Testing the Standard Model in boosted top quark production with the ATLAS experiment at the LHC

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ATLAS EXPERIMENT

Boosted top quarks and the SM

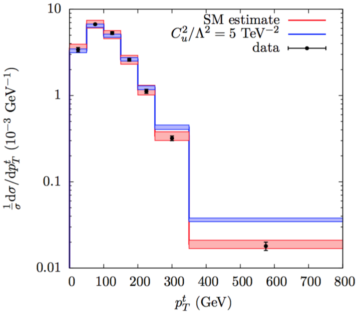
Testing the SM

- Peculiar features of the top quark
  - Large Yukawa coupling $\rightarrow$ connection to EWSB
  - Tests of QCD at multiple scales (p_T(top), m(top), $m(b)$)
- Large number of precise observables with current amount of data

Looking beyond the SM

- Test for potential UV physics
- Large sensitivity to several EFT operators

$$\mathcal{L}_\mathrm{eff} = \mathcal{L}_\mathrm{SM} + \mathcal{L}_1 + \ldots, \qquad \underbrace{\mathcal{L}_i = \sum_j \frac{1}{\Lambda^i} C_j O_j}_{\text{EFT terms of mass-dimension } 4+i}$$



A. Buckley et al, arXiv:1512.03360

Measurements in this Presentation

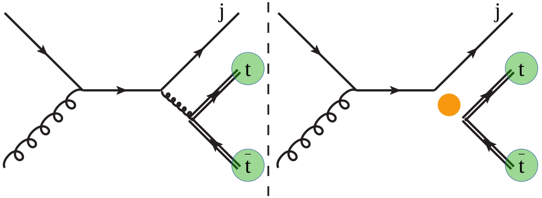
$t\bar{t}$ charge asymmetry

- Energy asymmetry in $t\bar{t}j$ (Eur.Phys.J.C82(2022)374)

$t\bar{t}$ differential cross-section

- Boosted all-hadronic final states [2205.02817]
- Boosted lepton+jets final states (JHEP06(2022)063)

Energy asymmetry in $t\bar{t}j$ production at 13 TeV (full Run 2)



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

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

$\rightarrow$ Reduce gg contributions

- Single lepton
- 1 R=1.0 jet (based on Pflow jets): top candidate (DNN tagging)
- Boost: $p_T^t > 350$ GeV

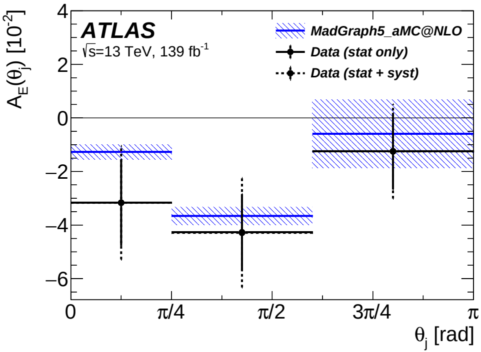
Motivation:

- Increase of asymmetry in boosted regime
- Expand previous $t\bar{t}$ asymmetry in rapidity observable to different phase space
- Sensitivity to BSM effects

- Asymmetry measured as function of θ_j
- Unfolding to particle level using fully Bayesian unfolding
- Interpretation in EFT framework

$t\bar{t}j$ energy asymmetry (Eur.Phys.J.C82(2022)374)

Measurement Results

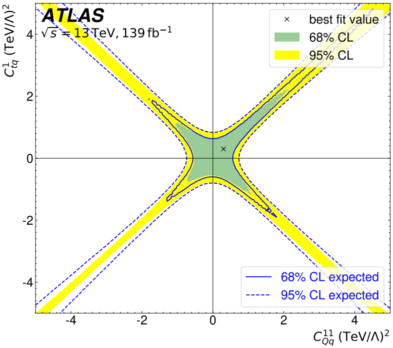


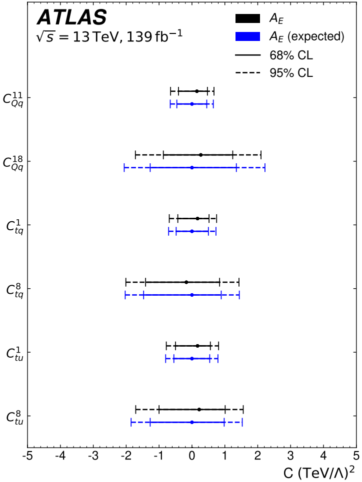
Scenario	ΔA_E [10^{-2}] $0 \leq \theta_j < \frac{\pi}{4}$	$\frac{\pi}{4} < \theta_j \leq \frac{3\pi}{5}$	$\frac{3\pi}{5} \leq \theta_j \leq \pi$
Data statistical uncertainty	1.60	1.40	1.40
$t\bar{t}$ modelling	0.08	0.87	0.34
$t\bar{t}$ response MC statistics	0.51	0.42	0.42
W+jets modelling and PDF	0.29	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

- Measured asymmetry in agreement with SM
- Data stat. unc. dominated
- Leading uncertainties:
  - $t\bar{t}$ FSR and tW modelling (central θ_j bin)
  - JER and $t\bar{t}$ modelling

EFT interpretation

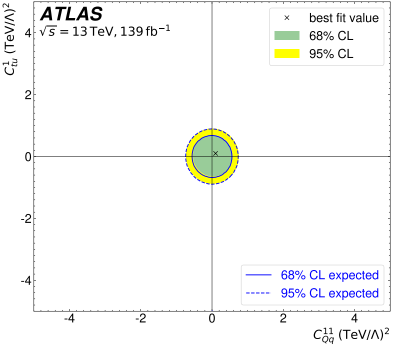
- Limits on several 4-quark Wilson coefficients
- Excellent disentanglement of effects in certain regions

