Top-quark couplings, cross-sections and SMEFT interpretations

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on behalf of the ATLAS collaboration

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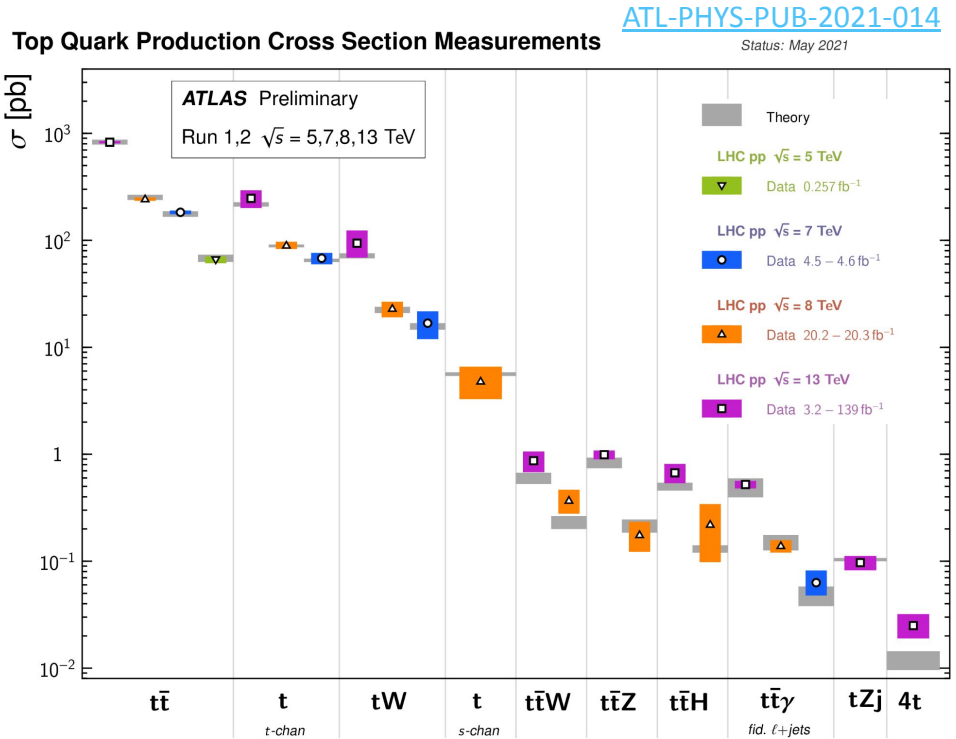
Introduction

The top-quark and its couplings play an important role in the Standard Model.

- The **heaviest particle** in the Standard Model (SM)
  ⟶ Special role in **beyond the SM** (BSM) theories.
- Decays before hadronization
  ⟶ Properties of a **bare quark**.
- Precision tests of **perturbative QCD**.
- Main **background** in many **BSM** searches.



Outline

Many interesting full Run 2 analysis covering top-quark rare processes, cross-sections and EFT interpretations with the ATLAS detector.

- Inclusive and differential cross-sections of a top-quark pair in association with a Z boson: Eur. Phys. J. C 81 (2021) 737.
- Search for flavour-changing neutral-current couplings between the top-quark and the Z boson: ATLAS-CONF-2021-049.
- Evidence for the 4-top production: Eur. Phys. J. C 80 (2020) 1085.
- Measurement of the 4-top production: arXiv:2106.11683.
- Measurement of the top-antitop energy asymmetry in jet-associated top-quark pair production: arXiv:2110.05453.
- Differential ttbar cross-section measurements using boosted top quarks: ATLAS-CONF-2021-031, ATLAS-CONF-2021-050.
- Single top-quark polarisation and EFT fit: ATLAS-CONF-2021-027.

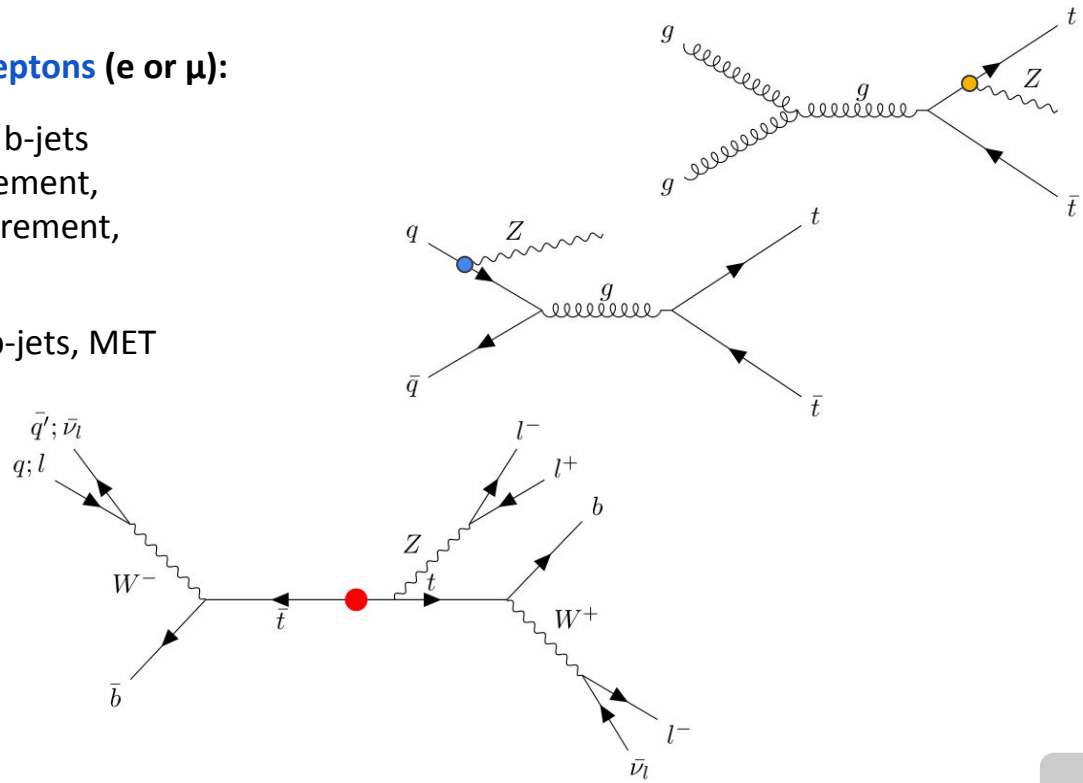
Top pair production with a Z boson

Eur. Phys. J. C 81 (2021) 737

A direct probe of the top-quark coupling to the Z boson → BSM?

Final states with three (3ℓ) or four (4ℓ) isolated leptons (e or μ):

- **3ℓ channel:** three isolated leptons, jets and b-jets
  → 2 signal regions for the inclusive measurement,
  → 1 signal region for the differential measurement,
  → WZ control region.
- **4ℓ channel:** four isolated leptons, jets and b-jets, MET
  → 4 signal regions,
  → ZZ control region.

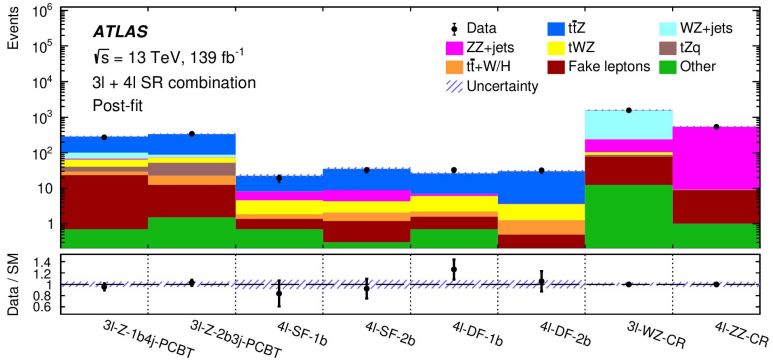


Top pair production with a Z boson

A simultaneous profile-likelihood fit to the **6 SRs and 2 CRs** is used to extract the **inclusive cross-section:**

NLO + NNLL SM prediction:

$$\sigma_{t\bar{t}Z}^{\mathrm{SM}} = 0.86^{+0.07}_{-0.08}(\mathrm{scale}) \pm 0.02(\mathrm{PDF})\ \mathrm{pb}$$

