ATLAS results on associated top quark production (Top + X)

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on behalf of the ATLAS Collaboration

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Introduction

- The LHC is a top-quark factory, providing unique access to rare associated top-quark production
- With the full Run 2 ATLAS dataset, Top + X processes can be explored in complementary regimes:
  - **Rare** final states
  - **High-energy** phase space
  - **Angular** observables
- ✓Results covered in this talk:

$t\bar{t}\gamma\gamma$, $t\bar{t}Wj_{EW}$, high-mass $t\bar{t}\ell^{+}\ell^{-}$, single-top angular decay rates

- Probes of **top-quark electroweak** interactions
- **Important backgrounds** to Higgs and BSM searches
- Sensitive to **Effective Field Theory** parameter

Observation of $t\bar{t}\gamma\gamma$

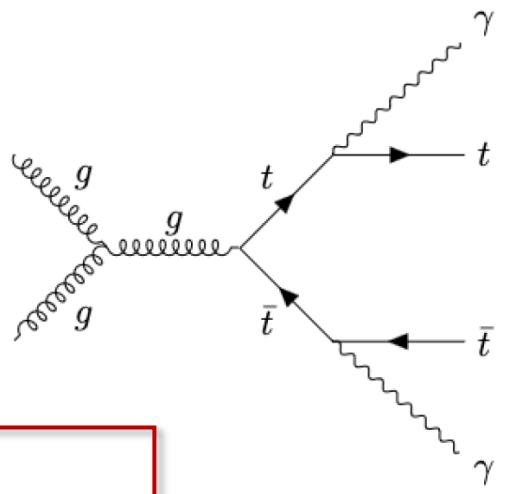
Phys. Lett. B 874 (2026) 140195

➢First **observation** of $t\bar{t}\gamma\gamma$ in lepton + jets channel

- Observed significance: $\mathbf{5.2\sigma}$

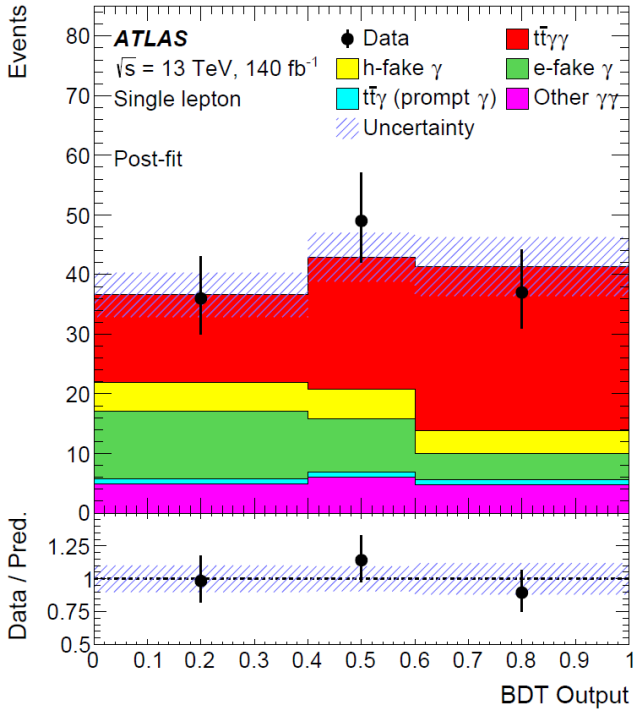
- **Fiducial cross section** measured

$$\sigma_{fid}(t\bar{t}\gamma\gamma) = 2.42^{+0.58}_{-0.53} fb$$
$$= 2.42^{+0.46}_{-0.38}(\text{stat.})^{+0.35}_{-0.38}(\text{syst.})$$



- Ratio to the $t\bar{t}\gamma$ cross section

$$R_{t\bar{t}\gamma\gamma/t\bar{t}\gamma} = \left(3.30^{+0.70}_{-0.65}\right) \times 10^{-3}$$
$$= \left(3.30^{+0.63}_{-0.55}(stat.)^{+0.32}_{-0.34}(syst.)\right) \times 10^{-3}$$



- **Reference** measurement for future theoretical developments
- Relevant **irreducible background** in measurement of $t\bar{t}H(H \to \gamma\gamma)$
- Ratio measurement benefits **reduces correlated uncertainties**
  - Sensitive observable to **anomalous dipole moments**

