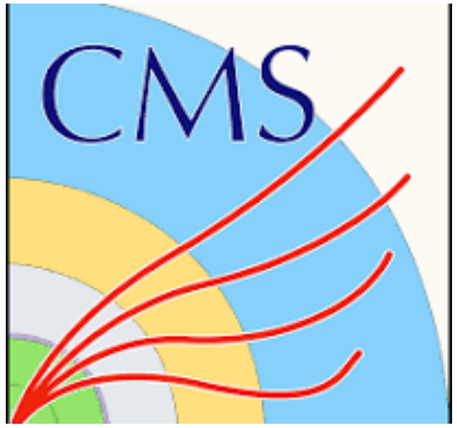
Searches in the Top Sector



Binbin Dong

On behalf of the ATLAS and CMS Collaborations

59th Rencontres de Moriond
23 - 30 March, 2025

MICHIGAN STATE
UNIVERSITY

Introduction

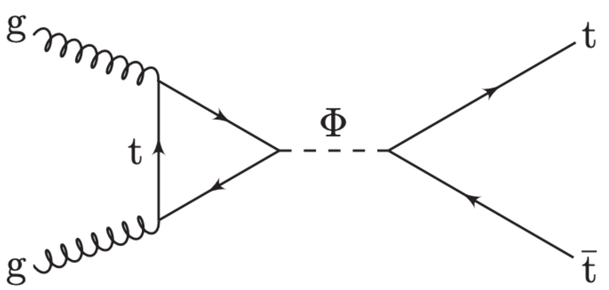
- The Top quark — a unique window to new physics
  - Heaviest fundamental particle → strongly coupled to the Higgs boson
  - Top Yukawa coupling ~ 1 → special role in electroweak symmetry breaking
  - Short lifetime, decay before hadronization

- Many BSM theories predict strong top interactions
  - Heavy resonances, composite Higgs, vector-like quarks → direct searches
  - There is a good chance that new physics is heavy, not enough energy to produce it yet at the LHC
    - Indirect searches are needed → SMEFT opens new directions

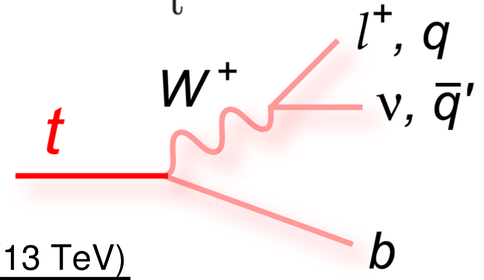
Direct Searches

Search for $gg \rightarrow H/A \rightarrow t\bar{t}$

CMS-HIG-22-013

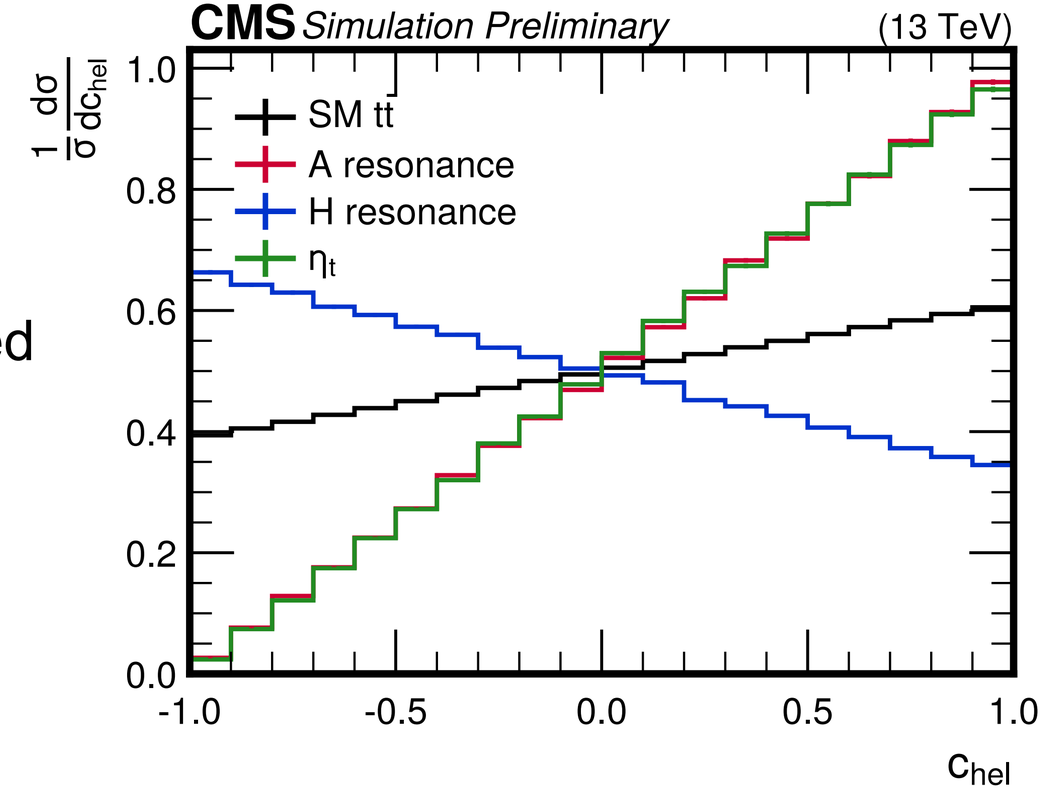


- Search for new spin-0 (pseudo) scalars in $t\bar{t}$ final states
  - (Pseudo-)scalar boson mass from 365 - 1000 GeV
  - Two orthogonal channels considered: dilepton and lepton+jets
- Strong interference with the SM $t\bar{t}$ process leads to a peak-dip structure
  - Pattern is strongly model dependent



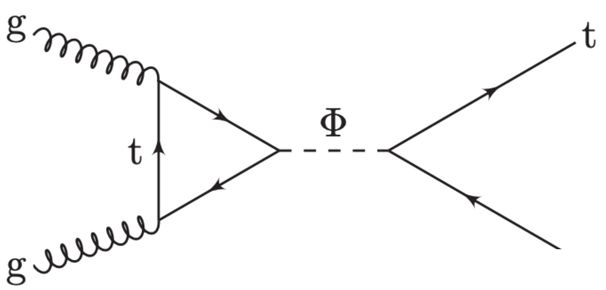
Dilepton channel

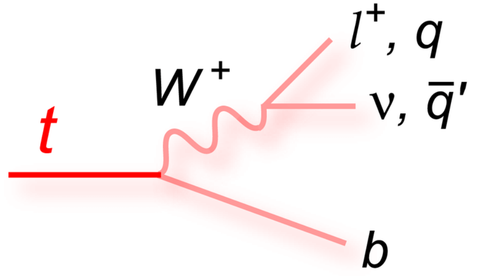
- Invariant $t\bar{t}$ mass spectrum
- 2 spin correlation observables constructed from tops and leptons



Search for $gg \rightarrow H/A \rightarrow t\bar{t}$

CMS-HIG-22-013





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Dilepton channel

- Invariant $t\bar{t}$ mass spectrum
- 2 spin correlation observables constructed from tops and leptons

