# Search for new physics in top quark production in multi-lepton final states using effective field theory

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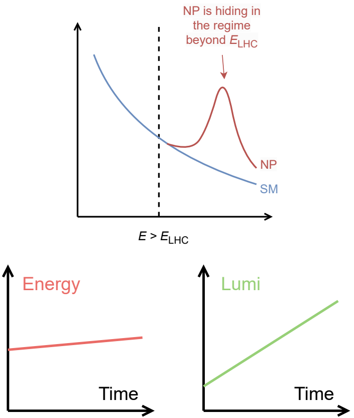
# Motivation

1. There are strong indications that new physics exist. However, new particles might not be light enough to be produced on-shell at the LHC.
2. The upgrade on the energy scale of the collider experiments is slow. Thus indirect searches for the new physics are becoming increasingly interesting.
3. Effective field theory (EFT) is a framework that offers such an indirect search approach, where heavy new physics can be parameterized in a mostly model-independent way.



# Introduction to Effective Field Theory

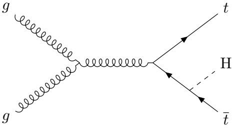
SMEFT describes the off-shell effects at an energy scale $\Lambda$, while treating the SM Lagrangian as the lowest order term in an expansion of higher dimensional operators.

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{c_i}{\Lambda}\mathcal{O}_i^{(5)} + \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \dots$$

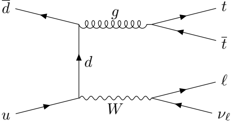
1. The coupling strength of the EFT interactions is parameterized as a set of Wilson coefficients $c_i$.
2. The higher order terms are further suppressed by the energy scale $\Lambda$.
3. This analysis focuses on a subset of dimension-six operators involving top quark.

# Analysis Overview

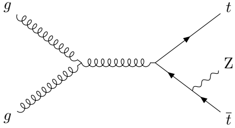
1. This analysis focuses on the subset of EFT operators that affect top production associated with leptons, bosons, and other heavy quarks.
2. Signal processes: $t\bar{t}H$ $t\bar{t}l\nu$ $t\bar{t}l\bar{l}$ $tHq$ $tl\bar{l}q$ $t\bar{t}t\bar{t}$



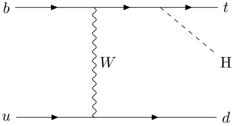

$t\bar{t}H$



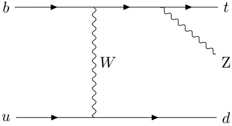

$t\bar{t}l\nu$



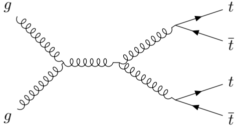

$t\bar{t}Z$




$tHq$



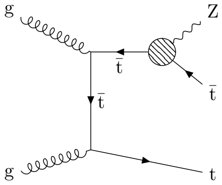

$tZq$



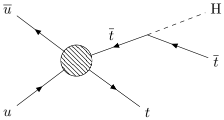

$t\bar{t}t\bar{t}$

# EFT Effects

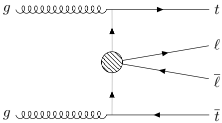
We study 26 WCs that significantly impact associated top processes. The operators can be classified into 4 main categories based on the particles that interact:



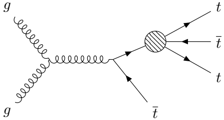

2 heavy with bosons




2 heavy 2 light




2 heavy 2 leptons




4 heavy

# Challenges of this Analysis

This analysis uses a global approach. We probe the effects of dim-6 operators involving top quarks on those processes simultaneously. It also leads to many analysis level challenges.

1. Multiple signal processes can contribute to the same final state signatures
2. Many WCs can affect the processes, interfere with each other and the SM
3. E.g. Many WCs ($c_{tZ}$, $c_{tG}$, etc.) can affect the process $t\bar{t}l\bar{l}$. $t\bar{t}l\bar{l}$ contributes to the $2\ell ss$ final state, along with $t\bar{t}l\nu$, $t\bar{t}H$, etc.

We want to know number of predicted events in a given detector-level observable bin, as a function all of the WCs, i.e. Yield(c1, c2, c3, ...) The predicted events in a given bin depends on the WCs quadratically.

# EFT Parameterization

This analysis takes a direct approach to model the EFT effects at the detector level.

