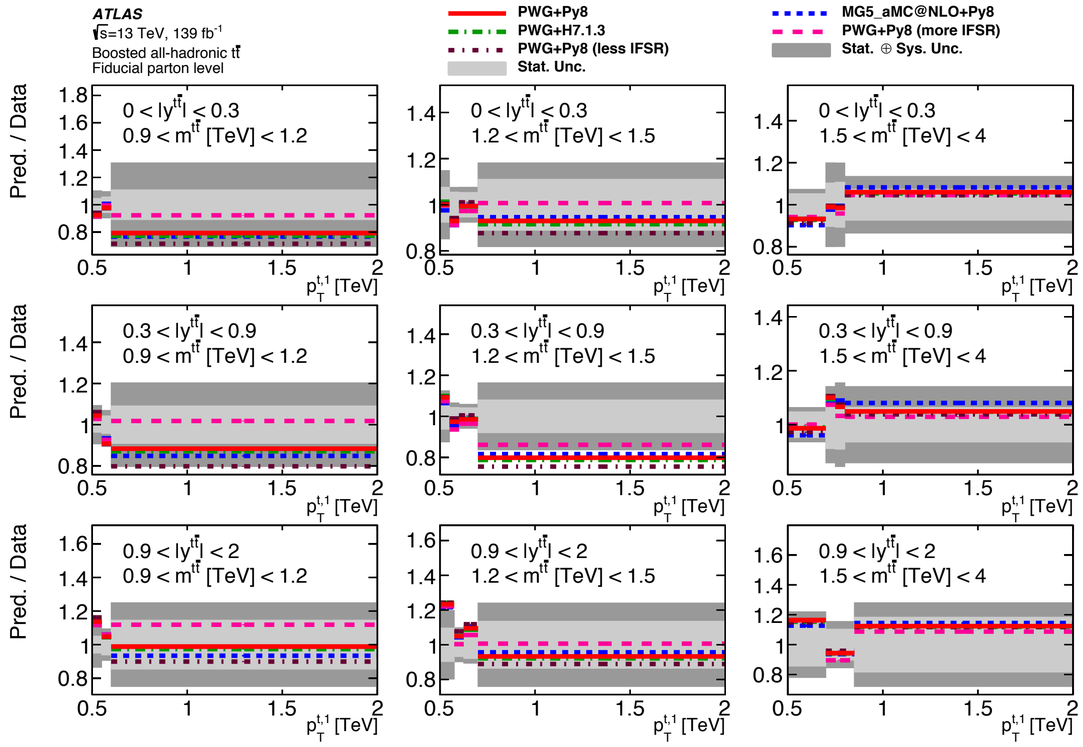

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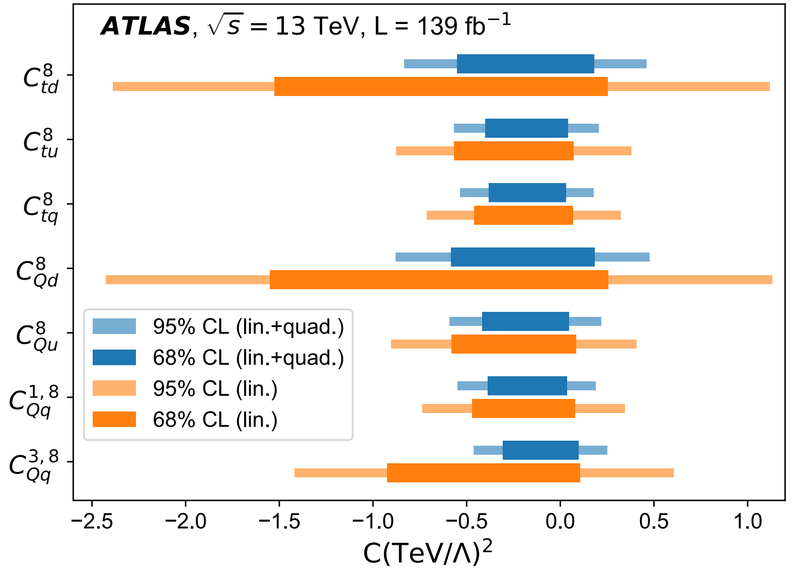
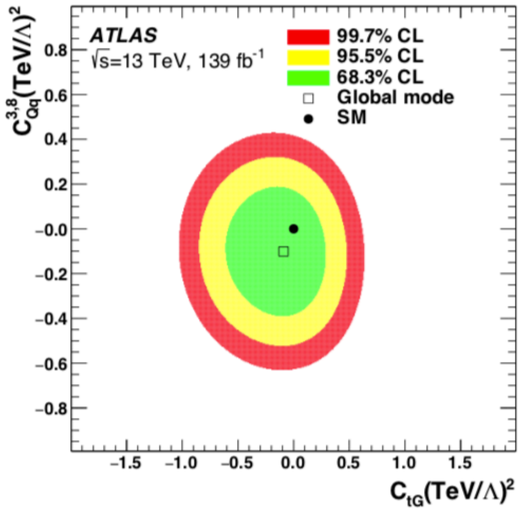
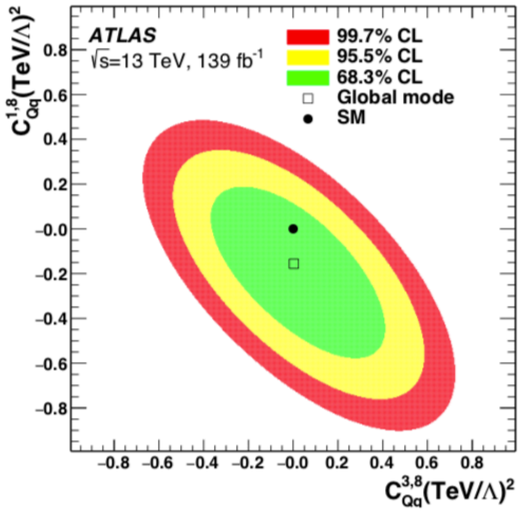
MEASUREMENTS OF $t\bar{t}$ DIFFERENTIAL CROSS-SECTIONS IN THE ALL-HADRONIC CHANNEL

- Set 68% and 95% credibility intervals for fits at order Λ^{-2} and Λ^{-4}
- Competitive or more stringent than existing limits from global EFT fits
- Measured Wilson coefficients consistent with standard model







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SUMMARY

- Presented results of two differential measurements involving $t\bar{t}$ production with large transverse momentum using the *ATLAS* detector
- Results unfolded to correct for limited detector resolution and compared with both NLO+PS and NNLO predictions
  - Measured inclusive $t\bar{t}$ production in boosted phase space indicates over-prediction in Monte Carlo models at NLO+PS with improved agreement when going to NNLO
  - NLO+PS predictions of single-, double- and triple-differential cross-sections generally in good agreement with data, but struggle with modelling of additional jets
- Unfolded measurements used to provide constraints on SMEFT extensions to the standard model
  - Limits set on Wilson coefficients are consistent with standard model predictions

BACKUP SLIDES

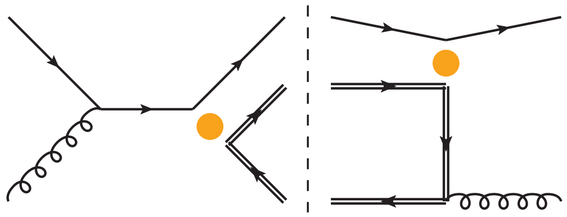
ATLAS EXPERIMENT

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

MEASUREMENT OF ENERGY ASYMMETRY IN $t\bar{t}j$

- Identify $t\bar{t}$ events produced in association with extra jet
- Measure top-anti-top energy difference, $\Delta E = E_t - E_{\bar{t}}$, as a function of jet angle, θ, relative to beamline