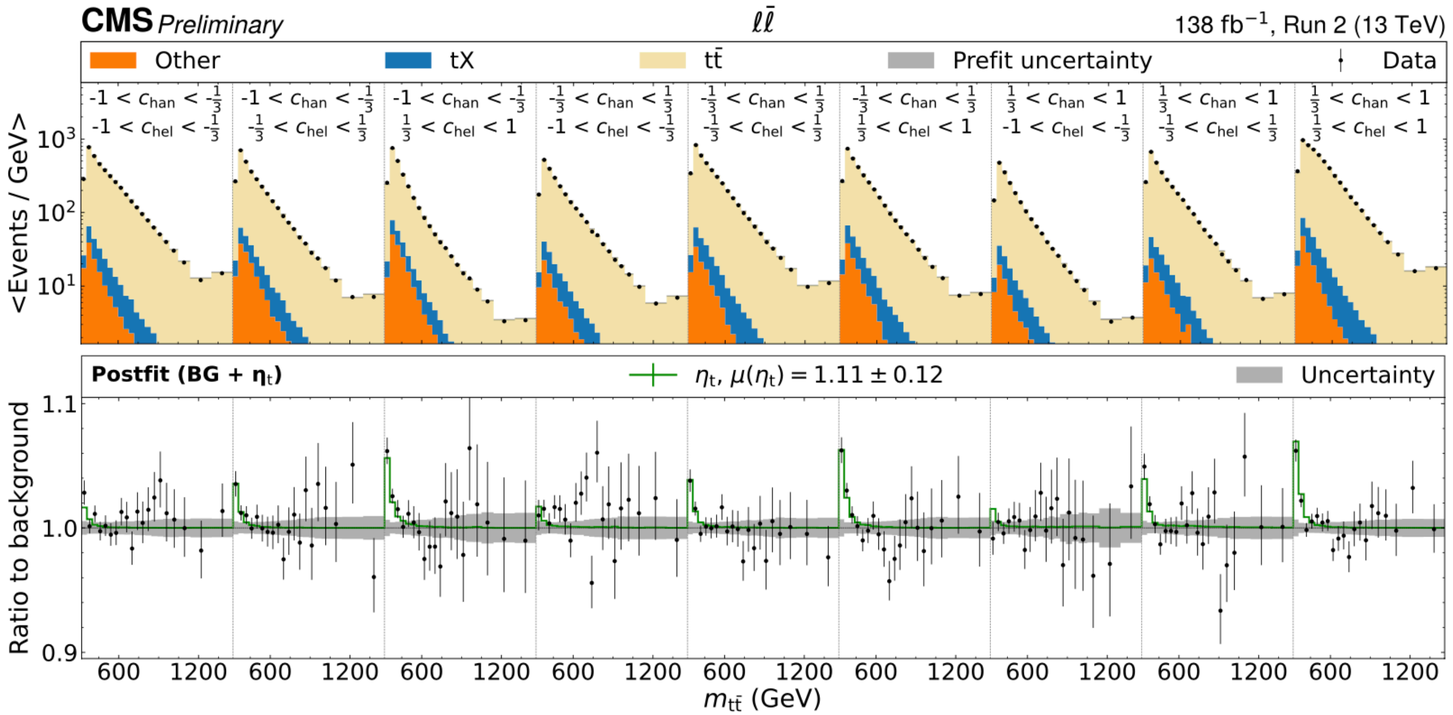
Lepton+jets channel

- Invariant $t\bar{t}$ mass spectrum
- 2D binning with $m_{t\bar{t}} \cdot |cos\theta^*|$
  - θ^*: angle between the lepton in the $t\bar{t}$ rest system and the $t\bar{t}$ in the lab frame

Search for $gg \to H/A \to t\bar{t}$

CMS-HIG-22-013

- Major irreducible background: SM $t\bar{t}$
  - Predictions differentially corrected to NNLO in QCD and NLO in EW



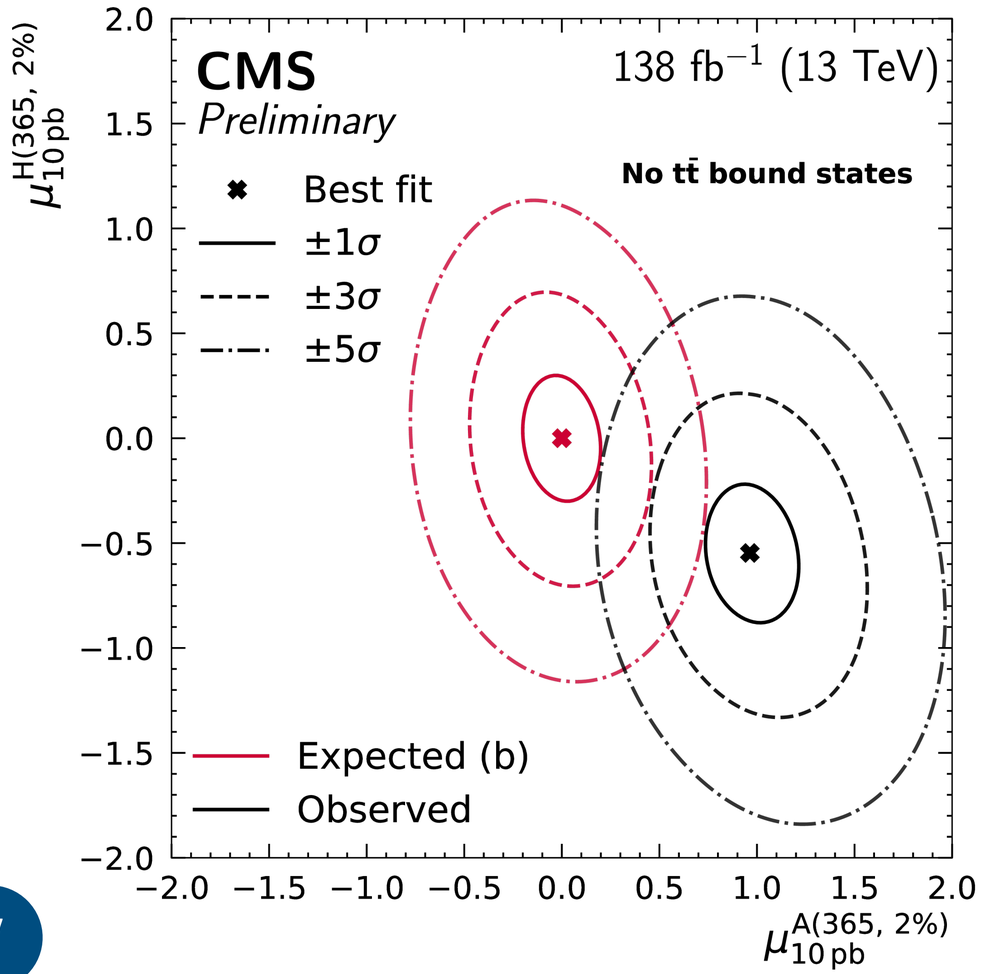
- Excess at low m_{tt} observed
  - Consistent with effects from $t\bar{t}$ bound-states $\sigma(\eta_t) = 7.1 \pm 0.8\,\mathrm{pb}$
  - Simpflied model of color-singlet pseudo-scalar for interpretation (PRD 104 (2021) 3, 034023)
  - Measured cross section agreeing with prediction from non-relativistic QCD

$$\sigma(\eta_t)^{\mathrm{pred}} = 6.43\,\mathrm{pb}$$

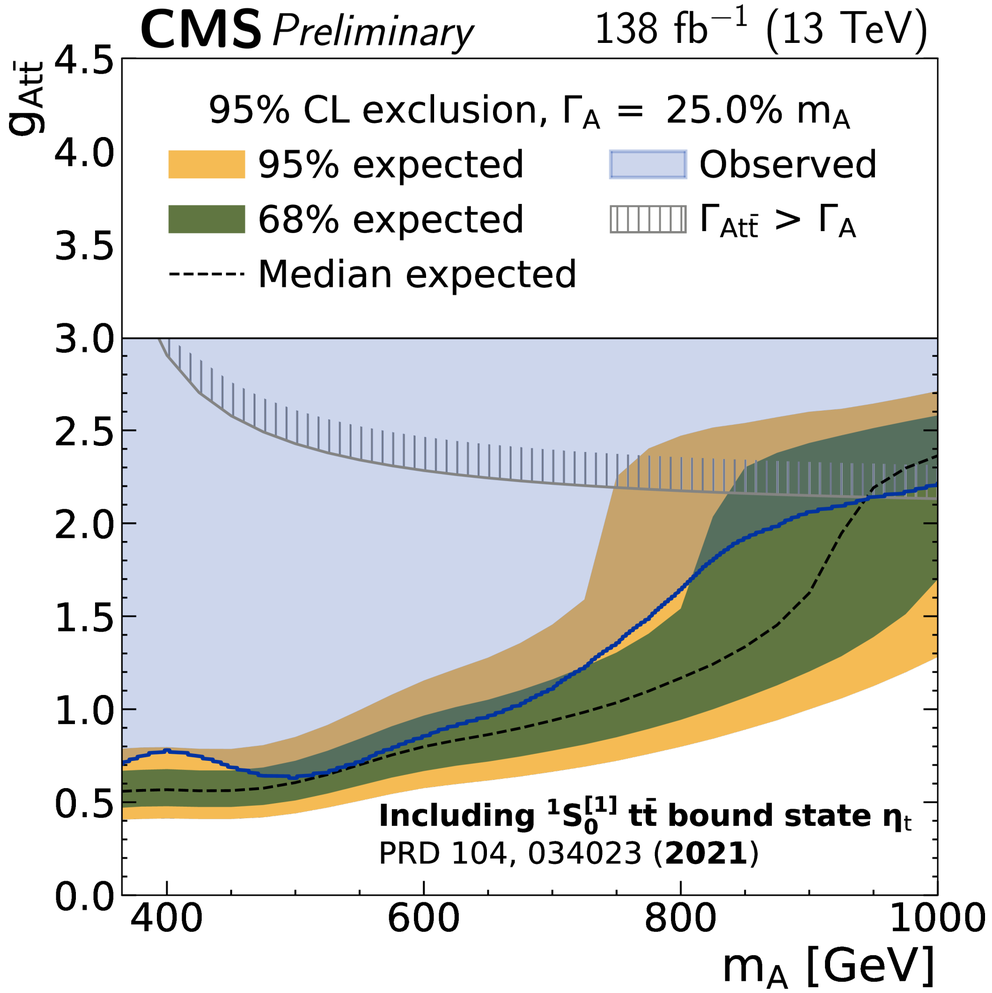
Search for $gg \to H/A \to t\bar{t}$

CMS-HIG-22-013

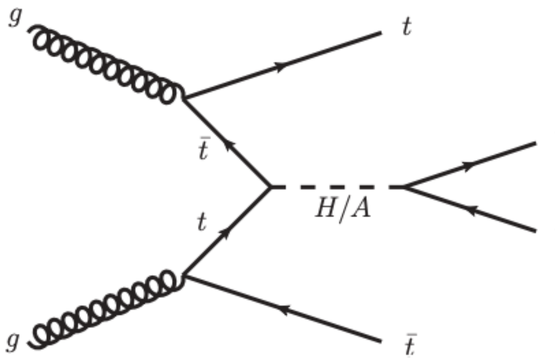
- Simultaneous fit of A/H to data
- Excess best compatible with pseudo-scalar hypothesis