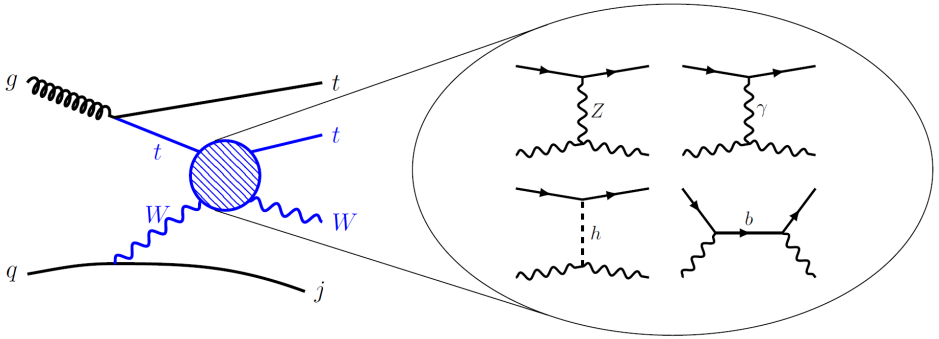
Search for $t\bar{t}Wj_{EW}$

arXiv:2509.19038
Submitted to Phys. Rev. D

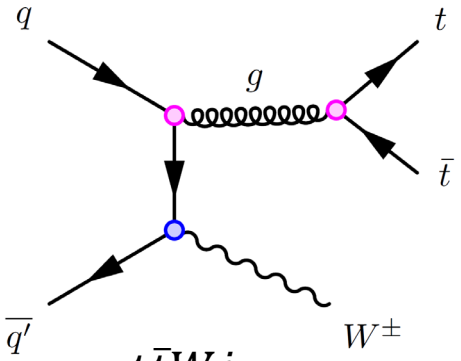
ATLAS EXPERIMENT

➢First direct probe of ***tW* scattering vertex**

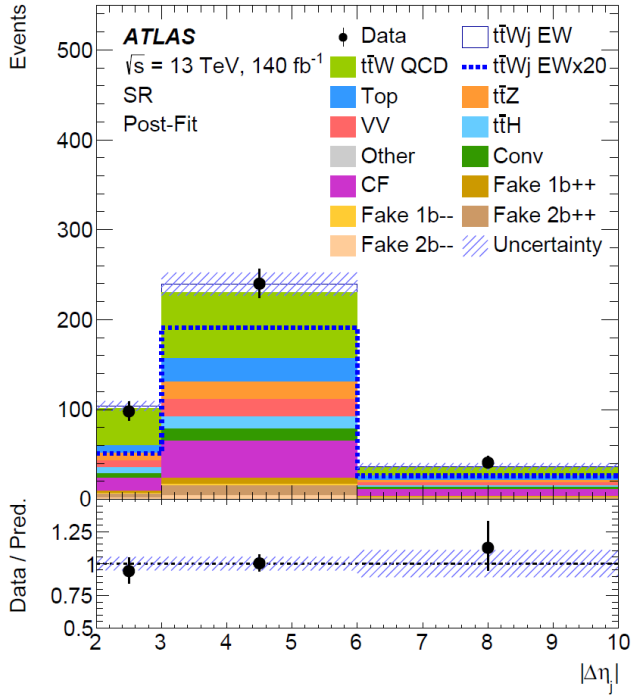
- Search in same-sign dilepton channel
- **Forward-jet topology** used to separate EW from QCD $t\bar{t}W$



$t\bar{t}Wj_{EW}$



$t\bar{t}Wj_{QCD}$



- $\mu_{t\bar{t}Wj_{EW}} = 0.9^{+2.4}_{-3.0}$
  $= 0.9^{+0.9}_{-0.9}(stat.)^{+2.2}_{-2.8}(syst.)$
- $\sigma_{t\bar{t}Wj_{EW}} < 251\text{fb}$ (95% CL)

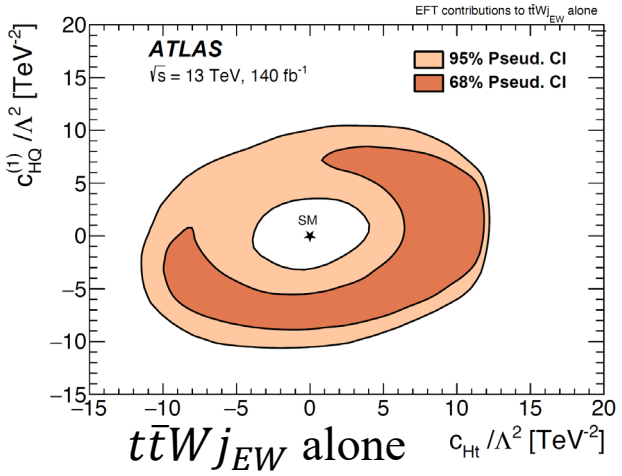
- Systematics dominated by $t\bar{t}W$ QCD modelling, jet & E_T^{miss}, and fake leptons

$t\bar{t}Wj_{EW}$ EFT Interpretation

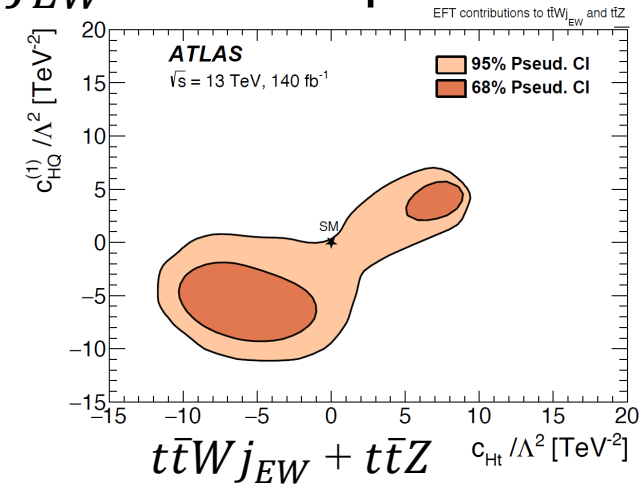
arXiv:2509.19038
Submitted to Phys. Rev. D