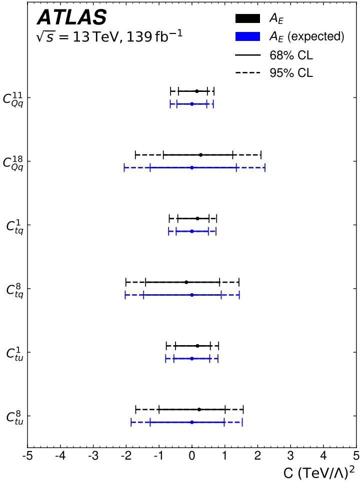




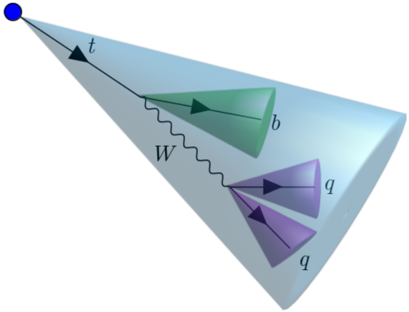
EFT interpretation

- Limits on several 4-quark Wilson coefficients
- Excellent disentanglement of effects in certain regions





$t\bar{t}$ Production in the Boosted All-Hadronic Channel at 13 TeV (full Run 2)



- $p_{\mathrm{T}}^{t_1} > 350$ GeV, $p_{\mathrm{T}}^{t_2} > 500$ GeV
- 2 large-R jets (topo-cluster based)
- DNN top-tagger

Motivation:

Precision Measurement

- Measure highly energetic top quarks
- Modelling of top quark system

BSM via EFT

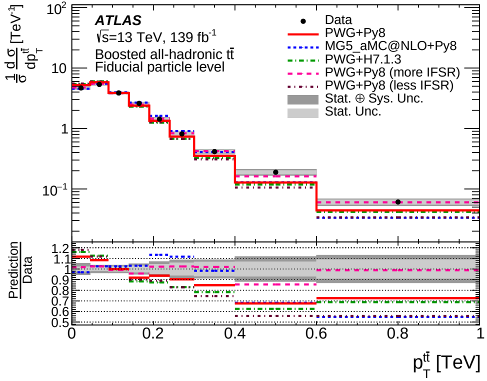
- Potential UV physics effects

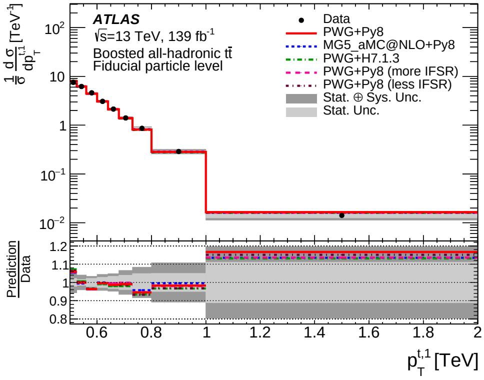
- Kin. variables for 1D, 2D and 3D diff. measurements
- Unfold to particle- and parton-level
  - Before and after t decay
- Comparison to NNLO rw. and MATRIX NNLO pred.

Boosted all-hadronic $t\bar{t}$ [2205.02817]

Measurement Results

Normalized differential rates





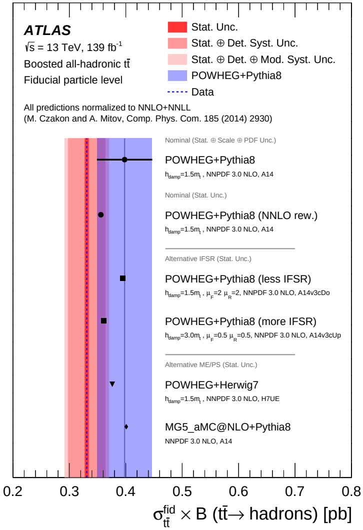
- Better agreement with increased IFSR
- Observed rates below predictions

Measurement Results

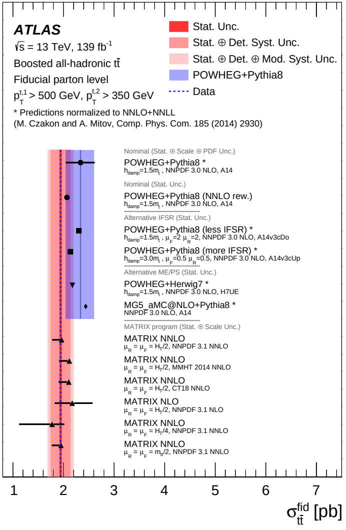
Fiducial cross-section

- Prediction overshooting data
- Better agreement with NNLO rew.
- Parton-level NNLO predictions with MATRIX show excellent agreement

Particle-level



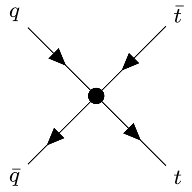
Parton-level

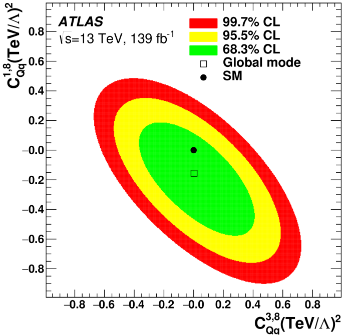


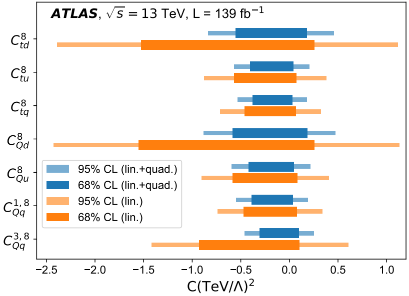
Boosted all-hadronic $t\bar{t}$ [2205.02817]

