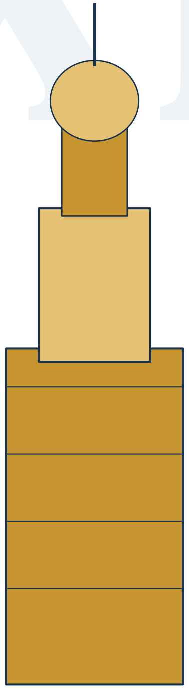
RSEF BIENNIAL

ATLAS · EFT in top-quark production & decay

A Finite-Basis Framework for Fully-Differential EFT Measurements

Orthogonal basis expansions of the decay rate, and a simultaneous fit of EFT Wilson coefficients with the ATLAS detector.



Torre del Oro · Sevilla

Research project: CNS2022-135718

Mariam Chitishvili

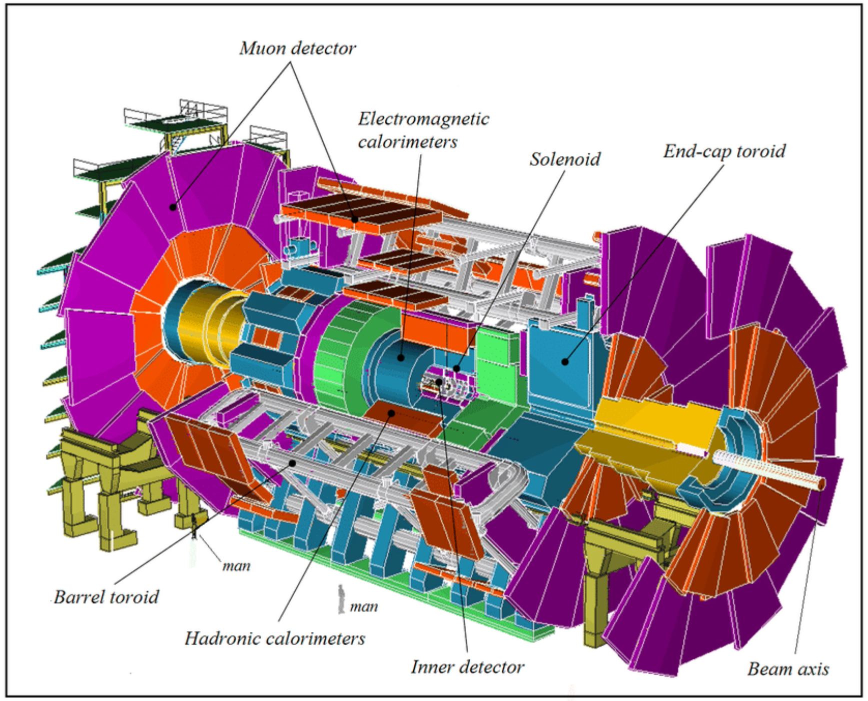
ATLAS Collaboration

The XL RSEF Physics Biennial

Sevilla · 20–24 July 2026

The ATLAS Experiment at the LHC

The largest general-purpose LHC detector — and a top-quark factory.



46 m long · 25 m tall · ~7000 tonnes of instrumentation

140 fb^{-1} pp collisions at $\sqrt{s}$ = 13 TeV (Run 2, 2015–2018)

~10^8 top-quark pairs produced — precision statistics

Millions of read-out channels reconstruct every charged lepton, jet and missing-energy vector — the raw material for precision top-quark physics.

New Physics with the SMEFT

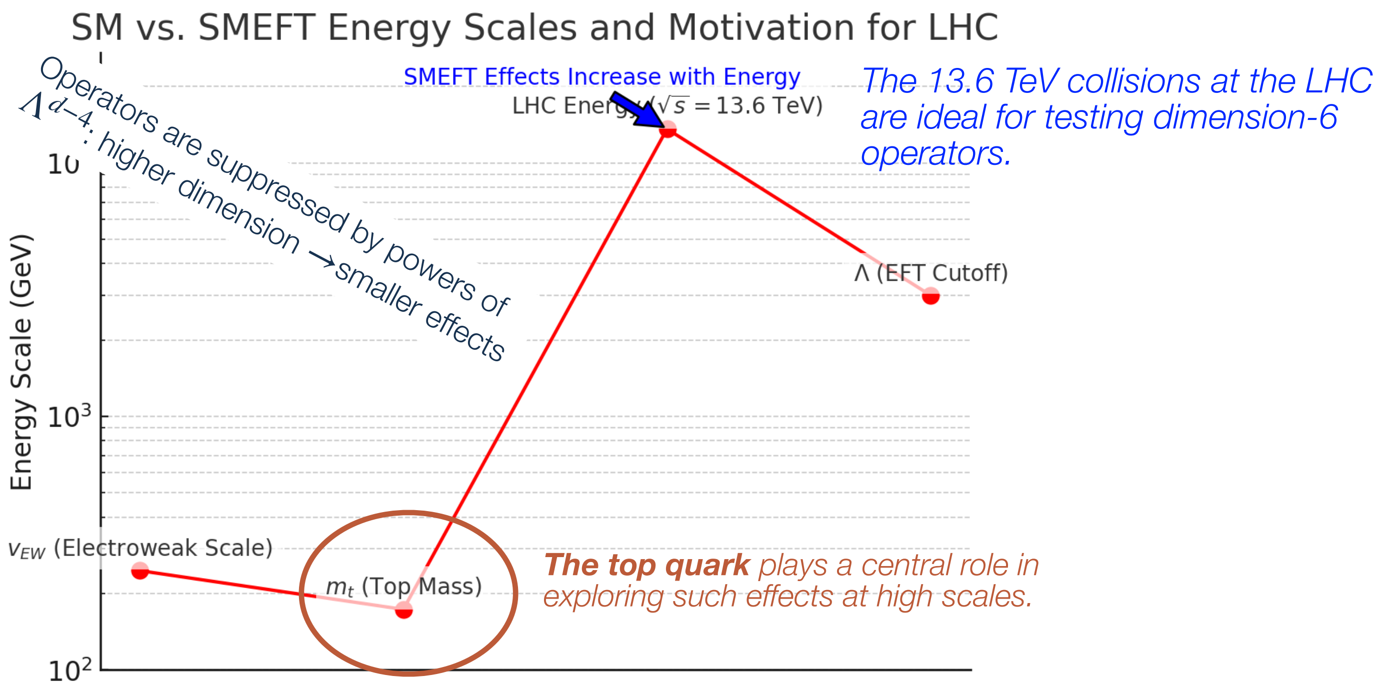
If heavy new physics lives at a scale Λ ≫ v_EW, it imprints on the SM as higher-dimensional operators.