1. The differential cross section $d\sigma(c_i)$ depends on the Wilson coefficients $c_i$ quadratically.

$$d\sigma(c_i) \propto |M_{SM} + \sum_i \frac{c_i}{\Lambda^2} M_i|^2 \propto s_0 + \sum_j s_j \frac{c_j}{\Lambda^2} + \sum_{j,k} s_{jk} \frac{c_j}{\Lambda^2} \frac{c_k}{\Lambda^2}$$

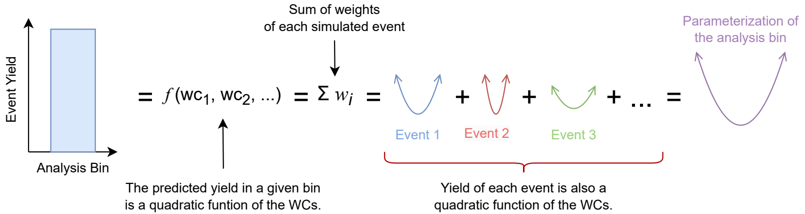
2. $s_0$, $s_j$ and $s_{jk}$ are constants representing the Pure SM, SM interference and pure EFT terms respectively.

# EFT Parameterization

1. One can assign quadratic EFT weight to an event since the quadratic dependence of the WCs extends to individual event.

$$\omega_{\mathrm{e}}(c) = s_{\mathrm{e}} + \sum_{j} s_{j\mathrm{e}} \frac{c_j}{\Lambda^2} + \sum_{j,k} s_{jk\mathrm{e}} \frac{c_j}{\Lambda^2} \frac{c_k}{\Lambda^2}$$

2. The quadratic parameterization for any observable bin can be obtained by summing the quadratic weight functions for every event that passes the selection criteria.



# Event Categories

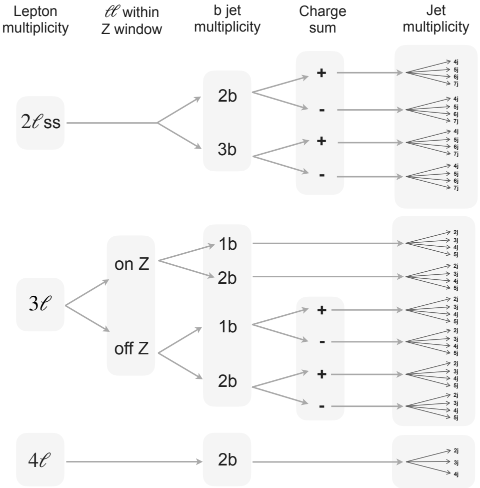
1. Jet multiplicity:

   $2\ell ss$ : 4 to 7+ jets
   $3\ell$ : 2 to 5+ jets
   $4\ell$ : 2 to 4+ jets

2. Kinematic distributions:

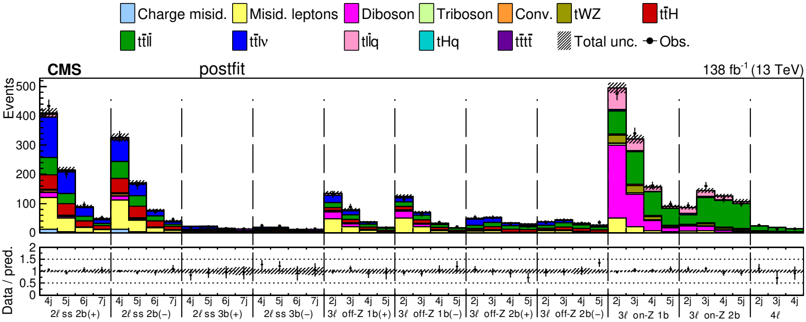
   $p_T(\ell j)_{max}$ : largest $p_T$ pairs of objects in the collections of leptons and jets
   $p_T(Z)$ : $p_T$ of the reconstructed Z boson

3. Major sources of background include dibosons and misid leptons.



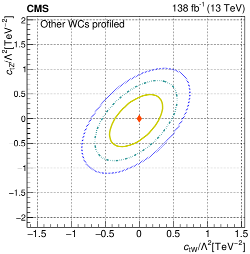
# Fit Results

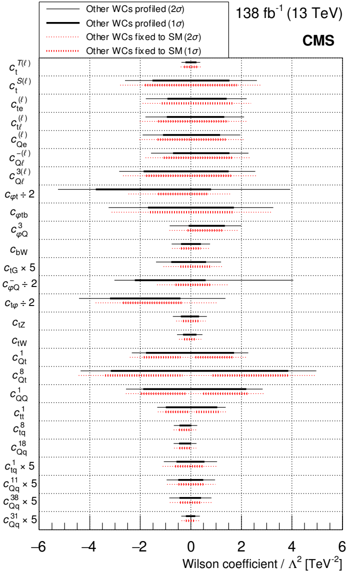
1. 178 total bins fit with CMS full RunII data.
2. Overall sensitivity to a WC comes from a diverse combination of bins.
3. Interference and correlations among WCs play also an important role.



