Searches for new physics breaking the *CP* and flavor symmetries in the top quark sector at CMS

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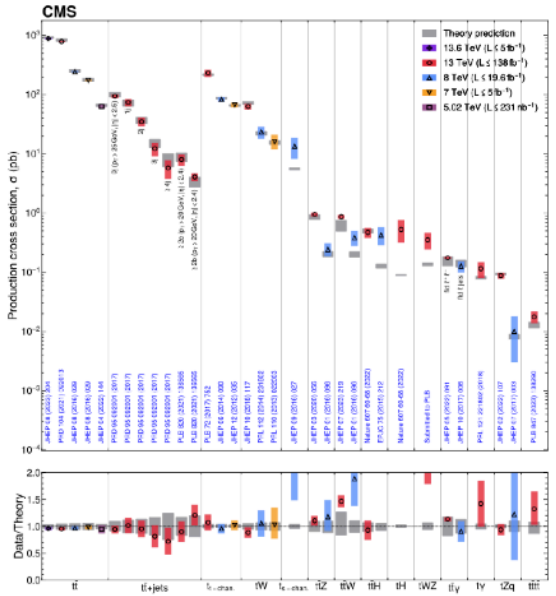
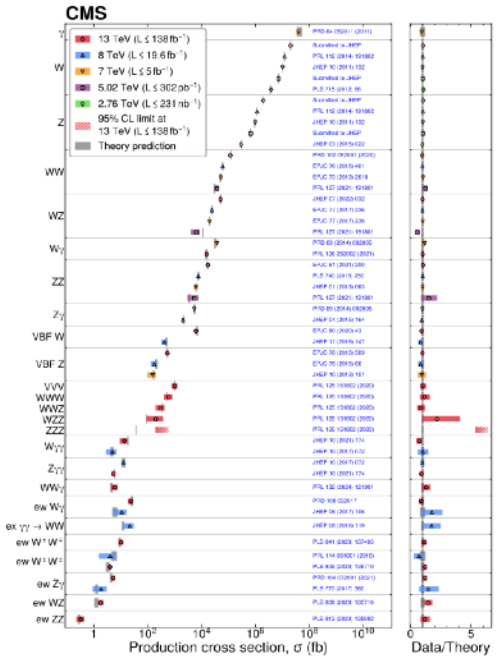
Introduction

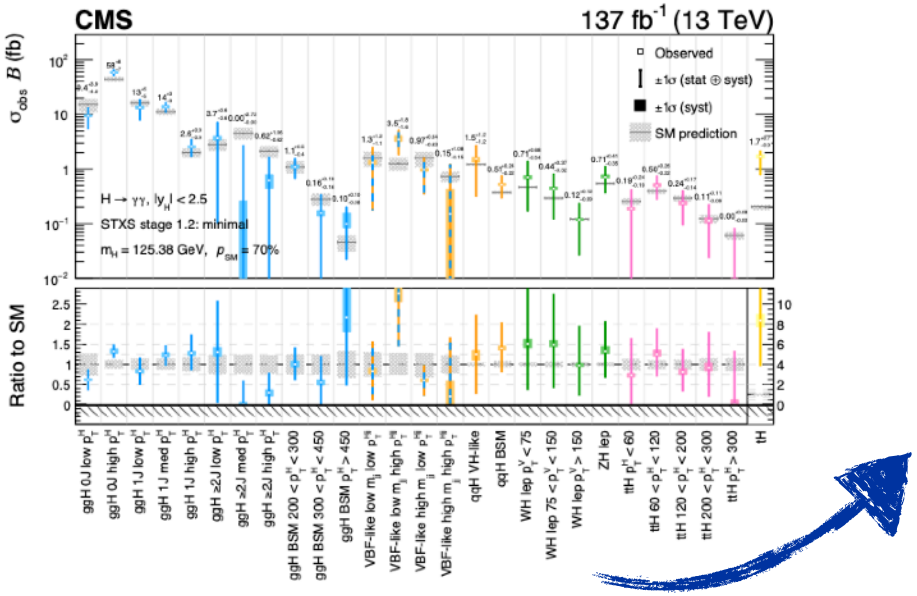
Comprehensive programme of measurements by CMS, interpreted in the EFT framework

