Recent Experimental EFT Results in the Top Quark sector

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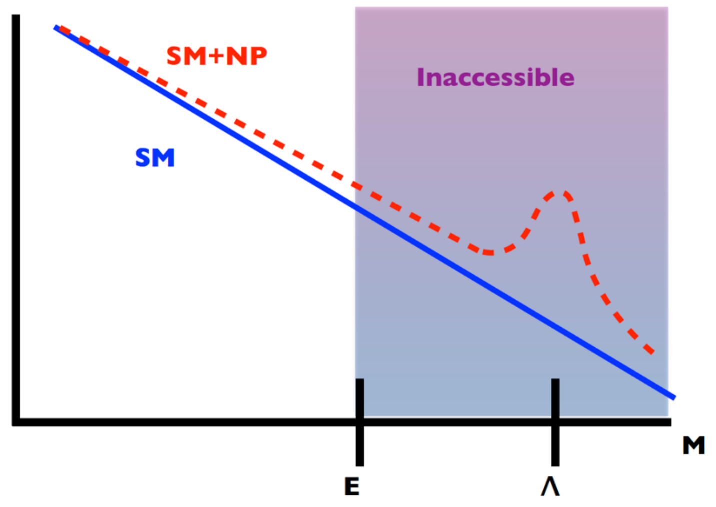
SMEFT - a look into new physics

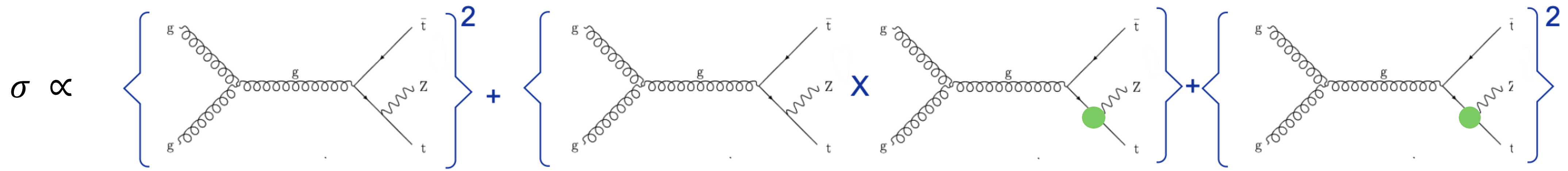
- No direct BSM observed → need a **model-independent** handle on subtle deviations
- SMEFT extends the SM with higher-dimensional operators:

$$\mathcal{L} = \mathcal{L}_{\text{SM}}^{(4)} + \Sigma_{i,D} c_i^{(D)} \frac{\mathcal{O}_i^{(D)}}{\Lambda^{D-4}}$$

  - C_i: Wilson coefficients, encode strength of new physics
  - Λ: New physics scale



- EFT series can be truncated at different orders with different dependence on the cut-off scales



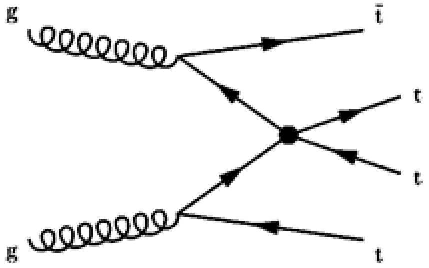
Why the Top Quark?

Heaviest:
likely the first to feel BSM effects

(mostly ☺) Unhadronized:
spin and decay structure preserved

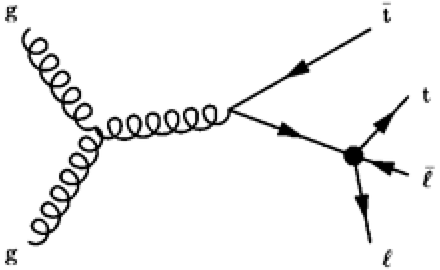
Couples to everything:
gauge, Higgs, flavour sectors

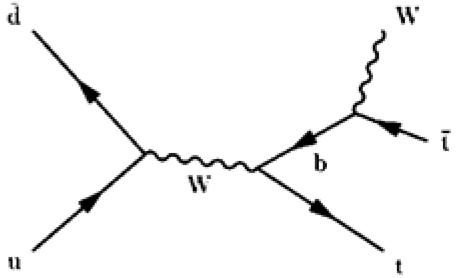
Accessible in many ways:
•Strong ($t\bar{t}$, 4t),
•electroweak (ttZ, tWZ),
•rare (same-sign tt)



4-heavy quark operators

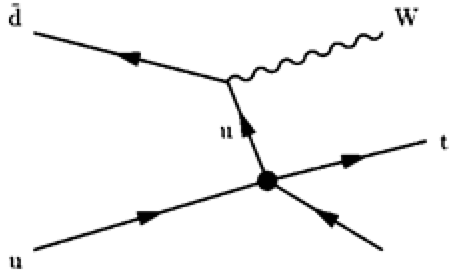
heavy quark +lepton operators





heavy quark + boson operators

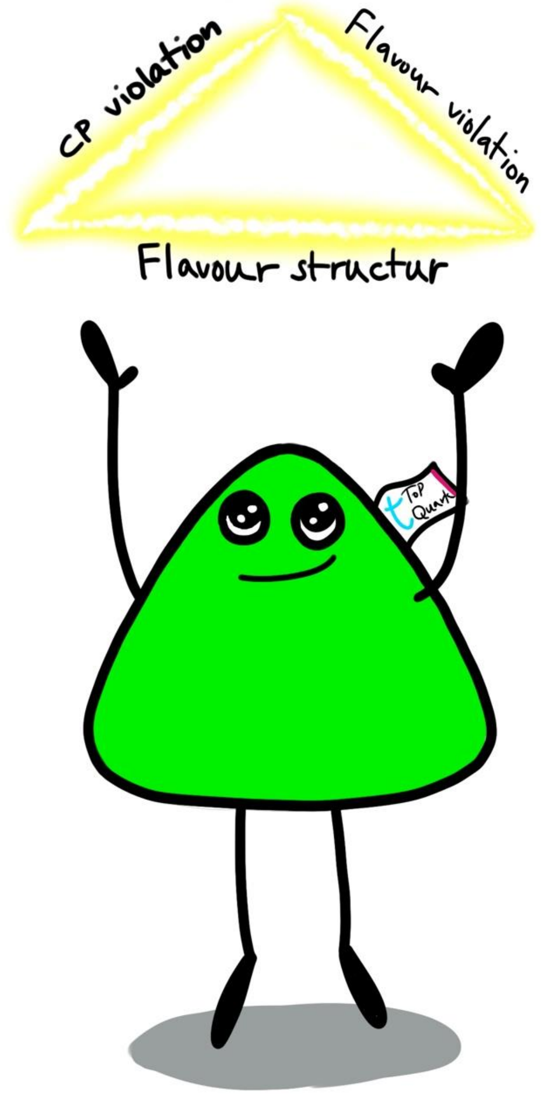
2-heavy 2-light quark operators



In this talk

EFT is a relatively general method. Each corner probes a distinct facet of the SMEFT landscape. This talk focuses on Top physics

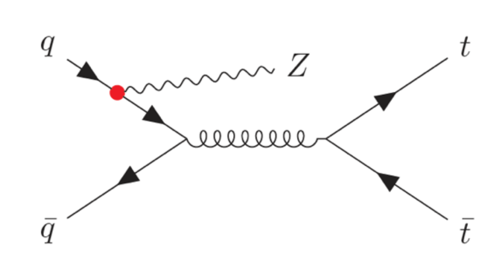
- **Flavour Structure**
  - — CMS Z-quark coupling in ttZ/WZ/ZZ
  - — ATLAS lepton-quark coupling in tt$\ell\ell$
- **CP Violation** — CMS CP-odd observables ttZ
- **Flavour Violation** — ATLAS same-sign tops