- A/H limits including η_t



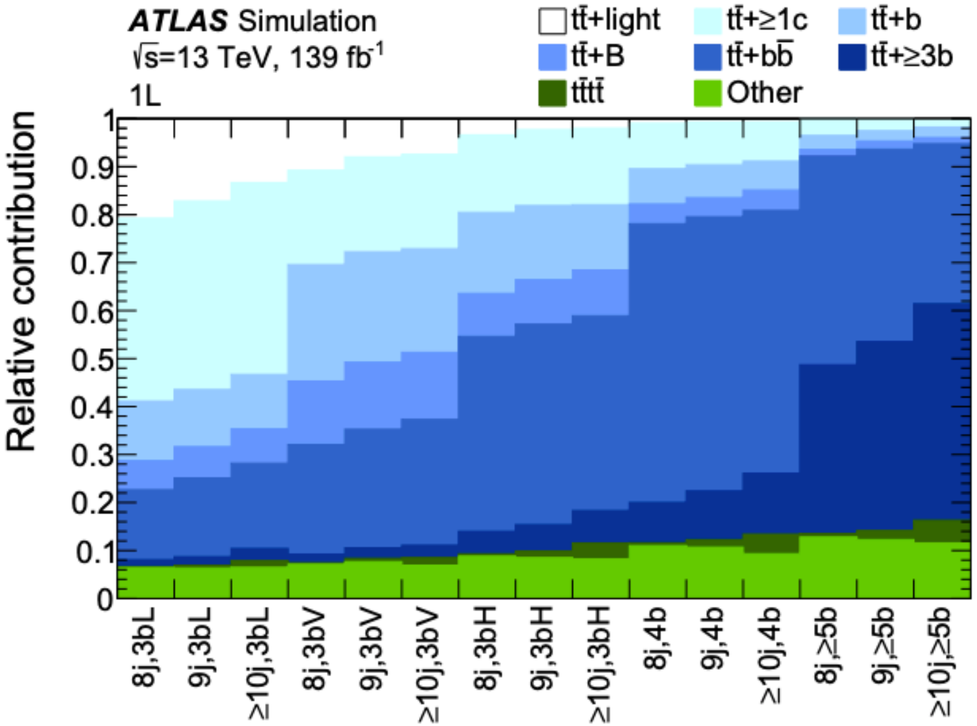
Search for $t\bar{t}A/H \rightarrow t\bar{t}t\bar{t}$



arxiv: 2408.17164

- $t\bar{t}A/H \rightarrow t\bar{t}t\bar{t}$ events feature high jet and b-jet multiplicities
  - Search in 2LSS/ML done in JHEP 07 (2023) 203
  - New search results in 1L/2LOS channel
  - Motivated by the enhanced cross section in the SM $t\bar{t}t\bar{t}$ measurement by ATLAS

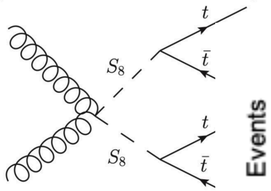
- Main background: $t\bar{t}$ + jets
  - b-tagging requirements to enhance separation between different $t\bar{t}$ subcategories: $t\bar{t}+\geq 1b$, $t\bar{t}+\geq 1c$ and $t\bar{t}+$ light
    - $t\bar{t}$+jets background modelling
      - Flavour rescaling factors correct overall normalisation of $t\bar{t}+\geq 1b$, $t\bar{t}+\geq 1c$ and $t\bar{t}+$ light
      - NN used for multi-dimensional kinematic reweighting, train as data vs $t\bar{t}$ simulation



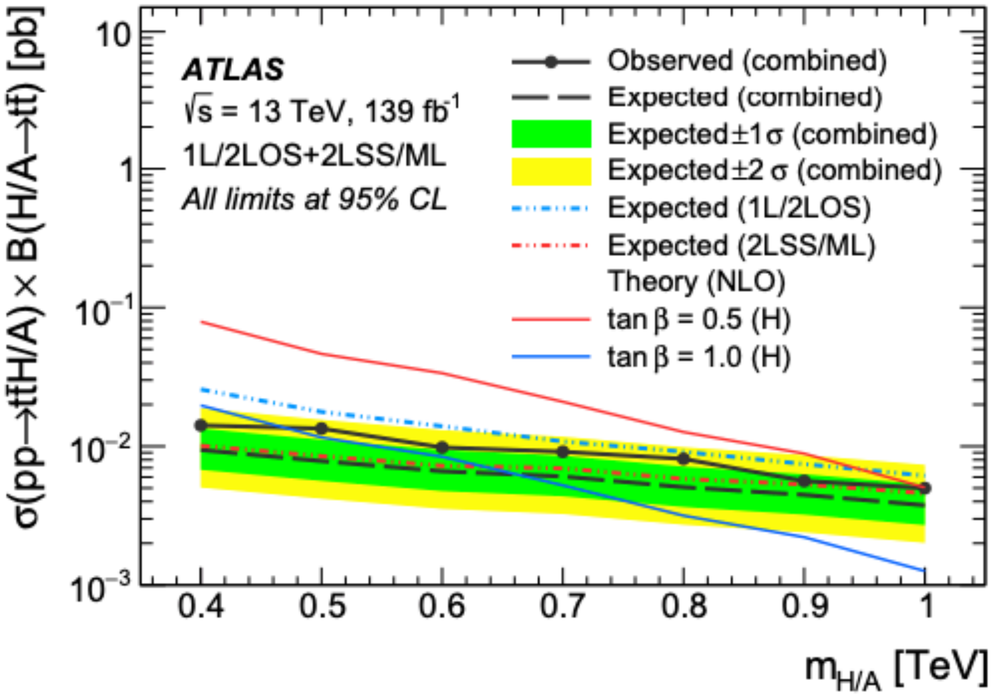
Search for $t\bar{t}A/H \rightarrow t\bar{t}t\bar{t}$

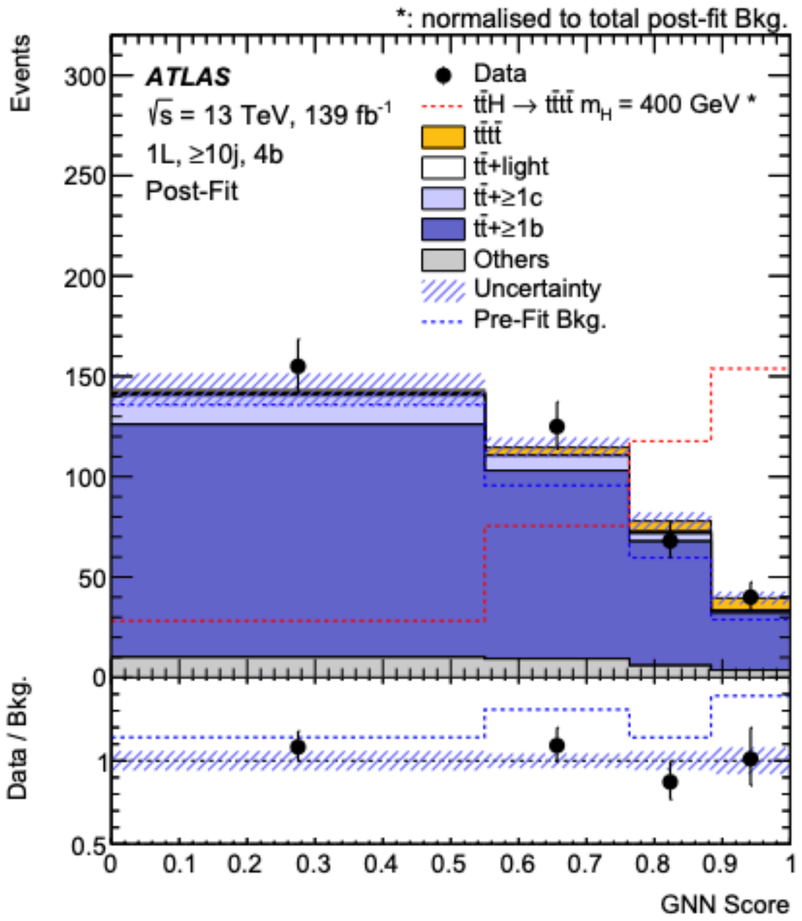
arxiv: 2408.17164

- Mass-parameterised GNN to optimize the signal-background discrimination
- SM $t\bar{t}t\bar{t}$ cross-section is fixed to the prediction in the final fit
- Small excess in the observed
  - 2.1 standard deviation observed at $m_{H/A} = 500$ GeV
  - Interpretation done on $S_8 S_8 \rightarrow t\bar{t}t\bar{t}$, excluded $m_{S_8} < 1.4$ TeV