ATLAS EXPERIMENT

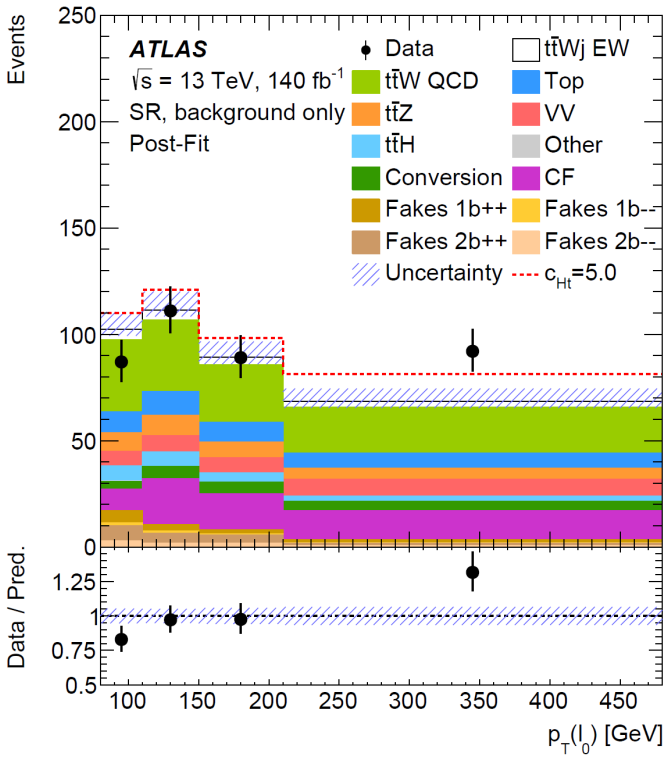
- **Quadratic** energy dependence to new physics
  - Operator considered: O_{Ht} and $O_{HQ}^{(1)}$
- Optimized signal region on $p_T(\ell_0)$, the leading lepton
- Fit EFT effects in both $t\bar{t}Wj_{EW}$ and $t\bar{t}Z$ productions



$t\bar{t}Wj_{EW}$ alone



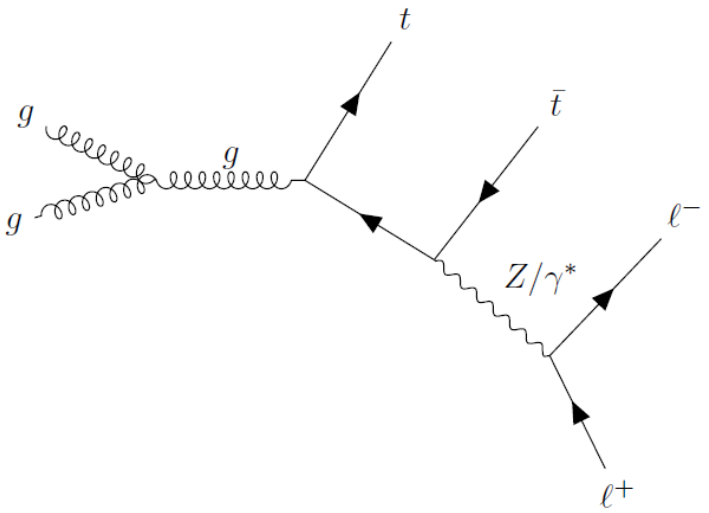
$t\bar{t}Wj_{EW} + t\bar{t}Z$



- **Highest-p_T bin** drives a preference for non-zero Wilson coefficients
- SM remains within the 95% confidence interval
- Combining $t\bar{t}Wj_{EW}$ with $t\bar{t}Z$ **reduces degeneracies** between O_{Ht} and $O_{HQ}^{(1)}$

High-mass $t\bar{t}\ell^+\ell^-$ production

Eur. Phys. J. C 85 (2025) 1434



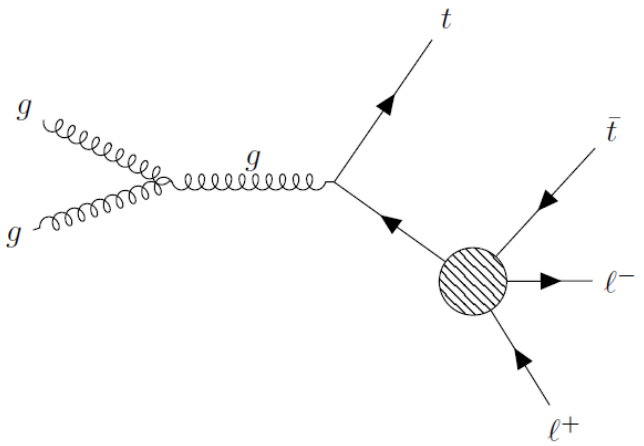
- Target the **off-shell/high-mass $t\bar{t}\ell^+\ell^-$** region
  - $m(\ell^+\ell^-) > m_Z + 10$ GeV
- Three-lepton final state with high $t\bar{t}\ell^+\ell^-$ purity
- Split into $t\bar{t}e^+e^-$ and $t\bar{t}\mu^+\mu^-$ channels
- Model-independent visible cross-section upper limits set at $m(\ell^+\ell^-) > 550$ GeV (**BSM-rich**)