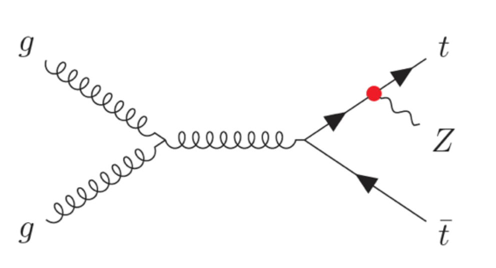


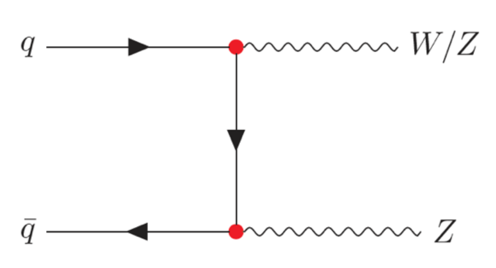
Measurement of the flavour structure of EFT couplings in multilepton final states

- **Goal:** Simultaneously constrain the **flavour structure** of dimension-6 EFT operators involving quark-Z couplings
- Investigating $b \rightarrow s\ell\ell$ anomalies observed by LHCb that violate flavour universality
- Reparametrize 2 coefficients to make the interpretation cleaner :
  - $C_{\phi q}^{(-)} = C_{\phi q}^{(1)} - C_{\phi q}^{(3)} \rightarrow$ pure Z coupling
  - $C_{\phi q}^{(3)} \rightarrow$ includes W coupling effects
- A RunII CMS analysis

Operator	Definition	WC
$O_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}\gamma^\mu q)$	$C_{\varphi q}^{(1)}$
$O_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar{q}\gamma^\mu \tau^I q)$	$C_{\varphi q}^{(3)}$
$O_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}\gamma^\mu u)$	$C_{\varphi u}$
$O_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{d}\gamma^\mu d)$	$C_{\varphi d}$
O_W	$\varepsilon^{ijk} W_\mu^{i\nu} W_\upsilon^{j\rho} W_\rho^{k\mu}$	C_W
$O_{\widetilde{W}}$	$\varepsilon^{ijk} \widetilde{W}_\mu^{i\nu} W_\upsilon^{j\rho} W_\rho^{k\mu}$	$C_{\widetilde{W}}$



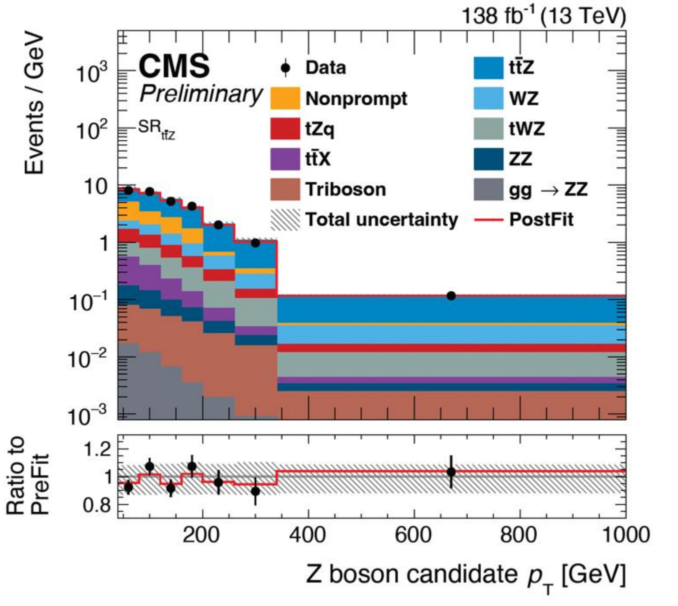


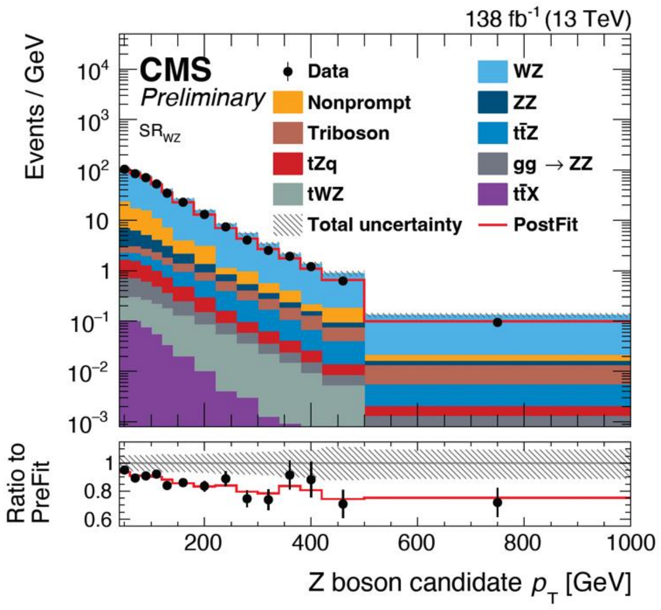


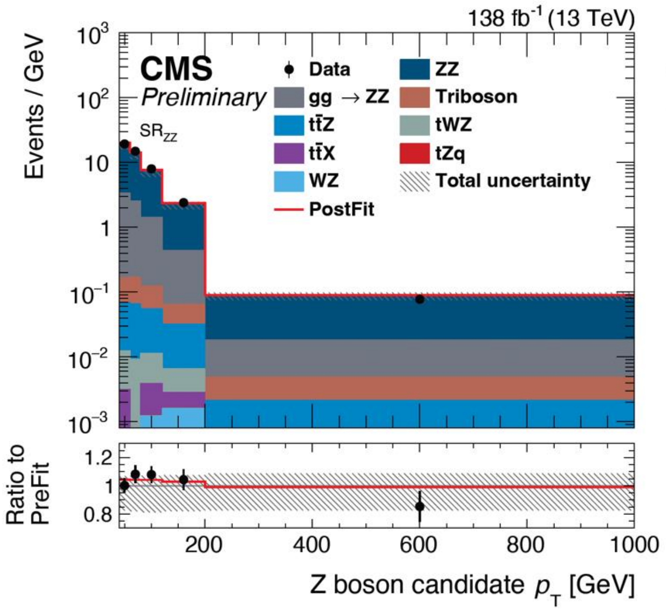
Analysis strategy:

- Each EFT operator is described by a 3×3 matrix. Only flavour diagonal entries are considered
- Divided into **heavy**(3rd generation) vs **light** (1st and 2nd generation)

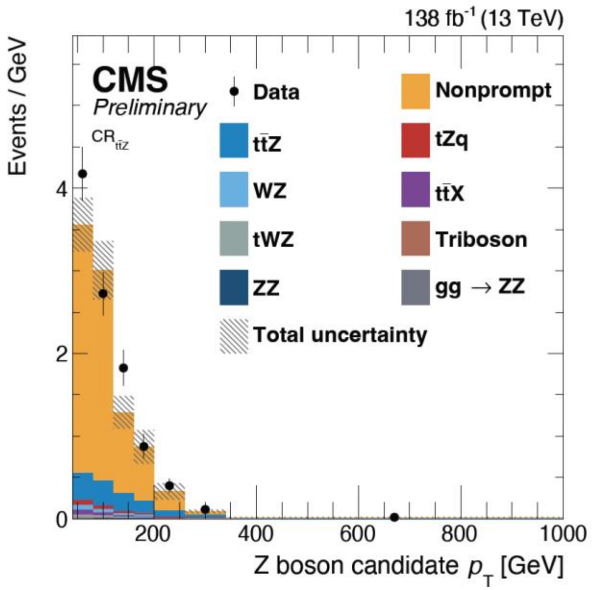
- **ttZ**:
  - o Sensitive to 3rd gen via top radiation
  - o but also to 1st/2nd gen via ISR diagrams!
- **WZ, ZZ**:
  - o Clean light-quark probes → Z/W from initial-state u/d/s quarks.





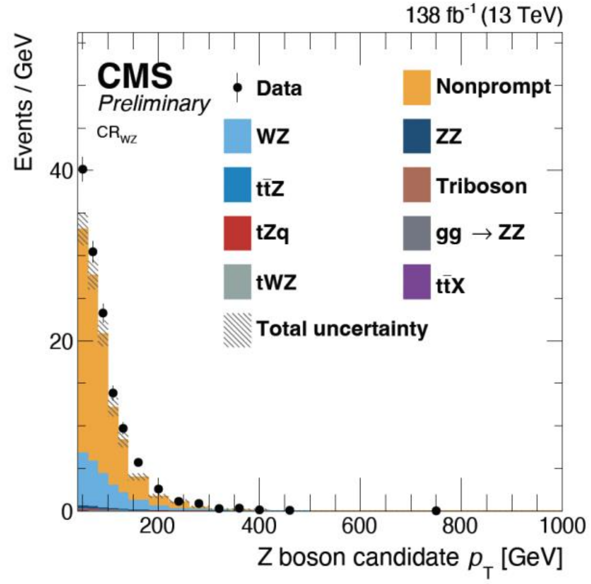


- Final states: **Multilepton** (≥3e/μ), from **ttZ**, **WZ**, and **ZZ** production.
- Simultaneous likelihood fit across **3 SRs** → flavour disentanglement of WC couplings.