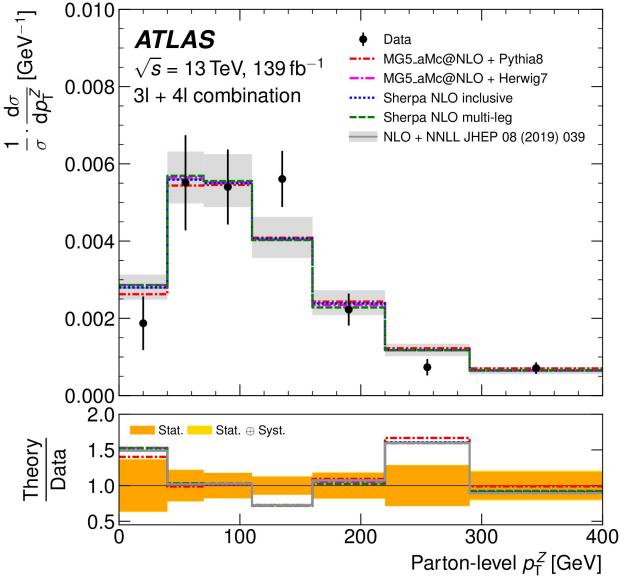


$$\sigma(pp \to t\bar{t}Z) = 0.99 \pm 0.05\,(\mathrm{stat.}) \pm 0.08\,(\mathrm{syst.})\ \mathrm{pb}$$

Dominant sources of the systematic uncertainty:

1. **ttZ parton-shower modelling,**
2. **tWZ modelling,**
3. **Jet flavour-tagging.**

An **iterative Bayesian unfolding (IBU)** is used to obtain **parton and particle level** unfolded distributions:



Dominant sources of uncertainty:

1. **Statistical uncertainty,**
2. **Signal modelling,**
3. **Jet flavour-tagging.**

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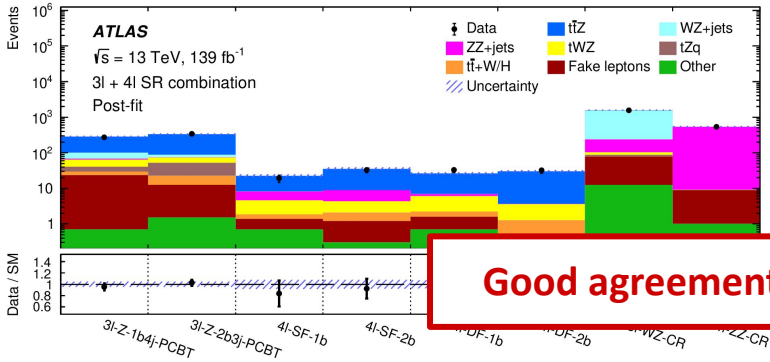

$$\sigma(pp \to t\bar{t}Z) = 0.99 \pm 0.05\,(\mathrm{stat.}) \pm 0.08\,(\mathrm{syst.})\ \mathrm{pb}$$

Good agreement of data with the SM predictions!

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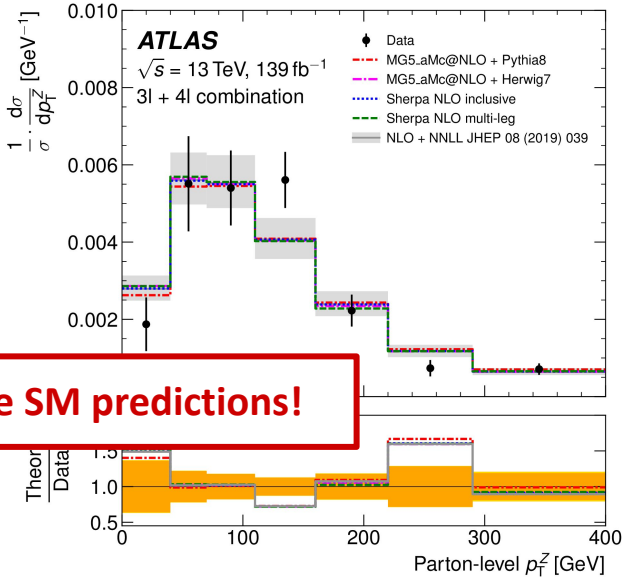

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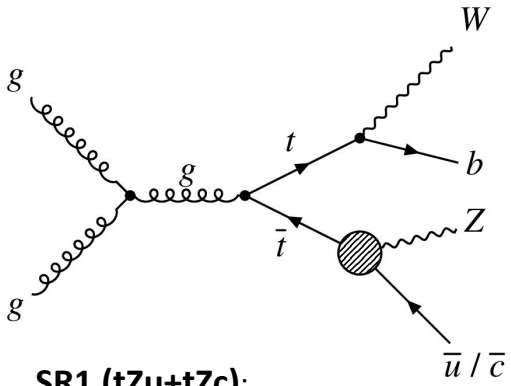
Search of the FCNC t-Z couplings

FCNC processes are forbidden at tree level in the SM and strongly suppressed at higher orders
→ potential for new physics.

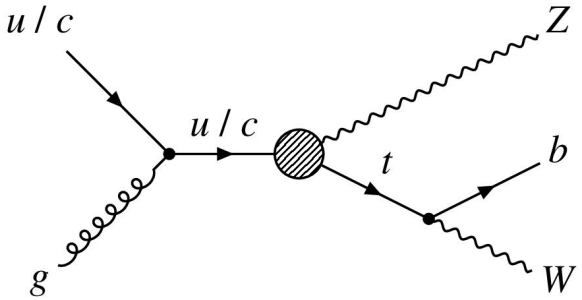
ATLAS-CONF-2021-049

FCNC top-quark pair



SR1 (tZu+tZc):
3 leptons,
≥ 2 jets of which 1 is b-tagged,
MET.

FCNC single top-quark



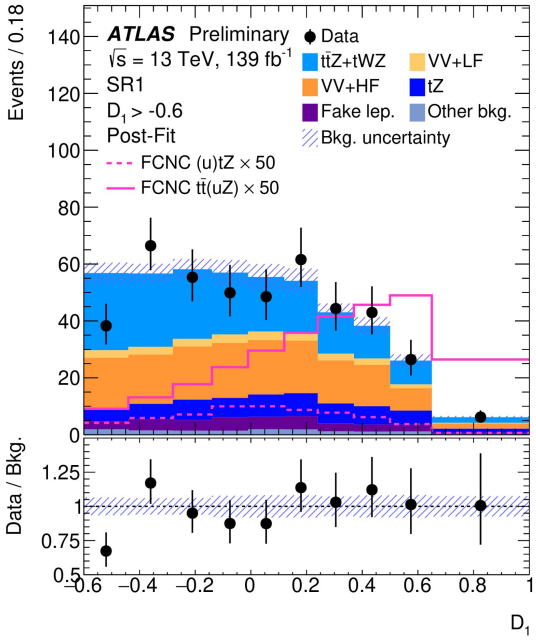
SR2 (tZu):
3 leptons,
1 b-tagged jet and ≤ 1 additional jet,
MET.

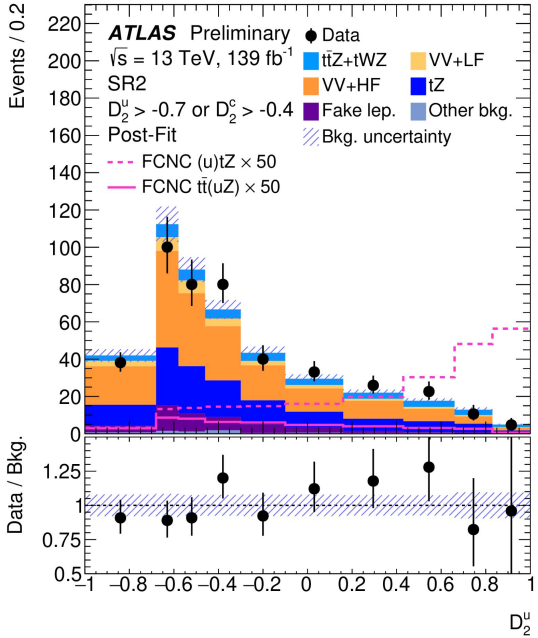
- Discrimintion of signal and background with Gradient BDT: D_1(tZu+tZc), D_2(tZu), D_2(tZc).
- 4 control regions: top-antitop CR, ttZ CR, mass side-band CR1, mass side-band CR2.