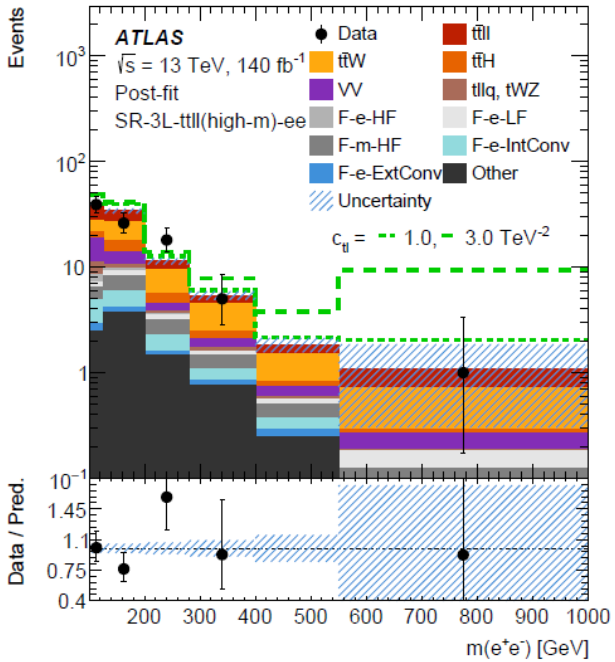
	$m(\ell^+\ell^-) > m_Z + 10$ GeV			$m(\ell^+\ell^-) > 550$ GeV
	$\mu(t\bar{t}\ell^+\ell^-)$	Significance	Exp. 95% CL upper limit	Obs. 95% CL upper limit
$t\bar{t}e^+e^-$	$0.8^{+0.6}_{-0.6}$	1.4σ	25.4 ab	26.9 ab
$t\bar{t}\mu^+\mu^-$	$1.1^{+0.5}_{-0.5}$	2.5σ	27.5 ab	26.0 ab
$t\bar{t}\ell^+\ell^-$	$1.0^{+0.4}_{-0.4}$	2.9σ	30.5 ab	30.8 ab

- **First direct probe** of the high-mass $t\bar{t}\ell^+\ell^-$ region
- **Compatible** with the SM

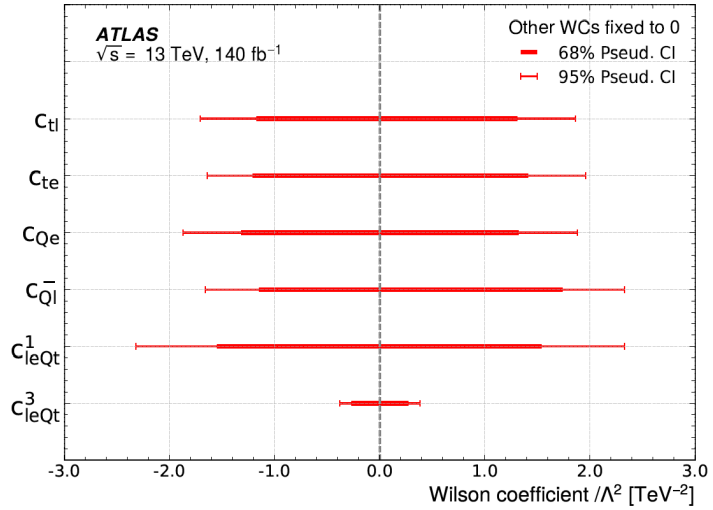
$t\bar{t}\ell^+\ell^-$ EFT Interpretation

Eur. Phys. J. C 85 (2025) 1434

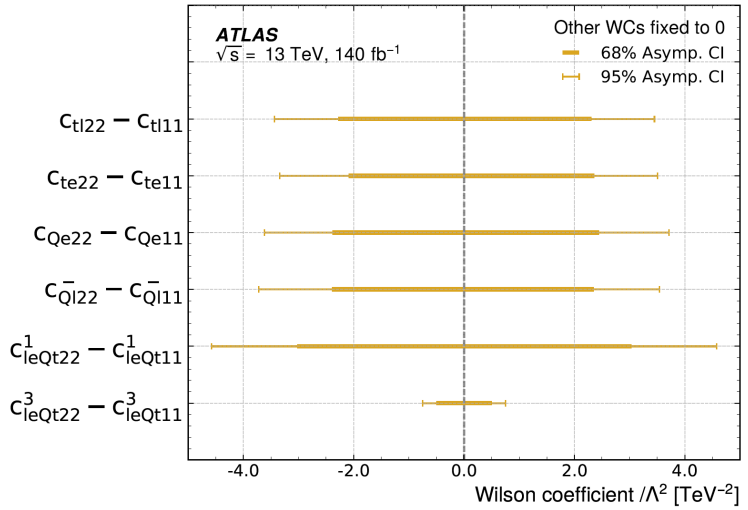




- ➢EFT effect is **enhanced at high $m(\ell^+\ell^-)$ region**
- Six operators considered:
  - O_{tl}, O_{te}, O_{Qe}, O_{Ql}^- $(O_{Ql}^1 - O_{Ql}^3)$, O_{leQt}^1, O_{leQt}^3
- ○ Inspiration from Lepton Flavor Universality (LFU)
  - Split between **lepton generations**
  - **Flavor-violation** test: $c_X^{(22)} - c_X^{(11)}$, $11: e^+e^-$, $22: \mu^+\mu^-$