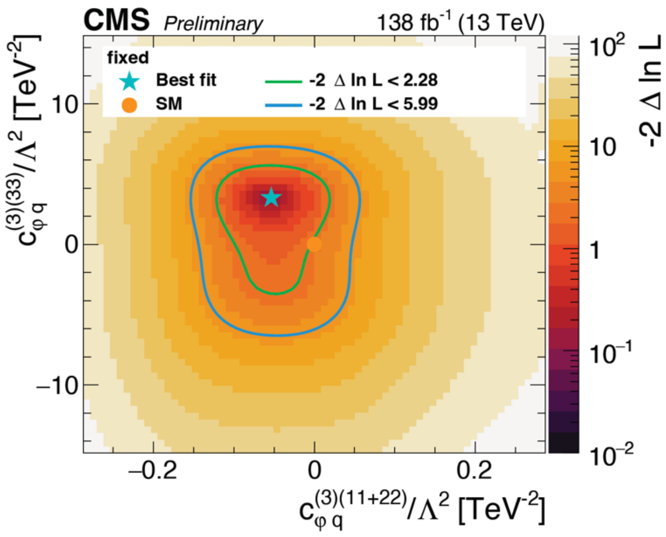


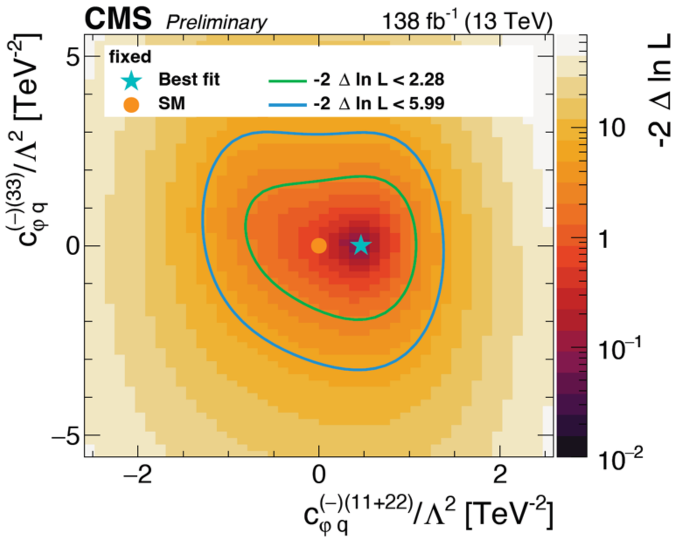
Key Uncertainties:

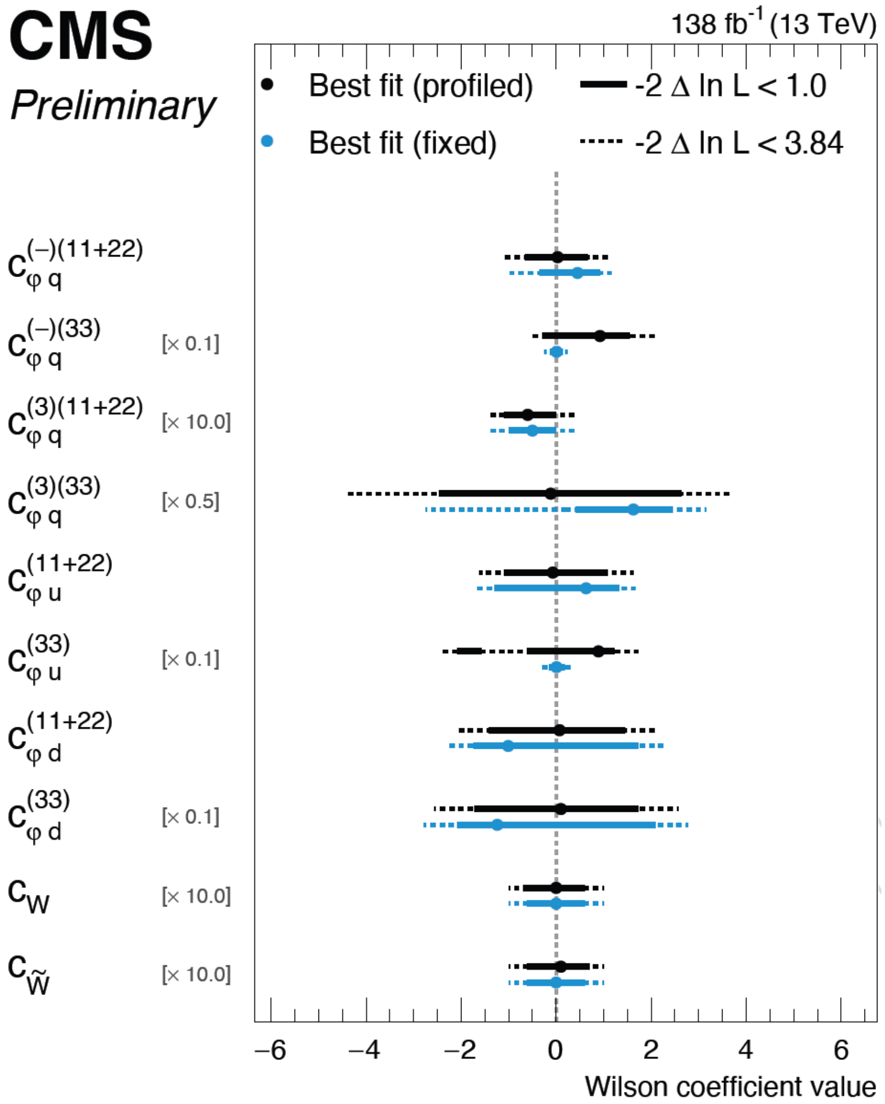
- Lepton fake rates
  - Derived in single lepton regions
- Largest impacts from normalization uncertainties



- All WCs **consistent with the SM**(i.e. , zero) within 95% CL.
- Most EFT analyses previously lumped all generations together or only considered top/bottom couplings
- This analysis distinguishes **first/second generation** from **third generation** couplings



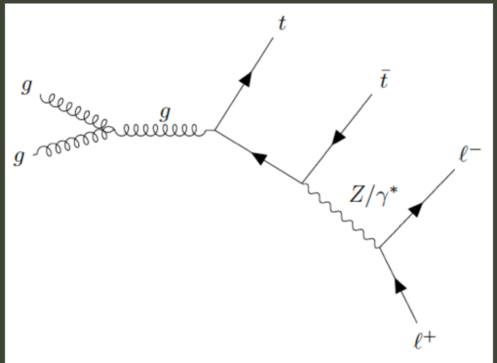


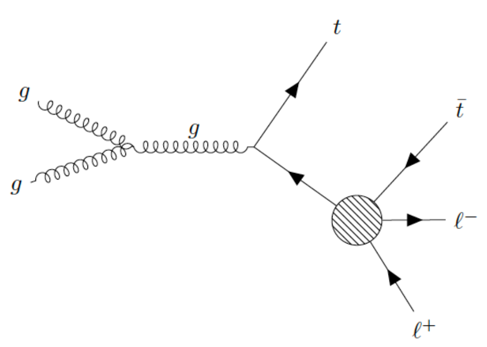


Measurement of high-mass $t\bar{t}\ell^+\ell^-$ production and Lepton Flavour Universality-inspired EFT interpretations

- New ATLAS measurement of off-shell $t\bar{t}\ell^+\ell^-$
- Targets high dilepton mass: $m_{\ell\ell}$>101.2 GeV
- Lepton Flavour Universality (LFU) tested via **flavour-separated** and **flavour-relative** EFT fits
- Operators include lepton-quark currents categorized by chiralities: RR, RL, LR, LL (singlet & triplet)
- A Run II ATLAS analysis