Gluon or 4-quark EFT Operator

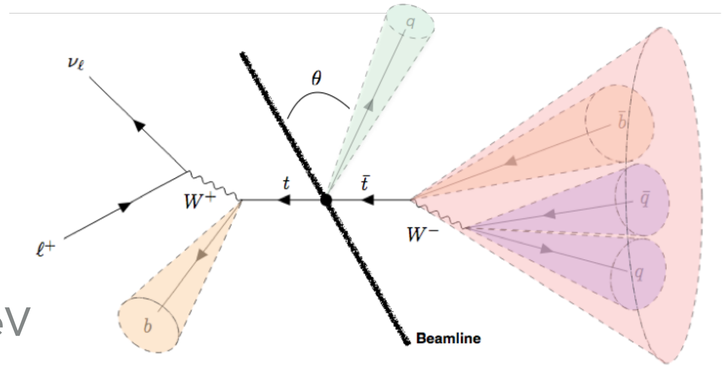


Associated Jet:

- R=0.4 anti-k_t jet w/ p_T > 100 GeV

Leptonic Top:

- e/μ w/ p_T > 27 GeV
- $E_T^{miss} \geq 20$ GeV
- $M_T^W \geq 60$ GeV
- R = 0.4 anti-k_t jet w/ p_T > 25 GeV



Hadronic Top:

- R = 1.0 anti-k_t jet w/ p_T > 350 GeV
- Top-tagged

Identified b-Jet:

- At least 1 R=0.4 jet b-tagged
- b-tagged jets must be associated with leptonic top or matched to hadronic top

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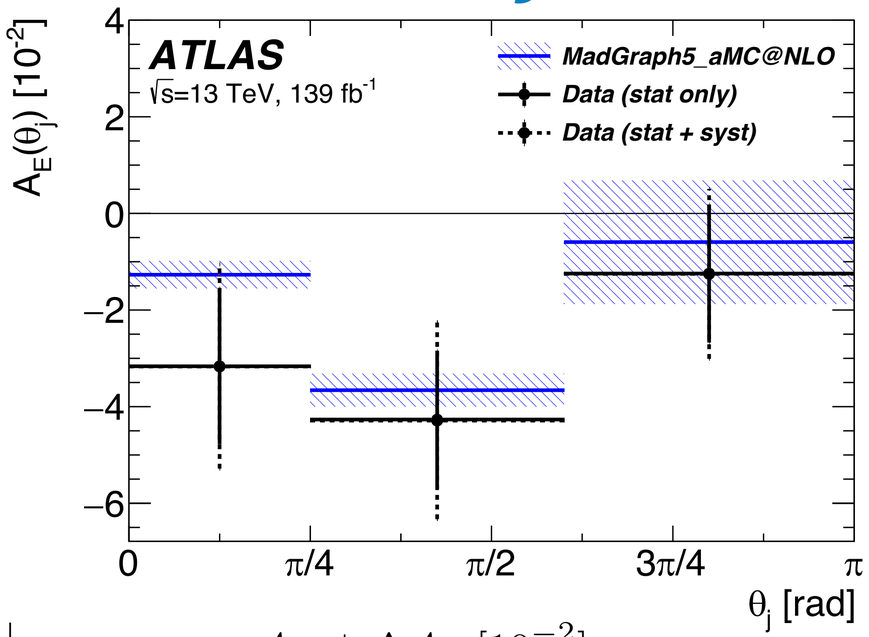
MEASUREMENT OF ENERGY ASYMMETRY IN $t\bar{t}j$

- Bins in ΔE and θ unfolded together using Full Bayesian method
- Asymmetry calculated from particle-level result

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

- Data statistics is largest uncertainty
- Results consistent with standard model



Scenario	$A_E \pm \Delta A_E\,[10^{-2}]$		
	$0 \le \theta_j \le \frac{\pi}{4}$	$\frac{\pi}{4} \le \theta_j \le \frac{3\pi}{5}$	$\frac{3\pi}{5} \le \theta_j \le \pi$
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