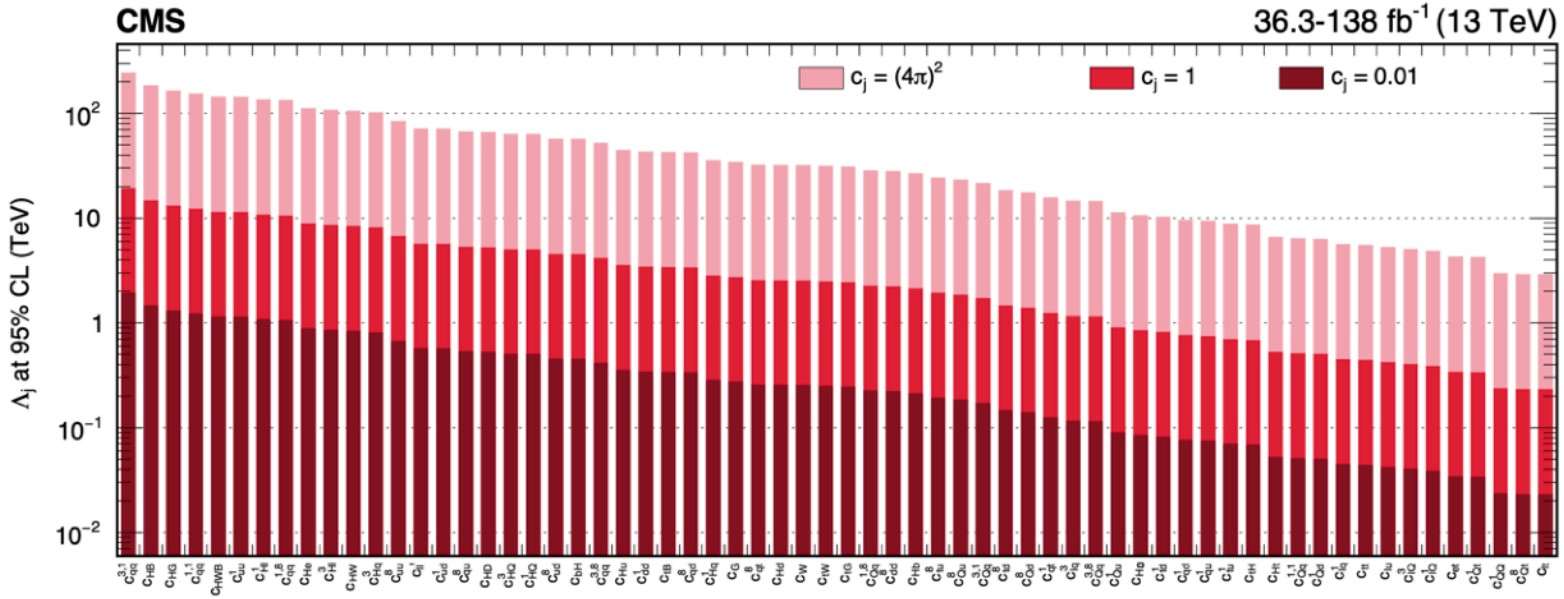




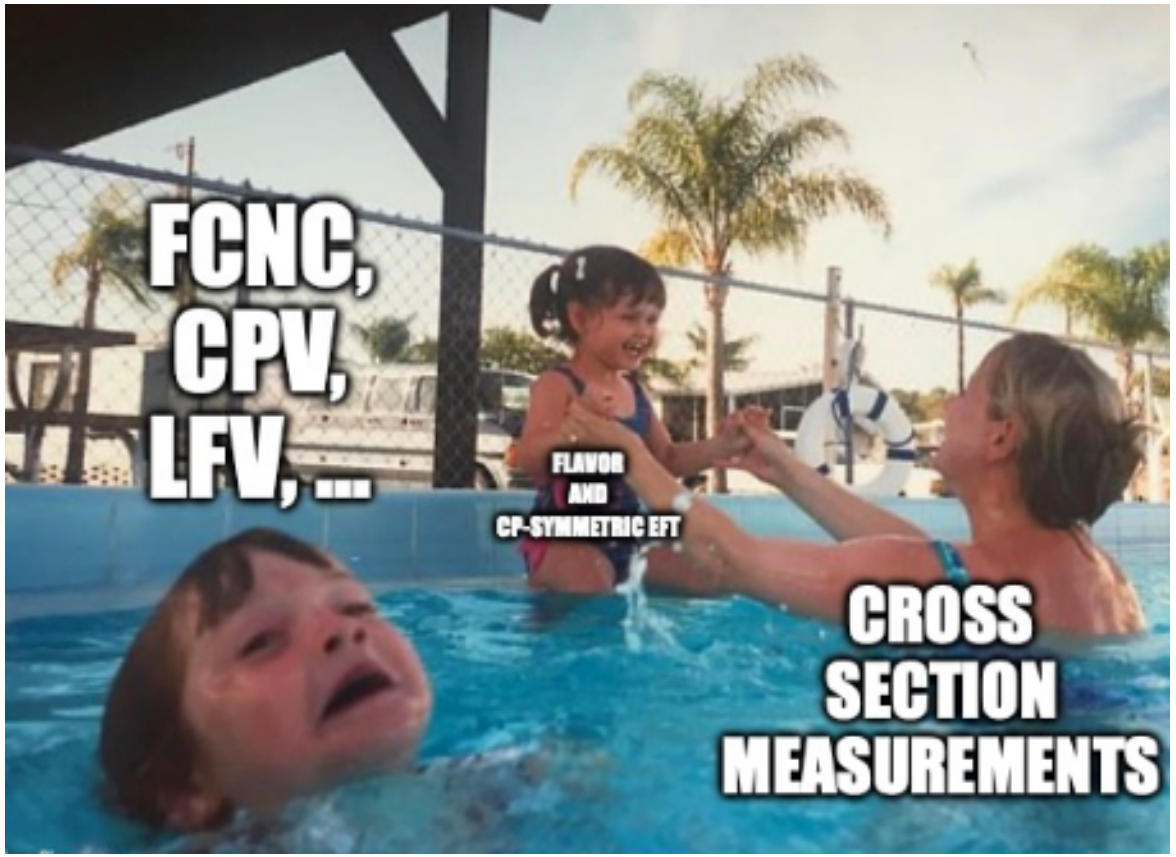
More on EFT combination in Ankita's talk

More on top measurements on Alberto, Clara, Enrique's talks





Introduction (II)



- SM cross section measurements often target **SM-like effects**
- **New physics could be much richer!**
- Broad program of measurements put together by CMS:
  - Baryon number violation (PRL 132 (2024) 241802)
  - Lepton number violation (JHEP 06 (2022) 082, arXiv:2504.08532, PRD 111 (2025) 012009)
  - Lorentz invariance violation (PLB 857 (2024) 138979)
  - Many results on FCNC!

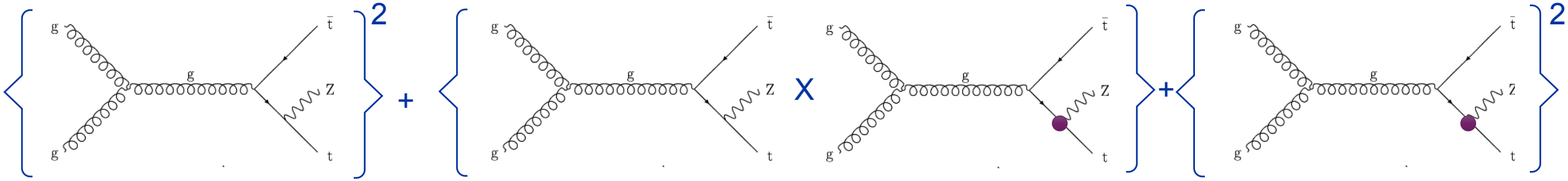
This presentation

- Results on *CP* violation in the top+Z (arXiv:2505.21206)
- EFT search beyond flavor assumptions (CMS-PAS-TOP-23-009)

Searching for *CP* violation in the SMEFT

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{d,i} \frac{c_i^d}{\Lambda^{d-4}} \mathcal{O}_i^d$$

- 1149 *CP*-odd operators in the SMEFT



SM contribution

Pure BSM contribution

SM-BSM interference

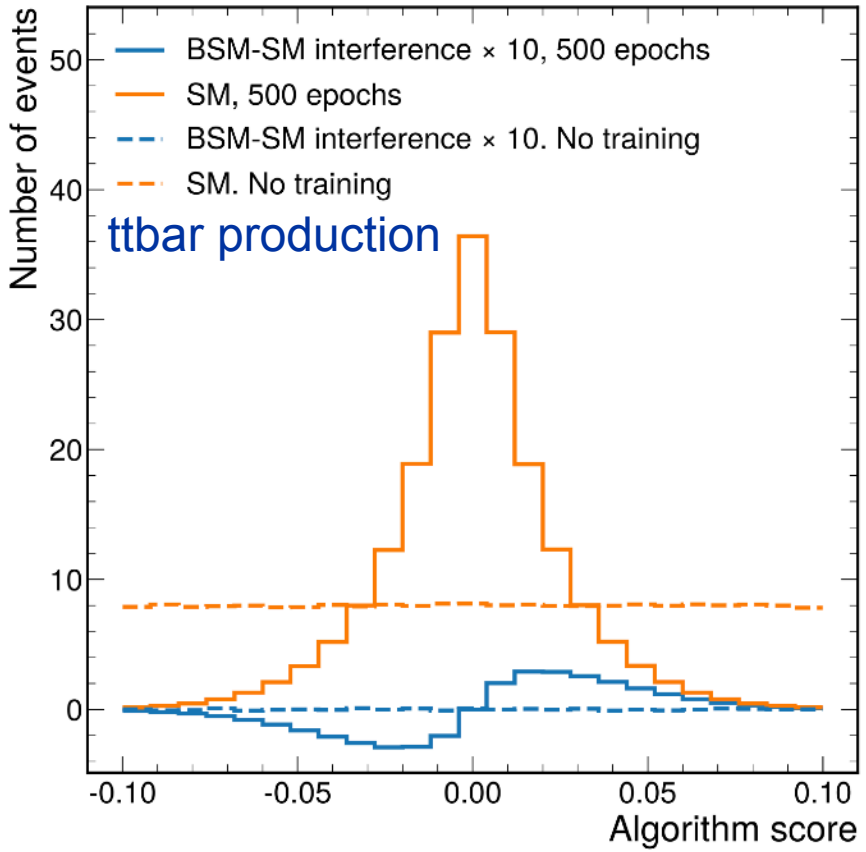
- Mostly *CP*-invariant at amplitude level
- Odd under *CP* transformations
- Particularly interesting from the theory standpoint (first order in 1/Λ expansions)