Search of the FCNC t-Z couplings: results

The current analysis provides the most stringent limits on the LH tZu and tZc couplings to date.

Good agreement between the data and the SM
→ **No evidence of a signal**.





The observed **95% CL** limit on the **FCNC LH tZu** branching ratio is **improved by a factor of 3**

$$\mathcal{B}(t \to Zu) = 6.2 \times 10^{-5}$$

The observed **95% CL** limit on the **FCNC LH tZc** branching ratio is **improved by a factor of 2**

$$\mathcal{B}(t \to Zc) = 13 \times 10^{-5}$$

Measurement of the 4-top production

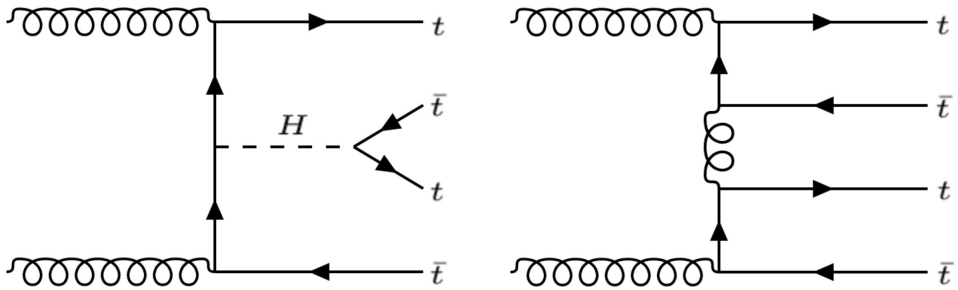
A very rare SM process and sensitivity to the 4-fermion couplings.

2LSS and **≥3L** channels: Eur. Phys. J. C 80 (2020) 1085

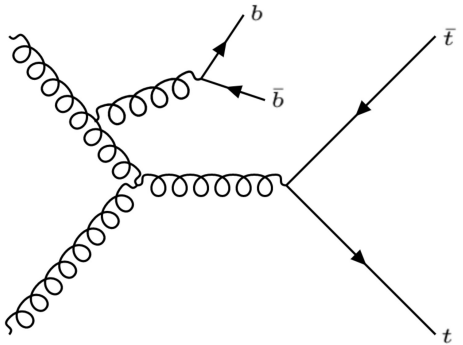
- $\ell^{\pm}\ell^{\pm}$ or ≥3ℓ: 12% BR, reduced backgrounds.
- Jet multiplicity, b-tagged jets, kinematics.
- BDT signal/background discriminant.
- **Four control regions**:
  NF_{ttW}, $NF_{\text{Mat. Conv.}}$, $NF_{\text{Low m}\gamma^*}$, $NF_{\text{HF e}}$, $NF_{\text{HF }\mu}$.

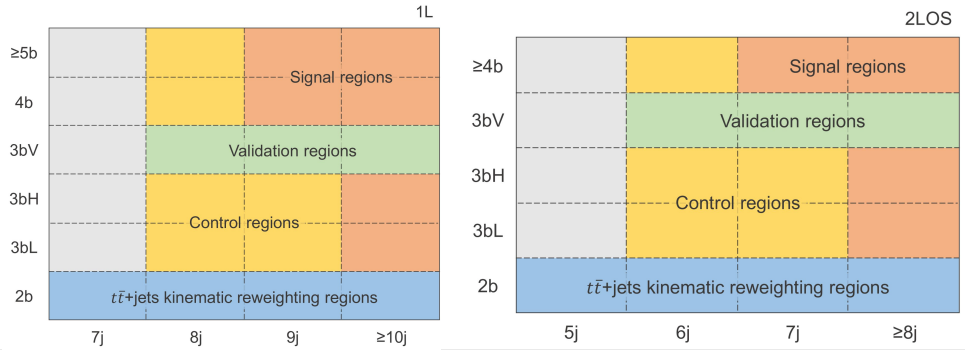
1L and **2LOS** channels: arXiv:2106.11683

- 1ℓ or $\ell^{\pm}\ell^{\mp}$: larger BR, larger backgrounds.
- Jet and b-jet multiplicities.
- BDT signal/background discriminant.



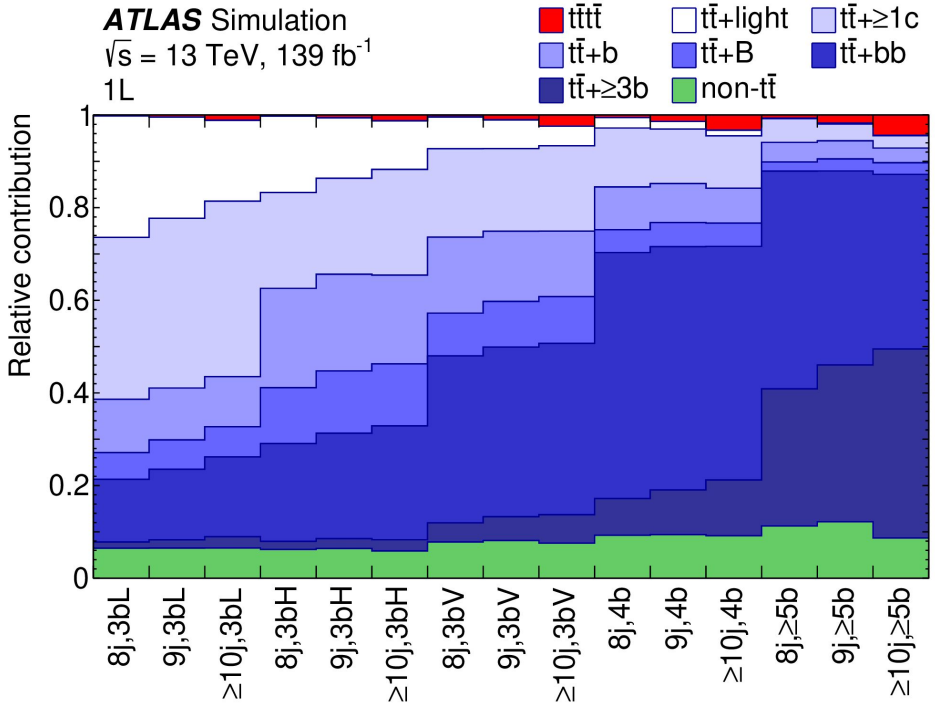
The dominant background is tt+jets.

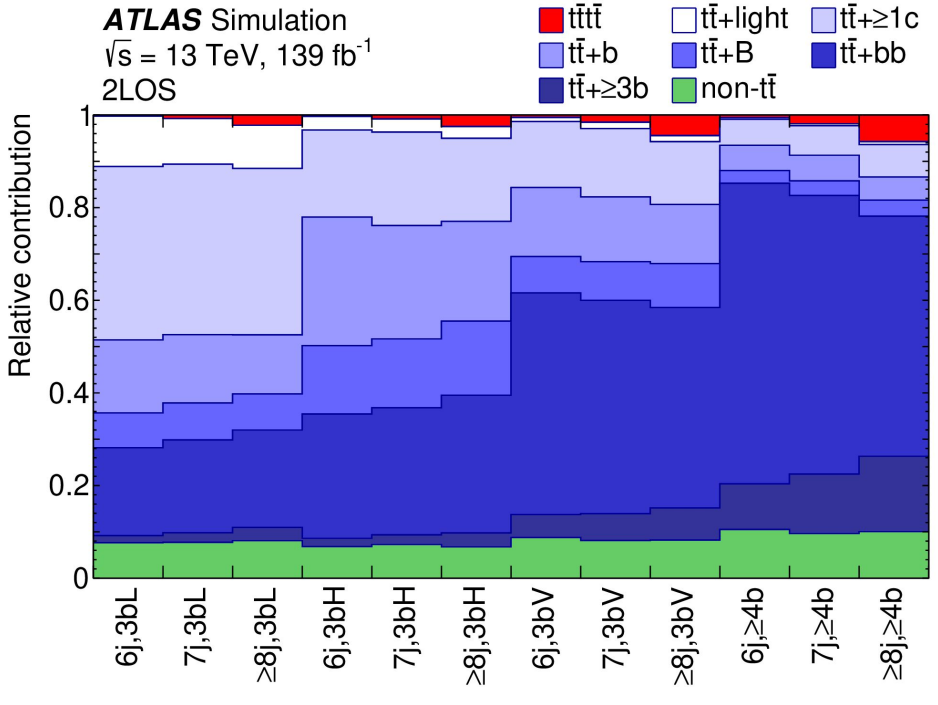




Measurement of the 4-top production

Signal-to-background ratio ≤ 6.1% in signal regions.