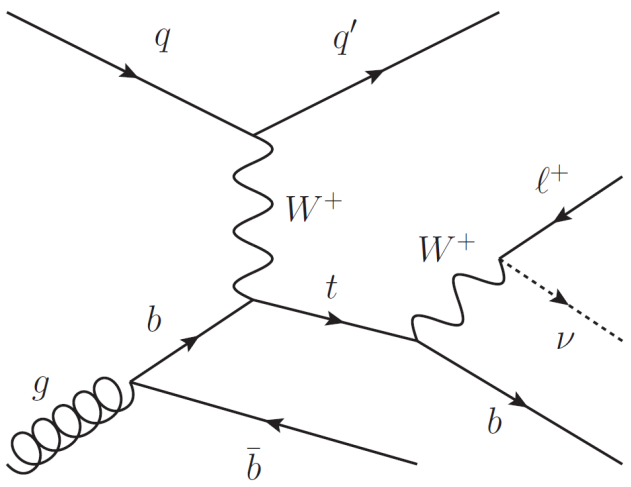
Flavor-inclusive assumption



LFU-violation test

Single-top Angular Decay Rates

arXiv:2510.23372
Submitted to JHEP



t-channel single-top

- Largest single-top production channel
- Probe the charged-current tWb vertex
- Produce **polarized** top quarks

EFT sensitivity

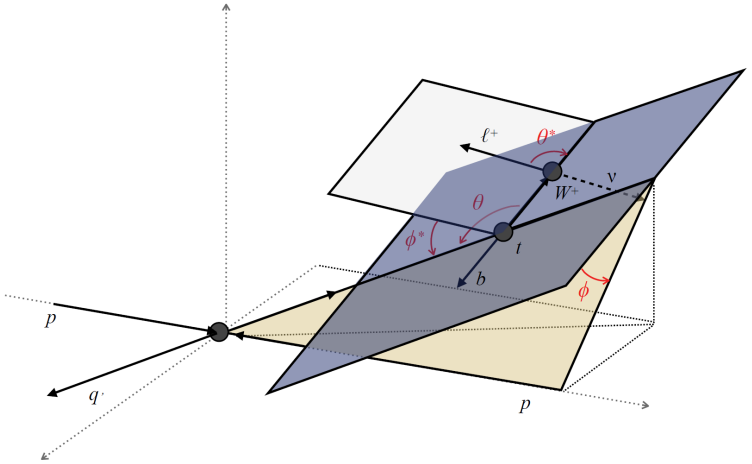
- Target dimension-six operators
- Angular observables provide access to **imaginary Wilson Coefficients**

➢ Fully described by four decay angles $(\boldsymbol{\theta}, \boldsymbol{\phi}, \boldsymbol{\theta}^*, \boldsymbol{\phi}^*)$

➢ Project the **quadruple-differential** angular rate onto **23** orthonormal M-functions

○ $(\mathbf{23} + 3\ \text{regions}) \times 2\ \text{lepton signs} \times 2\ \text{p}_\text{T}\ \text{bins} = \mathbf{104}$

