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ICTEA
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y Tecnologías Espaciales de Asturias

Probing EFT models using ttX in multiple lepton final states

CMS-PAS-TOP-22-006

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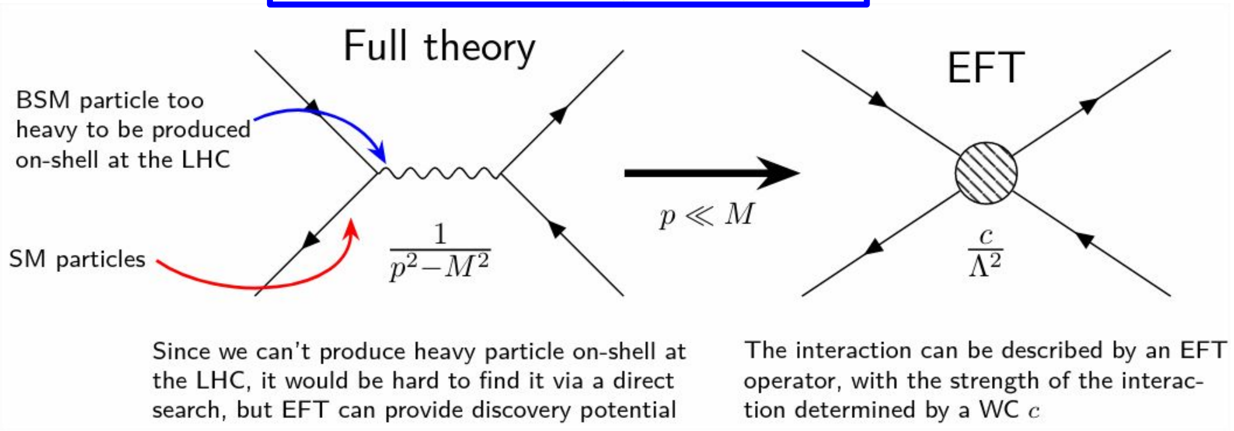
Motivation and Introduction

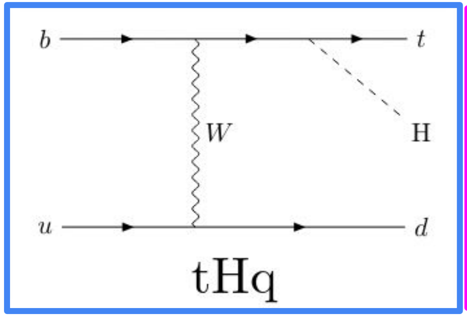
- Search new fundamental particles is motivated by the **strong evidence** for **phenomena not described by the SM**
- New particles may not be light enough to be produced at the LHC
- Indirect searches are needed if we want to probe these regimes
- Effective field theory (EFT) provides a framework for probing these higher energy scales

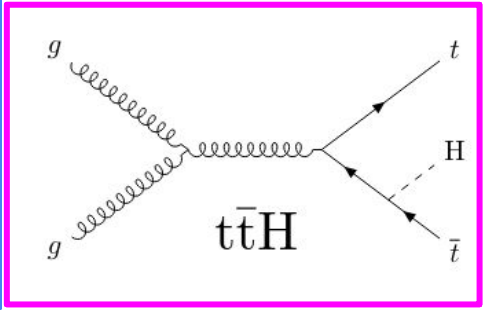
$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d,i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