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{\tilde{C}_j}{\Lambda^4}\mathcal{O}_j^{(8)} + \dots$$

$\mathcal{O}_i^{(d)}$ — **gauge-invariant operators**

C_i — **Wilson coefficients**

The energy handle. Dimension-6 effects scale as $\delta\sigma \propto (C_i/\Lambda^2)\,E^2$: high-energy top-quark interactions amplify new physics. Tied to the electroweak scale, the top quark is a prime window on these operators.



The Top Quark: A Unique Probe

The heaviest elementary particle — the only quark that decays before it hadronizes.

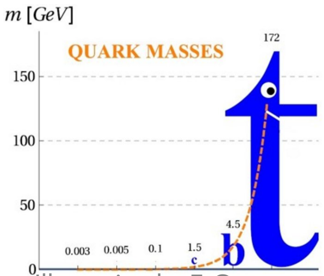
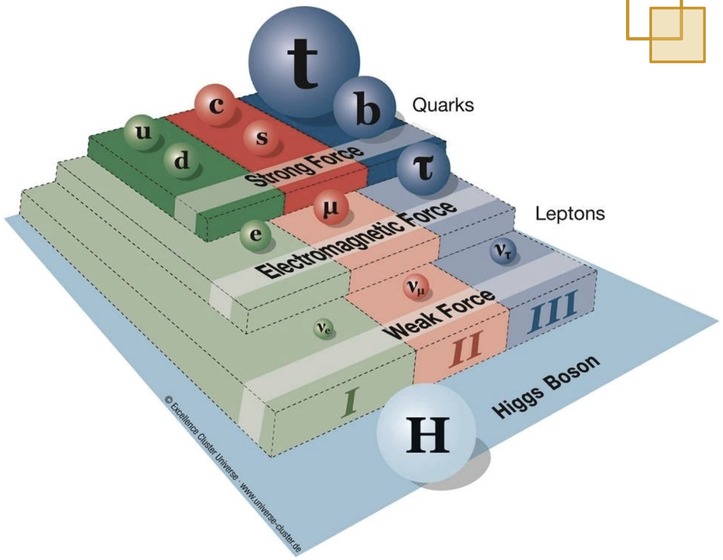


Illustration by F. Goertz



1

Heaviest of them all

$m_t \approx 172.5$ GeV — Its Yukawa coupling $y_t \approx 1$ ties it directly to the Higgs and electroweak symmetry breaking.

2

It decays as a free quark

$\tau_t \approx 5\times10^{-25}$ s, shorter than the hadronization time — so its spin is transferred, undiluted, to its decay products.

3

A clean decay chain

$t \to Wb$ with $|V_{t\beta}| \approx 0.999$ (>99%), then $W \to \ell\nu$. Leptons make an especially clean, fully-reconstructable final state.

4

Copiously produced at the LHC

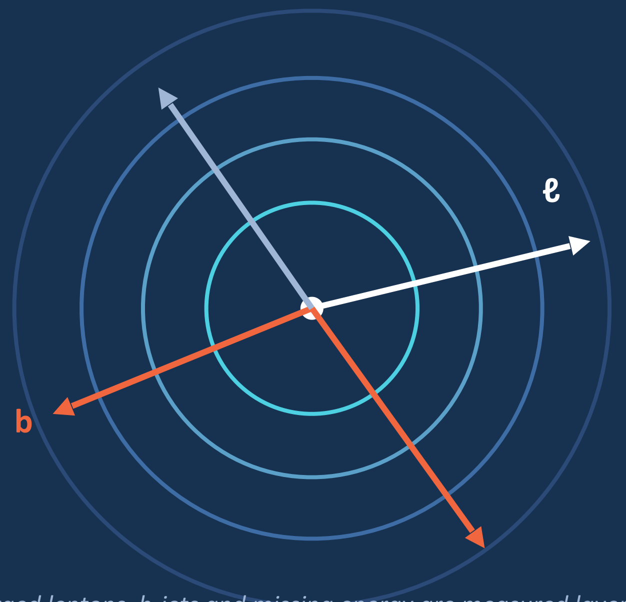
$\sigma(t\bar{t}) \approx 830$ pb and single-top (t-channel dominant) at 13 TeV — abundant events for differential studies.

Why it matters: the top's spin polarization survives into the **angles**. Those angular distributions are precision observables — and exactly where new physics leaves its fingerprint.

Angular Measurements: The Sharpest Tool

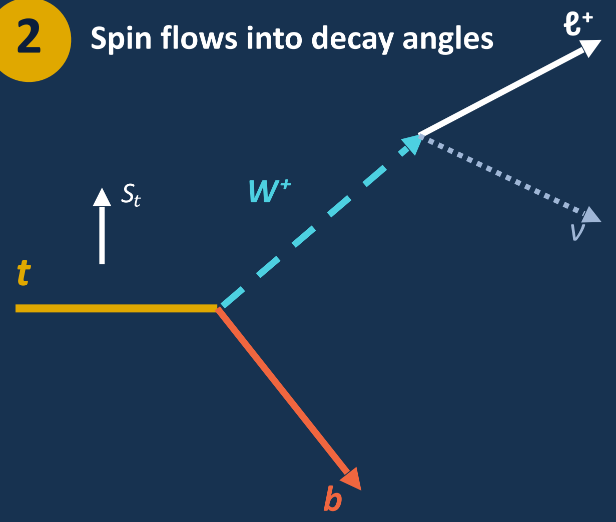
Top spin survives, so decay-product angles are precision observables — where SMEFT shows up most cleanly.

1 ATLAS reconstructs the products



Charged leptons, b-jets and missing energy are measured layer-by-layer, giving each decay product a precise momentum vector.

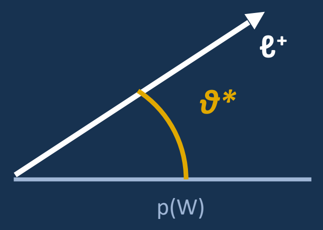
2 Spin flows into decay angles



$$t \to W^+ b\,,\quad W^+ \to \ell^+ \nu$$

The top decays before it can hadronize ($\tau \approx 5\times10^{-25}$ s), so its spin is transferred intact to the lepton — whose emission angle carries the polarization.