EFT Interpretation

- Leading top-quark p_{T} at parton-level used (MATRIX NNLO prediction)
- Limits on several 4-quark Wilson coefficients
- Excellent disentanglement of effects







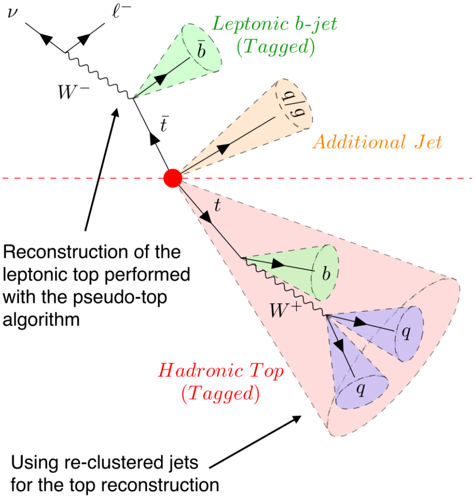
$t\bar{t}$ Production in the Boosted Lepton+Jets Channel at 13 TeV (full Run 2)

Motivation:

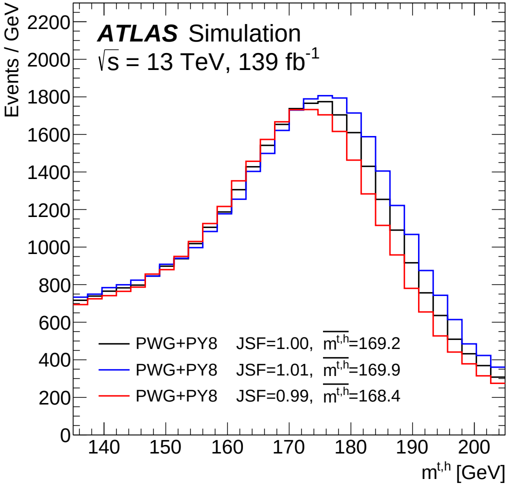
Precision Measurement | BSM via EFT

- Single lepton
- 1 RC-jet, $p_{\mathrm{T}} > 355$ GeV

- Reduce JES uncertainties: use correlation between the JES and the re-clustered jet mass to get an in-situ correction
- Unfold to particle-level using IBU



JSF Methodology

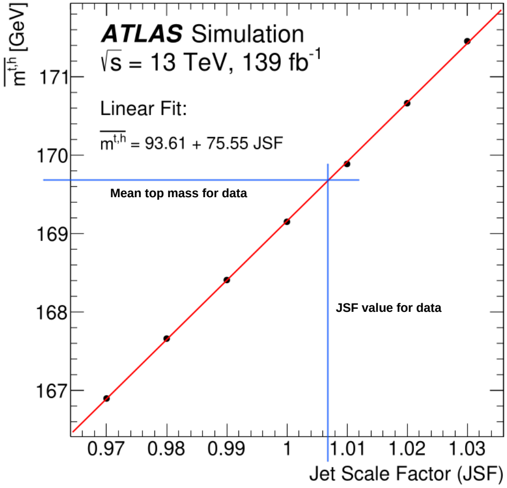


- Mass of reclustered top-tagged jet depends on the energy-scale of its small-R sub-jets
- Assume data and MC differ in small-R jet energy-scale by multiplicative factor: **Jet Scale Factor (JSF)**

$$E^{\text{corrected}}_{\text{jet,data}} = E^{\text{nominal}}_{\text{jet,data}} \times \frac{1}{\text{JSF}_{\text{data}}}$$

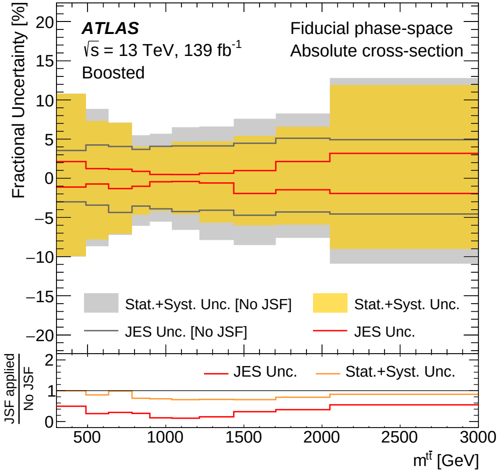
$$E^{\text{corrected}}_{\text{jet,MC}} = E^{\text{nominal}}_{\text{jet,MC}} \times \frac{1}{\text{JSF}_{\text{MC}}}$$

JSF Methodology



- Value derived from linear parametrisation between $\overline{m_{\text{top-jet}}}$ and JSF
- Scale energy of **all small-R jets** in signal+background MC and systematic variations, and data
- JSF can absorb an overall systematic difference between data and MC in jet energies

Results using JSF method

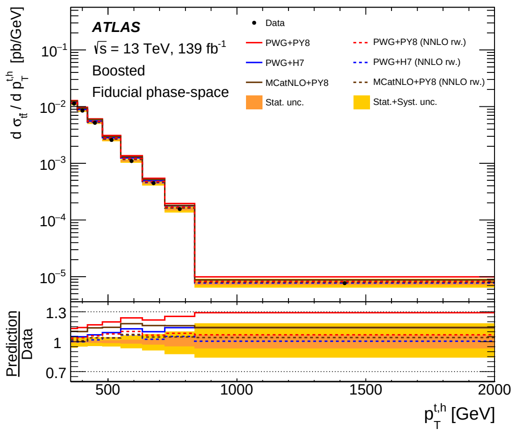


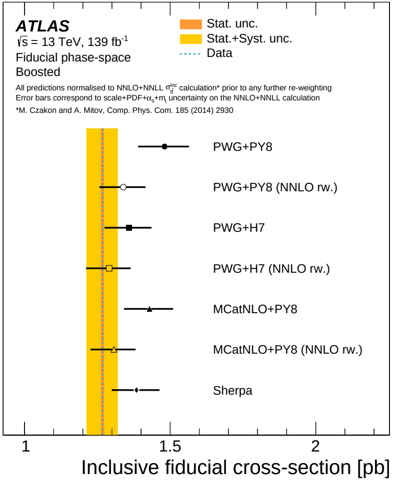
- JES uncertainties are not gone, but reduced (from $4.0\,\%$ to $0.4\,\%$ for σ_{tot})
- Significant smaller JES uncertainties across e.g. $m^{t\bar{t}}$
- $\sigma^{\text{fid}}_{\text{tot}} = 1.267 \pm 0.005\,(\text{stat}) \pm 0.053\,(\text{syst})\,\text{pb}$
- Relative precision at $4.2\,\%$