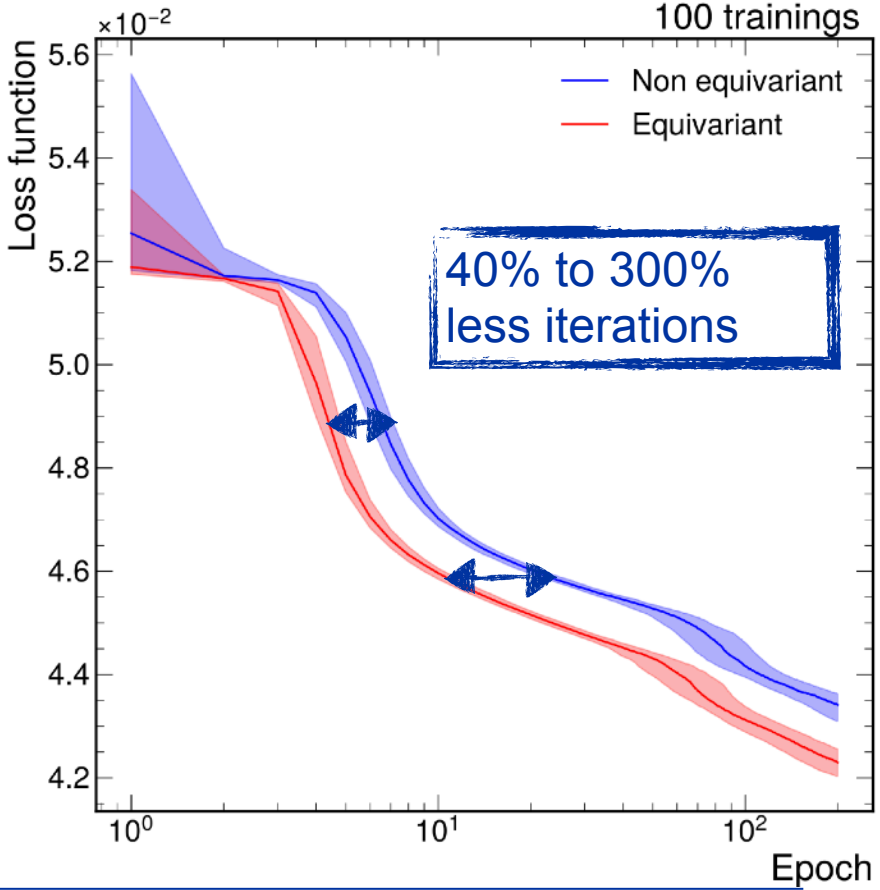
Equivariant networks for *CP* violation searches

- Using neural networks that are **equivariant (odd) with respect to the *CP* symmetry**
  - **SM contribution is symmetric**
  - **BSM-SM interference is antisymmetric**

PRD 110, 096023 (2024)

- These properties are fulfilled even when the training has not converged
- Faster convergence when imposing equivariance

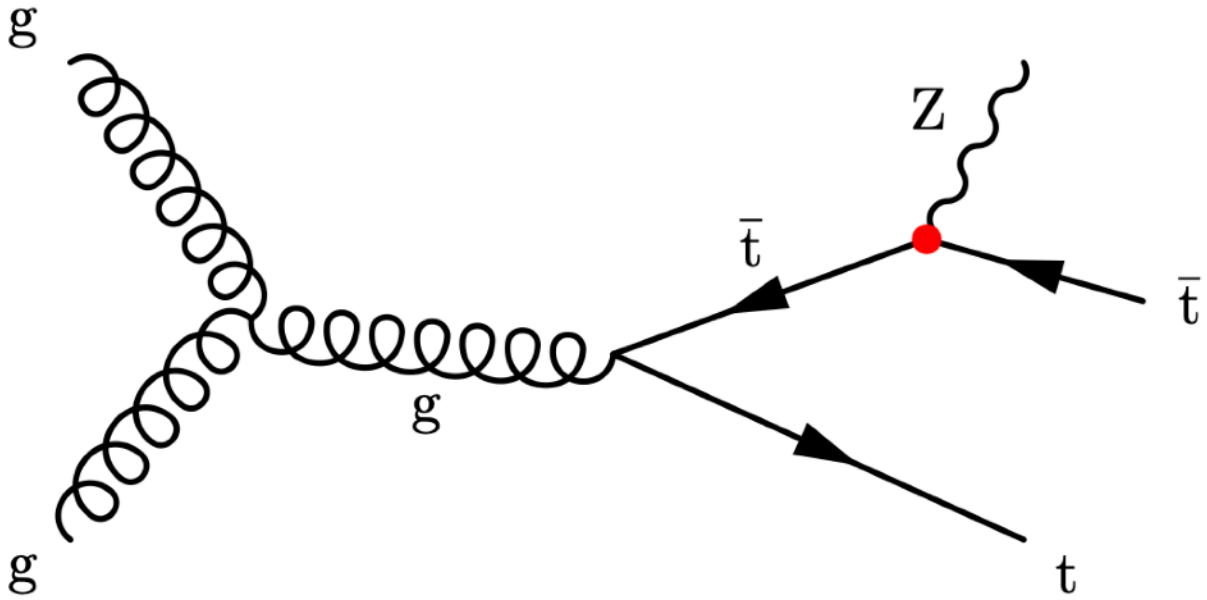


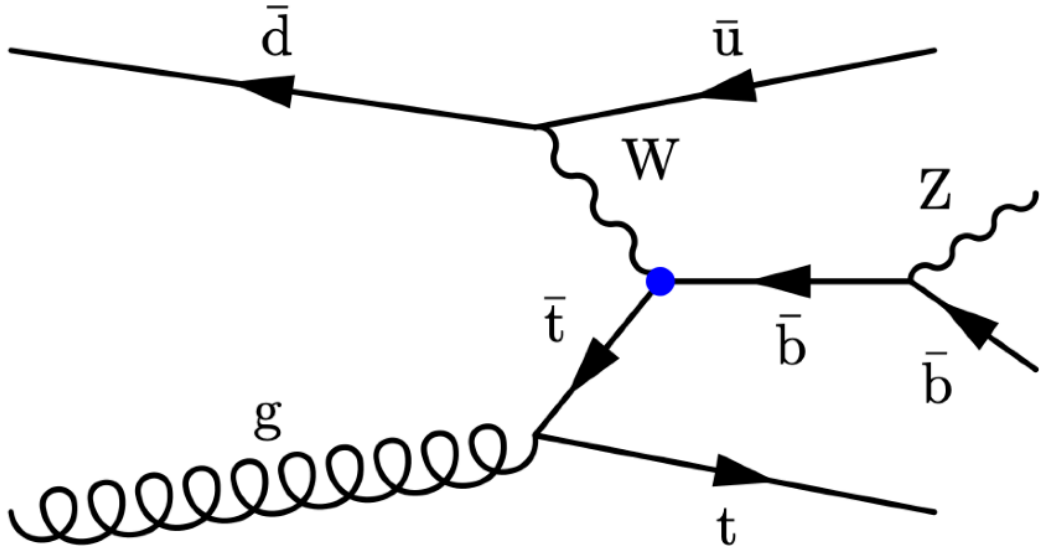


Search for *CP* violation in top+Z production

- Exploring new *CP*-violating interactions **affecting ttZ** or **tZq production**
- Using **2016-2018** (13 TeV) and **2022 data** (13.6 TeV)
  - Selecting events with 3 leptons, jets and b-tagged jets