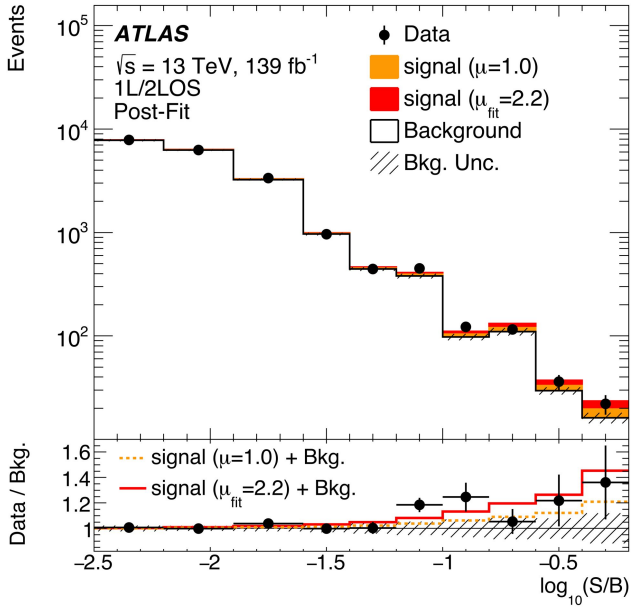




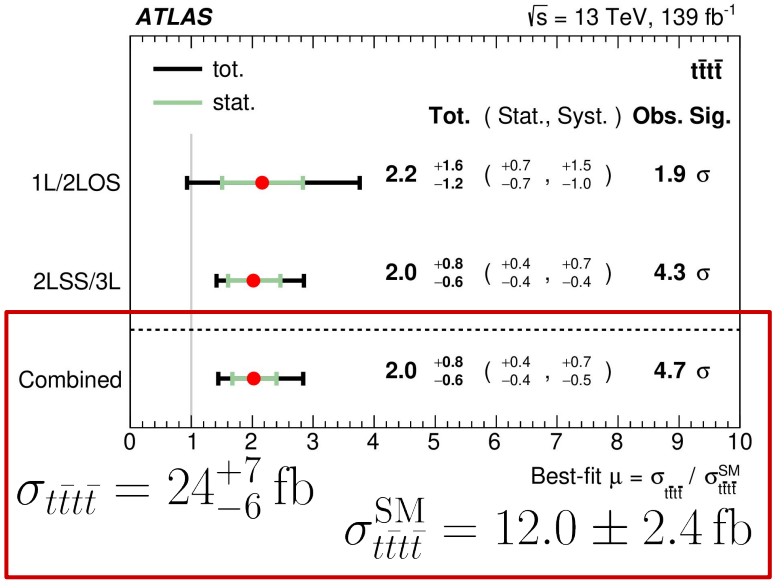
Measurement of the 4-top production

The significance of the combined 4-top cross-section is 4.7σ exceeding the expected 2.6σ significance.

A best-fit signal strength of μ = 2.2 is extracted from the data.



A binned profile likelihood fit extracts the 4-top signal strength.

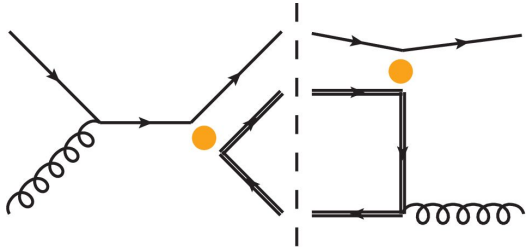


Energy asymmetry with the tt+j events

arXiv:2110.05453

The energy asymmetry is sensitive to the top-quark chirality in the SM.

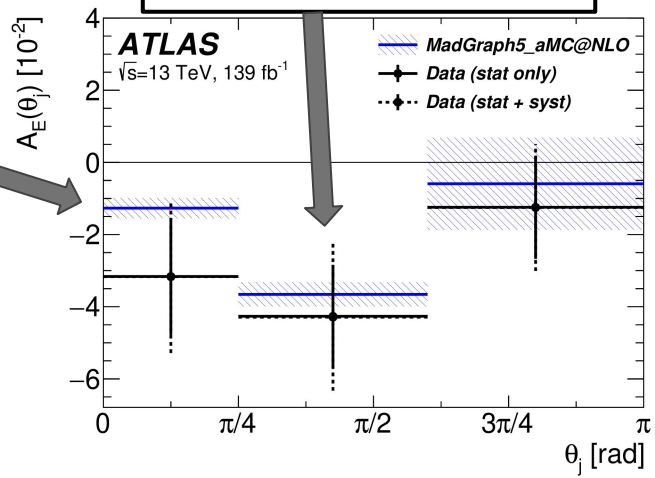
- **Anti-tops** tend to be produced more **perpendicular to the beam axis** → charge asymmetry.
- Lepton + jets boosted topology:
  - A hadronic large-R top-tagged jet,
  - An isolated lepton, a b-tagged jet, MET, an extra jet.
- **Detector effects** on the **jet angle** are corrected with the **Fully Bayesian unfolding**.
- **Largest uncertainty** is **from data statistics**.



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

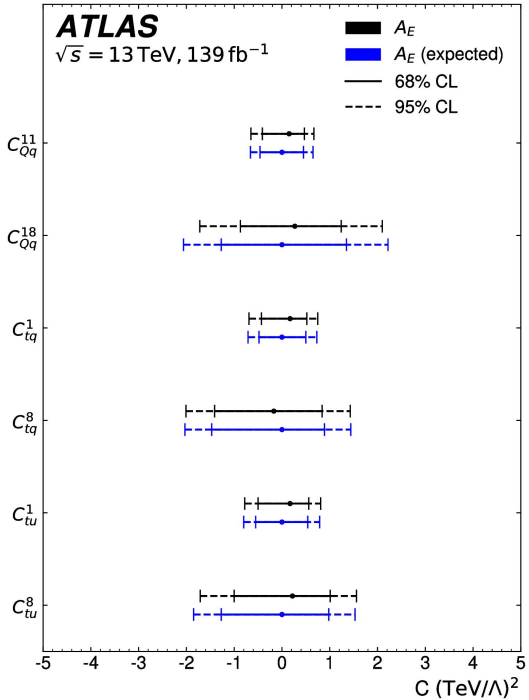
$$\sigma^{opt}(\theta_j) = \sigma(\theta_j \mid y_{t\bar{t}j} > 0) + \sigma(\pi - \theta_j \mid y_{t\bar{t}j} < 0),\ \theta_j \in [0, \pi$$

$A_E = -0.043 \pm 0.020$

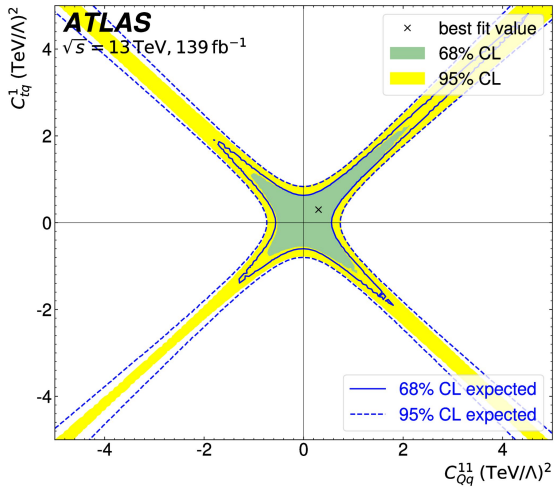


Energy asymmetry with the tt+j events

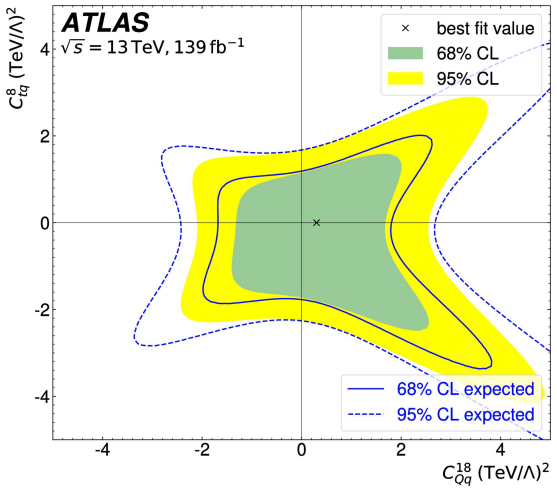
The energy asymmetry has sensitivity to individual four-quark operators and probes new directions in the parameter space of Wilson coefficients.