3 Angular observables test the SM



W helicity	SM (NNLO)	ATLAS
F_0 (long.)	0.687	0.709 ± 0.019
F_L (left)	0.311	0.299 ± 0.015
F_R (right)	0.0017	−0.008 ± 0.014

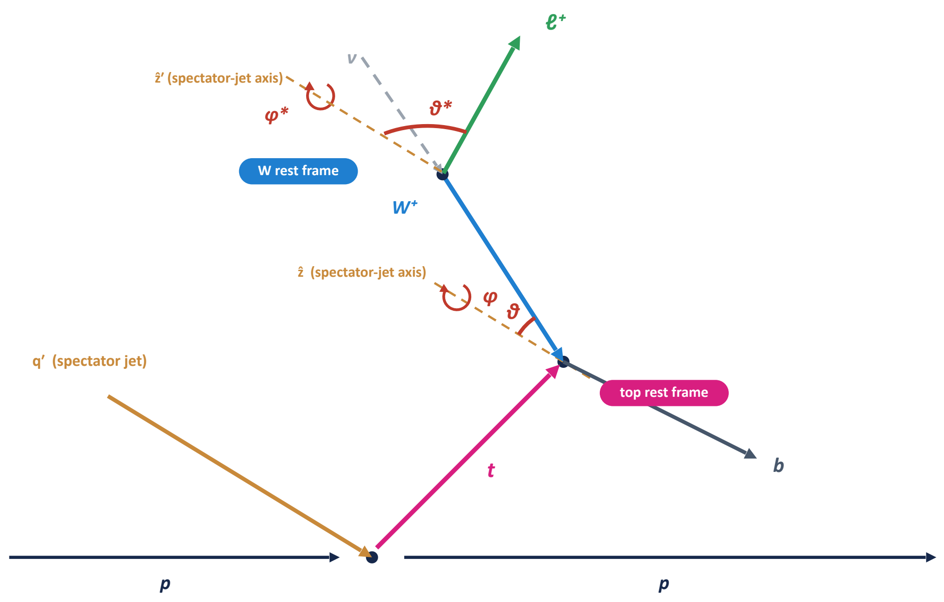
Phys. Rev. D ***81*** *(2010) 111503(R)* *Eur. Phys. J. C* ***77*** *(2017) 264*

Spin correlation & W-helicity fractions agree with the Standard Model to percent-level precision.

The through-line: ATLAS turns detector hits into decay-product 4-vectors → the **angular distributions** of those products encode top-quark polarization, W-helicity and $t\,\bar{t}$ spin correlation — precision tests of the SM.

The Challenge: a Fully-Differential Decay Rate

The $t \to Wb \to \ell\nu b$ decay is described by four angles — binning a 4-D distribution is hopeless.



Four angles fully specify the decay: **(θ, ϕ)** orient the W in the top rest frame; **(θ*, ϕ*)** orient the lepton in the W rest frame.

ATLAS · arXiv:2510.23372, Fig. 2

A finite-basis framework

The fully-differential rate of **$t \to Wb \to \ell\nu b$** is expanded in **orthogonal basis functions**. A finite set of coefficients captures the full multidimensional shape and normalisation — extracted directly from data by projection, then used to fit multiple EFT Wilson coefficients simultaneously. **140 fb^{-1} · ATLAS · 13 TeV.**

Why not just bin a histogram?

Curse of dimensionality. Even 5 bins per angle ⇒ $5^4 = 625$ — and $5^{10} \approx 10^7$ for the $t\bar{t}$ decay chain, far more than the available events. Projecting to 1-D discards correlations and needs assumptions about the unseen variables.

Most top measurements are projections of this space

W-helicity uses cos θ* alone; **spin correlation** uses azimuthal differences. Each is a 1-D/2-D slice of the same joint density — the M-function method keeps all of it at once.

A ladder runs from 1 angle (W-helicity) → 4 angles (this analysis) → 10 angles (full $t\bar{t}$). One formalism climbs all of it.

The Idea: Orthogonal-Series Density Estimation

Expand the density in an orthonormal basis; the coefficients are just averages over events.

1

Choose an orthonormal basis

The M-functions are built from Wigner D-functions — a product covering (θ,ϕ) and (θ*,ϕ*). They satisfy $\int M_n M_{n'}^* \, d\Omega = \delta_{nn'}$.

2

Expand the density

$\rho(\Omega) = \Sigma\, c_n M_n(\Omega)$. Completeness ⇒ the series carries all shape information, including correlations between angles.

3

Project to get coefficients

$c_n = \int \rho M_n^* \, d\Omega = \langle M_n^* \rangle$ — the coefficient is the average of the basis function over the events. No fit, no binning.

4

Errors come for free

The sample covariance $\mathrm{Cov}(c_n, c_m) = [\langle M_n M_m \rangle - \langle M_n^* \rangle \langle M_m^* \rangle] / N$ gives every coefficient a statistical uncertainty and full correlations.

The M-function

$$M^{j_1 j_2}_{m' m} = (2j_1+1)^{½} (2j_2+1)^{½} / 4\pi$$

$$\times\, D^{j_1}_{m' m}(\cos\theta, \varphi) \cdot D^{j_2}_{m,0}(\cos\theta^*, \varphi^*)$$

Wigner D-functions — the natural language of angular momentum and helicity.

Coefficient = average over data

$$c_n = \langle M_n^* \rangle = (\Sigma\, w_i M_n^*(\Omega_i)) / (\Sigma\, w_i)$$

Unbinned · analytic · every event contributes to every coefficient. A χ^2 distance in coefficient space compares data to model.

Why This Basis? The Physics Lives in 23 Numbers

The basis is chosen from the helicity structure of the decay — so the truncation is physics, not guesswork.

Helicity amplitudes ⇒ only four survive

Angular-momentum conservation in $t \to Wb \to \ell\nu$ leaves exactly four non-zero reduced amplitudes ($a_{1,\frac{1}{2}}$, $a_{0,\frac{1}{2}}$, $a_{0,-\frac{1}{2}}$, $a_{-1,-\frac{1}{2}}$). This dictates the harmonic content of the decay distribution.

Truncation with a clean cut

At parton level only **$j_1 < 1$, $j_2 < 2$** survive ⇒ exactly **23 coefficients** completely describe the decay. Detector effects leak power into higher j — which are dropped because the low-order terms carry the EFT physics.

Single top is special: the t-channel produces a **polarised** top quark — giving access to the **imaginary (CP-odd)** parts of the couplings through the ϕ, ϕ^* dependence.