arXiv:2505.21206

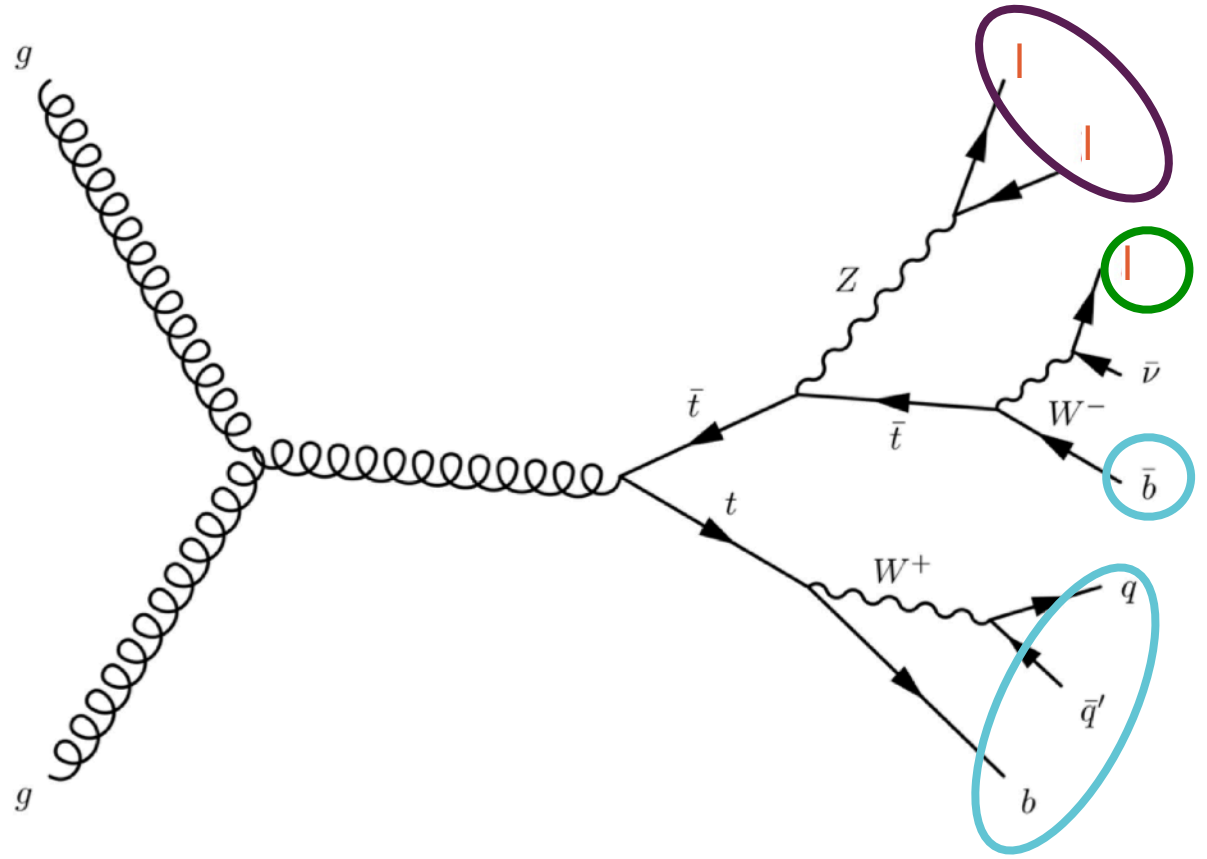




- Studying **two EFT operators**: c_{tW}^{I}, c_{tZ}^{I} $(\bar{q}_i \sigma^{\mu\nu} \tau^I u_j)\, \tilde{\varphi} W^I_{\mu\nu}$ $(\bar{q}_i \sigma^{\mu\nu} u_j)\, \tilde{\varphi} B_{\mu\nu}$

Input variables and network architecture

- Using **two neural networks**, **one for each operator**
- Building a Z boson candidate from the two leptons with an invariant mass closest to the Z
- W lepton is the third lepton
- Momentum of all particles and p_T^{miss} is used as an input
  - Also using jet b-tagging information



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

More details on the training

- Training network using **ttZ, tZq** and **WZ** simulations
  - EFT effects included in the simulations through weights (see LHC EFT prediction note)

$$w = w_{\mathrm{SM}} + \sum_i c_i^{\mathrm{I}} l_i + \sum_{ij} c_i^{\mathrm{I}} c_j^{\mathrm{I}} q_{ij}$$

- Loss function using the SALLY* method

$$L = w_{SM}(\text{parton kin.}) \left(f(\text{observables}) - \frac{l_i(\text{parton kin.})}{w_{SM}(\text{parton kin.})} \right)^2$$

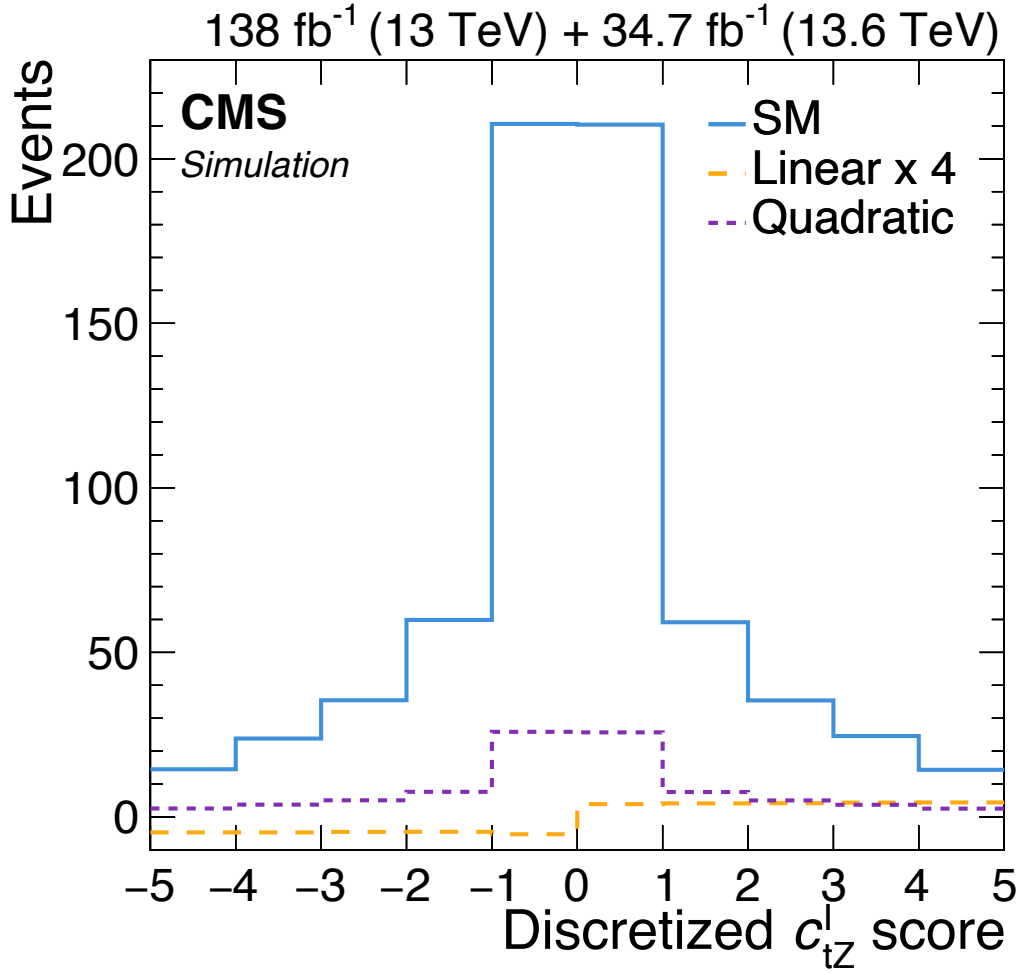
- Simultaneously performing **signal/background discrimination** and obtaining **EFT sensitivity**
- *CP* equivariance achieved by considering $f(\text{observables}) = g(\text{observables}) - g(CP(\text{observables}))$