$\sim \boldsymbol{N^4}$ observables in fourfold EFT templates, ×impractical

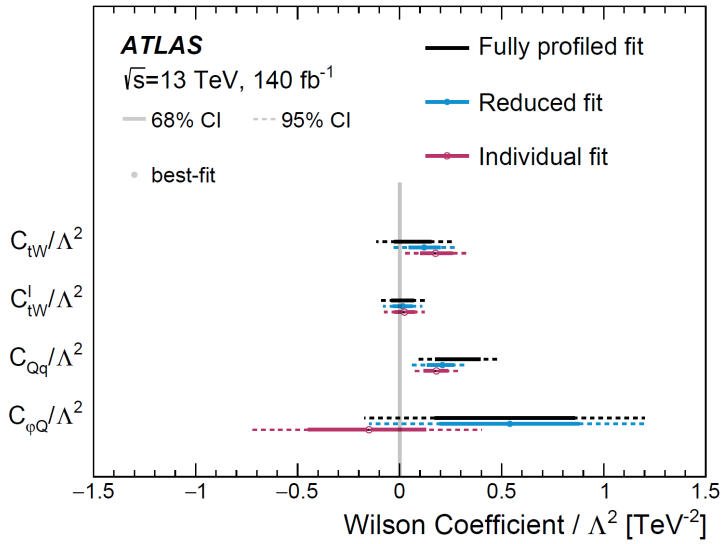


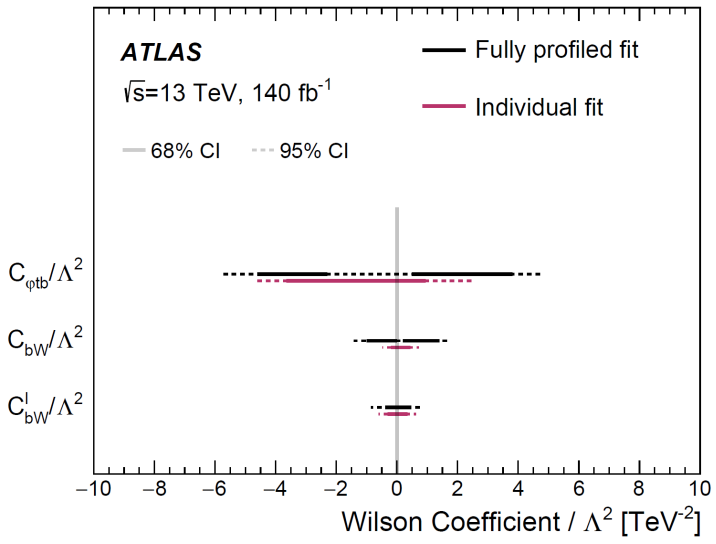
Single-top Angular – EFT

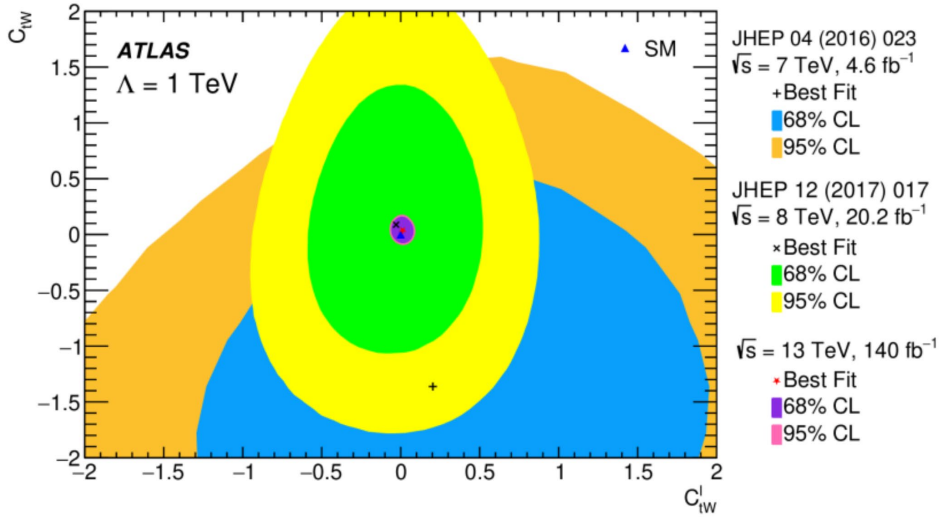
arXiv:2510.23372
Submitted to JHEP

- Both the SM hypothesis and the EFT best-fit describe the data well

SM prediction: $\chi^2 = 105.2\ (CL = 45\%), N_{DoF} = 104$
EFT best – fit: $\chi^2 = 87.4\ (CL = 70\%), N_{DoF} = 95$







History: 2 Angle → 3 Angle → 4 Angle

- Angular information improves sensitivity
- A mild $\boldsymbol{2.8\sigma}$ deviation in C_{Qq}, driven by **high-p_T** event yields
  - Not interpreted as BSM evidence, motivates further modelling studies

Summary

- Latest results on Top + X processes with full Run 2 data

$t\bar{t}\gamma\gamma$ | $t\bar{t}Wj_{EW}$ | $t\bar{t}\ell^+\ell^-$ | Single-top Angular

- Generally observed **good agreement** with the SM so far
- Important constraints on the **top-quark electroweak** sector
  - **EFT** effects in high-energy and angular observables

- Looking forward to more data in Run 3 and more advanced analysis/statistical methods!

BACKUP

$t\bar{t}\gamma\gamma$ systematics breakdown

Table 1: Summary of the relative impact of all the systematic uncertainties, in percentage, on the $t\bar{t}\gamma\gamma$ fiducial inclusive cross section and $R_{t\bar{t}\gamma\gamma/t\bar{t}\gamma}$ grouped into different categories. The category 'Jet' corresponds to the effect of JES, jet resolution and JVT uncertainties, 'Photon' and 'Leptons' include all experimental uncertainties related to photons and leptons (including trigger uncertainties), respectively.

Source	$\Delta\sigma_{t\bar{t}\gamma\gamma}/\sigma_{t\bar{t}\gamma\gamma}$ [%]	$\Delta R_{t\bar{t}\gamma\gamma/t\bar{t}\gamma}/R_{t\bar{t}\gamma\gamma/t\bar{t}\gamma}$ [%]
$t\bar{t}\gamma\gamma$ modelling	1.4	1.3
Prompt-photon background norm. & modelling	4.4	5.8
Fake-photon background estimates	6.5	0.5
Fake-lepton background estimate	–	0.9
Jet	9.7	5.9
Photon	6.5	4.0
b-tagging	3.4	1.0
Leptons	1.5	0.3
Luminosity	1.4	0.1
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.4	1.1
Pile-up	1.6	1.4
MC statistical uncertainties	2.5	2.8
Total systematic uncertainty	15.0	10.0

$t\bar{t}Wj_{EW}$ limitation

- $t\bar{t}Wj_{QCD}$ is the dominant irreducible background
  - constrained in dedicated 4j control regions
  - normalization free-floating in the profile likelihood
- Sensitivity relies on forward-jet topology
  - jet / MET uncertainties enter as leading systematics
- Fake leptons are data-driven but correlated with $t\bar{t}Wj_{QCD}$
  - Matrix Method with ttW-dependent fake estimate
  - adjusted self-consistently in the final fit