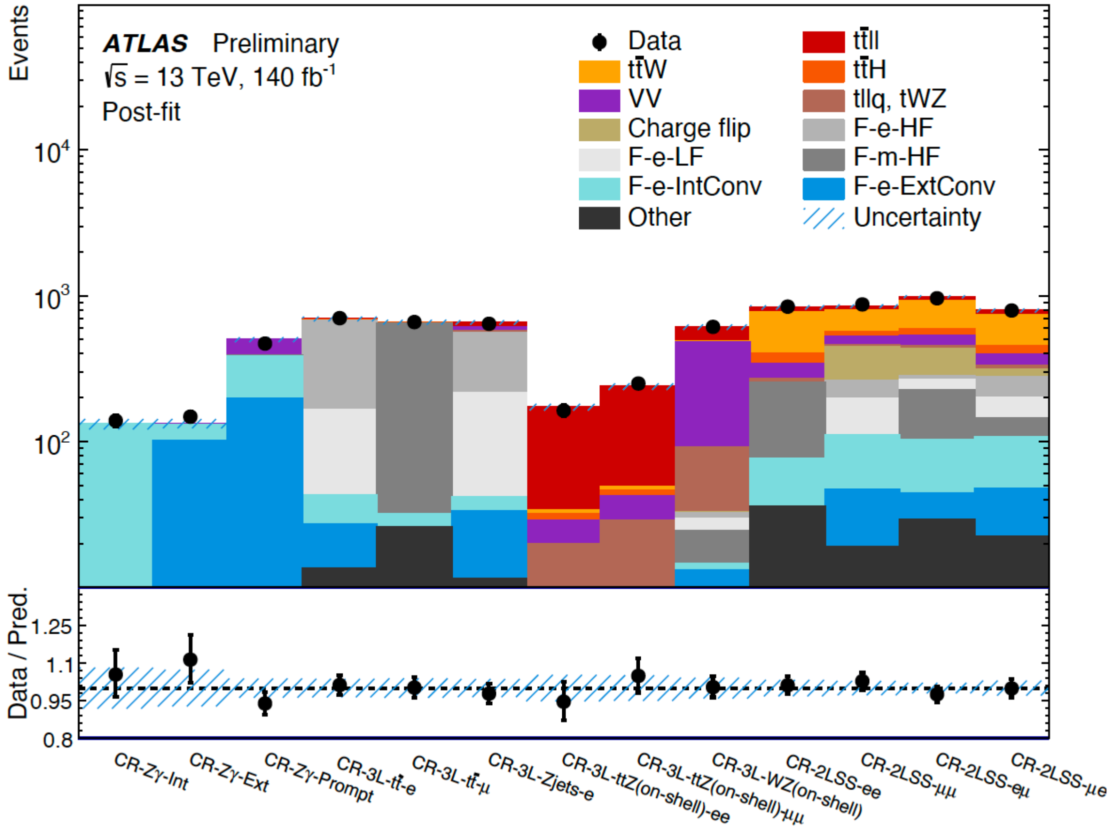
Operator	Definition	WC
O_{te}	$(\overline{e_P}\gamma_\mu e_r)(\bar{t}\gamma^\mu t)$	C_{te}
O_{Qe}	$(\bar{Q}\gamma_\mu Q)(\overline{e_P}\gamma^\mu e_r)$	C_{Qe}
O_{tl}	$(\overline{l_P}\gamma_\mu l_r)(\bar{t}\gamma^\mu t)$	C_{tl}
$O_{Ql}^{(1)}$	$(\overline{l_P}\gamma_\mu l_r)(\bar{Q}\gamma^\mu Q)$	$C_{Ql}^{(1)}$
$O_{Ql}^{(3)}$	$(\overline{l_P}\sigma^i\gamma_\mu l_r)(\bar{Q}\sigma^i\gamma^\mu Q)$	$C_{Ql}^{(3)}$
$O_{leQt}^{(1)}$	$(\overline{l_P^j}e_r)\varepsilon_{jk}(\overline{Q^k}t)$	$C_{leQt}^{(1)}$
$O_{leQt}^{(3)}$	$(\overline{l_P^j}\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\overline{Q^k}\sigma^{\mu\nu}t)$	$C_{leQt}^{(3)}$



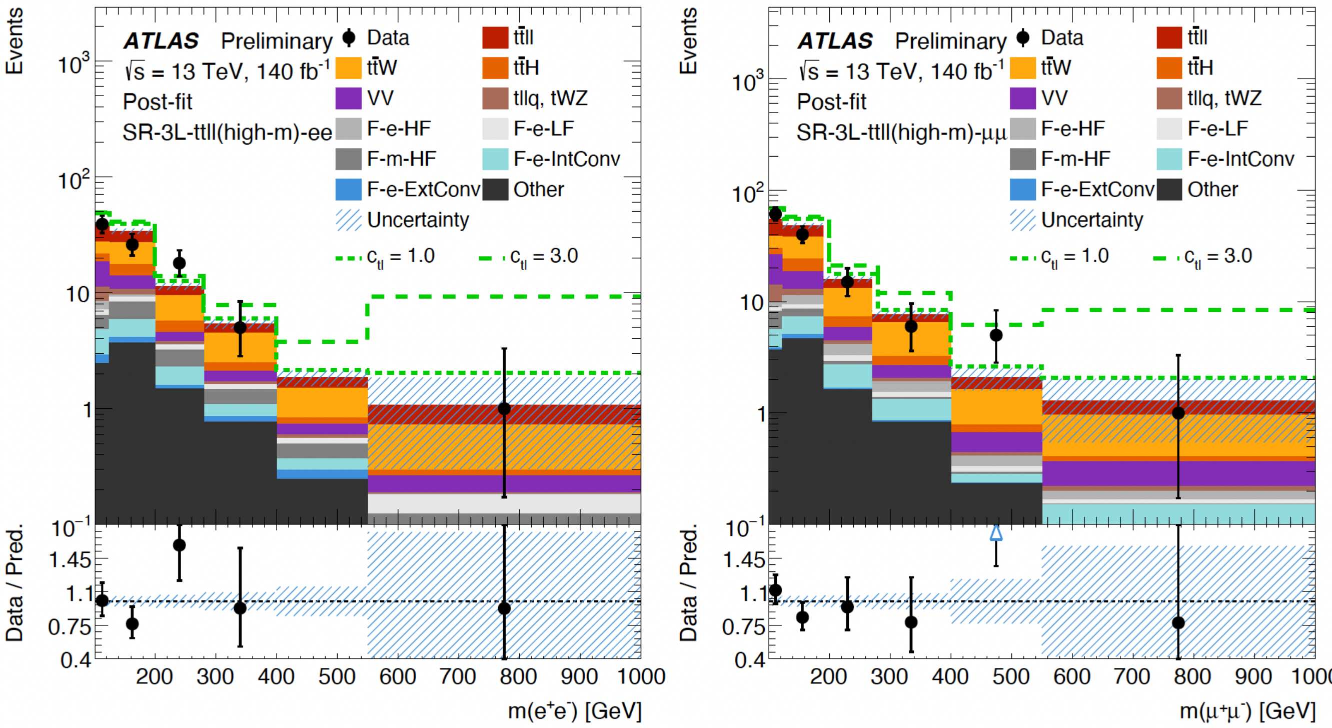


Event Selection & Region Strategy:

- Signal: 3-lepton final states, ≥1 OSSF pair,
- Requires ≥3 jets (≥1 b-tag)
- Signal split into ee and μμ for LFU sensitivity
- High-mass bins used to maximize impact.
- 13 Control Regions :
  - Constrain dominant backgrounds: ttZ, WZ, photon conversions, fakes
  - CRs binned in key observables (e.g.,p^{ll}_T , m_T) for shape constraints



- 3 EFT fit modes:
  - **Flavour-inclusive**: shared WC across all lepton flavours
  - **Flavour-split**: independent WCs for e and μ
  - **Flavour-relative**: test C^e - C^μ for LFU violation