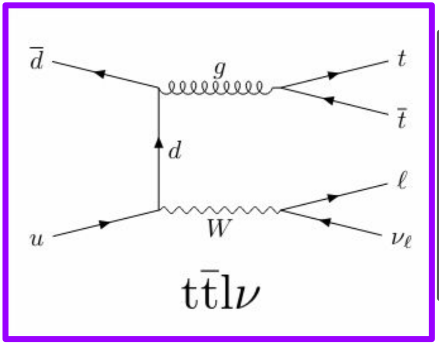


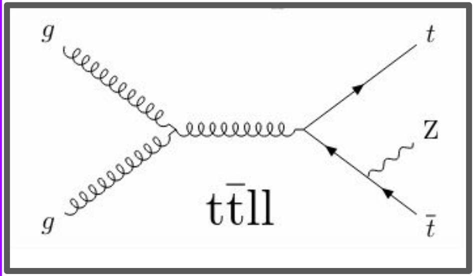
Analysis

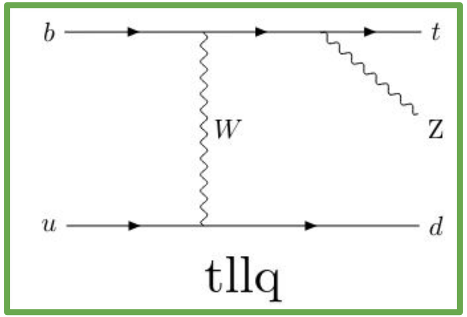
- Analysis focuses on operators that couple the **top quark** to leptons, bosons, and other heavy quarks
- Concentrates on **associated top processes** and model how EFT operators affect expected yields
  - 6 signal processes: **ttlv**, **ttll**, **tllq**, **ttH**, **tHq**, **tttt**
  - Low cross section processes
  - Clean well isolated signal region

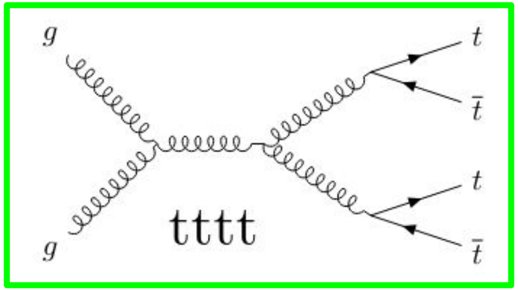






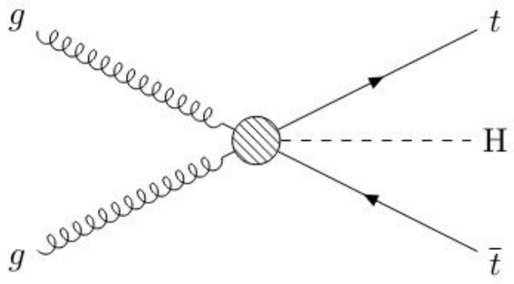




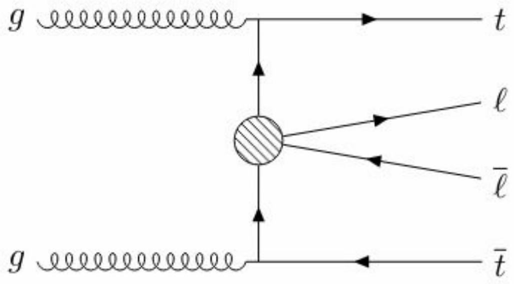


Analysis

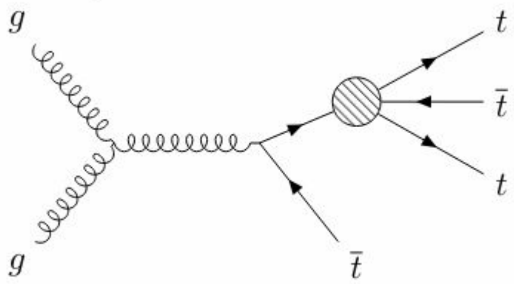
Focus on 26 operators, which can be grouped together into **4 different categories**



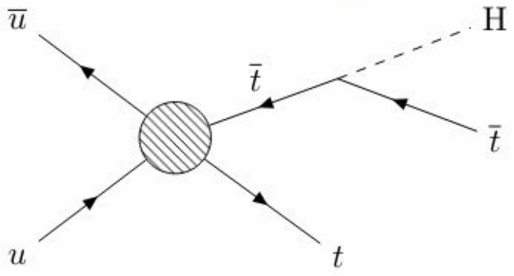
Operators involving heavy quarks and bosons



Operators involving 2 heavy quarks and 2 leptons



Operators involving 4 heavy quarks



Operators involving 2 heavy quarks and 2 light quarks

Analysis

Focus on 26 operators, which can be grouped together into **4 different categories**