→ Precision competitive with recent ATLAS resolved measurement Phys.Lett.B810(2020)135797

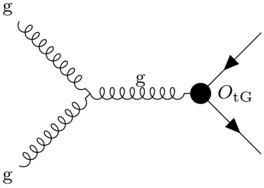
Measurement Results

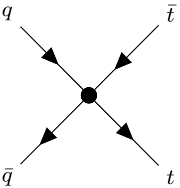
- Prediction overshooting data by approx. $10\,\%$
- Improved agreement when re-weighting NLO MC to NNLO



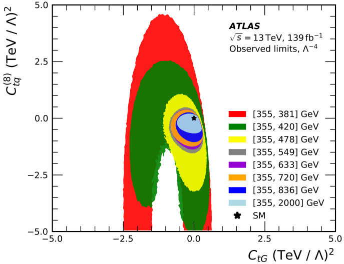


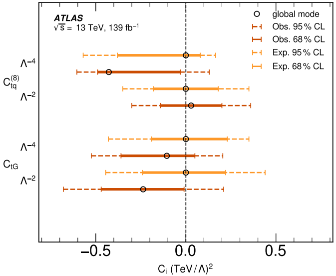
EFT Interpretation





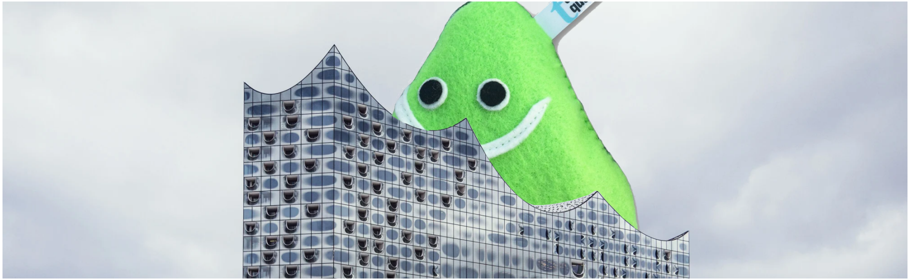
- Limits on two Wilson coefficients C_{tG} and $C_{tq}^{(8)}$
- Excellent disentanglement of effects
- High-p_{T} tails of boosted regime essential
- Limits on 4-fermion operator competitive with global fits





Conclusions

- Boosted top quarks essential in multiple ATLAS measurements
- One recent top charge asymmetry measurement
- Two precision differential cross-section measurements of $t\bar{t}$
- Significant improvements also in the methodology (e.g. JSF)
- Hints that full NNLO prediction significantly improves modelling
- Great sensitivity to BSM physics through EFT
- Very stringent limits on thus far little constrained 4-quark operators



Backup

- Boosted $t\bar{t}$ lepton+jets
- Boosted $t\bar{t}$ all hadronic
- $t\bar{t}\jmath$ charge asymmetry

EFT recipe - describing new physics with effective field theories

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_1 + \mathcal{L}_2 + \ldots, \qquad \underbrace{\mathcal{L}_i = \sum_j \frac{1}{\Lambda^i} C_j O_j}_{\text{EFT terms of mass-dimension } 4+i}$$

- EFT terms: **gauge-invariant**, higher dimensional terms built from **SM fields**.
- BSM energy scale Λ (1 TeV hereafter)
- measure for strength of operator: Wilson coefficients C_j
- only even-dimensional operators O_j can conserve lepton and baryon number

Dimension-6 operators in physics observables

$$\sigma = \sigma_{\text{SM}} + \frac{1}{\Lambda^2} \sum_i C_i \sigma_i^{\text{SM-EFT-interference}} + \frac{1}{\Lambda^4} \sum_{i,j} C_i C_j \sigma_{i,j}^{\text{EFT}}$$

$\mathcal{O}(\frac{1}{\Lambda^2})$ SM-dim6-interference terms
$\mathcal{O}(\frac{1}{\Lambda^4})$ pure dim6 contributions

Boosted $t\bar{t}$ lepton+jets

EFT analysis overview using EFT*fitter*.jl[1]

Parameters:
C_{tG} and $C_{tq}^{(8)}$

Observations:
- differential rates
- uncertainties
- correlations

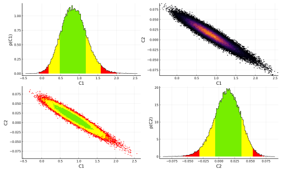
Model:
per bin model function
$\sigma_i(C_{tG}, C_{tq}^{(8)})$

EFT*fitter*:
Bayesian Analysis

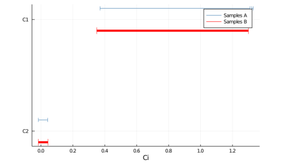
Observables:
Differential rates
(EFT + SM MC simulations)

Parameters:
Flat priors $\in [-5, 5]$

$$\Pi(C_i) \propto \begin{cases} 0, & \text{if } |C_i| > 5 \\ 1, & \end{cases}$$



Example taken from [2]



Example taken from [2]