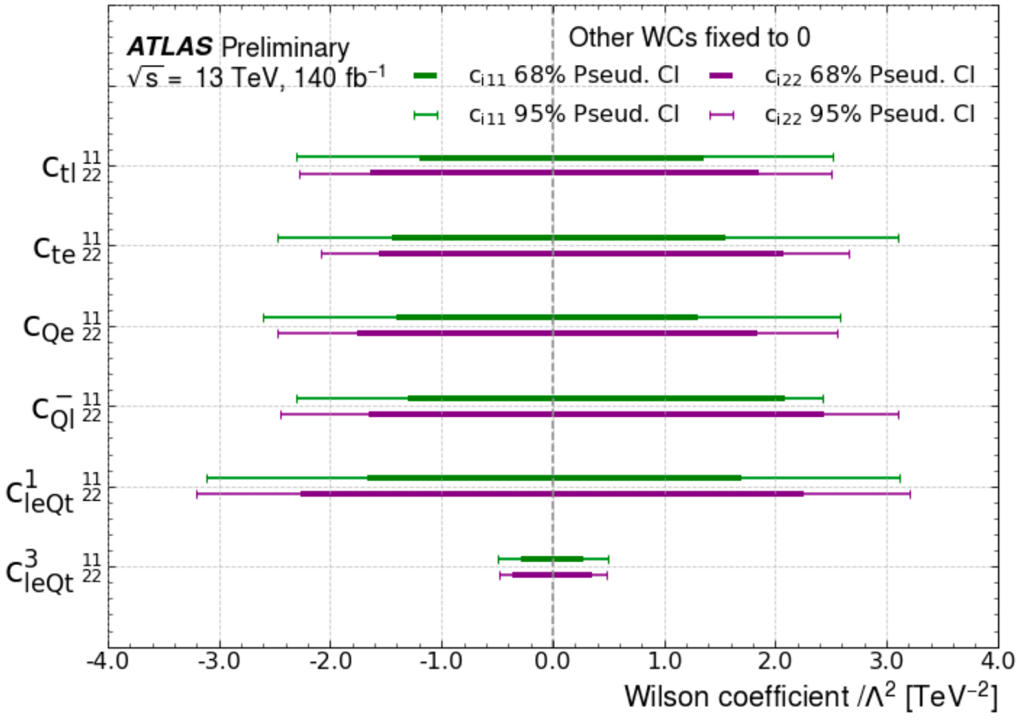


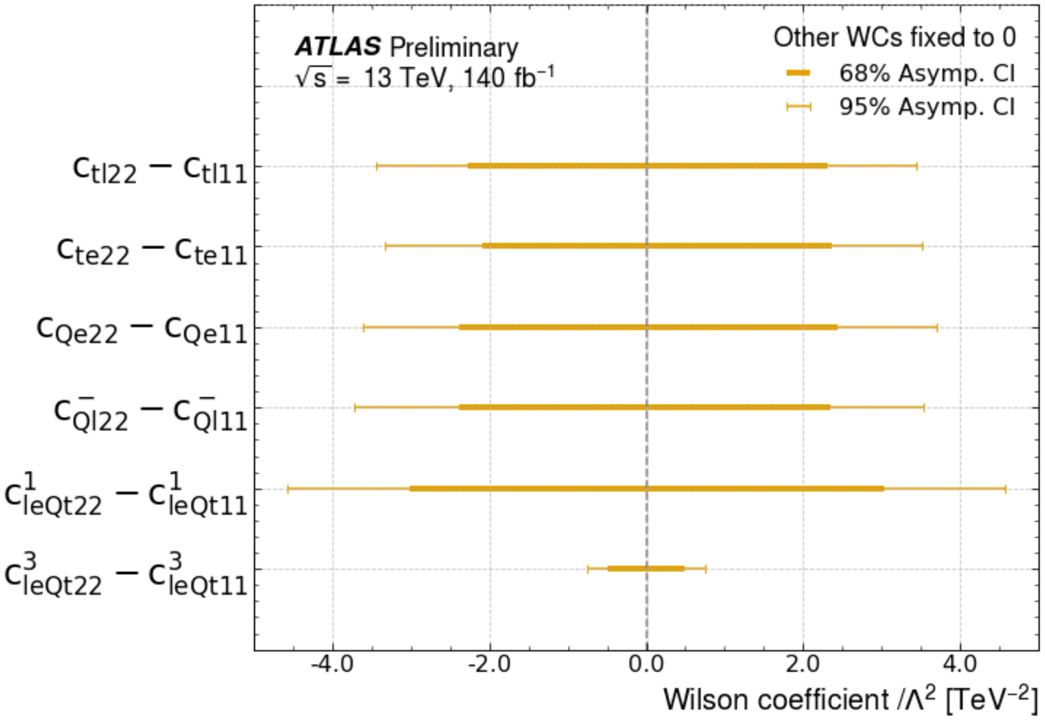
EFT Results:

- No significant deviation from the SM
- Wilson coefficients consistent with zero across all fit strategies

SM Signal Measurement:

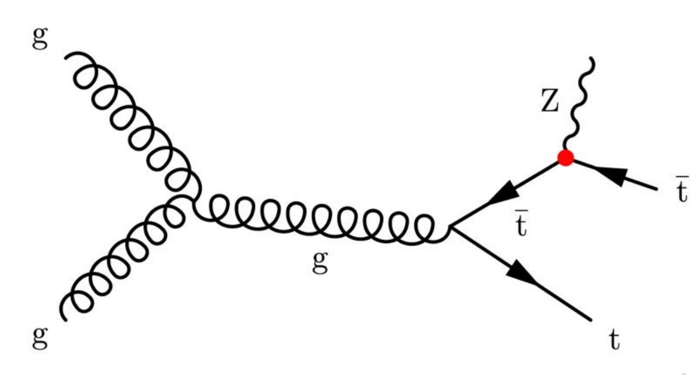
- $\mu(t\bar{t}\ell^+\ell^-) = 1.0 +0.4 -0.5$

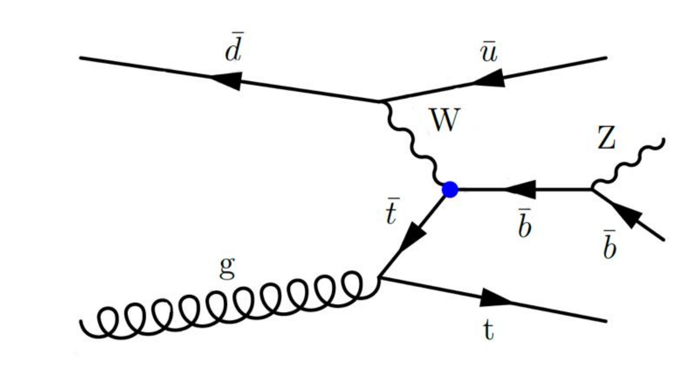




Search for CP violation in events with top quarks and Z bosons

- CP violation is essential to explain **baryon asymmetry**, yet the SM's only source is through CKM/PMNS phases—too small!
- This search targets **dimension-6 CP-odd EFT operators (**assuming that Wilson coefficients associated with CP-even operators are zero)
  - c_{tZ}^{I}: modifies ttZ vertex
  - c_{tW}^{I}: modifies tZq via tW coupling
- A RunII + early RunIII CMS analysis





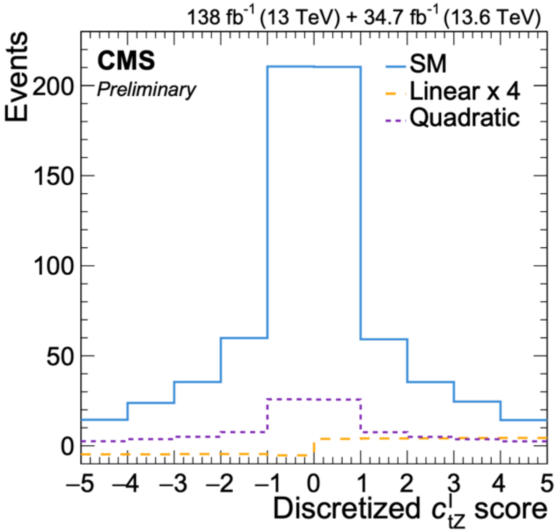
Operator	Definition	WC probed here
$O_{uW}^{(ij)}$	$(\bar{q}_i \sigma^{\mu\nu} \tau^I u_j)\, \tilde{\varphi} W_{\mu\nu}^I$	$C_{tW}^I = Im(C_{uW}^{(33)})$
$O_{uB}^{(ij)}$	$(\bar{q}_i \sigma^{\mu\nu} u_j)\, \tilde{\varphi} B_{\mu\nu}$	$C_{tZ}^I = Im(-s_W\, C_{uB}^{(33)} + c_W C_{uW}^{(33)})$