From a distribution to a short vector

$\cos\theta$ | φ | $\cos\theta^*$ | φ^*

4-D fully-differential decay rate

project onto M-functions

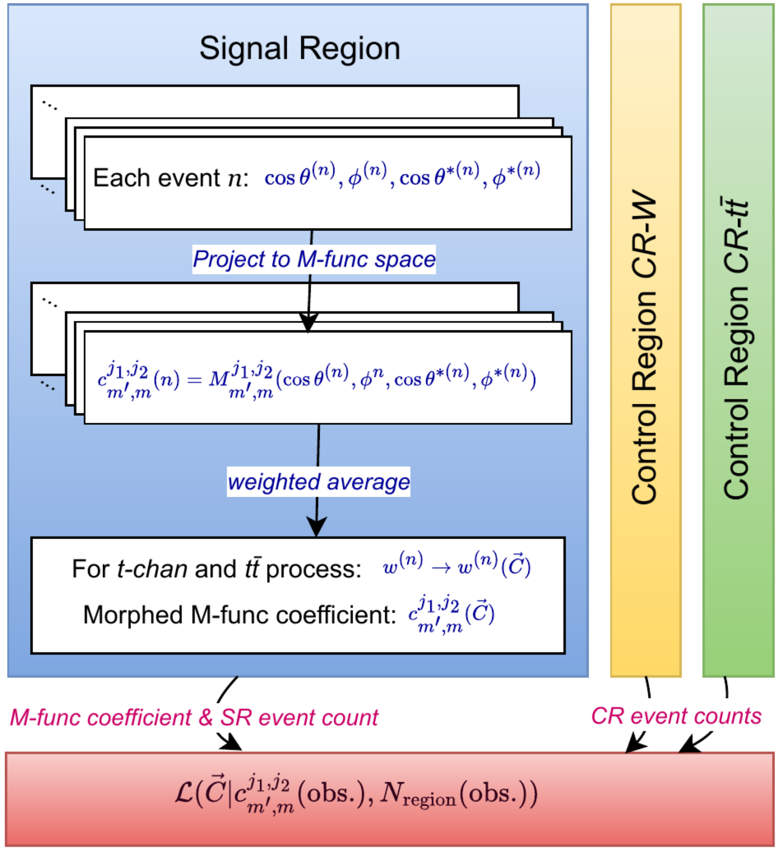
23

M-function coefficients

Complete · compact · each with a statistical error and correlations

From Events to Physics: Morphing & the Likelihood

Per event → M-functions → averaged coefficients → a likelihood built directly in coefficient space.



ATLAS · arXiv:2510.23372, Fig. 3

1 **Reconstruct & project**
Each selected event gives (cos θ, ϕ, cos θ*, ϕ*); the 23 M-functions are evaluated per event and averaged over the sample (weighted for MC).

2 **Morph the EFT dependence**
Every coefficient is a polynomial in the Wilson coefficients — a 203-term morphing function (up to 4th order), obtained by reweighting MC. Interference between operators is built in.

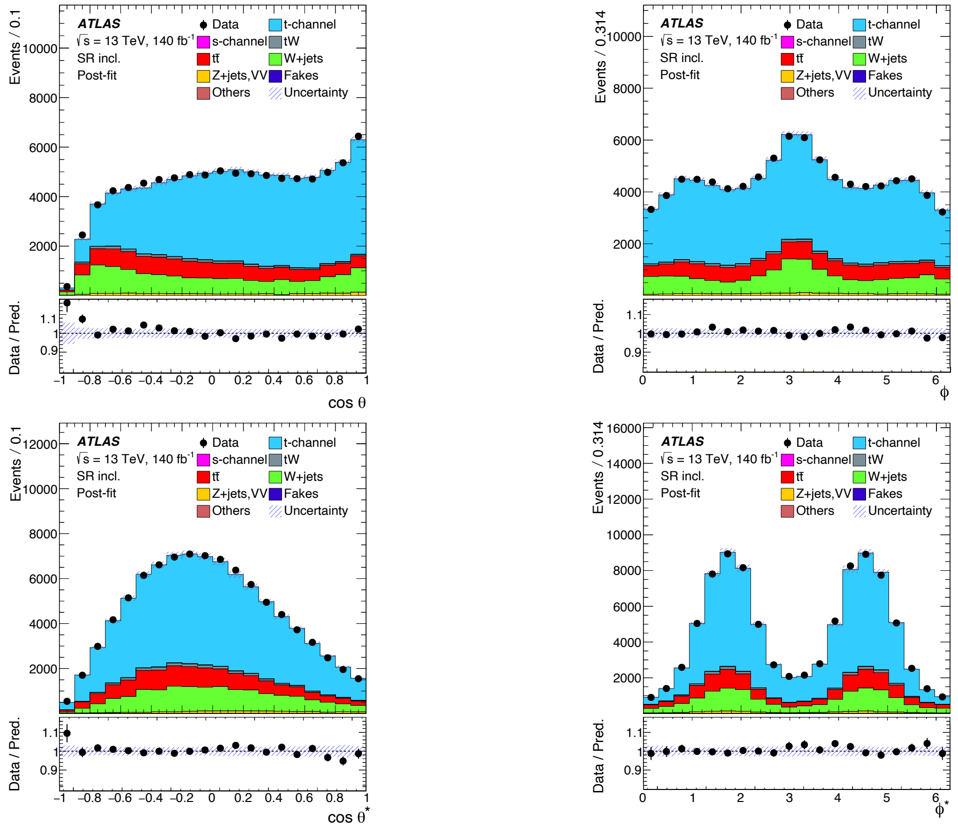
3 **Detector at reco level**
Resolution & acceptance push power into high-j coefficients; restricting to $j_1<1$, $j_2<2$ keeps the EFT-sensitive terms and suppresses detector effects.

4 **One Gaussian likelihood**
Observables = 23×4 coefficients (SR) + event yields (SR + 2 CRs). A χ^2 distance in coefficient space is minimised over the Wilson coefficients.

The Observables in ATLAS Data

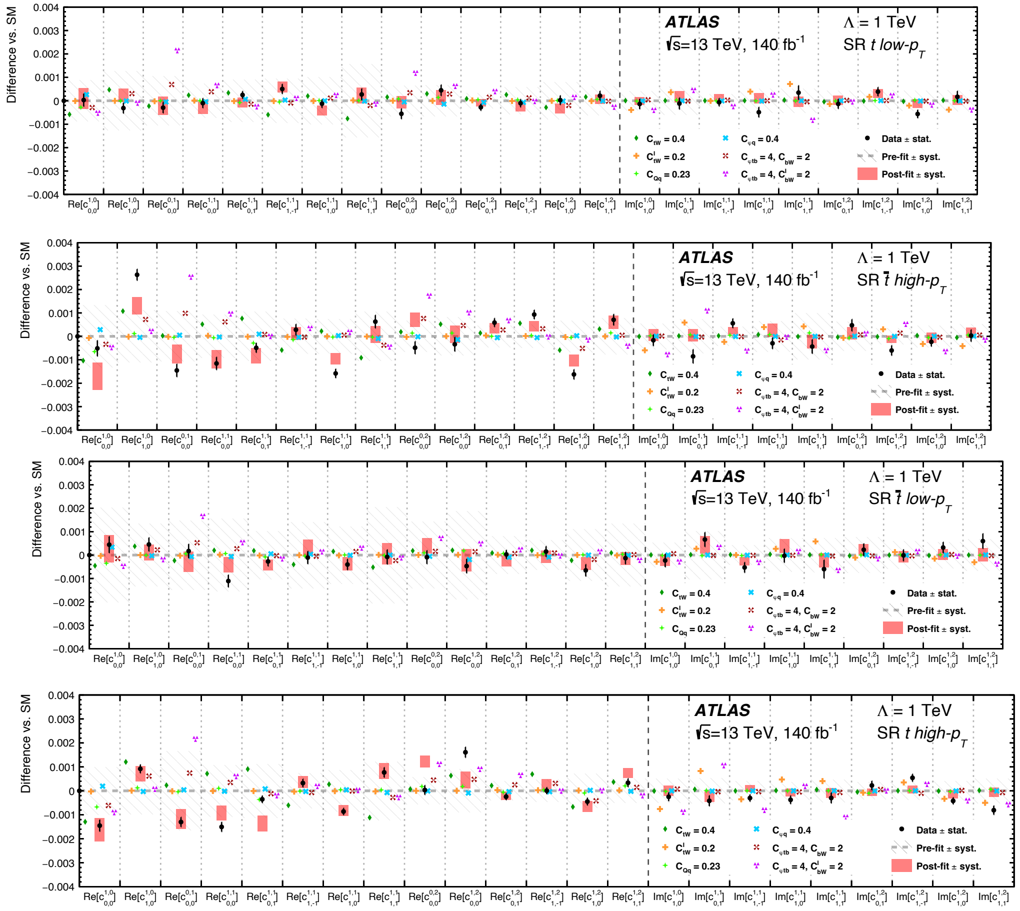
The same information, two views: the four angular shapes — and their compact coefficient encoding.