[1]https://tudo-physik-e4.github.io/EFTfitter.jl/stable/, arXiv:1605.05585

Cut	Detector-level		Particle-level
leptons	**Exactly 1 lepton in event**		**Exactly 1 lepton in event**
	Electrons	Muons	
	$p_T > 27$GeV	$p_T > 27$GeV	$p_T > 27$GeV
	$\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.47$	$\|\eta\| < 2.5$	$\|\eta\| < 2.5$
b-tagging	DL1r tagger at 77% working point		Ghost-matched b-hadron
Small-R jets (R=0.4) (EMPFlow)	$p_T > 26$GeV $\|\eta\| < 2.5$		Same as detector-level
b-tagged jets (R=1.0) (EMPFlow)	**≥ 1 b-tagged jet is constituent of top-jet** **≥ 1 b-tagged jet near lepton:** ΔR(lepton,lep-b-jet) < 2.0 ΔR(top-jet,lep-b-jet) > 1.0		Same as detector-level
Hadronic top-jet (R=1.0) (EMPFlow subjets)	**≥ 1 top-tag RC-jet candidate** $p_T > 355$GeV $\|\eta\| < 2.0$ $120\text{GeV} < M < 220\text{GeV}$ ≥ 1 b-tagged sub-jet		Same as detector-level
MET & m_T^W	MET > 20GeV MET $+ m_T^W > 60$GeV		Same as detector-level
Electron Isolation	ΔR(electron,top-jet) > 1.0		None
mlb	$m_{\ell,b} < 180$GeV		Same as detector-level

Uncertainties

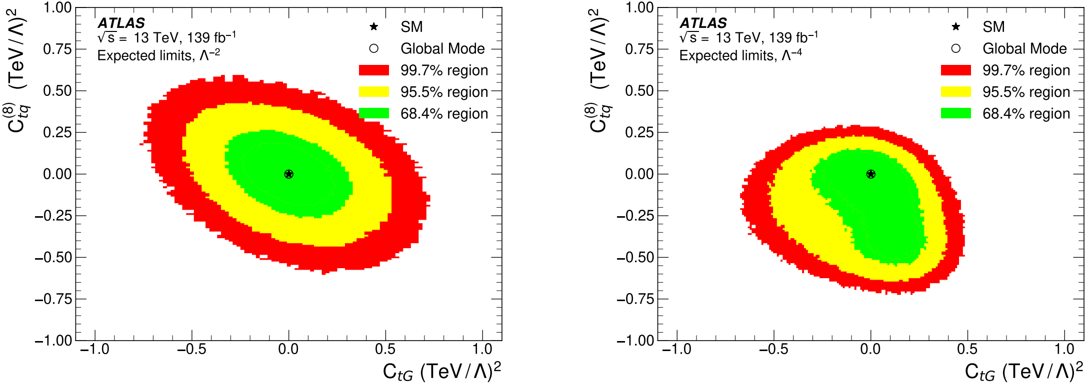
Source	Uncertainty [%]	Uncertainty [%] (no JSF)
Statistical (data)	± 0.4	± 0.4
JSF statistical (data)	± 0.4	—
Statistical (MC)	± 0.2	± 0.1
Hard scatter	± 0.5	± 0.8
Hadronisation	± 2.0	± 1.8
Radiation (IFSR + h_{damp})	$+1.0$ -1.6	$+1.4$ -2.3
PDF	± 0.1	± 0.1
Top-quark mass	$+0.8$ -1.1	± 0.1
Jets	± 0.7	± 4.2
b-tagging	± 2.4	± 2.4
Leptons	± 0.8	± 0.8
$E_{\mathrm{T}}^{\mathrm{miss}}$	± 0.1	± 0.1
Pileup	± 0.4	± 0.0
Luminosity	± 1.8	± 1.8
Backgrounds	± 0.7	± 0.6
Total systematics	$+4.1$ -4.3	$+5.8$ -6.0
Total	$+4.1$ -4.3	$+5.8$ -6.0

EFT model function

$$\sigma^j\left(C_{tG}, C_{tq}^{(8)}\right) = p_0^j + p_1^j \cdot C_{tG} + p_2^j \cdot C_{tq}^{(8)} + p_3^j \cdot (C_{tG})^2 + p_4^j \cdot \left(C_{tq}^{(8)}\right)^2 + p_5^j \cdot C_{tG} \cdot C_{tq}^{(8)}$$

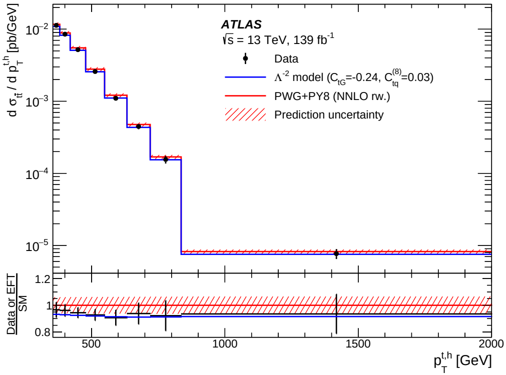
- Quadratic model introduces degeneracy
- Limits will be skewed towards negative values or have a second island in Λ^{-4} model

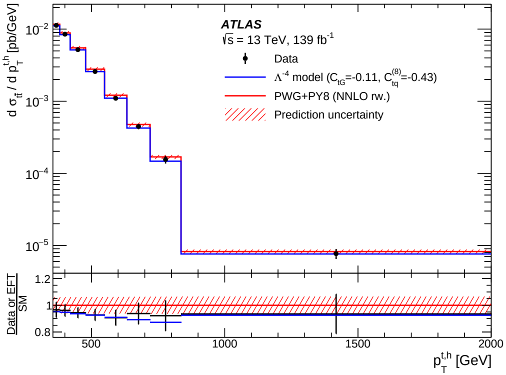
Expected EFT limits



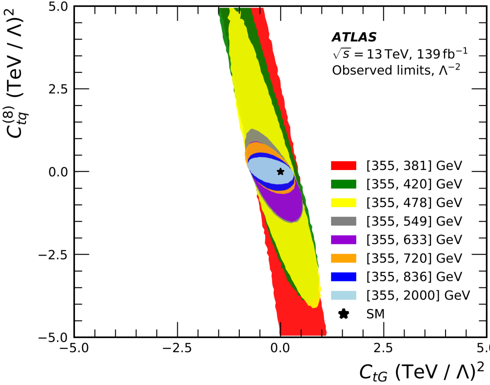
- The expected asymmetry due to the degeneracy of the quadratic model is seen in the posterior