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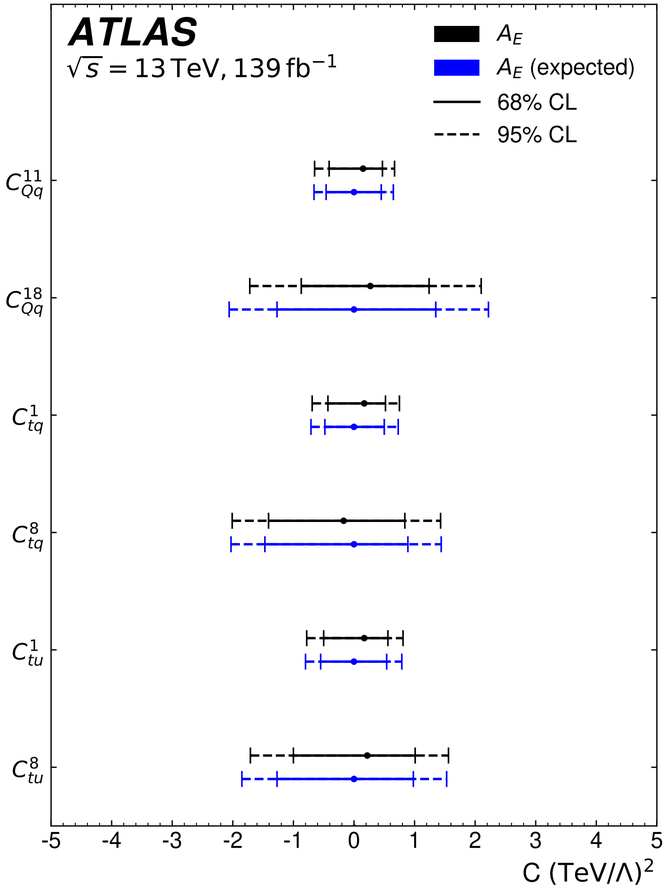
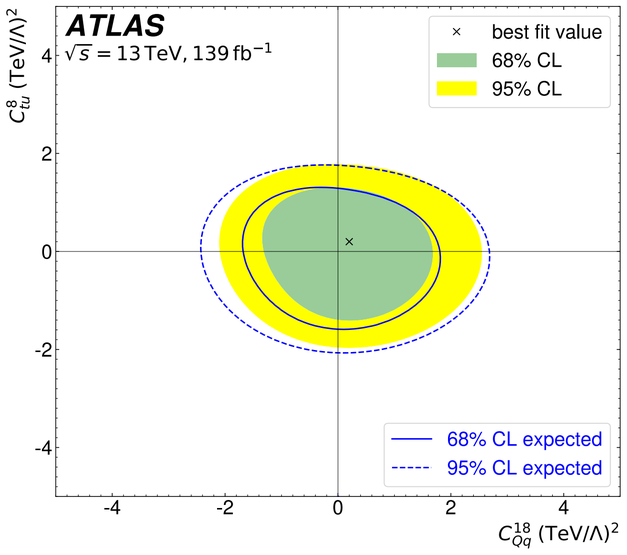
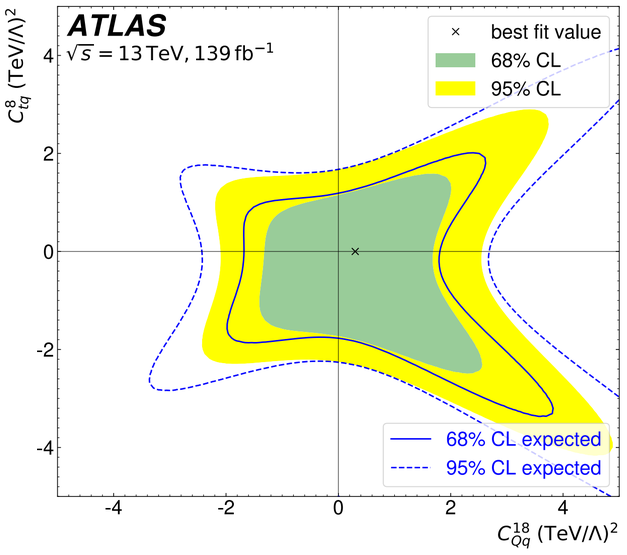
MEASUREMENT OF ENERGY ASYMMETRY IN $t\bar{t}j$



- Evaluate 68% and 95% confidence limits assuming all Wilson coefficients are zero except one/two being fit
- Constrains different directions in parameter space than does measurements of rapidity asymmetry: ATL-PHYS-PUB-2021-043





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