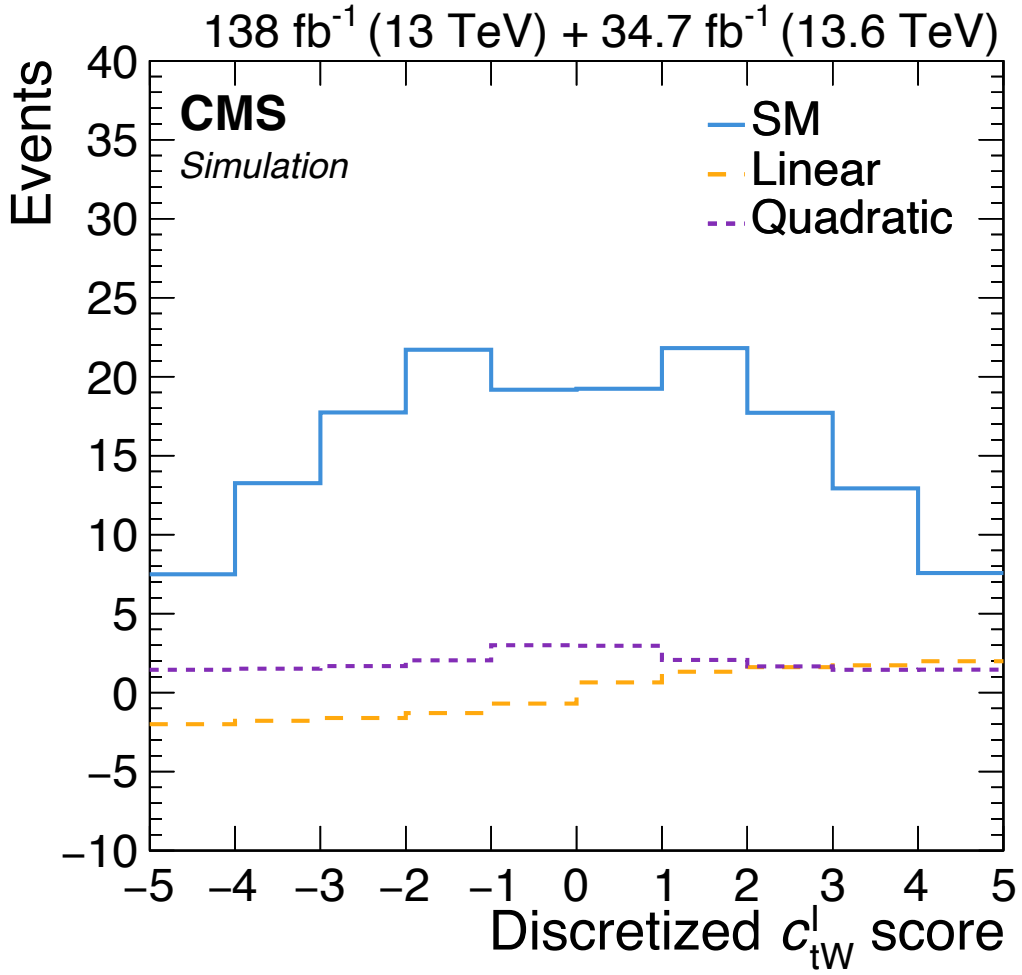
Input variables

x	$\vec{p}_{\ell^{\mathrm{Z}+}}$	$\vec{p}_{\ell^{\mathrm{Z}-}}$	$\vec{p}_{\ell^{\mathrm{W}}}$	$\vec{p}_{\mathrm{j}_i}$	$Q_{\ell^{\mathrm{W}}}$	$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$	bscore_i	era
$CP(x)$	$-\vec{p}_{\ell^{\mathrm{Z}-}}$	$-\vec{p}_{\ell^{\mathrm{Z}+}}$	$-\vec{p}_{\ell^{\mathrm{W}}}$	$-\vec{p}_{\mathrm{j}_i}$	$-Q_{\ell^{\mathrm{W}}}$	$-\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$	bscore_i	era

*SALLY method: PRL 121, 111801 (2018)

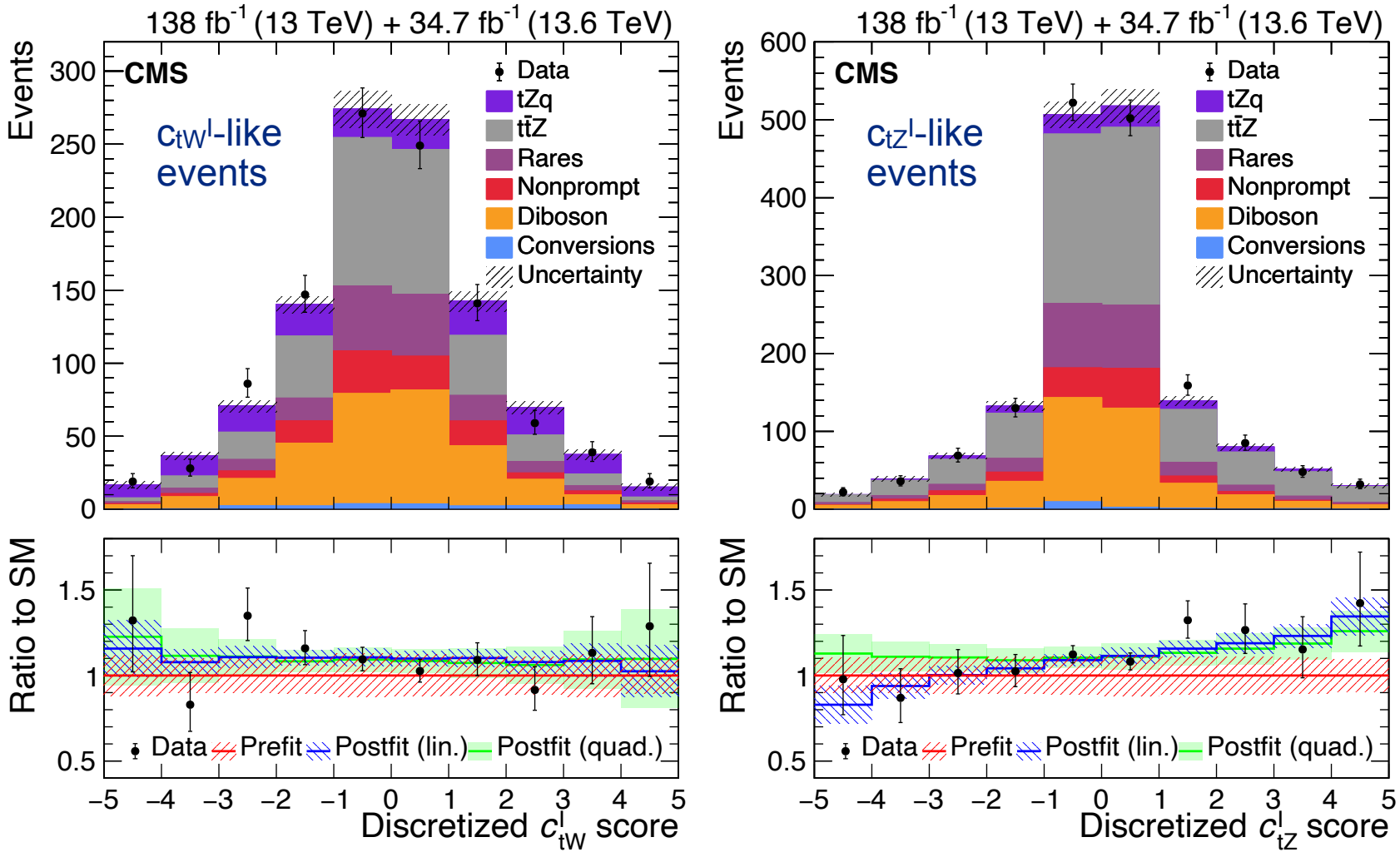
Training results





- SM → symmetric, BSM → asymmetric
- Categorizing events as c_{tW}^{I} or c_{tZ}^{I}-like