The four angular distributions



ATLAS · arXiv:2510.23372, Fig. 4

… encoded as M-function coefficients



ATLAS · arXiv:2510.23372, Fig. 6 — deviations of the 23×4 coefficients from the SM

The 4-D distribution on the left is compressed, with no loss, into the coefficient vector on the right — each point an unbinned measurement with its own error, directly sensitive to the Wilson coefficients.

One Formalism, Many Angles: 2 → 3 → 4 → 10

The same machinery scales from a single helicity angle to the full $t\bar{t}$ production-and-decay chain.

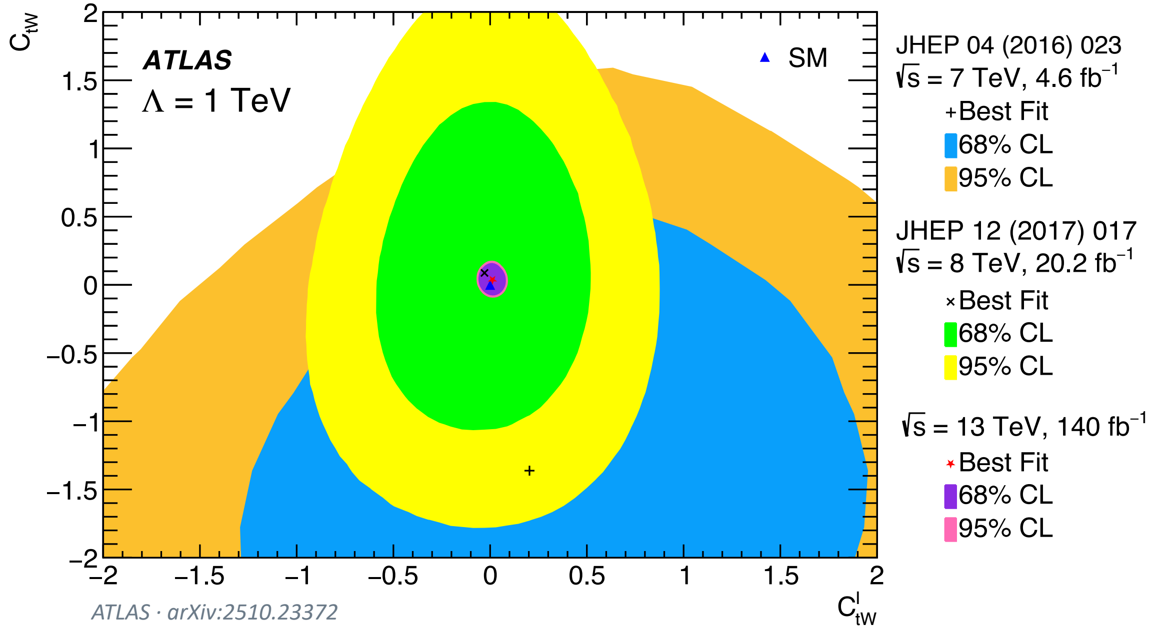
10 **10 angles** — Full $t\bar{t}$: both decays + production angle + rapidity Y. The next frontier.

4 **4 angles** — Full t → Wb → ℓνb decay — 23 coefficients. This ATLAS single-top analysis.

3 **3 angles** — Add a production/plane angle — partial spin information and CP-sensitive azimuths.

2 **2 angles** — Top polarisation — first handle on the couplings.

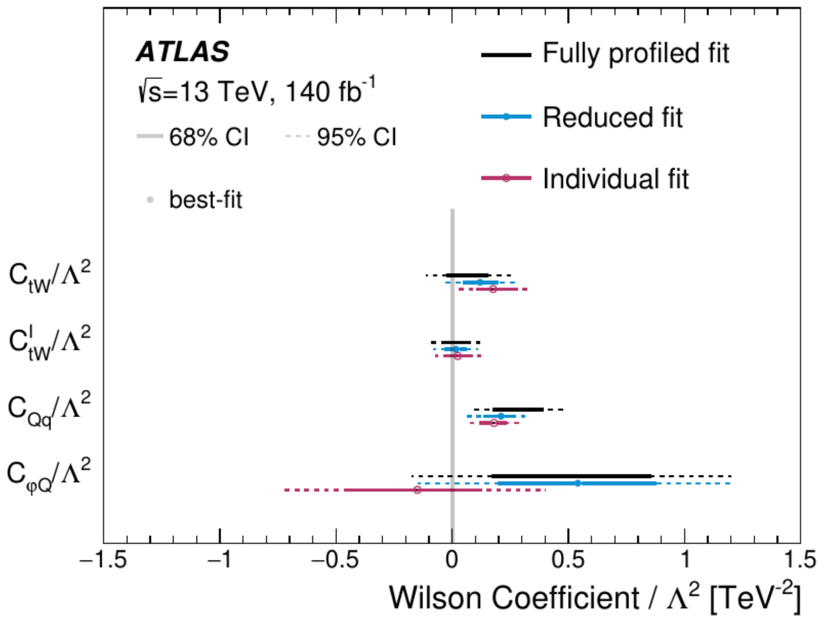
increasing angular dimensionality → increasing physics reach



ATLAS · arXiv:2510.23372

Results — Wilson-Coefficient Constraints

Seven EFT coefficients fitted simultaneously in 140 fb^{-1} — all best-fit points consistent with the Standard Model.