- Combined with 2LSS/ML results
  - 2LSS/ML drives the sensitivity
  - A larger improvement in the sensitivity due to combination in the high mass regime

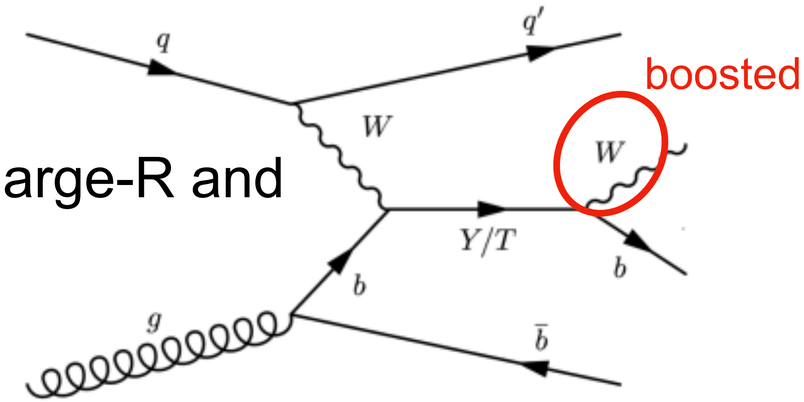


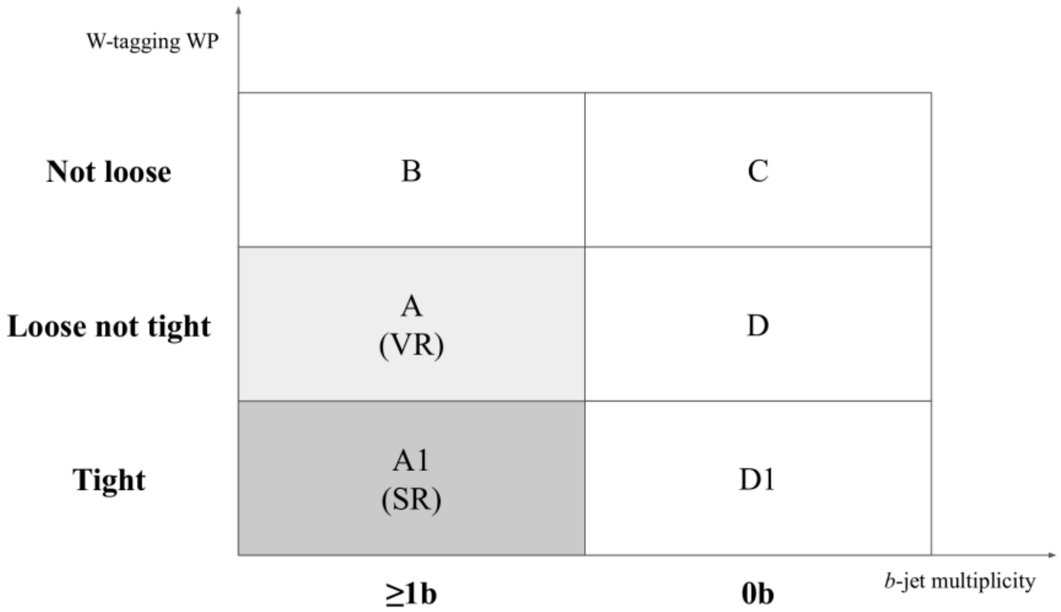


Vector-like Quarks

JHEP 02 (2025) 075

- First search of T and Y vector-like quarks (VLQ) in fully hadronic final state
- Mass of VLQ reconstructed as the discriminating variable
  - Requires at least one large-R, one small-R jet
  - Mass defined as vector sum of the four momenta of the leading large-R and leading small-R jets
- Signal explored in T-quark mass from 1 - 2.7 TeV
  - Large angular separation of the two leading jets



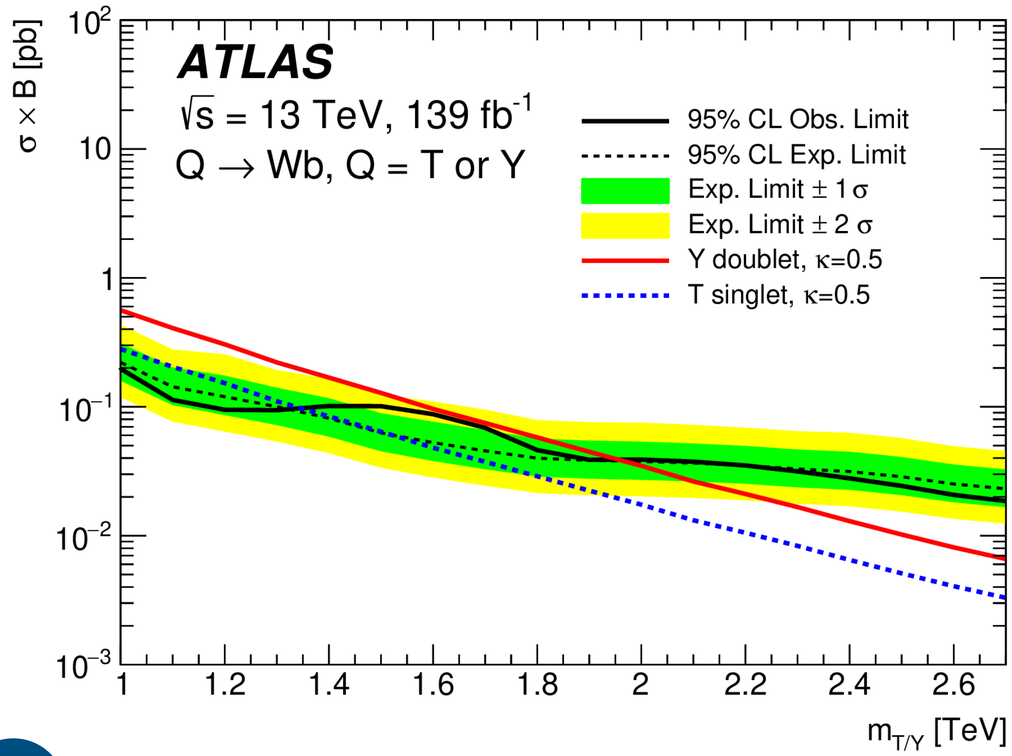


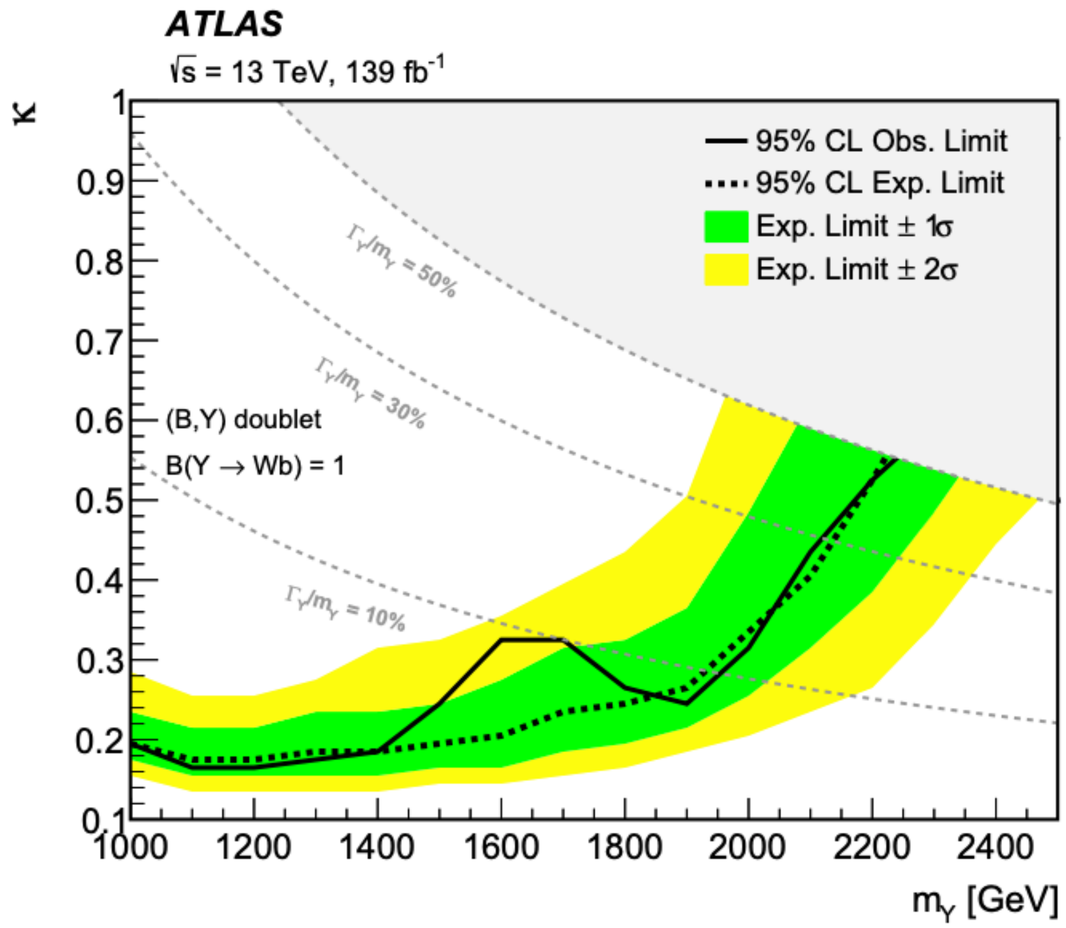
- Main background: QCD multi-jet production
  - data-driven: ABCD method
  - bin-by-bin corrections are applied to the m_{VLQ} distribution