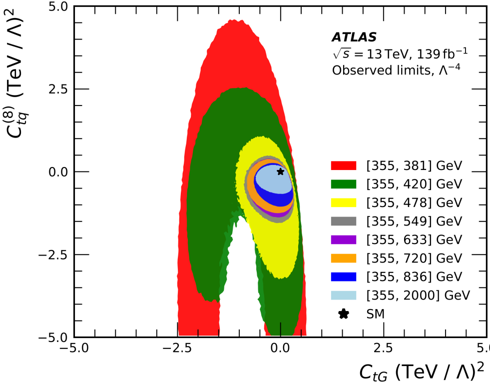
EFT in Data


ATLAS
√s = 13 TeV, 139 fb-1
Data
Λ-2 model (CtG=-0.24, Ctq(8)=0.03)
PWG+PY8 (NNLO rw.)
Prediction uncertainty
d σtt̄ / d pTt,h [pb/GeV]
Data or EFT / SM
pTt,h [GeV]


ATLAS
√s = 13 TeV, 139 fb-1
Data
Λ-4 model (CtG=-0.11, Ctq(8)=-0.43)
PWG+PY8 (NNLO rw.)
Prediction uncertainty
d σtt̄ / d pTt,h [pb/GeV]
Data or EFT / SM
pTt,h [GeV]

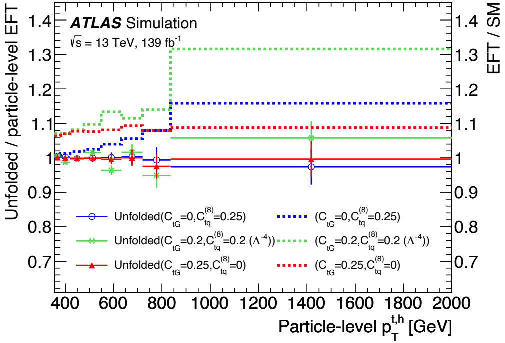
EFT in Data


ATLAS
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
Observed limits, Λ^{-2}
[355, 381] GeV
[355, 420] GeV
[355, 478] GeV
[355, 549] GeV
[355, 633] GeV
[355, 720] GeV
[355, 836] GeV
[355, 2000] GeV
SM
$C_{tq}^{(8)}$ (TeV / Λ)^2
C_{tG} (TeV / Λ)^2
5.0
2.5
0.0
−2.5
−5.0


ATLAS
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
Observed limits, Λ^{-4}
[355, 381] GeV
[355, 420] GeV
[355, 478] GeV
[355, 549] GeV
[355, 633] GeV
[355, 720] GeV
[355, 836] GeV
[355, 2000] GeV
SM
$C_{tq}^{(8)}$ (TeV / Λ)^2
C_{tG} (TeV / Λ)^2
5.0
2.5
0.0
−2.5
−5.0

Unfolding

- Unfolding stress test performed for linear and quadratic model
- In linear case: create EFT samples at Wilson coefficient = 0.25 by scaling MC distributions
- In quadratic case: requested additional stat. independent sample at $(C_{tG}, C_{tq}^{(8)}) = (0.2, 0.2)$