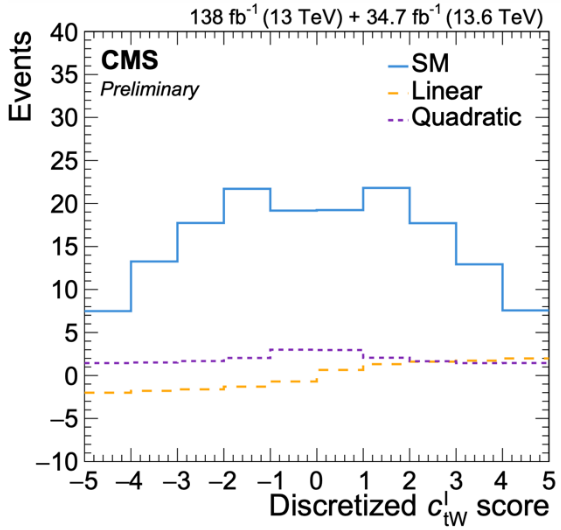
ML vs the Universe — Observables that Know Physics

- CMS pioneers the use of CP-odd observables in this topology!
- Observables constructed via CP-equivariant function :

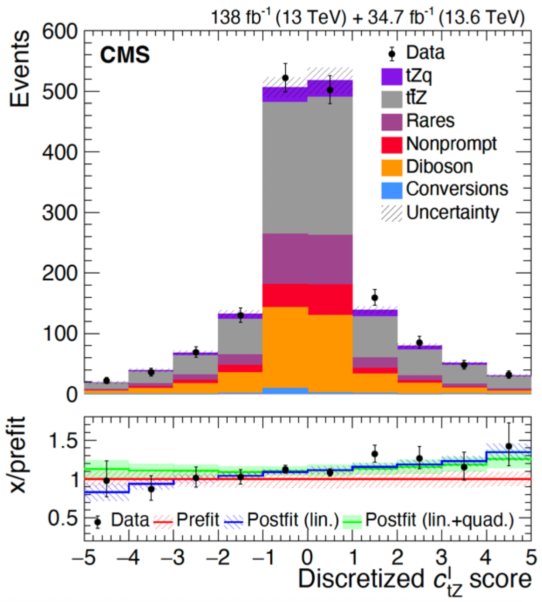
$$f_i(x) = g_i(x) - g_i(CP(x))$$

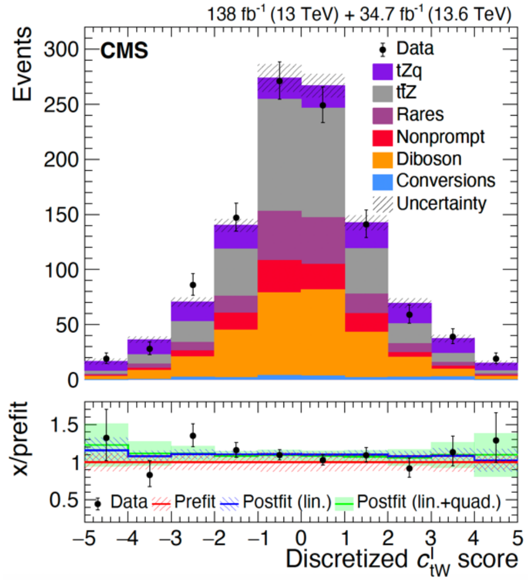
- Two networks trained separately:
  - g_{tZ}, sensitive to $C_{tZ}{}^{I}$
  - g_{tW}, sensitive to $C_{tW}{}^{I}$
- Each network output is a CP-odd score → should be symmetric under SM
- Asymmetry ≠ SM → a signature of new CPV physics



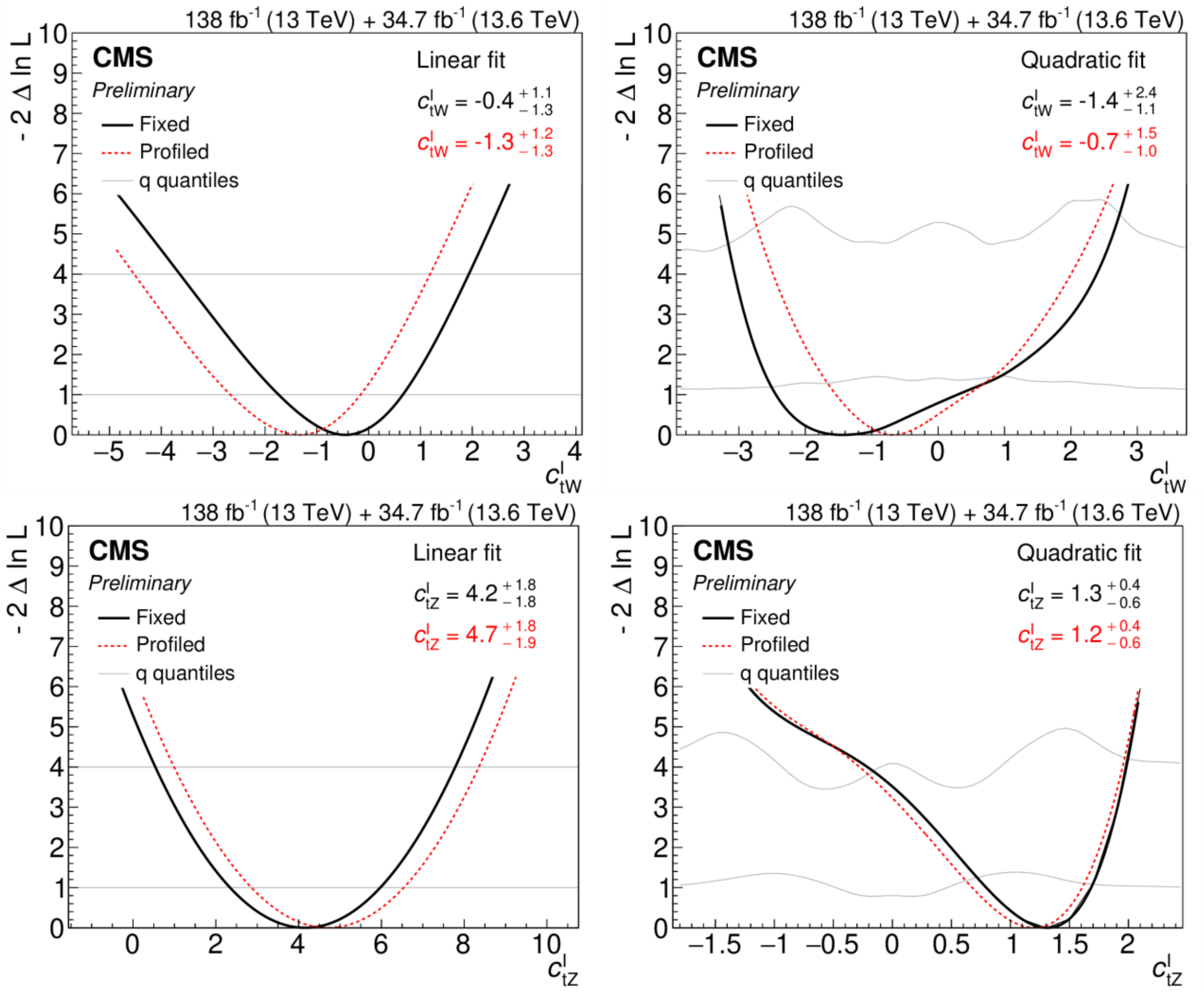


- Final state: 3-lepton + ≥2 jets (≥1 b-tag)
- include both signal and WZ events in the training ⟹ observables sensitive to
    - EFT effects present in the ttZ and tZq signal processes
    - discriminate between them and WZ (the leading source of backgrounds)
- Key Uncertainties:
    - Statistical uncertainty dominates — still systematics-limited in signal-rich regions
    - theoretical uncertainty on signal processes