Colour-singlet operators



Colour-octet operators

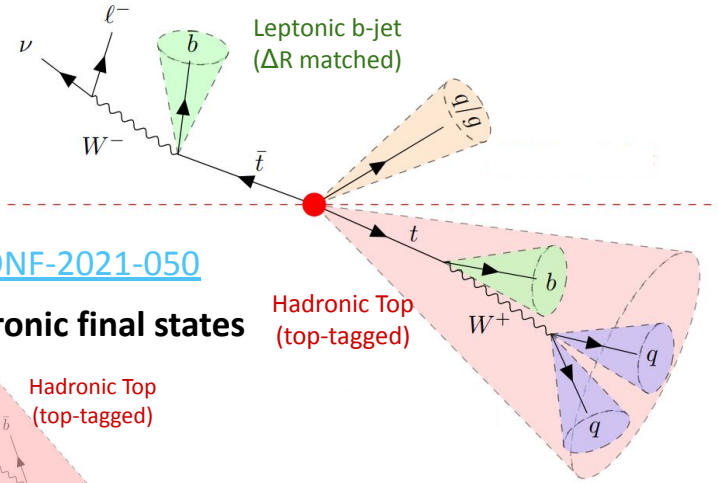


Boosted top quarks

The high rate of top-quark pair production allows to look for deviations from the SM.

Lepton+jets final states

ATLAS-CONF-2021-031



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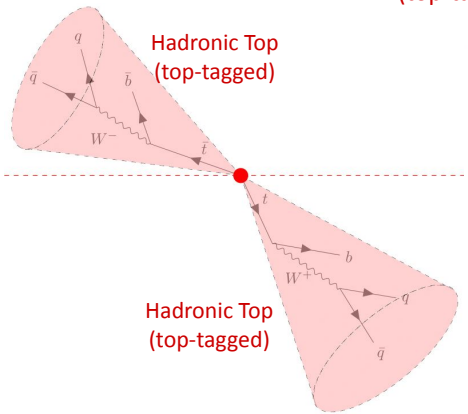
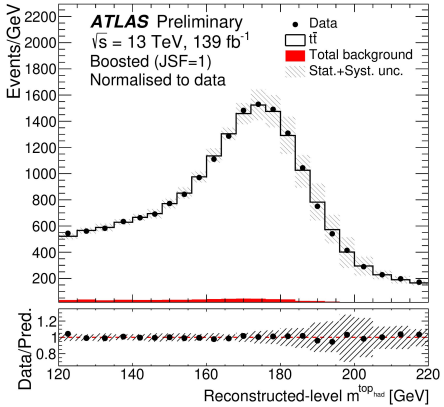
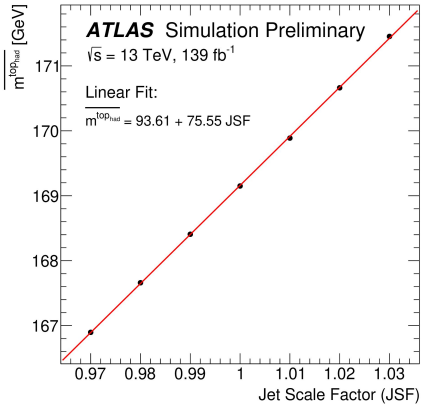
All-hadronic final states



Correction of the jet energy





Multijet backgrounds estimated with the ABCD method

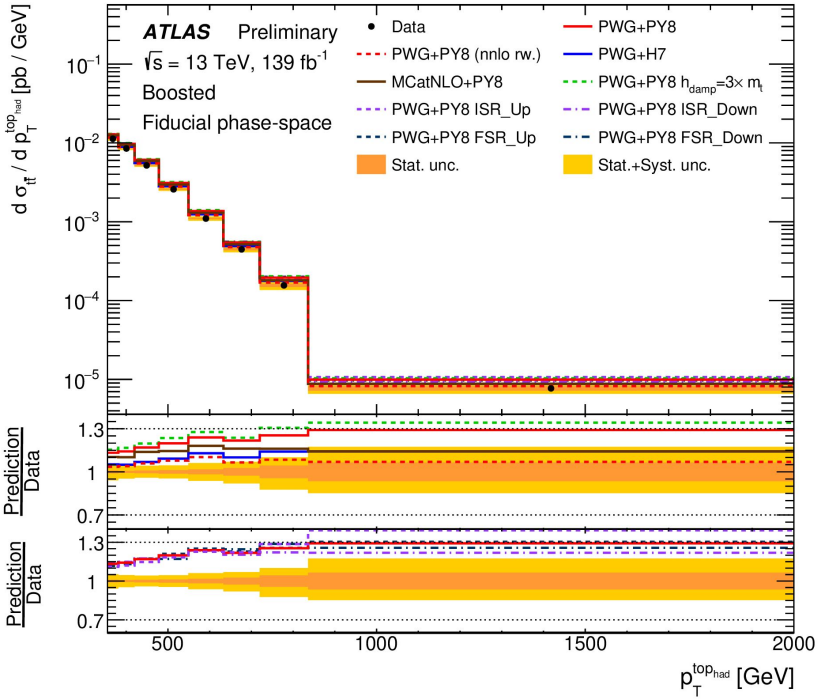
2nd large-R jet \ Leading large-R jet	0t0b	1t0b	0t1b	1t1b
1t1b	J (7.0%)	K (25%)	L (39%)	S
0t1b	B (1.2%)	D (5.0%)	H (9.0%)	N (47%)
1t0b	E (0.5%)	F (2.3%)	G (4.9%)	M (31%)
0t0b	A (0.09%)	C (0.5%)	I (1.1%)	O (9.0%)

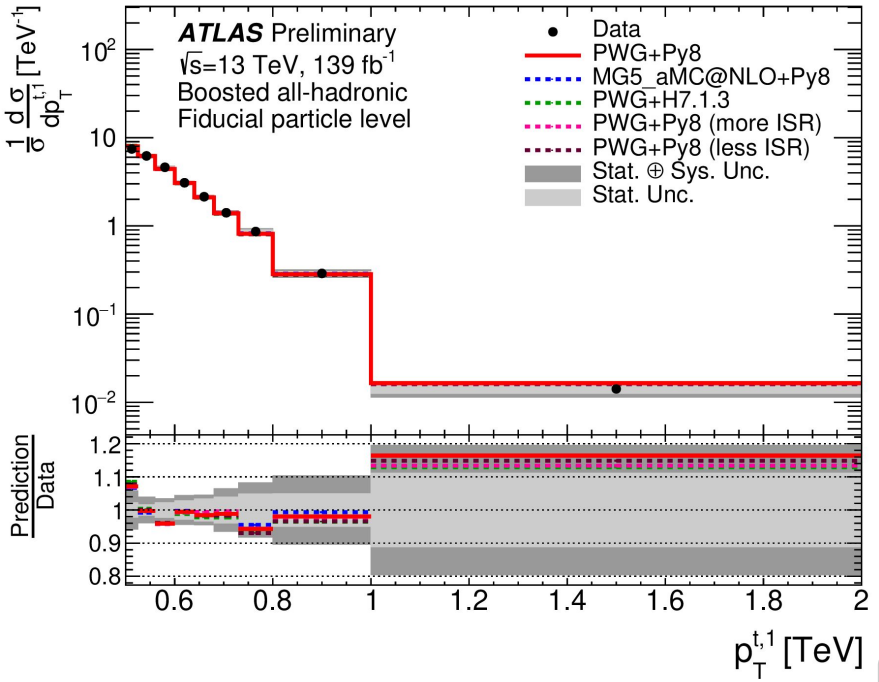
Boosted top quarks

Most precise top-quark pair production measurements in the boosted topology.