Vector-like Quarks

JHEP 02 (2025) 075

- No significant excess observed
- Lower limits are set on the mass of T/Y-VLQ with global coupling parameter as $\kappa = 0.5$, $\kappa = 0.7$
- Interpretation performed on κ as a function of Y VLQ mass





Indirect Searches

EFT based Searches

NEW!

- SM Effective Field Theory (EFT) is a powerful tool to study effects from BSM phase space not directly accessible at the LHC.

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

c_i^d: Wilson coefficients (WCs)
$\mathcal{O}_i^d$: Higher dimension operators
Λ: Energy scale of new physics

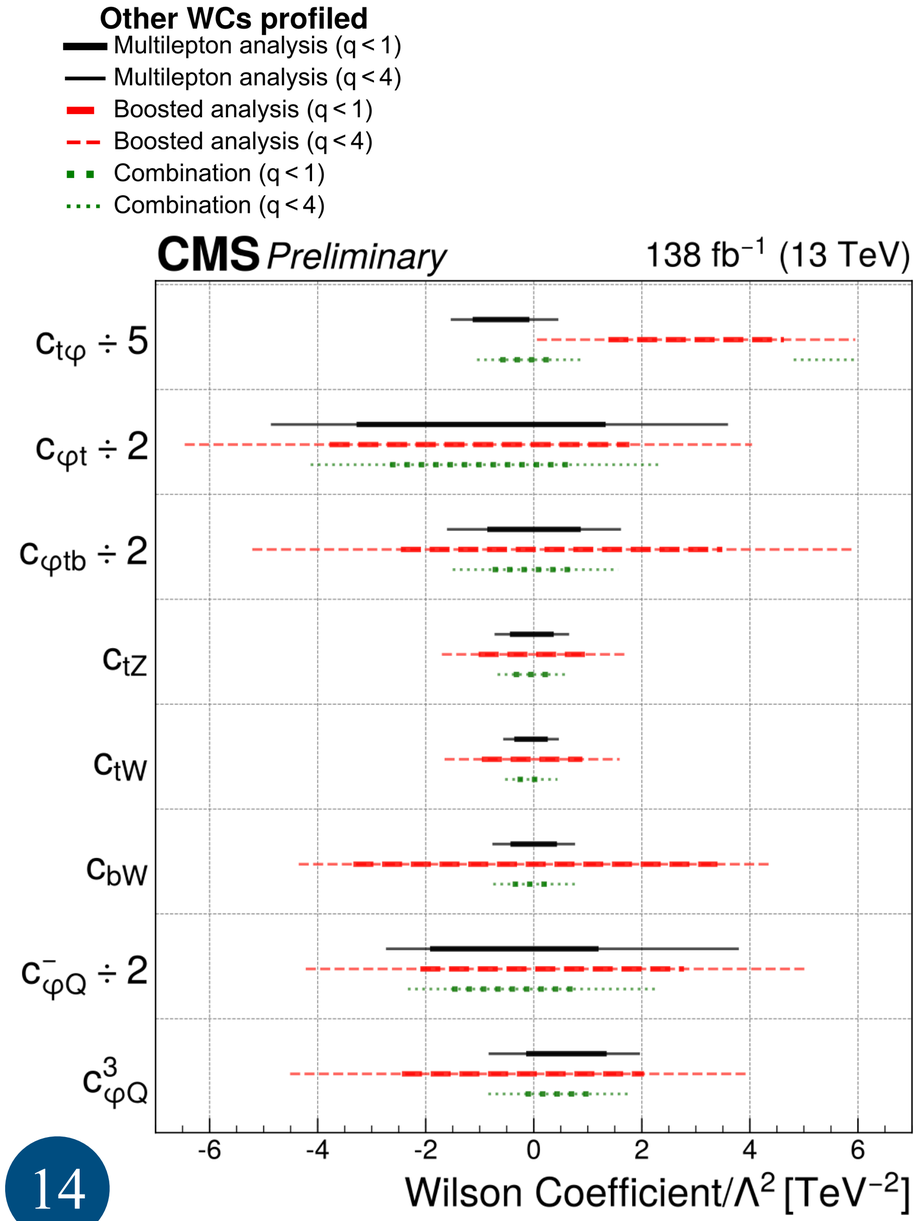
- EFTs induce effects in many channels, ideal framework for combination!
- EFT fit combining different precision measurements, using dimension-six operators:
  - "boosted analysis": $t\bar{t}Z$ and $t\bar{t}H$, $Z/H \to b\bar{b}$ with boosted topology ⟶ exactly one lepton
  - "multilepton analysis": $t\bar{t}lv, t\bar{t}ll, t\bar{t}H, t\bar{t}t\bar{t}, tHq$, and $tllq$ ⟶ at least two leptons

WCs of interest:

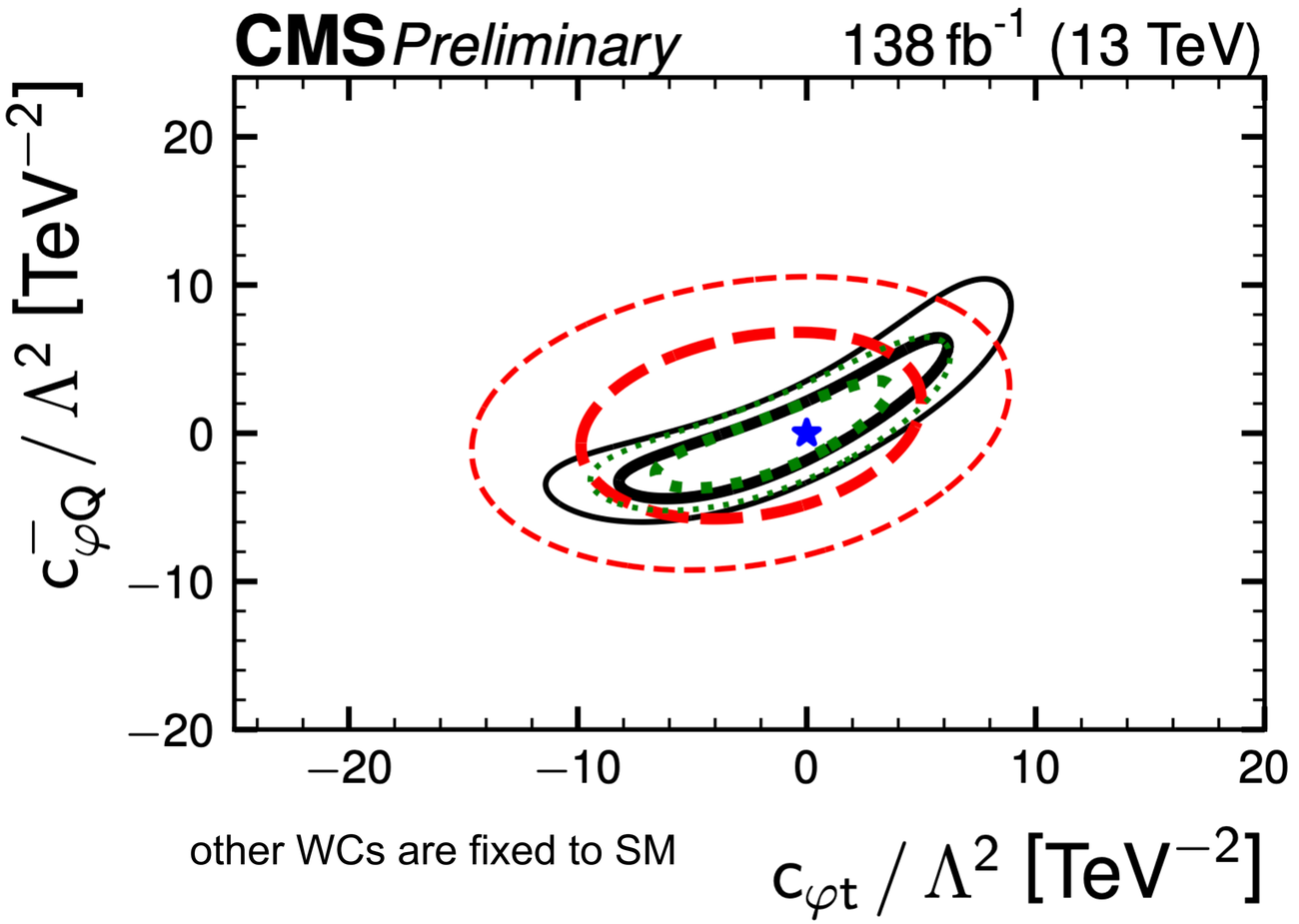
- $c_{t\varphi}$, $c_{\varphi t}$: modification to the top Yukawa coupling; modifications to the high-pT tails in the t, H, W, and Z spectra
- $c_{\varphi tb}$: couples the t and b via the Higgs field
- $c_{\varphi Q}^-$, $c_{\varphi Q}^3$: couple third generation quarks to the Higgs field
- c_{tW}, c_{tZ}, c_{bW}: couple third generation quarks to the W/Z before electroweak symmetry breaking

EFT based Searches

NEW!