ATLAS · arXiv:2510.23372, Fig. 12(a) — Re/Im c_tW, C_Qq, C_φQ (fine scale)

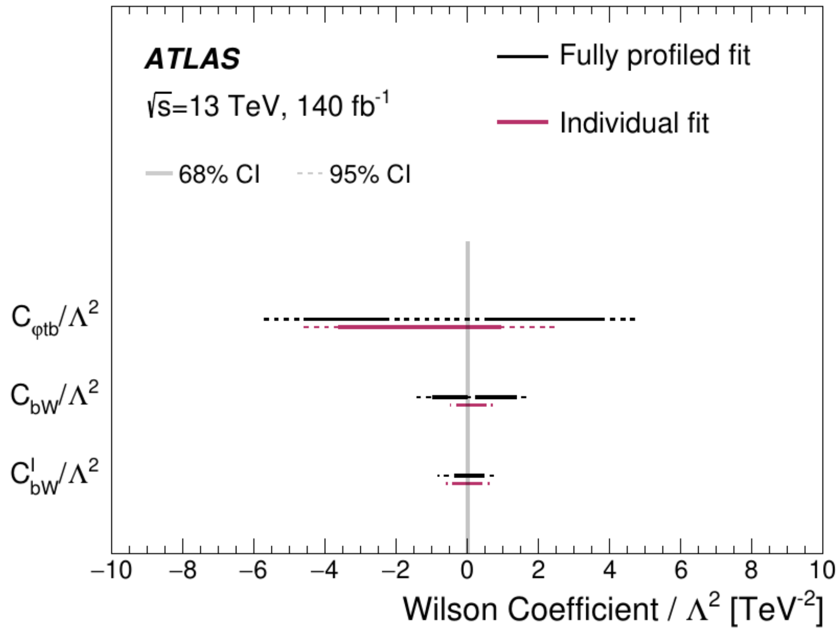


Fig. 12(b) — c_φtb, c_bW, Im c_bW (wide scale; less SM interference)

68% CI (thick) · 95% CI (dotted) · best-fit points · fully-profiled / reduced / individual fit schemes

Tightest on c_tW

The most restrictive limits are on Re and Im **c_tW**. This improves the best previous C_tW bound (8 TeV W-helicity) by a **factor of 2** — without assuming the other WCs vanish.

Access to the CP-odd sector

Imaginary parts (**C^I_tW**, and c_ϕtb c_bW) are constrained by the **imaginary M-function coefficients**; negligible C_tW–C^I_tW correlation. c_bW, c_ϕtb also break a direction to which F_R is blind.

Rate + shape together

C_ϕQ and C_Qq come from event yields in two p_T bins. **C_Qq shows a 2.8σ** high-p_T deviation (data vs Powheg) — flagged for NNLO follow-up.

All best-fit points consistent with the SM · seven Wilson coefficients, three fitting schemes · 140 fb^{-1}, √s = 13 TeV, ATLAS Run 2

The 10-Angle $t\bar{t}$ Analysis: the Full Picture

One likelihood fit to the tenfold-differential production-and-decay rate of $t\bar{t}$ pairs.

Ten kinematic variables

θ_+ , φ_+	**Top decay $t \to W^+b$** direction of W^+ in the top rest frame
θ_- , φ_-	**Antitop decay $\bar{t} \to W^-\bar{b}$** direction of W^- in the antitop rest frame
θ^*_+ , φ^*_+	**$W^+ \to \ell^+\nu$** lepton direction in the W^+ rest frame
θ^*_- , φ^*_-	**$W^- \to \ell^-\bar{\nu}$** lepton direction in the W^- rest frame
θ , Y	**Production** top angle in the ZMF · rapidity of the $t\bar{t}$ system

Lepton+jets channel (~44%) — the only channel allowing full angular reconstruction (dilepton hides two neutrinos). b- and c-tagging identify the fermions.

The 10-angle $t\bar{t}$ analysis

A single likelihood fit to the tenfold differential production + decay rate. The M-function generalises to a product:

$$M = Y(\theta_+,\varphi_+)\, Y(\theta_-,\varphi_-)\, Y(\theta^*_+\ldots)\, Y(\theta^*_-\ldots) \cdot \tilde{P}_l(\cos\theta) \cdot \tilde{h}_n(Y)$$

spherical harmonics × Legendre (production) × Hermite (rapidity)

Dimensionality explodes: $(N+1)^{10}$ coefficients — 59,409 at N=2, ~10^6 at N=3.

Tamed automatically: project onto the SM-tangent subspace (1st + 2nd order), then prune covariance degeneracies → ~27 sensitive discriminants $\tilde{Q}$ carrying spin correlation, both W-helicities, all tWb couplings, even chromo-dipoles.

Taming the Dimensionality

A complete basis is astronomically large — a physics-driven projection keeps only the sensitive directions.

From a complete basis...

$(N+1)^{10}$

$\approx 10^6$ (N=3) · 59,409 (N=2)

project onto SM-tangent + 2nd order

35 directions

1st + 2nd-order variations

drop null directions

32 directions

null directions removed

prune covariance degeneracies

27 $\tilde{Q}$

sensitive discriminants

1. **Restrict to the SM-tangent subspace**
   As the parameters vary, the coefficient vector $\vec{c}(a)$ sweeps a submanifold whose dimension is just the number of physics parameters. Keep only the directions tangent to it at the SM point — deviations $\hat{e}^{(i)}$ that form the rows of a transfer matrix H.

2. **Add second-order sensitivity**
   Parameters that don't interfere with the SM have a vanishing linear response. Quadratic and bilinear terms are added so they aren't lost.

3. **Drop null directions**
   Some $\hat{e}$, $\vec{f}$ vanish identically and carry no information — removed empirically, taking 35 → 32 directions.

4. **Prune degeneracies**
   Diagonalise the covariance $C = A\,D\,A^T$ and cut eigenvalues below ~1% of the largest. Symmetries of the cross-section collapse together, leaving 27 independent discriminants $\tilde{Q}$.

~10^6 possible coefficients → 27 physics-carrying discriminants. A physics-derived analogue of PCA — sensitivity, not variance, sets the axes.

The 10-Angle M-Function: the Mathematics

Same construction as the 4-angle case — a direct product over the ten variables of $t\bar{t}$ production and decay.

Basis function — a product over the ten kinematic variables

$$M_n(\Omega) = Y_{l_1 m_1}(\theta_+,\varphi_+) \cdot Y_{l_2 m_2}(\theta_-,\varphi_-) \cdot Y_{l_3 m_3}(\theta^*_+,\varphi^*_+) \cdot Y_{l_4 m_4}(\theta^*_-,\varphi^*_-) \cdot \tilde{P}_l(\cos\theta) \cdot \tilde{h}_n(Y)$$

collective index $n = \{ l_1,l_2,l_3,l_4, m_1,m_2,m_3,m_4, l, n \}$ $\tilde{P}_l(x) = \sqrt{(2l+1)/2}\, P_l(x)$ $h_n(x) = e^{(-x^2/2)} H_n(x) / (\pi^{1/4} \sqrt{(2^n\, n!)})$

Orthonormal & complete

$$\int M_n\, M_{n'}^*\, d\tilde{\Omega} = \delta_{nn'}$$

with $d\tilde{\Omega} = d\Omega_+\, d\Omega_-\, d\Omega^*_+\, d\Omega^*_-\, d\theta\, dY$. Spherical harmonics, Legendre and Hermite are each orthogonal on their own domain — so the product is a complete orthonormal basis.