Uncertainty Source	$\Delta\mu_{t\bar{t}Wj_{EW}}$	
Total Statistical and Systematic	+2.4	/−3.0
Total Systematic	+2.2	/−2.8
Total Statistical	+0.9	/−0.9
$t\bar{t}W_{QCD}$ normalization	+1.6	/−2.2
Jets and E_T^{miss}	+1.6	/−2.2
$t\bar{t}Wj_{EW}$ modeling	+0.4	/−1.5
$t\bar{t}W_{QCD}$ modeling	+0.6	/−1.2
MC statistical	+0.7	/−0.9
Fake leptons	+0.5	/−0.7
Pileup	+0.2	/−0.5
$t\bar{t}Z$ normalization	+0.3	/−0.4
$t\bar{t}Z$ modeling	+0.23	/−0.27
Background cross sections	+0.18	/−0.31
Electron ID and isolation	+0.09	/−0.09
b-tagging	+0.09	/−0.09
Muons	+0.07	/−0.07
tZq modeling	+0.07	/−0.07
Luminosity	+0.034	/−0.034
Electron energy scale and resolution	+0.024	/−0.024
JVT	< 0.01	

$t\bar{t}Wj_{EW}$ EFT evolution

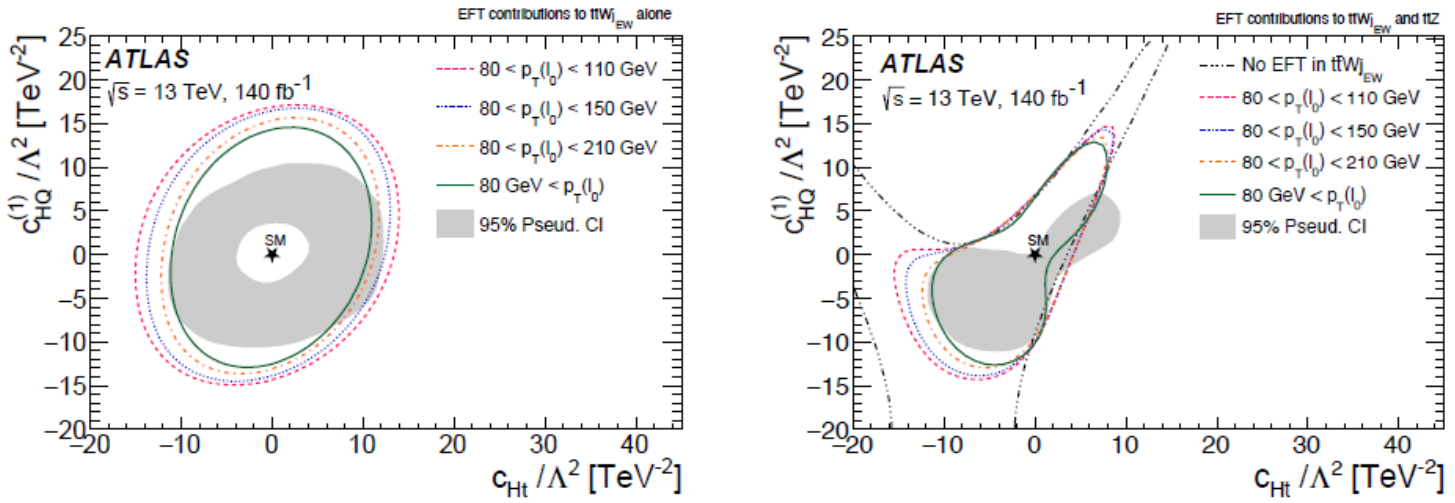
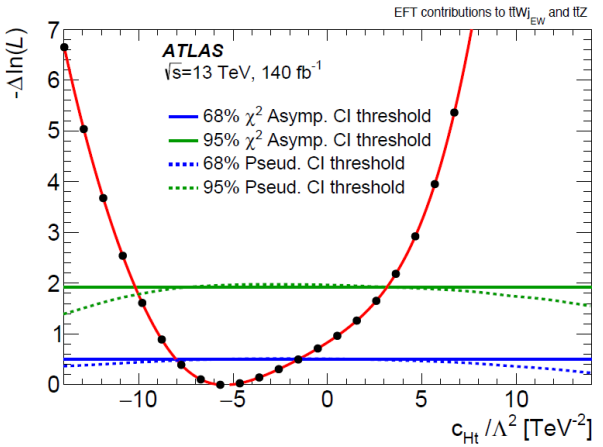
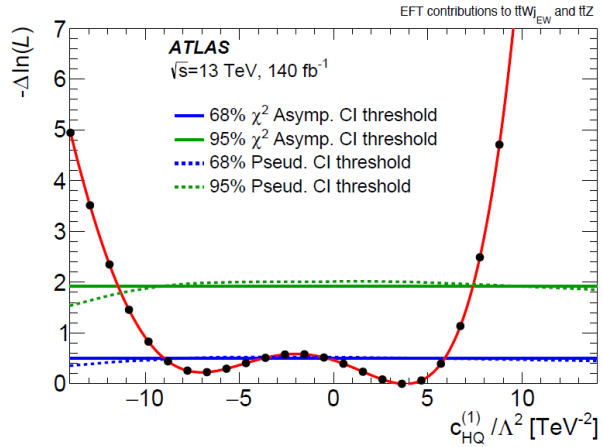
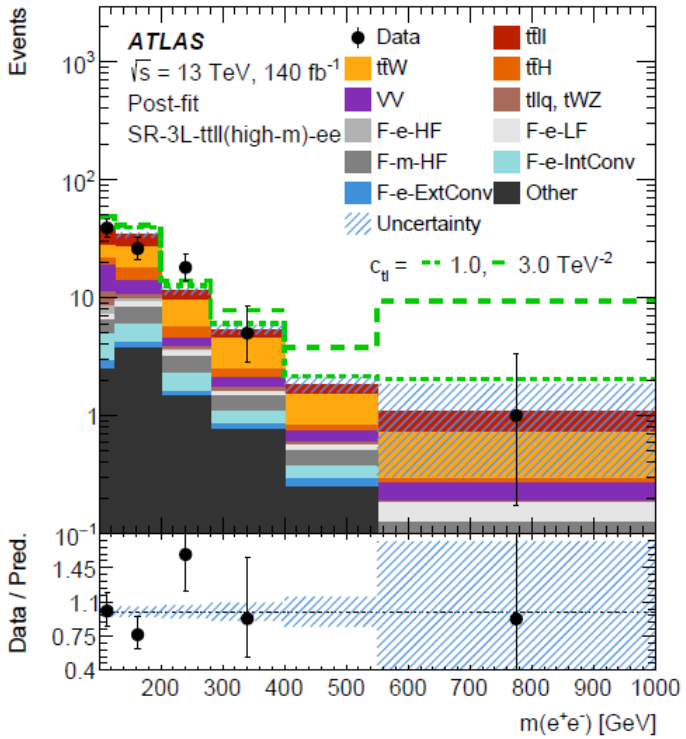
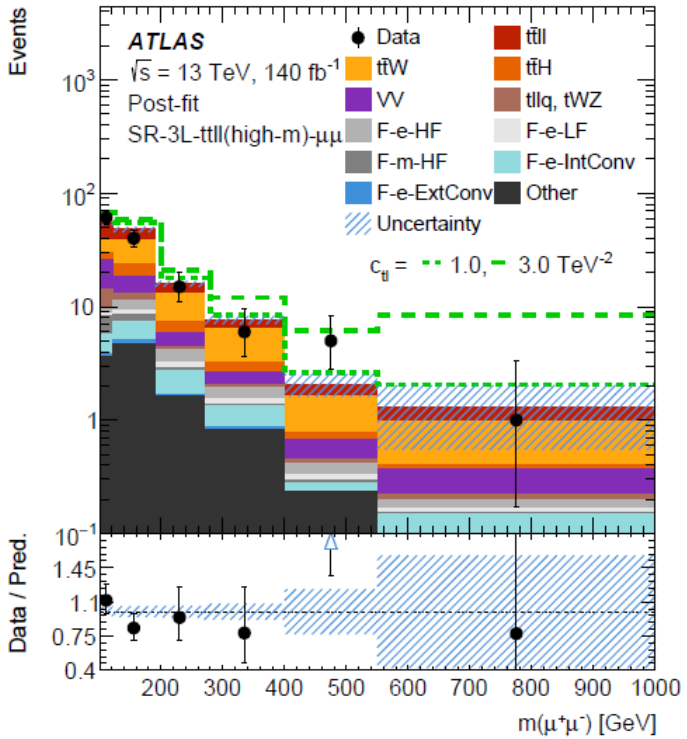