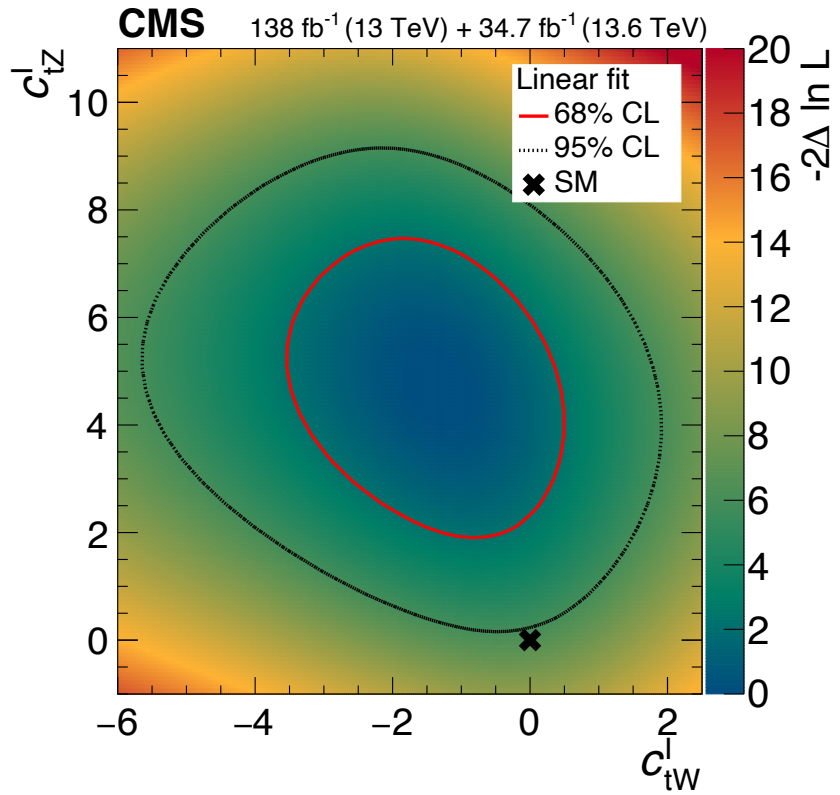
Results: observed yields



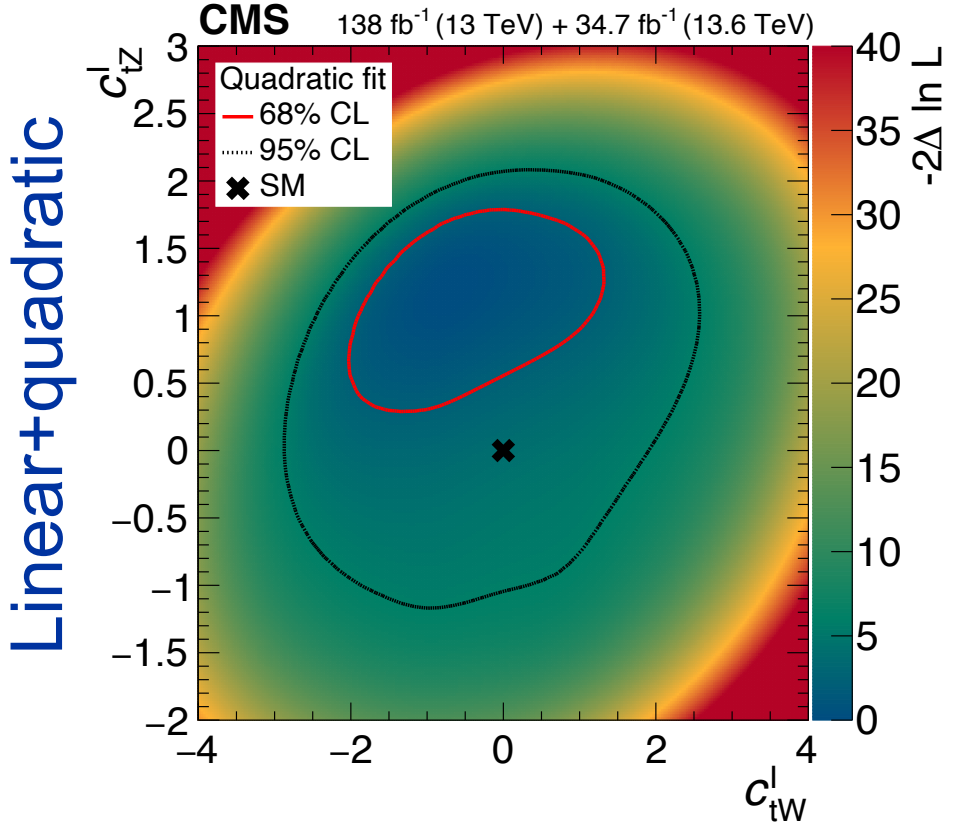
- **Consistent with SM predictions within two standard deviations**
- Slight excess of events, consistent with previous measurements
- No sign of asymmetry in the c_{tW}^{l} score distribution
- **Slight asymmetry in the c_{tZ}^{l} score distribution**

Results: interpretation

Linear-only



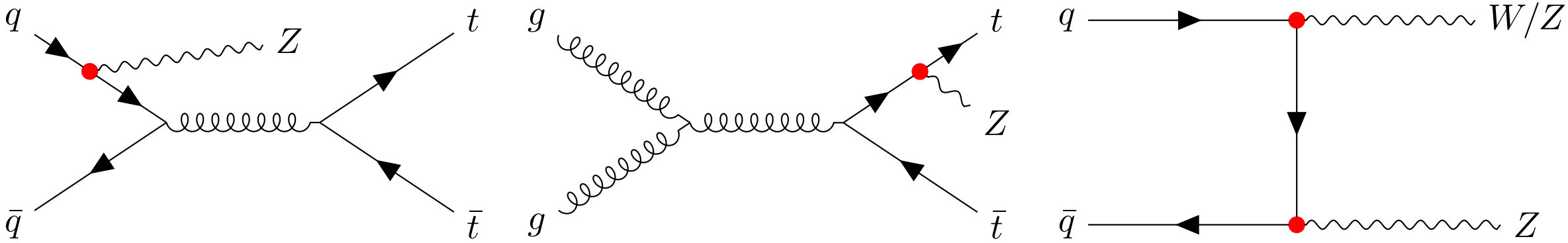
Linear+quadratic



- Inference in the Wilson coefficients performed from event yields $w = w_{SM} + \sum_i c_i^I l_i + \sum_{ij} c_i^I c_j^I q_{ij}$
- Simultaneous measurement of c_{tW}^{I} and c_{tZ}^{I} → SM within 2 s.d.
- c_{tZ}^{I} consistent with positive values due to asymmetry observed
  - Local significance between 1.9 and 2.6 s.d.

Flavor structure of SMEFT

CMS-PAS-TOP-23-009



- Measuring Z-quark couplings separately for 1st-2nd and 3rd generations
- Studying events with 3l and 4l, in different jet and b-tag multiplicity categories
- Studying quark+Z interactions, c_W and $c_{W\tilde{}}$

$$\mathcal{O}_{\varphi q}^{(1)(ab)} = \left(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi\right)\left(\overline{q_a}\gamma^\mu q_b\right),$$

$$\mathcal{O}_{\varphi q}^{(3)(ab)} = \left(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi\right)\left(\overline{q_a}\gamma^\mu \tau^I q_b\right),$$

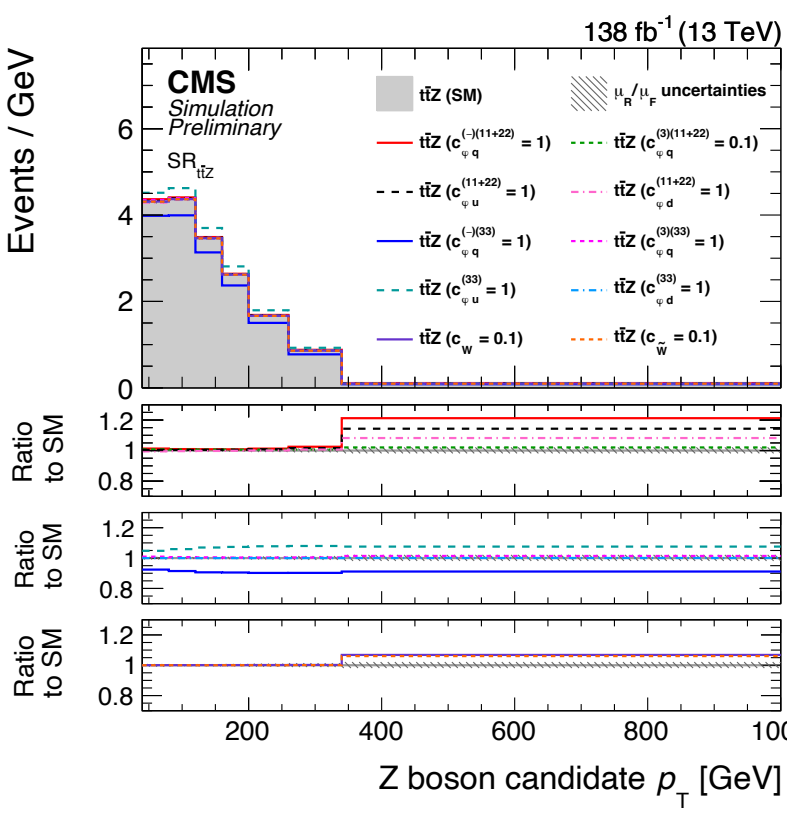
$$\mathcal{O}_{\varphi u}^{(ab)} = \left(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi\right)\left(\overline{u_a}\gamma^\mu u_b\right),$$