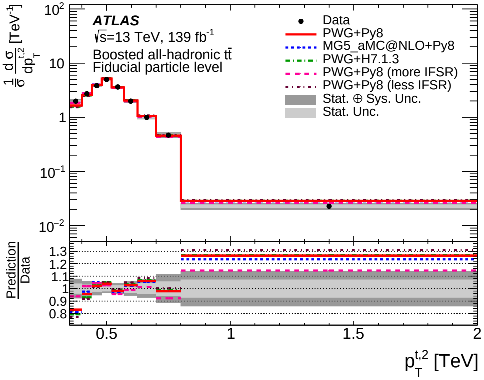


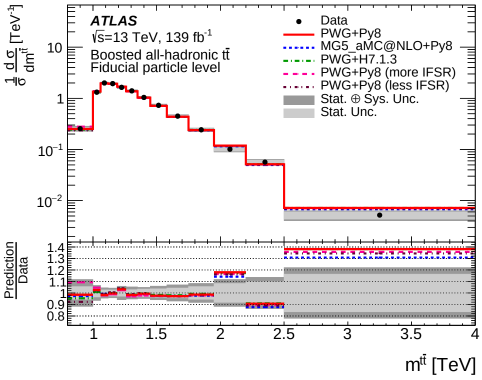
JSF method

$$\mathsf{JSF}_{\mathsf{data}} = 0.99965 \pm 0.00087$$

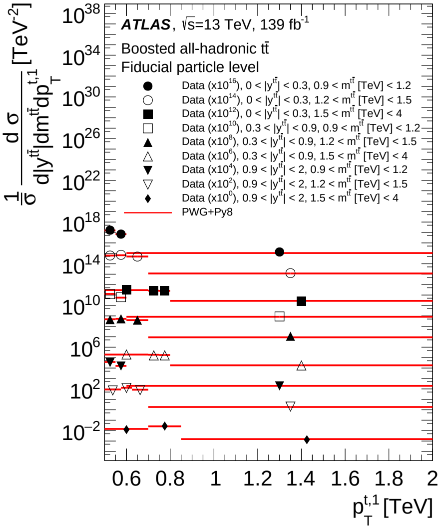
Boosted $t\bar{t}$ all-hadronic

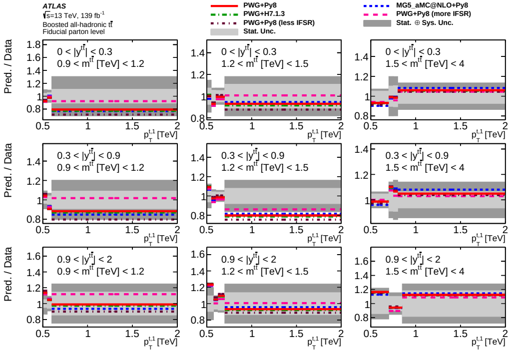
Differential distributions



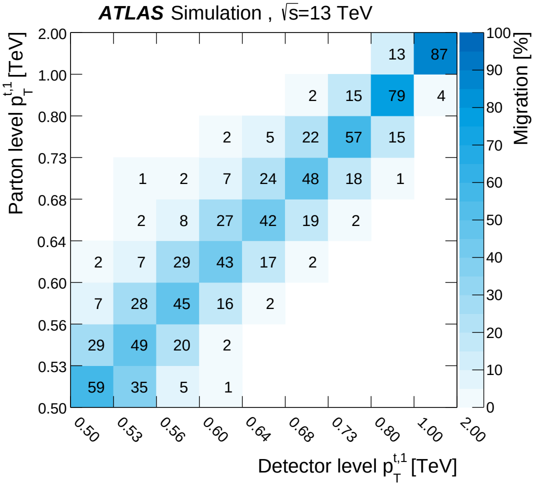


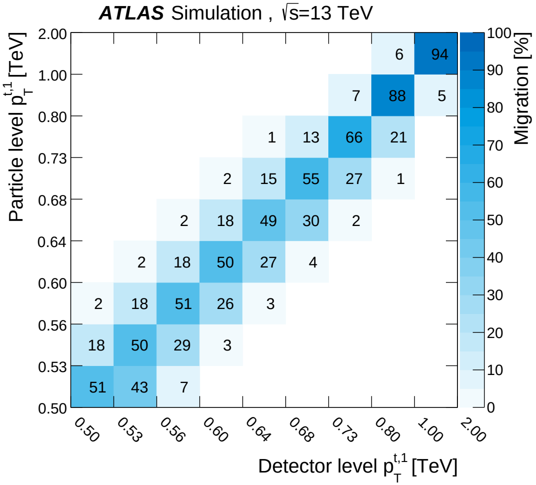
Differential distributions



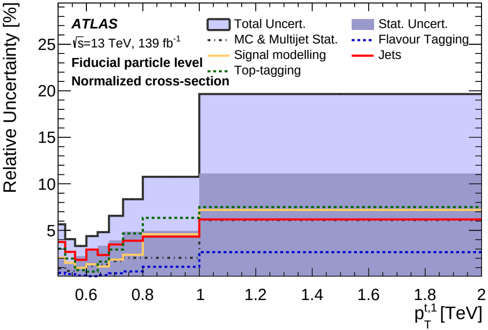


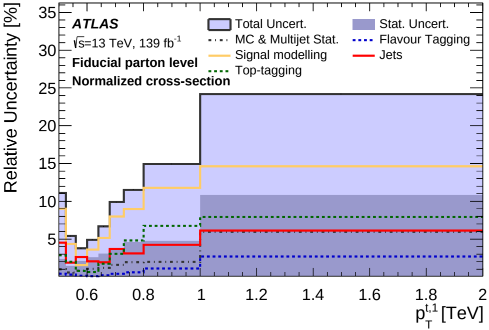
Unfolding


ATLAS Simulation , √s=13 TeV
Parton level $p_T^{t,1}$ [TeV]
Detector level $p_T^{t,1}$ [TeV]
Migration [%]


ATLAS Simulation , √s=13 TeV
Particle level $p_T^{t,1}$ [TeV]
Detector level $p_T^{t,1}$ [TeV]
Migration [%]

Fractional uncertainties



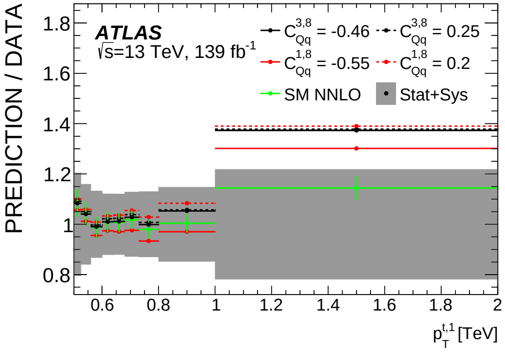


Uncertainties

Source	Relative Uncertainty [%]
Top-tagging	7.8
JES $\oplus$ JER	4.2
JMS $\oplus$ JMR	1.1
Flavor tagging	2.9
Alternative hard-scattering model	5.3
Alternative parton-shower model	2.8
ISR/FSR + scale	5.9
PDF	0.9
Luminosity	1.7
Monte Carlo sample statistics	0.4
Systematics	12.9
Statistics	1.0
Total Uncertainty	13.0