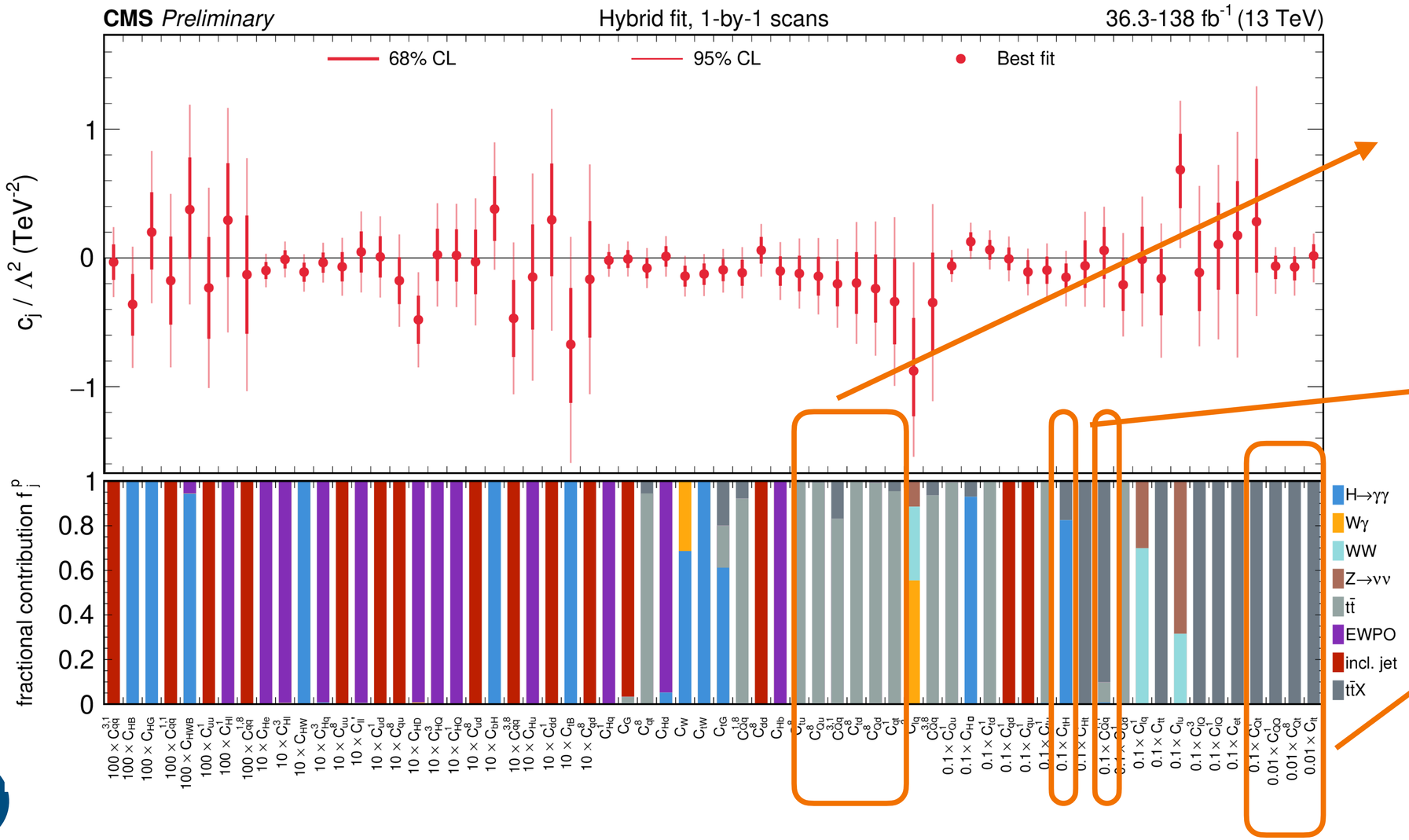
Multilepton is the main driver of the combination



other WCs are fixed to SM

Combined EFT interpretation

- Broader combination, covering multiple sectors via simultaneous likelihood fit



two-heavy-two-light operators constrained from a combination of $t\bar{t}X$ and $t\bar{t}$

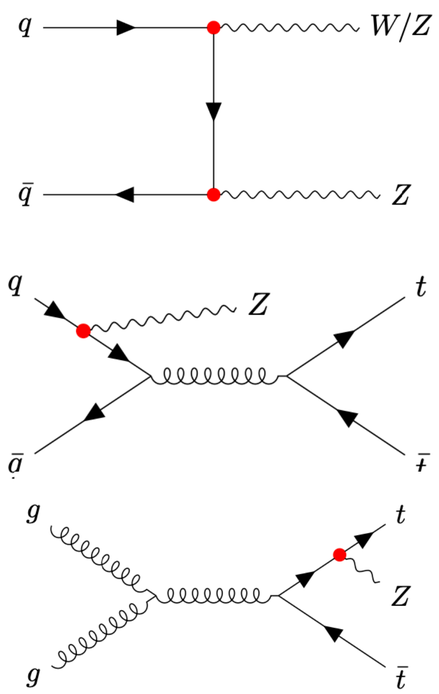
Top-Higgs coupling sensitivity increased by combination of $t\bar{t}X$ and $H \to \gamma\gamma$

Sensitivity to 4-heavy operators from $t\bar{t}X$ only

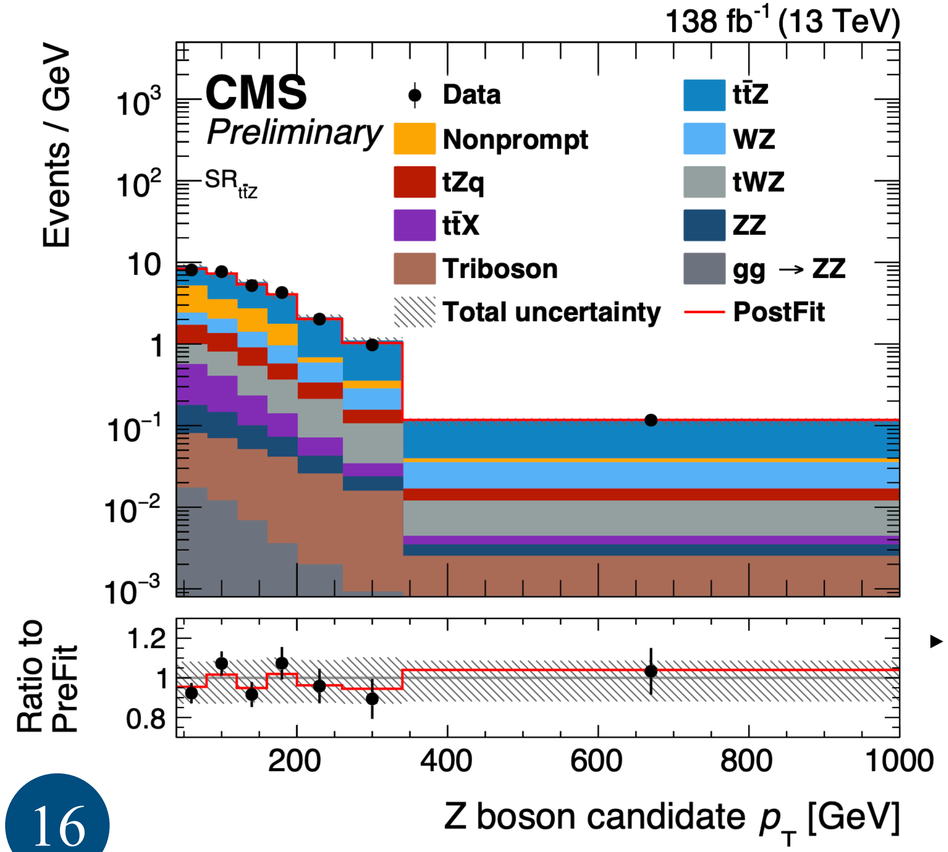
EFT based Searches

NEW!