# Limits and Sensitivity

1. Very challenging fit running over 26 POIs and 178 analysis bins
2. The $1\sigma$ and $2\sigma$ confidence intervals of the frozen and **profiled** scans.
3. No significant deviation from the SM.
4. 2D scans are also performed, for example, the $c_{tW}$ and $c_{tZ}$ profiled scan:



# Summary

1. We have searched for the new physics in top production in the multi-lepton final states.
   1. We fitted data corresponding to 138 $\mathrm{fb}^{-1}$ of collisions.
   2. We set confidence intervals on 26 WCs simultaneously.
   3. The results are consistent with the SM.
2. Potential directions to improve and expand the current analysis:
   1. Improve the stats.
   2. More advanced EFT modeling.
   3. Additional signal processes and final states.
   4. Combination with other analyses.

# Thank you!

This analysis has been accepted by JHEP currently.
To learn more about the analysis, please check:
Arxiv: https://arxiv.org/abs/2307.15761

# Backup

# EFT Reweighting

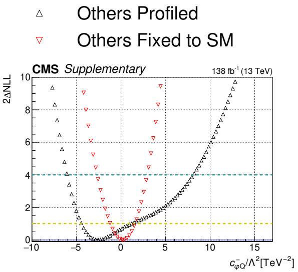
1. To fully determine the quadratic parameterization, one would need $(N+2)(N+1)/2$ constants for $N$ WCs.
2. If we consider all 26 WCs, there can be as many as 378 constants in the quadratic parameterization, meaning 378 MC unique simulated samples at 378 unique points are needed per signal process!
3. Instead, one can calculate the quadratic dependence on the event basis.

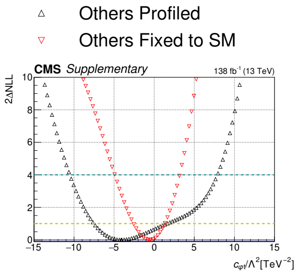
# Modeling EFT Effects

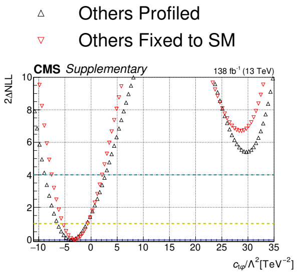
1. The dim6top model was used to model the EFT effects
   1. Uses Warsaw basis
   2. Includes all LO diagrams, with an extra jet to account for an extra parton for $t\bar{t}X$ signal samples.
   3. 26 WCs were found to contribute to the signal processes significantly
2. Those 26 dim6 EFT operators can be broken down into four categories based on the EFT vertex:

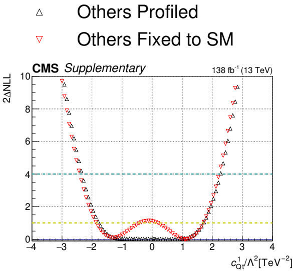
| Operators Category | WCs |
|---|---|
| Two heavy quarks with bosons | $c_{t\varphi}$, $c^{-}_{\varphi Q}$, $c^{3}_{\varphi Q}$, $c_{\varphi t}$, $c_{\varphi tb}$, $c_{tW}$, $c_{tZ}$, $c_{bW}$, $c_{tG}$ |
| Two heavy quarks two leptons | $c^{3(\ell)}_{Q\ell}$, $c^{-(\ell)}_{Q\ell}$, $c^{(\ell)}_{Qe}$, $c^{(\ell)}_{t\ell}$, $c^{(\ell)}_{te}$, $c^{TI(\ell)}_{t}$, $c^{S(\ell)}_{t}$ |
| Two light quarks two heavy quarks | $c^{31}_{Qq}$, $c^{38}_{Qq}$, $c^{11}_{Qq}$, $c^{18}_{Qq}$, $c^{1}_{tq}$, $c^{8}_{tq}$ |
| Four heavy quarks | $c^{1}_{QQ}$, $c^{1}_{Qt}$, $c^{8}_{Qt}$, $c^{1}_{tt}$ |