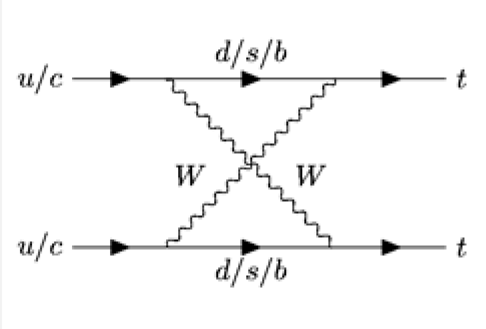
- Data mostly consistent with SM
- Observed 95% CL limits:
  - $-2.7 < C_{tW}^{I} < 2.5$
  - $-0.2 < C_{tZ}^{I} < 2.0$
- CP violation sensitivity is mostly driven by the linear term (interference with SM)
- First-ever limits on the linear (interference) term of C_{tZ}^{I}
- CPV observables open a new EFT testing ground
- Complementary to CP-even fits



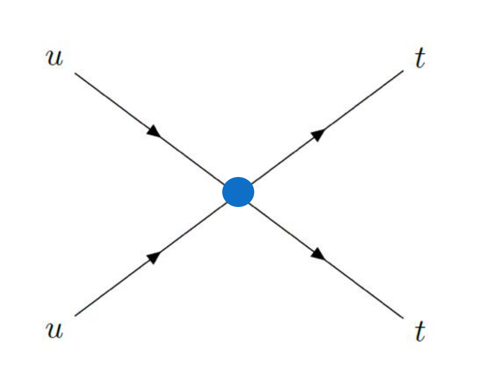
Search for same-charge top-quark pair production

- **Same-sign tt / t̄t̄ production**:
  - Forbidden at LO in the Standard Model.
  - Only viable via ultra-rare $W^{\pm}W^{\pm}$ scattering → $\sigma_{SM} \sim 10^{-15}$ pb.
  - Possible in **SMEFT** via **contact 4-fermion operators**.

- The EFT interpretation uses **flavour-universal** couplings
- A Run II ATLAS analysis



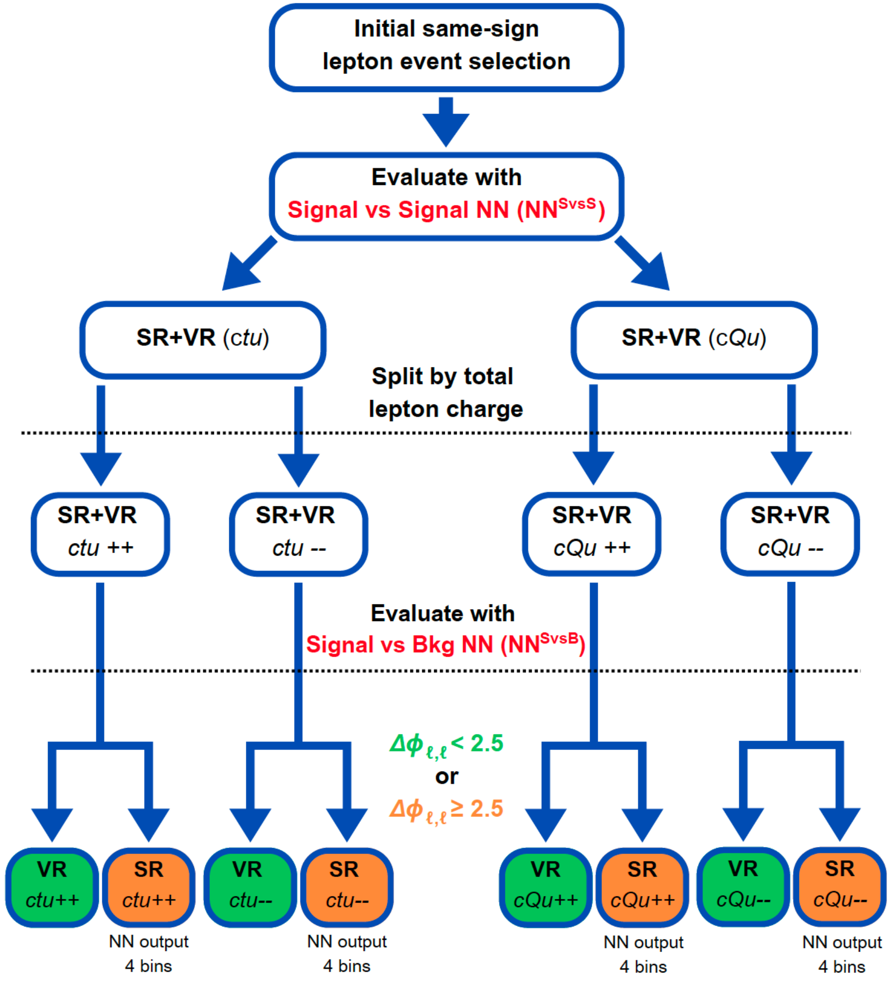
Operator	Definition	WC
$O_{tu}^{(1)}$	$(\bar{t}_R\gamma^{\mu}u_R)(\bar{t}_R\gamma_{\mu}u_R)$	$C_{tu}^{(1)}$
$O_{Qu}^{(1)}$	$(\bar{Q}_L\gamma^{\mu}q_L)(\bar{t}_R\gamma_{\mu}u_R)$	$C_{Qu}^{(1)}$
$O_{Qu}^{(8)}$	$(\bar{Q}_L\gamma^{\mu}T^{A}q_L)(\bar{t}_R\gamma_{\mu}T^{A}u_R)$	$C_{Qu}^{(8)}$



ML for EFT: Sorting Quarks from Quirks

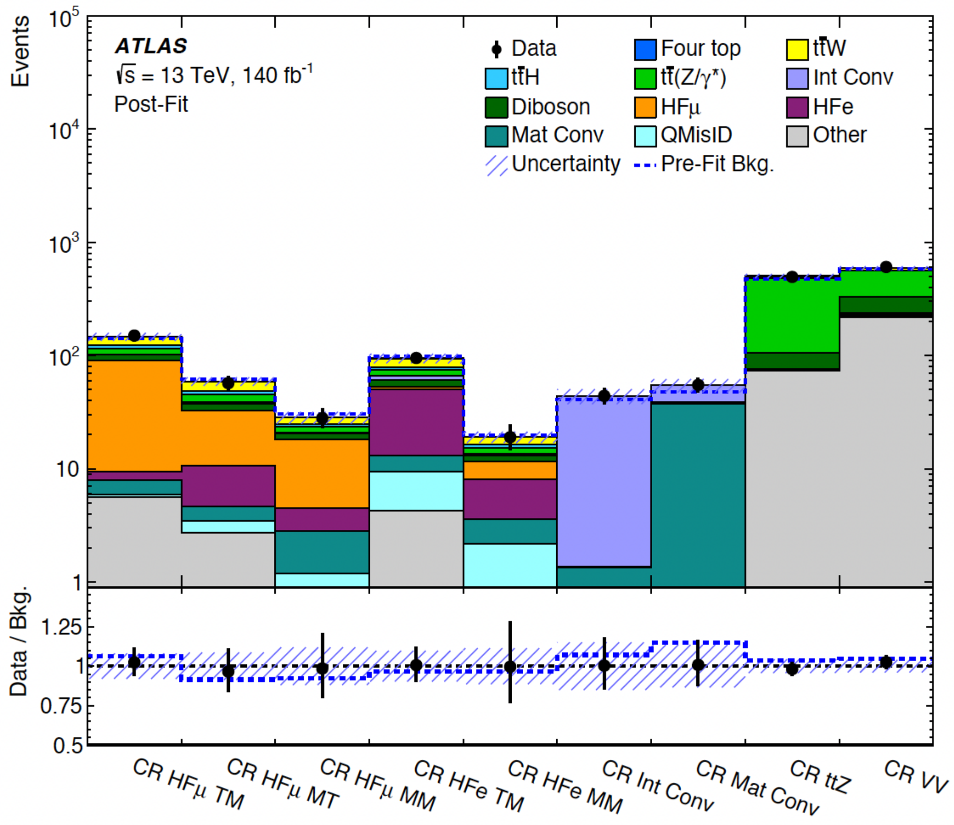
- First ever ATLAS analysis with **NN-based operator discrimination**:
- Analysis workflow:
  - Step 1: Neural Network (NN^{SvsS}) to separate c_{tu} vs c_{Qu} -like signals
  - Step 2: Split by total lepton charge **(++/--)**
  - Step3 : Signal vs validation region based on the azimuthal angle between the two charged leptons
  - Step 4 : NN^{SvsB} used in SRs to reject background