Density = a series

$$\rho(\Omega) = \Sigma_n\, c_n\, M_n(\Omega)$$

Coefficients follow by Fourier projection — which is just a weighted average over events: $c_n = \langle M_n^* \rangle = (\Sigma_i\, w_i\, M_n^*(\Omega_i)) / (\Sigma_i\, w_i)$.

Measurement space

$$\chi^2 = (\Delta c)^T (C_d + C_{mc})^{-1} (\Delta c)$$

Covariance $\hat{C}_{nm} = \langle M_n^*\, M_m^* \rangle - \langle M_n^* \rangle \langle M_m^* \rangle$. The MC coefficients depend on the physics parameters, so $\chi^2(a)$ maps the whole space.

In Preparation: EFT Reach of the 10-Angle $t\bar{t}$ Fit

A simultaneous fit to 11 EFT directions — four-quark production, top decay, and both.

Production — four-quark operators, effective (V–A) basis

C_VV | C_VV′ → **rate** & cos θ production-angle shape

C_AA | C_AA′ → **$t\bar{t}$ charge (forward–backward) asymmetry** & spin correlation

C_AV | C_VA | C_AV′ → **top-quark polarisation** (parity-violating)

V / A = vector / axial (light × top currents) · primes = colour-singlet vs colour-octet. Falkowski & Mahmoudi, JHEP 03 (2011) 125.

11 EFT directions fitted simultaneously

7 production · 2 decay · 2 both

Decay — dipole

ctW_Re | ctW_Im

O_tW · right-handed tensor coupling

Production + decay — chromo-dipole

ctG_Re | ctG_Im

O_tG · chromo-magnetic $\hat{\mu}_t$ & chromo-electric $\hat{d}_t$

Imaginary parts ctW_Im and ctG_Im are CP-odd — a direct handle on CP violation.

STATUS · analysis in preparation

Common $t\bar{t}$ EFT sample requested for Run 2 (mc20) & Run 3 (mc23)

MadGraph5 + SMEFTsim 3.0 (top, M_W scheme) · Pythia 8 (A14, NNPDF2.3LO) · Λ = 1 TeV · single + pairwise reweighting grid

Conclusions

Why the M-function angular analysis is so powerful

1 **Unbinned & complete**
No histograms, no empty bins. Completeness means the coefficients carry every correlation in the full angular density.

2 **Compact**
A 4-D distribution becomes 23 numbers; the tenfold $t\bar{t}$ rate reduces to ~27 discriminants. Maximal information, minimal observables.

3 **Errors built in**
Each coefficient is a simple event average, so uncertainties and correlations follow analytically from the sample covariance.

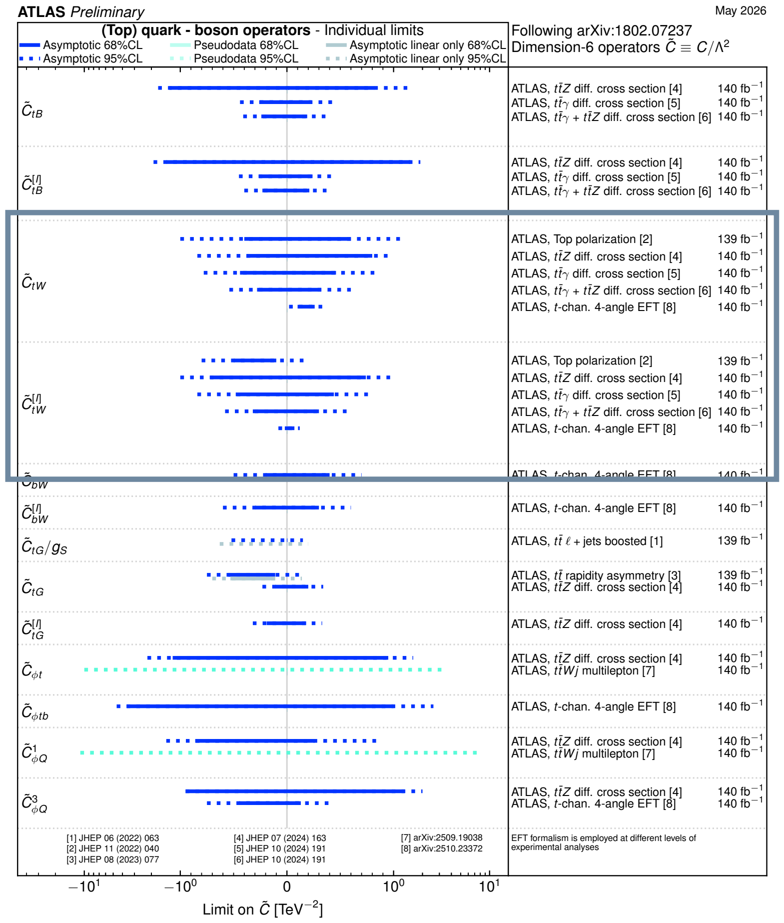
4 **Physically motivated**
The basis follows the helicity structure of the decay, so a clean truncation isolates the EFT-sensitive terms from detector effects.

5 **Sensitive to CP**
Polarised single tops expose the imaginary parts of the couplings through ϕ, ϕ^* — inaccessible to rate-only measurements.

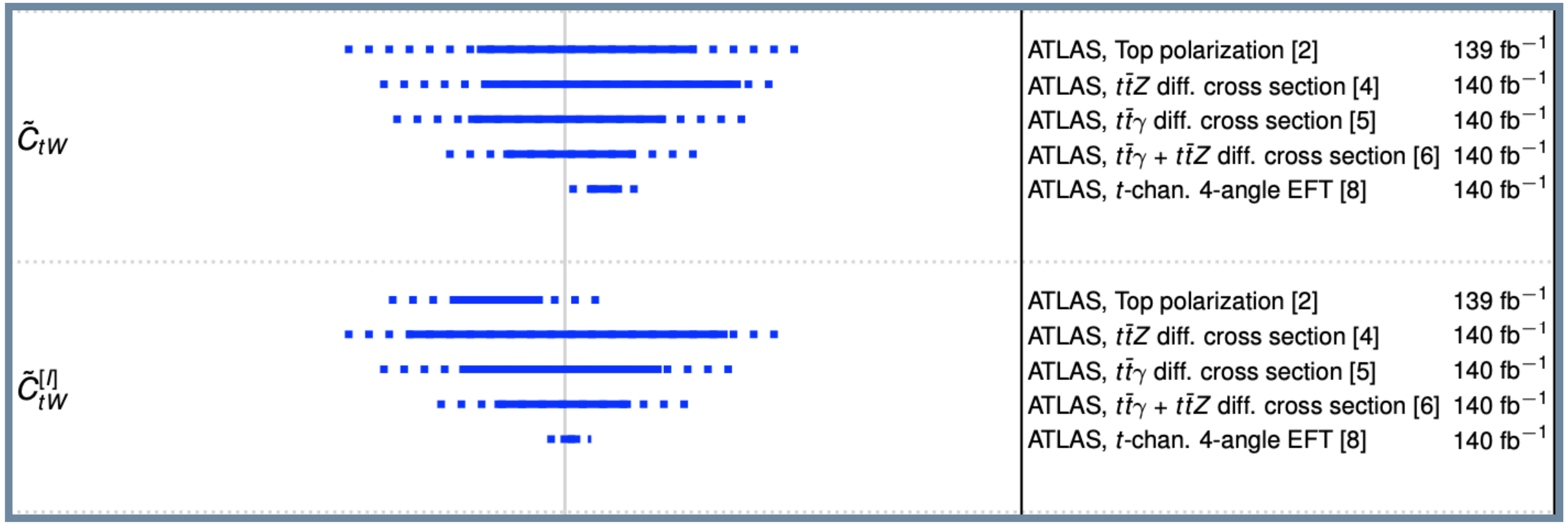
6 **Scalable & unified**
One formalism from 1 to 10 angles: shape + rate combined, ready for future differential and EFT interpretations.