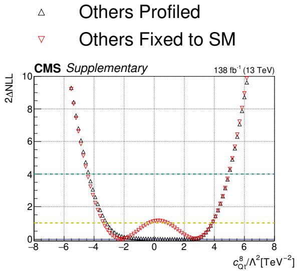
# 1D Scans

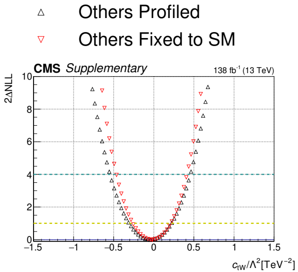

Others Profiled
Others Fixed to SM
CMS Supplementary
138 fb$^{-1}$ (13 TeV)
2ΔNLL
0 2 4 6 8 10
−10 −5 0 5 10 15
$c_{\varphi Q}^{-}/\Lambda^2$[TeV$^{-2}$]


Others Profiled
Others Fixed to SM
CMS Supplementary
138 fb$^{-1}$ (13 TeV)
2ΔNLL
0 2 4 6 8 10
−15 −10 −5 0 5 10 15
$c_{\varphi t}/\Lambda^2$[TeV$^{-2}$]


Others Profiled
Others Fixed to SM
CMS Supplementary
138 fb$^{-1}$ (13 TeV)
2ΔNLL
0 2 4 6 8 10
−10 −5 0 5 10 15 20 25 30 35
$c_{t\varphi}/\Lambda^2$[TeV$^{-2}$]


Others Profiled
Others Fixed to SM
CMS Supplementary
138 fb$^{-1}$ (13 TeV)
2ΔNLL
0 2 4 6 8 10
−4 −3 −2 −1 0 1 2 3 4
$c_{Qt}^{1}/\Lambda^2$[TeV$^{-2}$]


Others Profiled
Others Fixed to SM
CMS Supplementary
138 fb$^{-1}$ (13 TeV)
2ΔNLL
0 2 4 6 8 10
−8 −6 −4 −2 0 2 4 6 8
$c_{Qt}^{8}/\Lambda^2$[TeV$^{-2}$]

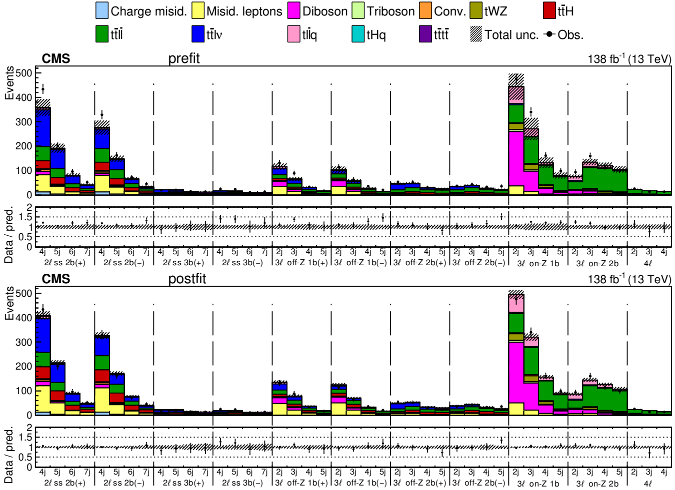

Others Profiled
Others Fixed to SM
CMS Supplementary
138 fb$^{-1}$ (13 TeV)
2ΔNLL
0 2 4 6 8 10
−1.5 −1 −0.5 0 0.5 1 1.5
$c_{tW}/\Lambda^2$[TeV$^{-2}$]

Any processes that are not sensitive to 26 WCs are considered as the background processes.

1. Reducible: $t\bar{t}$ nonprompt and $\gamma \rightarrow e^{+}e^{-}$ charge flips
   Modelled with data-driven method
2. Irreducible: Mainly diboson processes (WZ, ZZ, WW)
   Modelled with MC simulation

# Prefit-Postfit Plots

For the purpose of visualization, the following plot combines all the kinematic bins, resulting only the 43 bins of jet multiplicity.