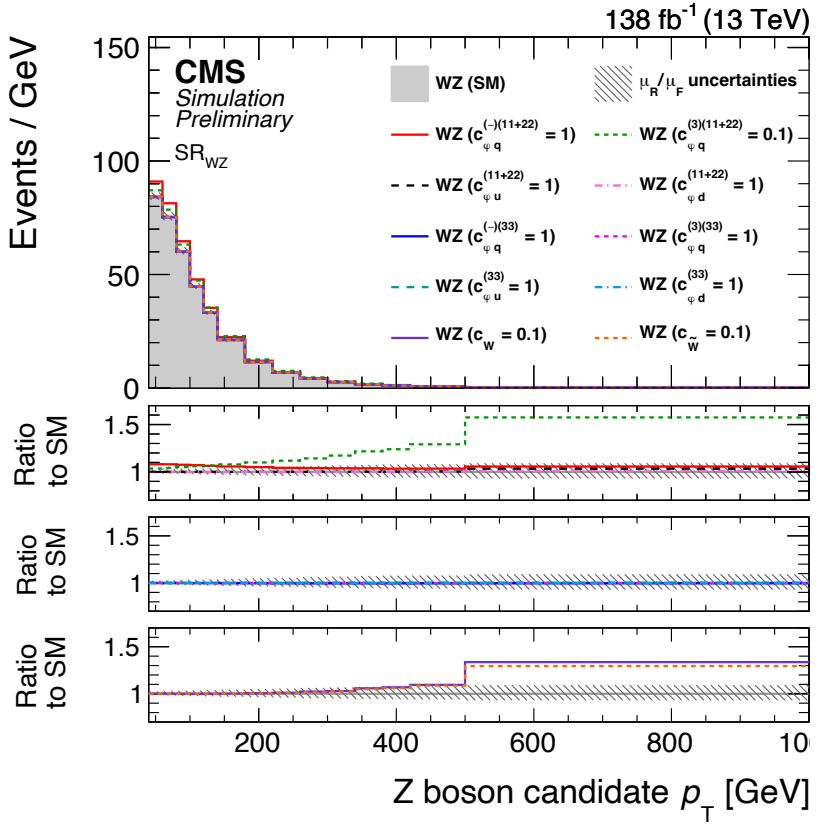
$$\mathcal{O}_{\varphi d}^{(ab)} = \left(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi\right)\left(\overline{d_a}\gamma^\mu d_b\right),$$

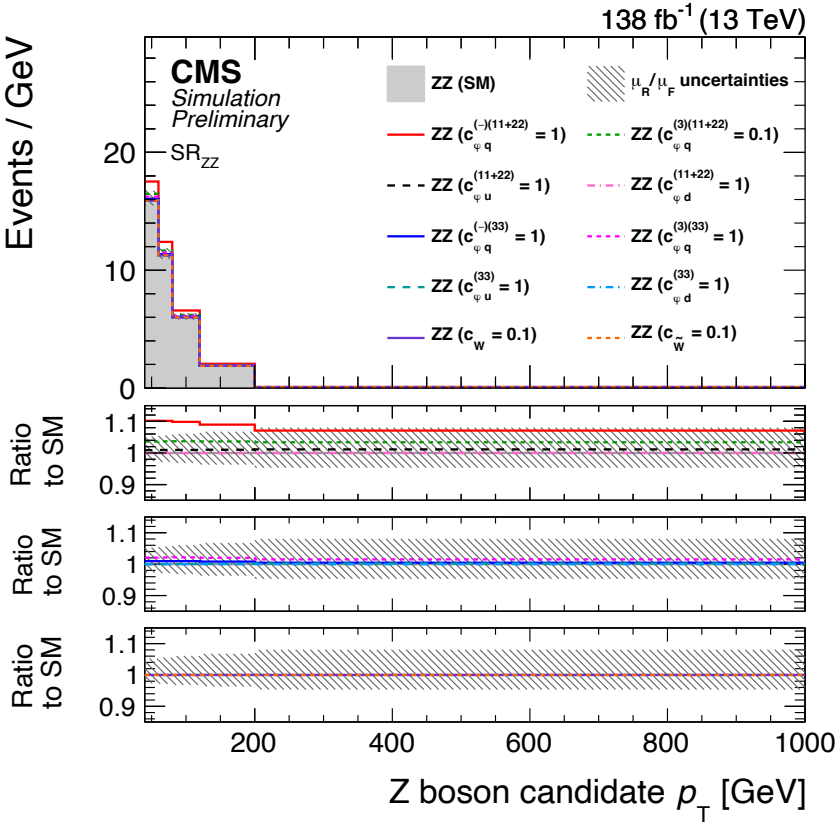
$$\mathcal{O}_W = \epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$$

$$\mathcal{O}_{\widetilde{W}} = \epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$$