Outlook — the M-function coefficients are, in effect, a **tomography of the top-quark spin density matrix**. For the dedicated quantum-tomography measurement, see the companion talk by **Guillem** [slides to be linked].

Results



ATLAS Preliminary
May 2026
(Top) quark - boson operators - Individual limits
Following arXiv:1802.07237
Dimension-6 operators $\tilde{C} \equiv C/\Lambda^2$
Asymptotic 68%CL
Asymptotic 95%CL
Pseudodata 68%CL
Pseudodata 95%CL
Asymptotic linear only 68%CL
Asymptotic linear only 95%CL
$\tilde{C}_{tB}$
ATLAS, $t\bar{t}Z$ diff. cross section [4] 140 fb^{-1}
ATLAS, $t\bar{t}\gamma$ diff. cross section [5] 140 fb^{-1}
ATLAS, $t\bar{t}\gamma$ + $t\bar{t}Z$ diff. cross section [6] 140 fb^{-1}
$\tilde{C}_{tB}^{[I]}$
ATLAS, $t\bar{t}Z$ diff. cross section [4] 140 fb^{-1}
ATLAS, $t\bar{t}\gamma$ diff. cross section [5] 140 fb^{-1}
ATLAS, $t\bar{t}\gamma$ + $t\bar{t}Z$ diff. cross section [6] 140 fb^{-1}
$\tilde{C}_{tW}$
ATLAS, Top polarization [2] 139 fb^{-1}
ATLAS, $t\bar{t}Z$ diff. cross section [4] 140 fb^{-1}
ATLAS, $t\bar{t}\gamma$ diff. cross section [5] 140 fb^{-1}
ATLAS, $t\bar{t}\gamma$ + $t\bar{t}Z$ diff. cross section [6] 140 fb^{-1}
ATLAS, t-chan. 4-angle EFT [8] 140 fb^{-1}
$\tilde{C}_{tW}^{[I]}$
ATLAS, Top polarization [2] 139 fb^{-1}
ATLAS, $t\bar{t}Z$ diff. cross section [4] 140 fb^{-1}
ATLAS, $t\bar{t}\gamma$ diff. cross section [5] 140 fb^{-1}
ATLAS, $t\bar{t}\gamma$ + $t\bar{t}Z$ diff. cross section [6] 140 fb^{-1}
ATLAS, t-chan. 4-angle EFT [8] 140 fb^{-1}
$\tilde{C}_{bW}$
ATLAS, t-chan. 4-angle EFT [8] 140 fb^{-1}
$\tilde{C}_{bW}^{[I]}$
ATLAS, t-chan. 4-angle EFT [8] 140 fb^{-1}
$\tilde{C}_{tG}/g_S$
ATLAS, $t\bar{t}$ ℓ + jets boosted [1] 139 fb^{-1}
$\tilde{C}_{tG}$
ATLAS, $t\bar{t}$ rapidity asymmetry [3] 139 fb^{-1}
ATLAS, $t\bar{t}Z$ diff. cross section [4] 140 fb^{-1}
$\tilde{C}_{tG}^{[I]}$
ATLAS, $t\bar{t}Z$ diff. cross section [4] 140 fb^{-1}
$\tilde{C}_{\phi t}$
ATLAS, $t\bar{t}Z$ diff. cross section [4] 140 fb^{-1}
ATLAS, $t\bar{t}Wj$ multilepton [7] 140 fb^{-1}
$\tilde{C}_{\phi tb}$
ATLAS, t-chan. 4-angle EFT [8] 140 fb^{-1}
$\tilde{C}_{\phi Q}^{1}$
ATLAS, $t\bar{t}Z$ diff. cross section [4] 140 fb^{-1}
ATLAS, $t\bar{t}Wj$ multilepton [7] 140 fb^{-1}
$\tilde{C}_{\phi Q}^{3}$
ATLAS, $t\bar{t}Z$ diff. cross section [4] 140 fb^{-1}
ATLAS, t-chan. 4-angle EFT [8] 140 fb^{-1}
[1] JHEP 06 (2022) 063
[2] JHEP 11 (2022) 040
[3] JHEP 08 (2023) 077
[4] JHEP 07 (2024) 163
[5] JHEP 10 (2024) 191
[6] JHEP 10 (2024) 191
[7] arXiv:2509.19038
[8] arXiv:2510.23372
EFT formalism is employed at different levels of experimental analyses
-10^1
-10^0
0
10^0
10^1
Limit on $\tilde{C}$ [TeV^{-2}]



$\tilde{C}_{tW}$
ATLAS, Top polarization [2] 139 fb^{-1}
ATLAS, $t\bar{t}Z$ diff. cross section [4] 140 fb^{-1}
ATLAS, $t\bar{t}\gamma$ diff. cross section [5] 140 fb^{-1}
ATLAS, $t\bar{t}\gamma$ + $t\bar{t}Z$ diff. cross section [6] 140 fb^{-1}
ATLAS, t-chan. 4-angle EFT [8] 140 fb^{-1}
$\tilde{C}_{tW}^{[I]}$
ATLAS, Top polarization [2] 139 fb^{-1}
ATLAS, $t\bar{t}Z$ diff. cross section [4] 140 fb^{-1}
ATLAS, $t\bar{t}\gamma$ diff. cross section [5] 140 fb^{-1}
ATLAS, $t\bar{t}\gamma$ + $t\bar{t}Z$ diff. cross section [6] 140 fb^{-1}
ATLAS, t-chan. 4-angle EFT [8] 140 fb^{-1}