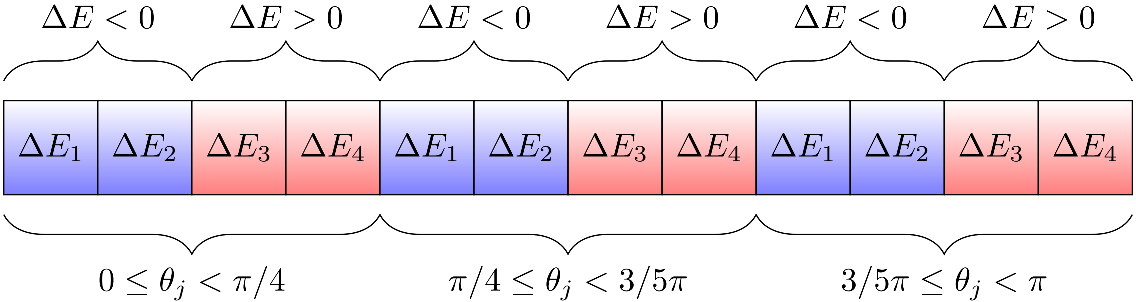
EFT

$C(\text{TeV}/\Lambda)^2$	$\mathcal{O}(\Lambda^{-4})$ 68% CL	$\mathcal{O}(\Lambda^{-4})$ 95% CL	$\mathcal{O}(\Lambda^{-2})$ 68% CL	$\mathcal{O}(\Lambda^{-2})$ 95% CL
$C_{Qq}^{3,8}$	$[-0.31, 0.10]$	$[-0.46, 0.25]$	$[-0.93, 0.10]$	$[-1.42, 0.61]$
$C_{Qq}^{1,8}$	$[-0.39, 0.04]$	$[-0.55, 0.19]$	$[-0.47, 0.08]$	$[-0.74, 0.34]$
C_{Qu}^{8}	$[-0.42, 0.05]$	$[-0.59, 0.22]$	$[-0.58, 0.08]$	$[-0.90, 0.41]$
C_{Qd}^{8}	$[-0.58, 0.18]$	$[-0.88, 0.48]$	$[-1.55, 0.26]$	$[-2.43, 1.13]$
C_{tq}^{8}	$[-0.38, 0.03]$	$[-0.54, 0.18]$	$[-0.46, 0.07]$	$[-0.71, 0.32]$
C_{tu}^{8}	$[-0.40, 0.04]$	$[-0.57, 0.21]$	$[-0.57, 0.07]$	$[-0.88, 0.38]$
C_{td}^{8}	$[-0.55, 0.18]$	$[-0.83, 0.46]$	$[-1.53, 0.25]$	$[-2.39, 1.12]$



$t\bar{t}j$ charge asymmetry: energy

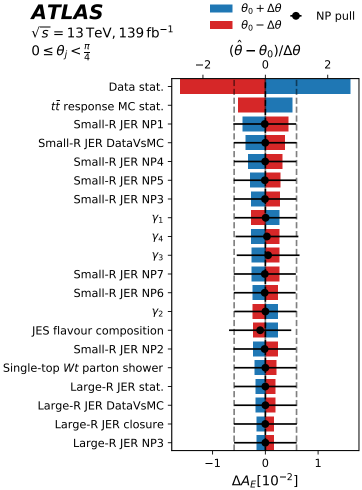
Charge asymmetry regions

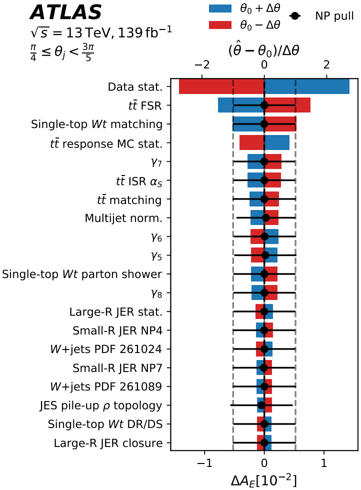


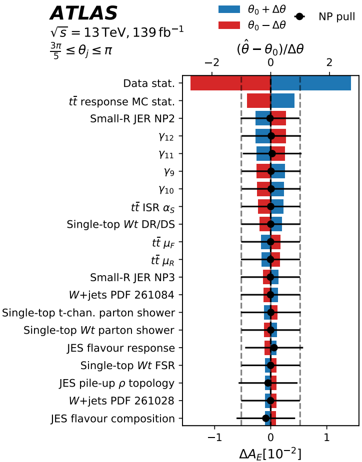
Charge asymmetry uncertainties

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

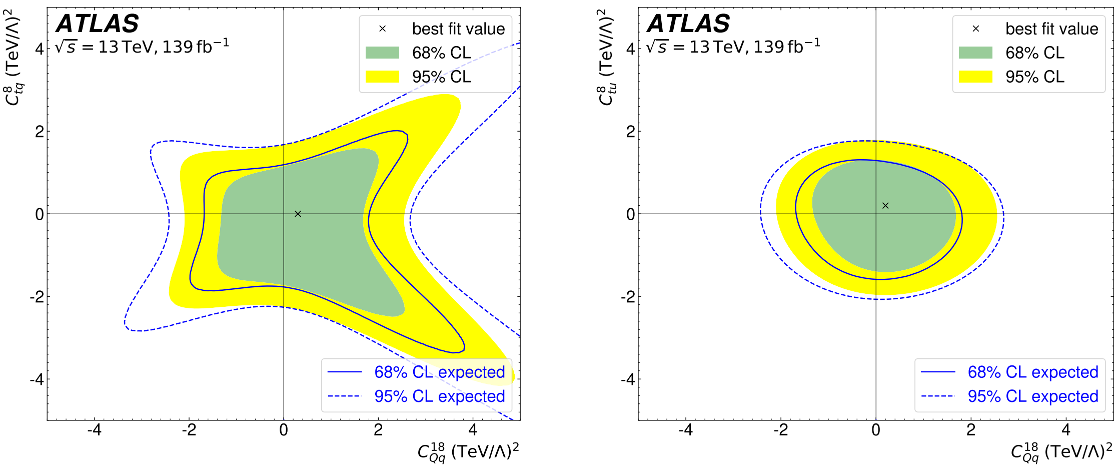
Charge asymmetry impacts







2D EFT Limits



2D EFT Limits