Detector effects corrected with the iterative Bayesian unfolding method.

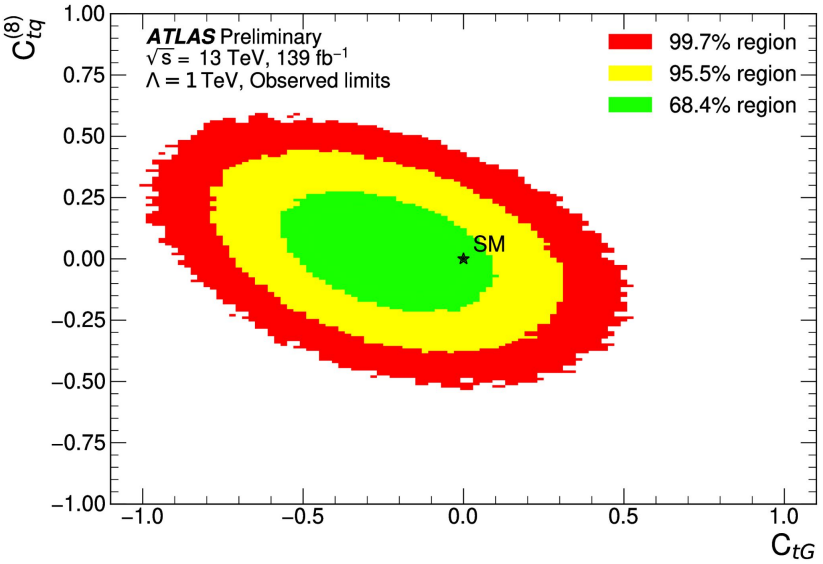
Reweighting the MC prediction to the NNLO parton-level prediction significantly **improves** the **Data/MC** agreement.



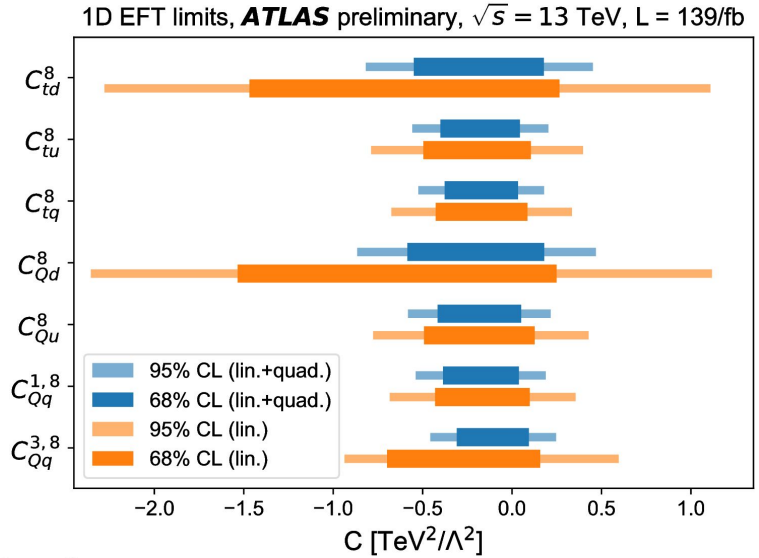


Boosted top quarks and SMEFT

The fitted Wilson coefficients (linear term only) are consistent with zero.



The 95% CL limits are within the range of [-0.8, +0.5] TeV^2/Λ^2 (linear and quadratic terms).



Wilson coefficient	Marginalised 95% intervals		Individual 95% intervals		
	Expected	Observed	Expected	Observed	Global fit
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]

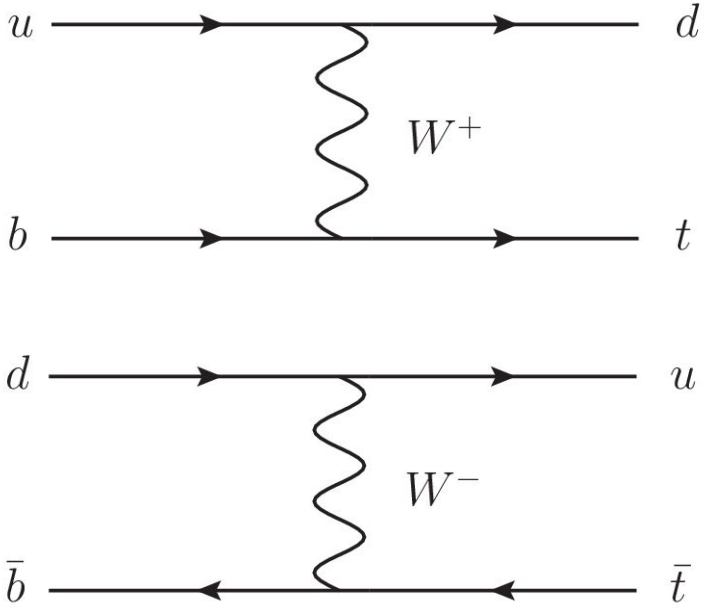
The t-channel single-top production

Polarisation observables are sensitive to new physics phenomena affecting the tWb vertex.

ATLAS-CONF-2021-027

General analysis strategy:

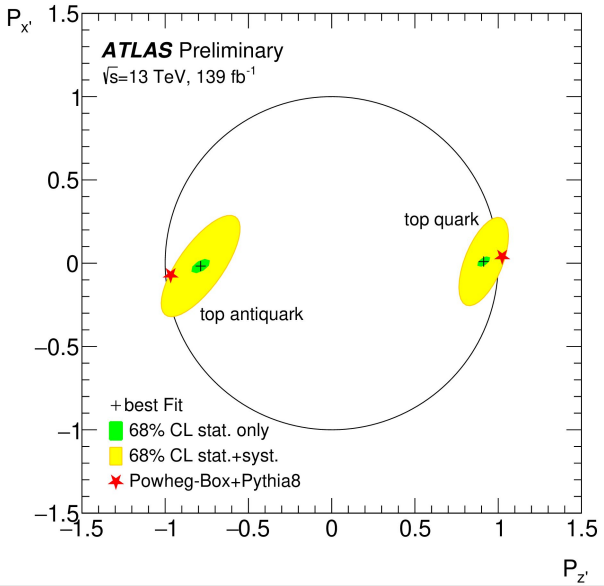
- W-boson decays to an electron or muon are considered.
- Signal events:
  - Exactly one isolated lepton,
  - Significant MET,
  - Exactly two jets one of which is b-tagged.
- Two background-enriched control regions:
  - CR ttbar and
  - CR W+jets.
- The differential angular distributions are unfolded to particle level using the iterative Bayesian unfolding.



Polarisation measurements

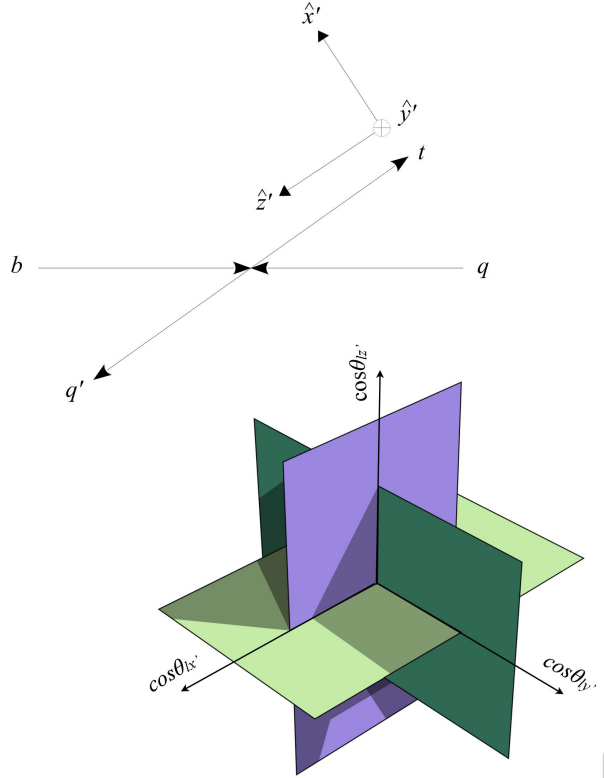
Profile likelihood fit to the 16 SRs and 4 CRs bins extracts the polarisation vectors of the top quark and antiquark.