Event selection and EFT effects





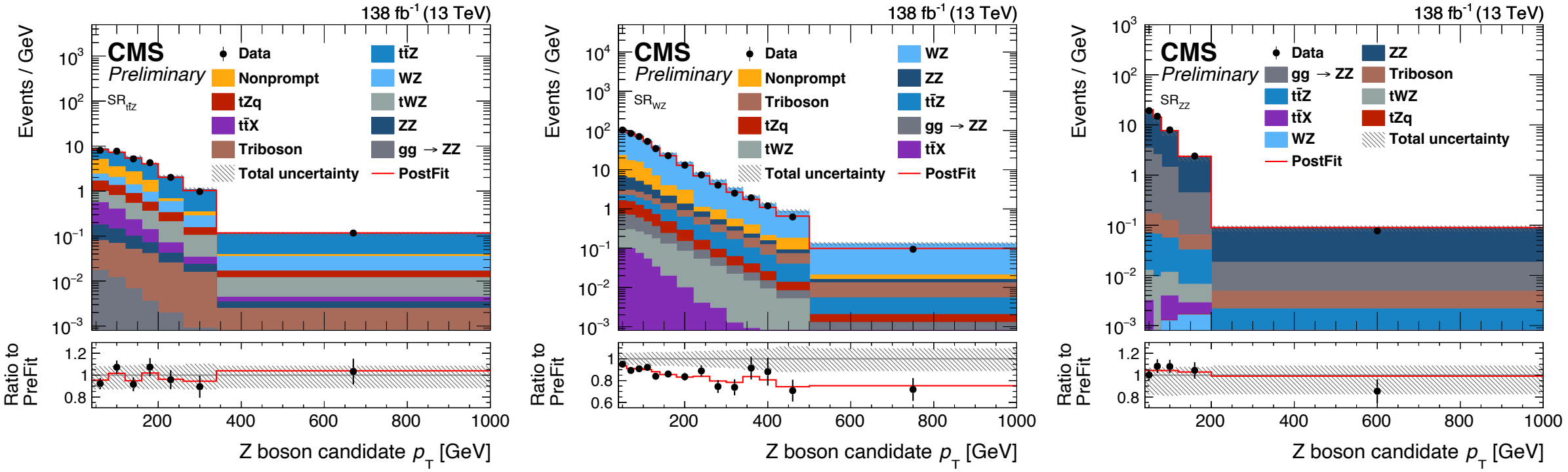


ttZ region: 3 leptons
1 Z candidate
jets
b tagged jets

WZ region: 3 leptons
1 Z candidate
no b tagged jets

ZZ region: 4 leptons
2 Z candidates

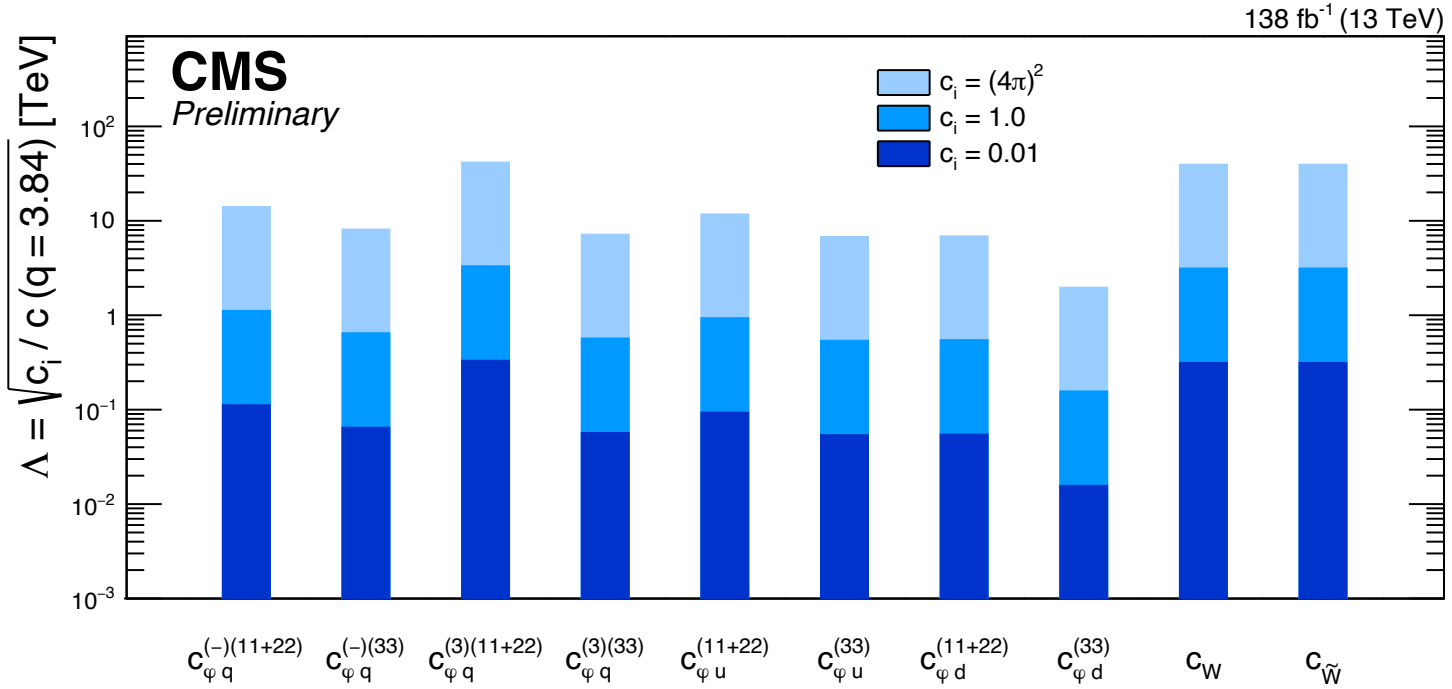
Event selection and EFT effects

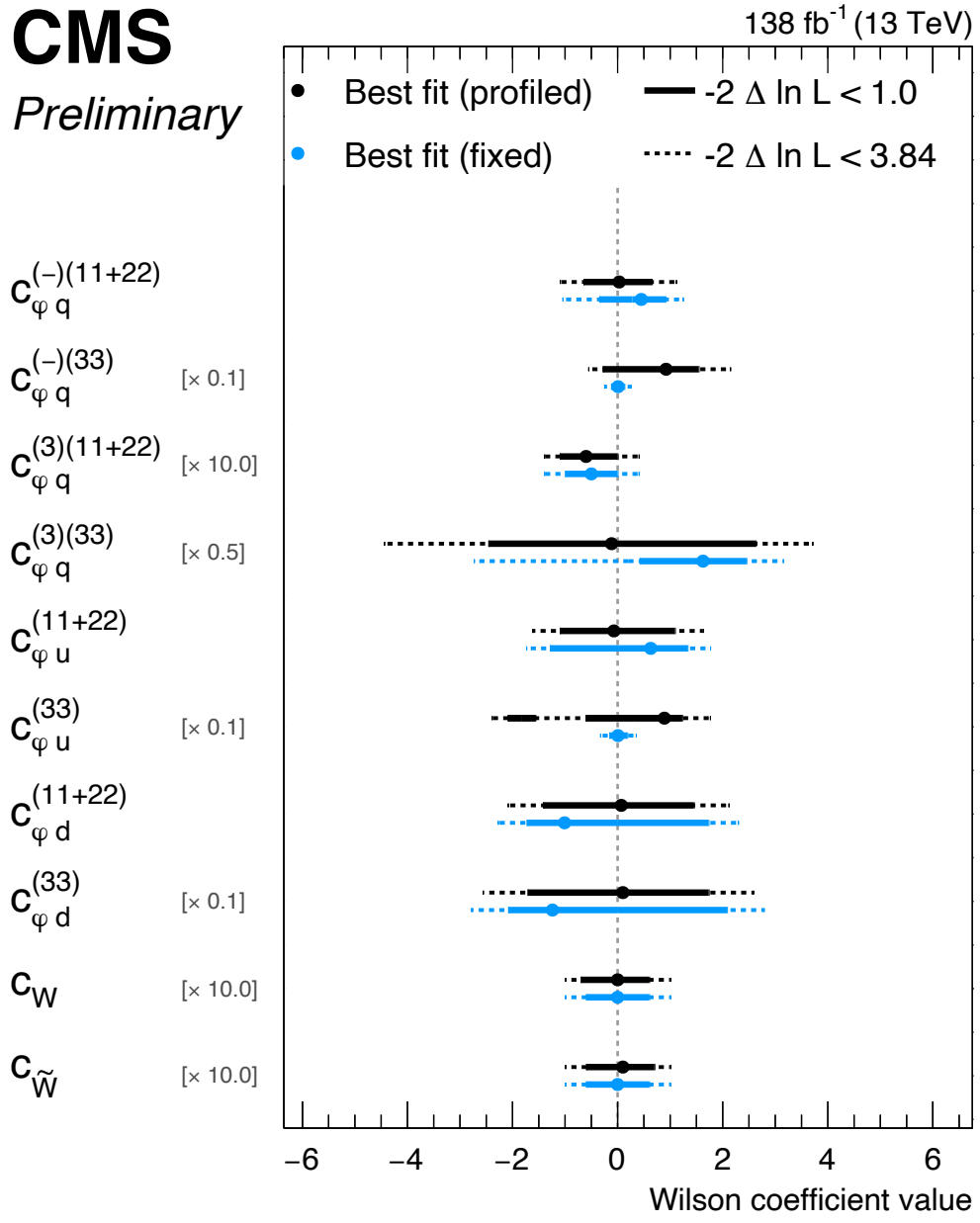


- Using Z boson candidate p_T to set limits on signals
- EFT effect estimated with weights: $w_i\left(\frac{\vec{c}}{\Lambda^2}\right) = s_{0i} + \sum_i s_{1ij}\frac{c_j}{\Lambda^2} + \sum_i s_{2ij}\frac{c_j^2}{\Lambda^4} + \sum_{i,k} s_{3ijk}\frac{c_j}{\Lambda^2}\frac{c_k}{\Lambda^2}$
- Good agreement between data and postfit

Results

- Results obtained measuring one coefficient a time and all simultaneously
- Results consistent with the SM





Summary

- Presented recent searches for new physics with *CP* violation and beyond usual EFT flavor assumptions
- Results consistent with the SM in both measurements within 2 s.d.
  - Slight tension on a *CP*-odd observables, 1.9-2.6 s.d. local
- A long way ahead of us, results performed with < half of the collected data!
  - Keep posted for more interesting results
  - Read our physics briefings 👀
    - Broken mirrors (link)
    - The flavour of new physics (link)