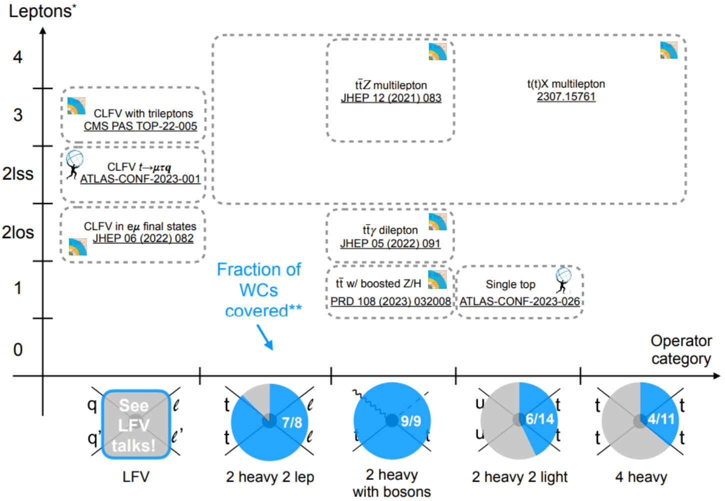


# Uncertainty Intervals on WCs

The $2\sigma$ uncertainty intervals are shown for the profiled and frozen case.

| WC/$\Lambda^2$ [$\text{TeV}^{-2}$] | $2\sigma$ CI (other WCs profiled) | $2\sigma$ CI (other WCs fixed to SM) |
|---|---|---|
| WC category 2hq2$\ell$ | | |
| $c_{t}^{T(\ell)}$ | [−0.37, 0.37] | [−0.40, 0.40] |
| $c_{t}^{S(\ell)}$ | [−2.60, 2.62] | [−2.80, 2.80] |
| $c_{te}^{(\ell)}$ | [−1.78, 2.21] | [−1.91, 2.39] |
| $c_{t\ell}^{(\ell)}$ | [−1.80, 2.11] | [−2.02, 2.20] |
| $c_{Qe}^{(\ell)}$ | [−1.91, 1.96] | [−2.04, 2.12] |
| $c_{Q\ell}^{-(\ell)}$ | [−1.58, 2.28] | [−1.80, 2.33] |
| $c_{Q\ell}^{3(\ell)}$ | [−2.84, 2.55] | [−2.69, 2.58] |
| WC category 2hqV | | |
| $c_{\varphi t}$ | [−10.52, 7.87] | [−4.93, 3.18] |
| $c_{\varphi tb}$ | [−3.25, 3.26] | [−3.14, 3.18] |
| $c_{\varphi Q}^{3}$ | [−0.84, 2.00] | [−0.85, 1.89] |
| $c_{bW}$ | [−0.76, 0.76] | [−0.75, 0.75] |
| $c_{tG}$ | [−0.28, 0.24] | [−0.22, 0.25] |
| $c_{\varphi Q}^{-}$ | [−6.06, 8.12] | [−2.68, 2.94] |
| $c_{t\varphi}$ | [−8.85, 2.75] | [−7.54, 2.11] |
| $c_{tZ}$ | [−0.71, 0.64] | [−0.58, 0.59] |
| $c_{tW}$ | [−0.55, 0.46] | [−0.47, 0.41] |
| WC category 4hq | | |
| $c_{Qt}^{1}$ | [−2.34, 2.27] | [−2.41, 2.22] |
| $c_{Qt}^{8}$ | [−4.37, 4.97] | [−4.45, 4.96] |
| $c_{QQ}^{1}$ | [−2.56, 2.84] | [−2.57, 2.89] |
| $c_{tt}^{1}$ | [−1.33, 1.38] | [−1.31, 1.43] |
| WC category 2hq2lq | | |
| $c_{tq}^{8}$ | [−0.68, 0.25] | [−0.68, 0.24] |
| $c_{Qq}^{18}$ | [−0.68, 0.22] | [−0.67, 0.21] |
| $c_{tq}^{1}$ | [−0.21, 0.21] | [−0.22, 0.20] |
| $c_{Qq}^{11}$ | [−0.19, 0.19] | [−0.19, 0.20] |
| $c_{Qq}^{38}$ | [−0.17, 0.16] | [−0.17, 0.16] |
| $c_{Qq}^{31}$ | [−0.08, 0.07] | [−0.08, 0.07] |

# A map of detector-level top EFT analyses




(courtesy to K. Mohrman)