- Fitting of **P = {Px', Py', Pz'}** for top **quarks** and **antiquarks** → **6 parameters**.
- The **measured polarisations** are **consistent with theory**.



Top quark
Px' = 0.01 ± 0.18
Py' = -0.029 ± 0.027
Pz' = 0.91 ± 0.10

Top antiquark
Px' = -0.02 ± 0.200
Py' = -0.007 ± 0.051
Pz' = -0.79 ± 0.16

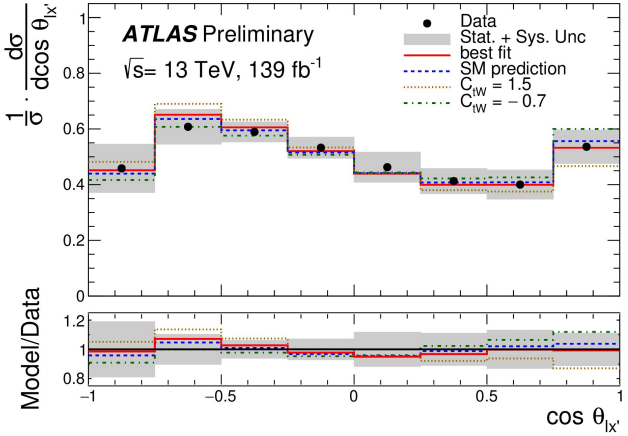


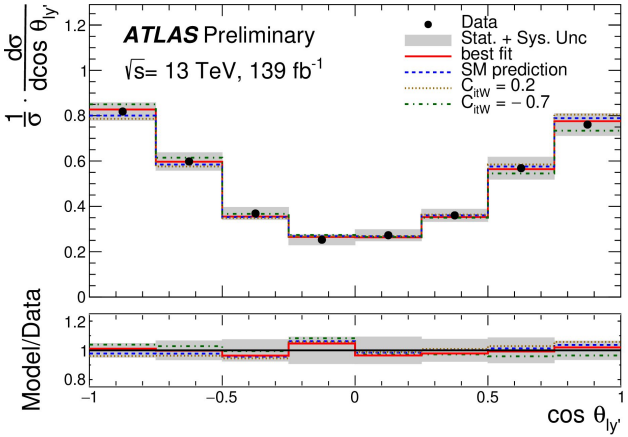
Bounds on complex Wilson coefficients

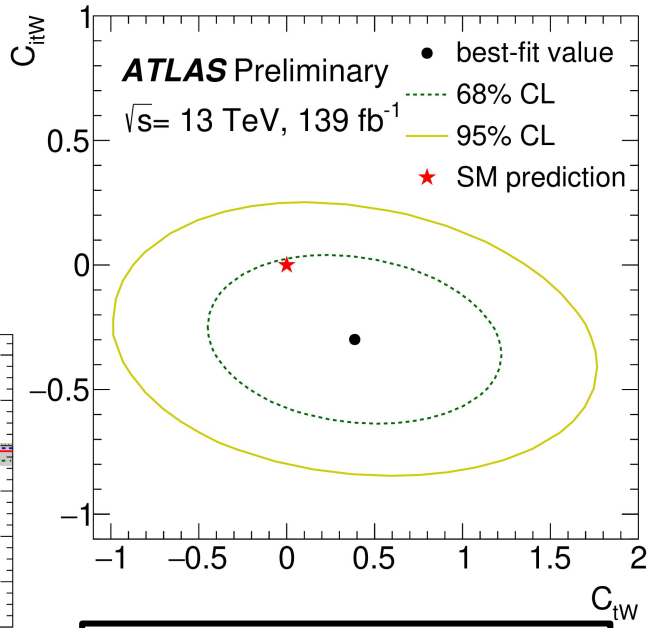
Measured differential cross-sections of the $\cos(\theta_{lx'})$ and $\cos(\theta_{ly'})$ variables are fitted to an EFT prediction.

- $\theta_{lx'}$ and $\theta_{ly'}$ are angles of the charged lepton.
- The measurements are consistent with SM predictions.

- Angular distributions as a function of C(tW) and C(itW) coefficients
  → Good agreement between the model and the data,
  → Good agreement with the SM prediction.



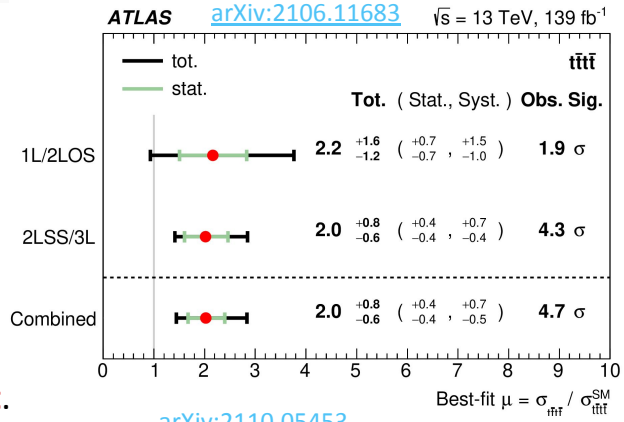




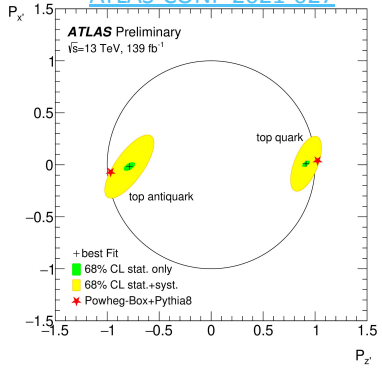
Best fit values at 95% CL:
C_{tW} = 0.4 ± 1.1
C_{itW} = -0.3 ± 0.4 (improvement)

Summary of ATLAS Top Public Results

- The presented measurements show **good agreement with the SM predictions**.
- Limits on **LH BR(t→Zu) improved 3 times** and **LH BR(t→Zc) 2 times**.
- **4.7σ significance** is achieved in the **4-top** cross-section measurements.
- The top-quark pair cross-section measurements in boosted topology show that **higher-order predictions for the additional jets** may be needed.
- Several analyses demonstrate **promising results** to improve the **global EFT fit**.



ATLAS-CONF-2021-027



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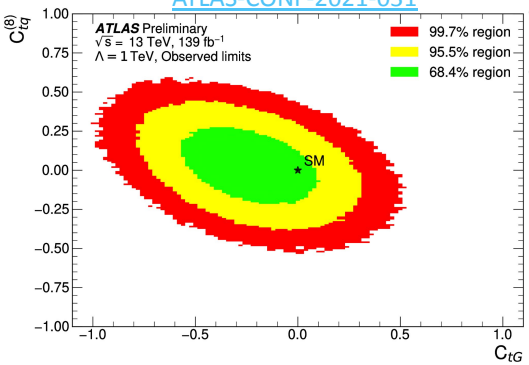

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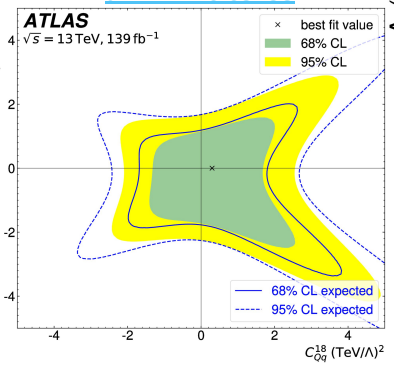