Figure 11: Two-dimensional 68% and 95% confidence intervals for the simultaneous EFT fit to data of the Wilson coefficients c_{Ht} and $c^{(1)}_{HQ}$, considering their impact on (a) the $t\bar{t}Wj_{\mathrm{EW}}$ process alone or (b) on both the $t\bar{t}Wj_{\mathrm{EW}}$ and $t\bar{t}Z$ processes. The dashed, dotted and solid line contours use the asymptotic likelihood approach, and highlight the energy-growth behavior of the EFT operators. On (b), the outermost open contour shows the confidence interval when considering the EFT operators on $t\bar{t}Z$ only. Subsequently, on both (a) and (b) the closed contours consider the EFT operators also on $t\bar{t}Wj_{\mathrm{EW}}$ in the four p_{T} bins in the signal region. The outer closed contour uses only the first p_{T} bin and moving inwards the contours include higher energy information for the 2-bin, 3-bin and 4-bins confidence intervals. The solid filled region is the 95% confidence interval determined using pseudo-datasets (Pseud.) and the full signal region.






ATLAS
√s = 13 TeV, 140 fb-1
Post-fit
SR-3L-ttll(high-m)-ee
Data
tt̄W
VV
F-e-HF
F-m-HF
F-e-ExtConv
Uncertainty
tt̄ll
tt̄H
tllq, tWZ
F-e-LF
F-e-IntConv
Other
ctl = 1.0, 3.0 TeV-2
Events
Data / Pred.
m(e+e-) [GeV]


ATLAS
√s = 13 TeV, 140 fb-1
Post-fit
SR-3L-ttll(high-m)-μμ
Data
tt̄W
VV
F-e-HF
F-m-HF
F-e-ExtConv
Uncertainty
tt̄ll
tt̄H
tllq, tWZ
F-e-LF
F-e-IntConv
Other
ctl = 1.0, 3.0 TeV-2
Events
Data / Pred.
m(μ+μ-) [GeV]

Something more about C_{Qq} exceed

- C_{Qq} modifies the production side of t-channel single-top events through a four-quark interaction
- Its effect is more pronounced in the high-pT region
- Driven by high-pT SR event yields vs Powheg Box v2 prediction
- Further studies of higher-order modelling, e.g. NNLO effects, are needed