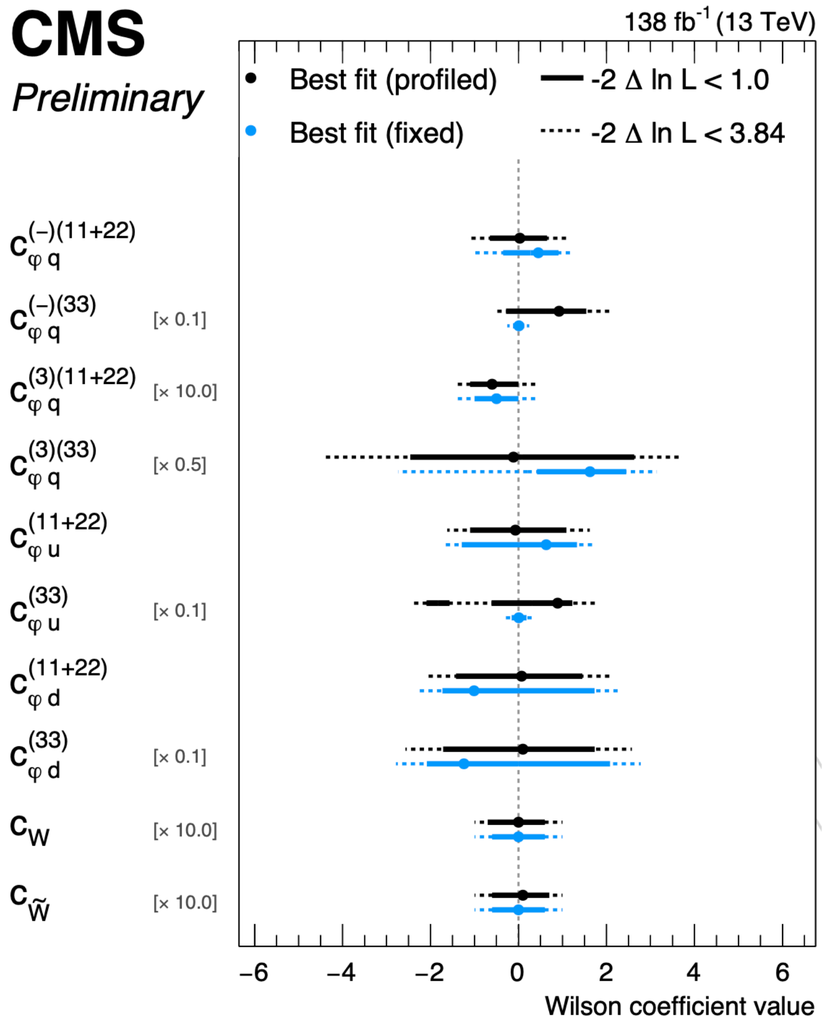
- Extension of the EFT programme to measure the quark couplings with a Z boson
  - Simultaneously measure it for 1st, 2nd vs 3rd generation quarks
  - Probed in ttZ, WZ and ZZ processes



- Multilepton channel used



- Results consistent with SM



Summary

- Presented an overview of recent ATLAS and CMS results of searches for new physics in top sector

- Explored both direct and indirect searches
  - Significant excess in the search for (pseudo-)scalar $t\bar{t}$ production at CMS
  - Results well compatible with contributions from $t\bar{t}$ bound states

- An exciting search program for Run 3 awaits

BACKUP

Search for $gg \rightarrow H/A \rightarrow t\bar{t}$

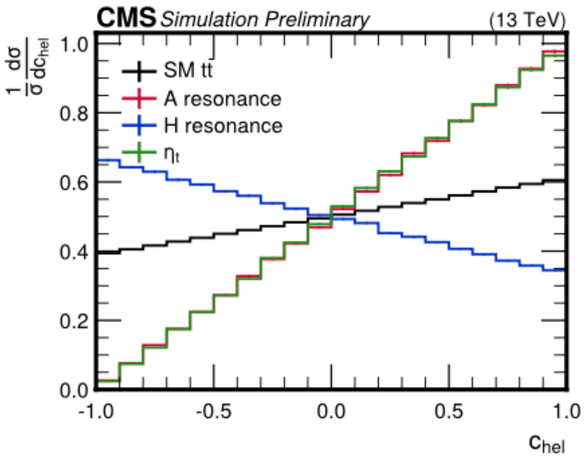
CMS-HIG-22-013

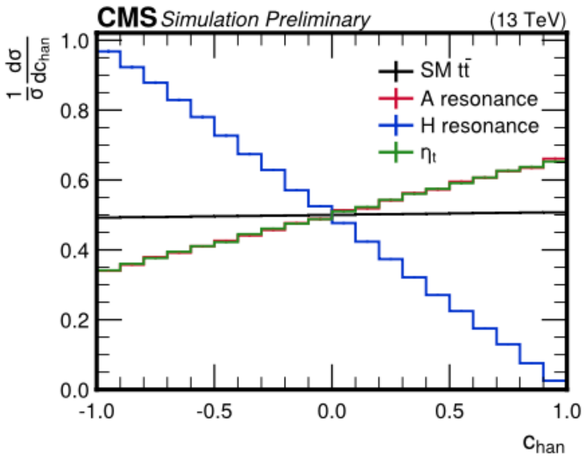
Lepton+jets channel

- Require one lepton, $\geq$ 3 jets, $\geq$ 2 b-jets
- Split into 4 categories:
  - e vs μ
  - 3 jets vs $\geq$ 4 jets
- Reconstruct $t\bar{t}$ with NeutrinoSolver algorithm
- 2D binning with $m_{t\bar{t}} \cdot |cos\theta^*|$
  - θ^*: scattering angle of leptonic top quark

Dilepton channel

- Require two OS leptons, $\geq$ 2 jets, $\geq$ 1 b-jets
- Split by lepton flavour: ee, eμ and $\mu\mu$
- Analytic reconstruction of $t\bar{t}$ system:
  - Assumption: tops/Ws on-shell
  - Assign b jets using likelihood based on m_{lb}

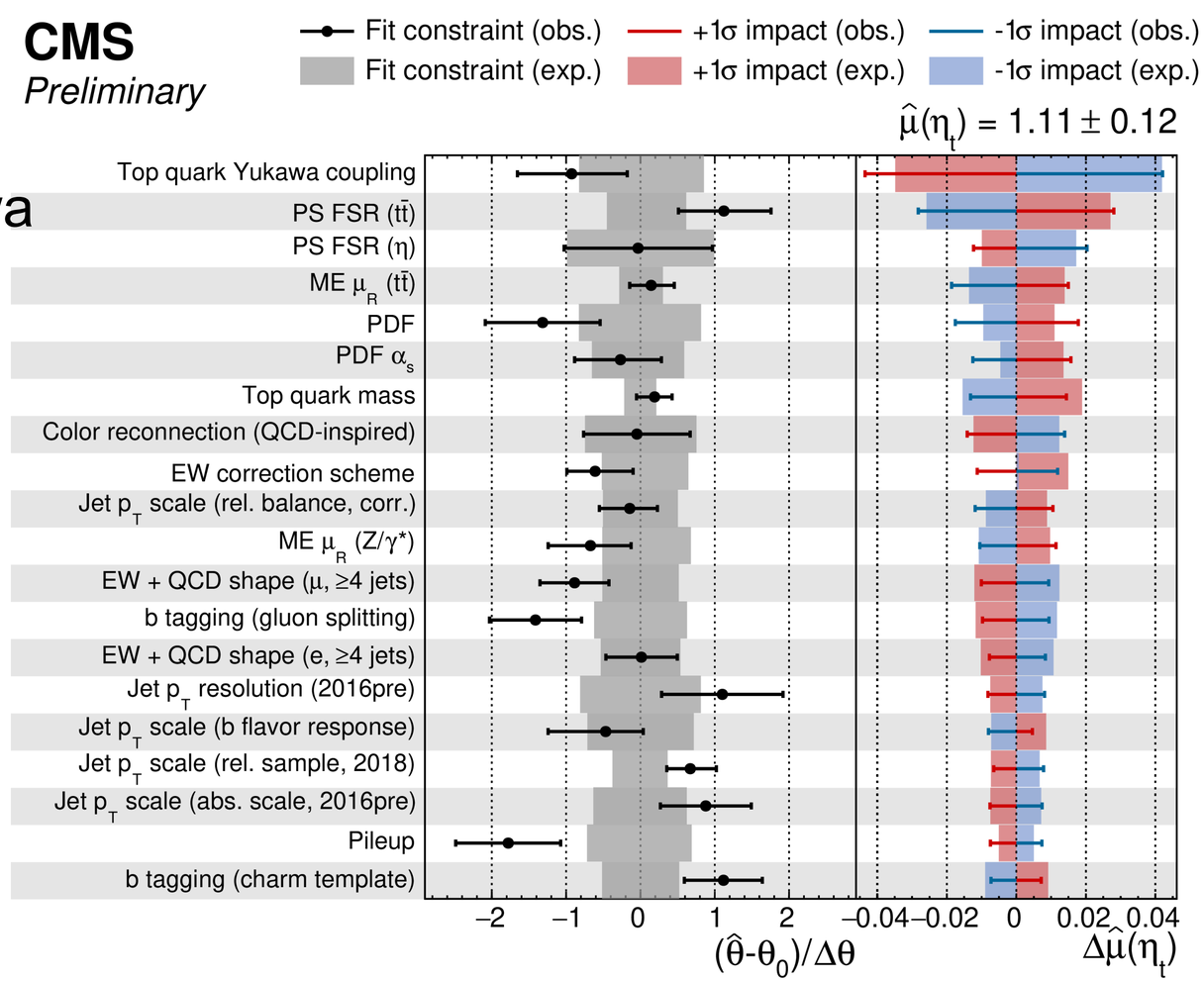




Search for $gg \rightarrow H/A \rightarrow t\bar{t}$

- Uncertainty on bound state cross section dominated by background modelling
- Leading systematics sources:

  - EW corrections, including SM top Yukawa coupling
  - Parton showe scale
  - Missing higher orders
  - PDF
  - Top mass



Search for $t\bar{t}A/H \to t\bar{t}t\bar{t}$

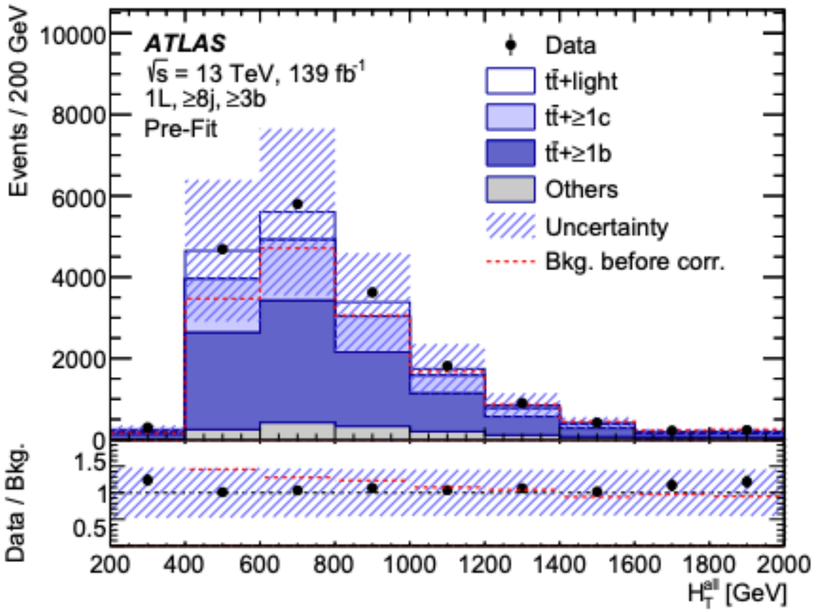
arxiv: 2408.17164

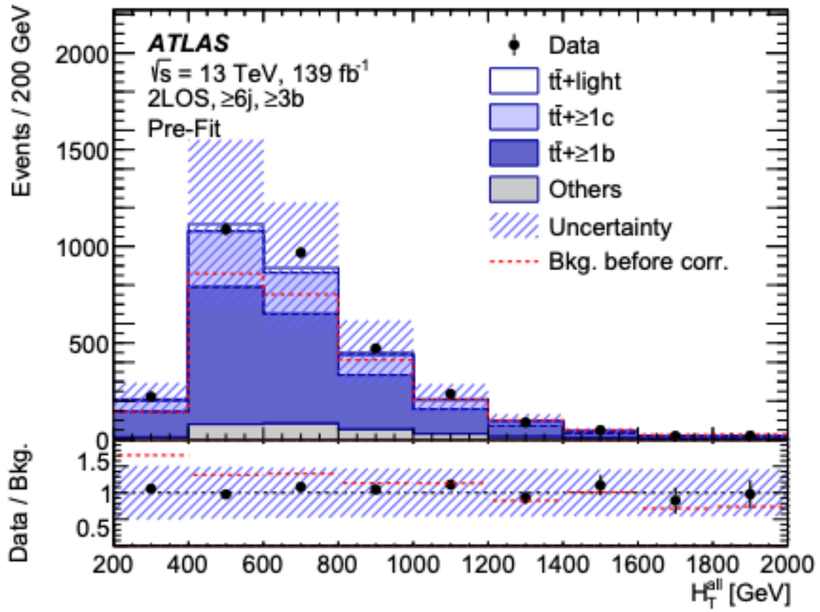
- NN used for multi-dimensional kinematic reweighting, trained as data vs $t\bar{t}$ simulation

$$O(\mathbf{x}) = P(\text{data}|\mathbf{x}) = \frac{\alpha_{\text{data}} P_{\text{data}}(\mathbf{x})}{\alpha_{\text{data}} P_{\text{data}}(\mathbf{x}) + \alpha_{\text{sim}} P_{\text{sim}}(\mathbf{x})}$$

- Event-by-event reweighting factor:

$$w(\mathbf{x}) = \frac{\alpha_{\text{data}} P_{\text{data}}(\mathbf{x})}{\alpha_{\text{sim}} P_{\text{sim}}(\mathbf{x})} = \frac{O(\mathbf{x})}{1 - O(\mathbf{x})}$$





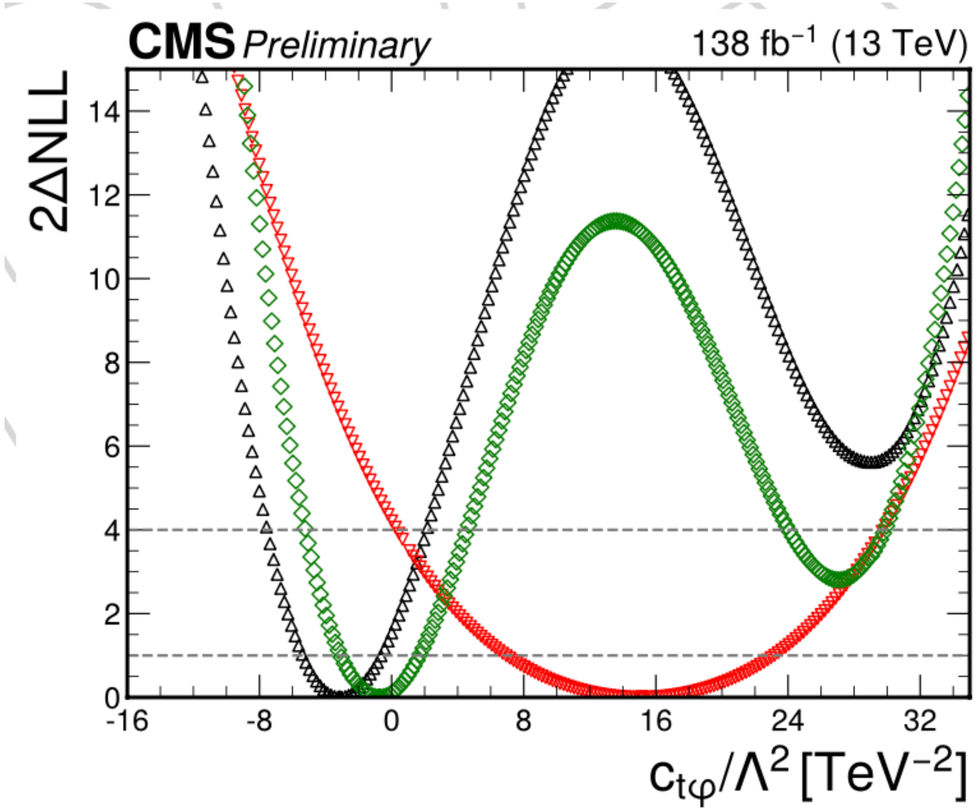
VLQs

JHEP 02 (2025) 075

- Main background: QCD multijet
  - data-driven: ABCD method
  - bin-by-bin correction factor applied

$$N_{\mathrm{A/A1}}^{\text{multijet estimate}}[i] = R_{\mathrm{corr}}[i] \times (N_{\mathrm{B}}^{\mathrm{Data}}[i] - N_{\mathrm{B}}^{\text{SM MC backgrounds}}[i]) \times \frac{(N_{\mathrm{D/D1}}^{\mathrm{Data}}[i] - N_{\mathrm{D/D1}}^{\text{SM MC backgrounds}}[i])}{(N_{\mathrm{C}}^{\mathrm{Data}}[i] - N_{\mathrm{C}}^{\text{SM MC backgrounds}}[i])}$$

EFT based Searches



Other WCs profiled

- △ Multilepton analysis
- ▽ Boosted analysis
- ◇ Combination