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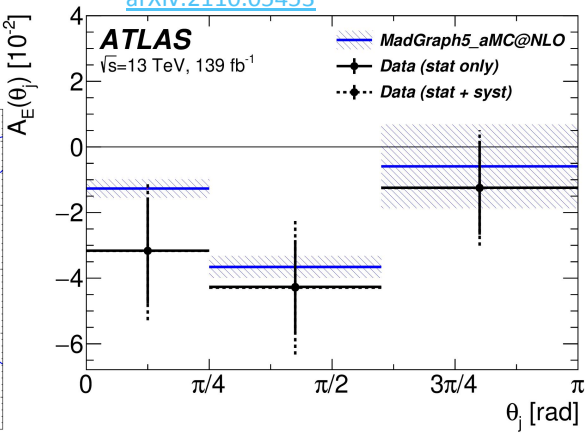
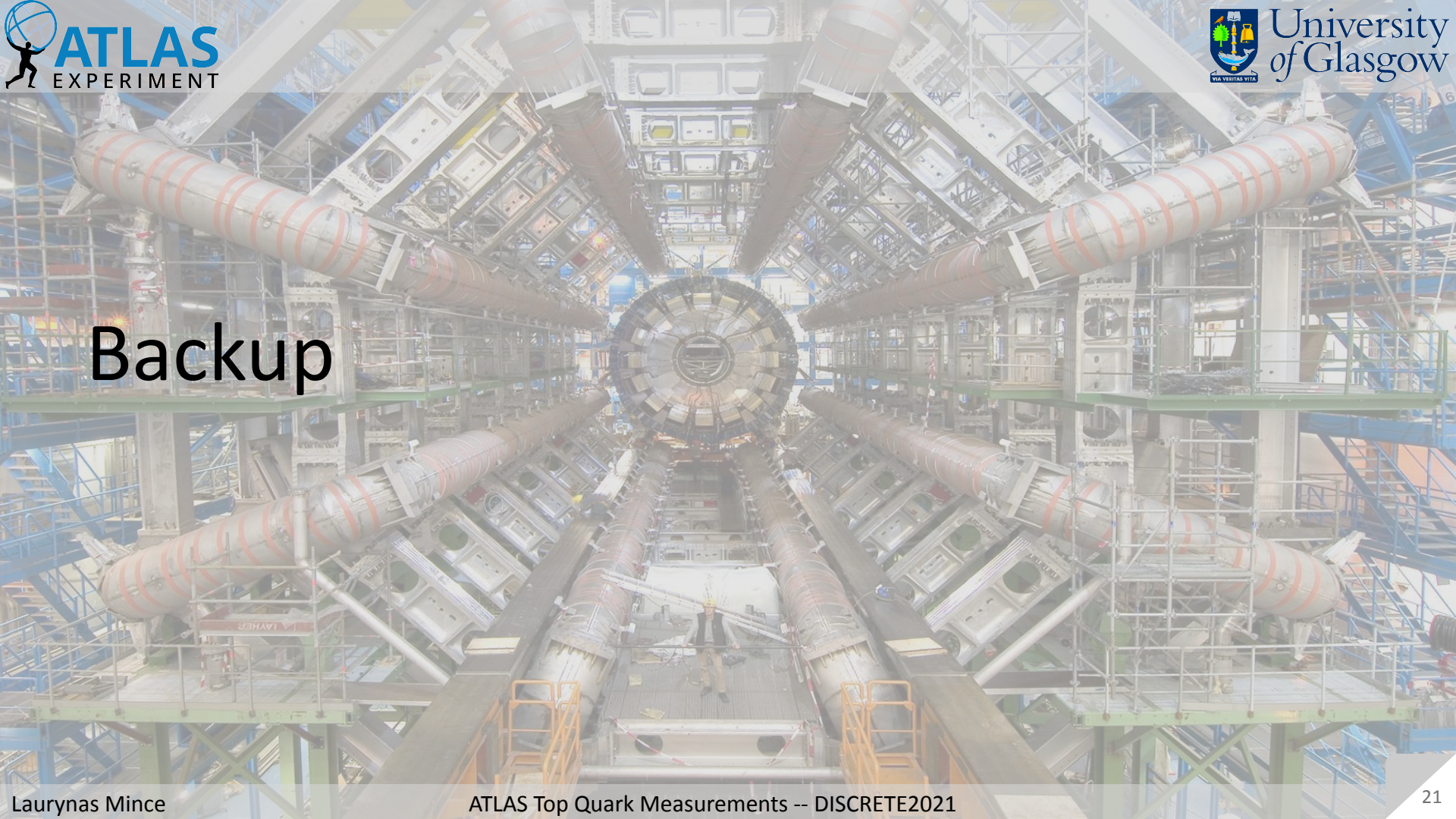
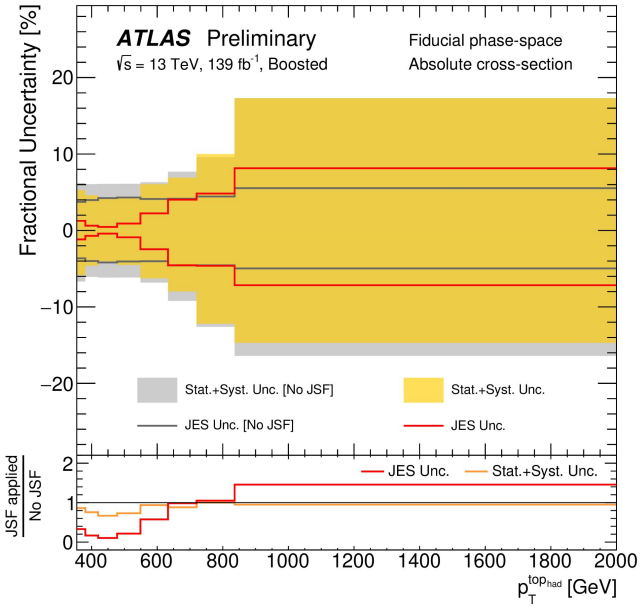
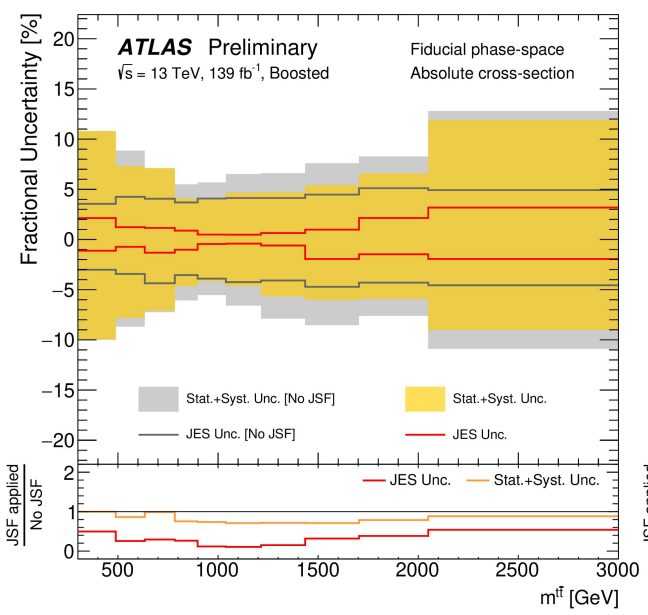
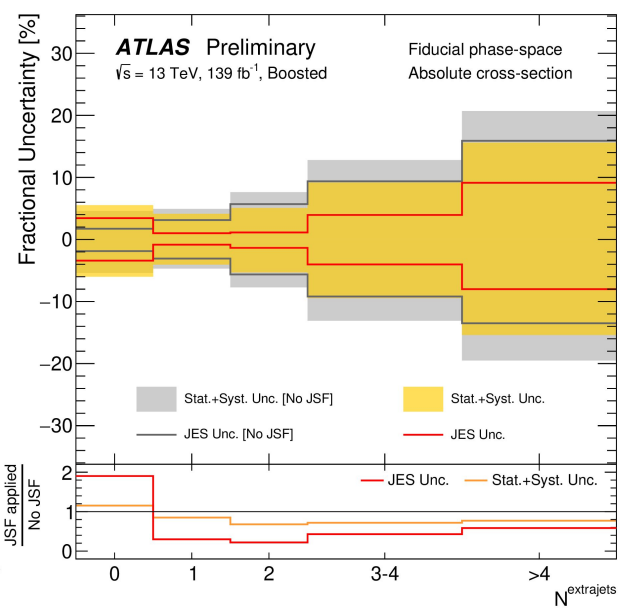



ATLAS
EXPERIMENT
University of Glasgow
Backup

Boosted tops: JSF impact







Boosted tops: JSF impact

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	$^{+4.1}_{-4.3}$	$^{+5.8}_{-6.0}$