  $\Rightarrow$ **4 Signal Regions (tu/Qu, ++/--)**



Background-Enriched Regions:

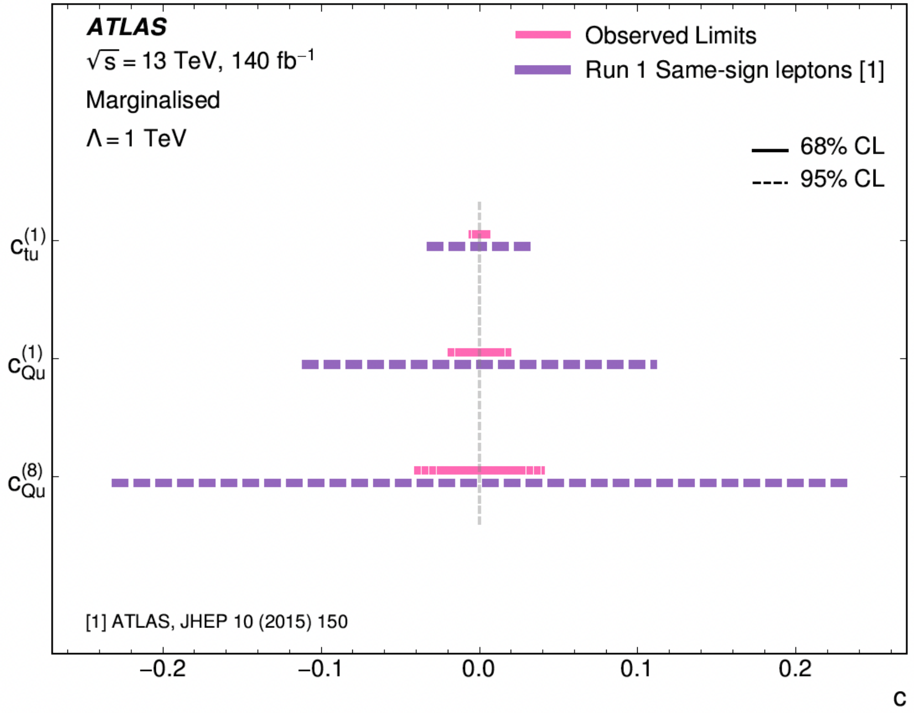
- ttW background (dominant): normalization constrained from the first bins of the SRs
- Dedicated CRs for irreducible backgrounds :
  - CR ttZ , CR VV
- Reducible backgrounds: Estimated using data-driven techniques
  - Seven CRs targeting Nonprompt leptons using lepton ID categories
  - Separate CRs for photon conversions



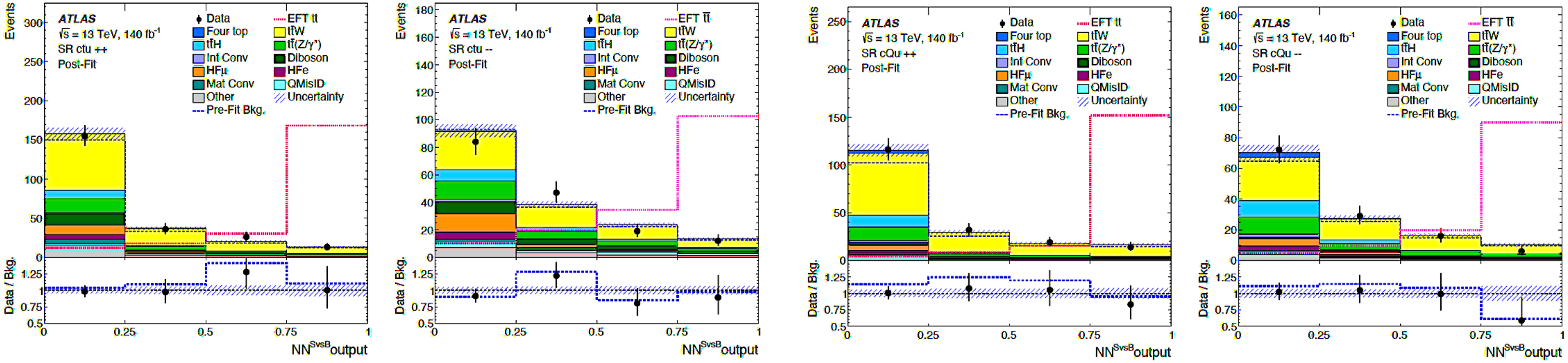
Major Uncertainties

- Statistical uncertainties
- ttW modelling

- Simultaneous binned likelihood fit across SRs and CRs
- **No excess** seen → All WCs consistent with SM zero
- Upper limits at 95% CL:
  - $|c^{(1)}_{tu}| < 0.0068\ (0.0071)$
  - $|c^{(1)}_{Qu}| < 0.020\ (0.022)$
  - $|c^{(8)}_{Qu}| < 0.041\ (0.046)$

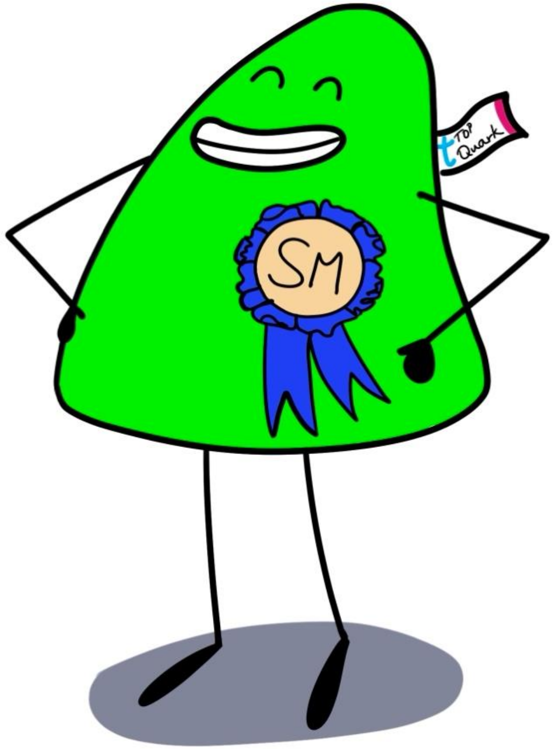


- No evidence of flavour-changing new physics in the top sector



Summary — Top Quark, Symmetries, and SMEFT

- Across ATLAS & CMS, we have new constrains on:
  - **Flavour violation** in four-fermion contact terms (same-sign tt)
  - **Z–quark flavour structure** in heavy vs light generation (ttZ, WZ, ZZ)
  - **Lepton-quark flavour structure** in four-fermion operators ($tt\ell\ell$)
  - **CP-odd interactions** via direct collider observables (ttZ)
- All results are consistent with the SM
- ML contributes strongly
- Run 3 and HL-LHC will bring:
  - More statistics for rare channels
  - Enhanced EFT sensitivity with ML-assisted observables
  - Combined fits with richer flavour resolution and operator correlations



Backup

- Input variables used for the CP-equivariant neural networks, with the CP-transformed value given in the second row

	Input variables							
x	$\vec{p}_{\ell Z+}$	$\vec{p}_{\ell Z-}$	$\vec{p}_{\ell W}$	$\vec{p}_{j_i}$	$Q_{\ell W}$	$\vec{p}_T^{miss}$	bscore$_i$	era
$CP(x)$	$-\vec{p}_{\ell Z-}$	$-\vec{p}_{\ell Z+}$	$-\vec{p}_{\ell W}$	$-\vec{p}_{j_i}$	$-Q_{\ell W}$	$-\vec{p}_T^{miss}$	bscore$_i$	era