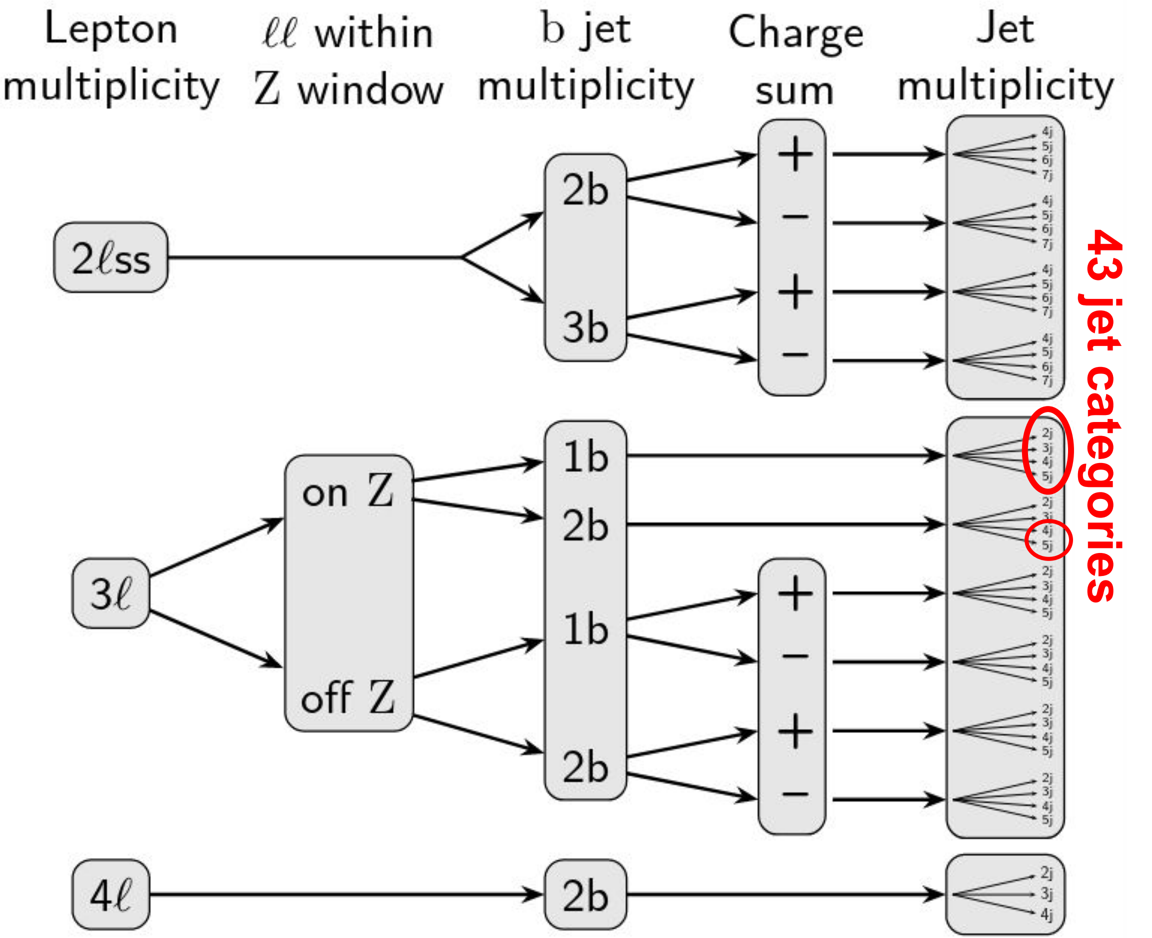
[**Reference:** *Interpreting top-quark LHC measurements in the standard-model effective field theory*]

Operator category	WCs
Two heavy quarks	$c_{t\varphi}, c^{-}_{\varphi Q}, c^{3}_{\varphi Q}, c_{\varphi t}, c_{\varphi tb}, c_{tW}, c_{tZ}, c_{bW}, c_{tG}$
Two heavy quarks two leptons	$c^{3(\ell)}_{Q\ell}, c^{-(\ell)}_{Q\ell}, c^{(\ell)}_{Qe}, c^{(\ell)}_{t\ell}, c^{(\ell)}_{te}, c^{S(\ell)}_{t}, c^{T(\ell)}_{t}$
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	$c^{1}_{QQ}, c^{1}_{Qt}, c^{8}_{Qt}, c^{1}_{tt}$

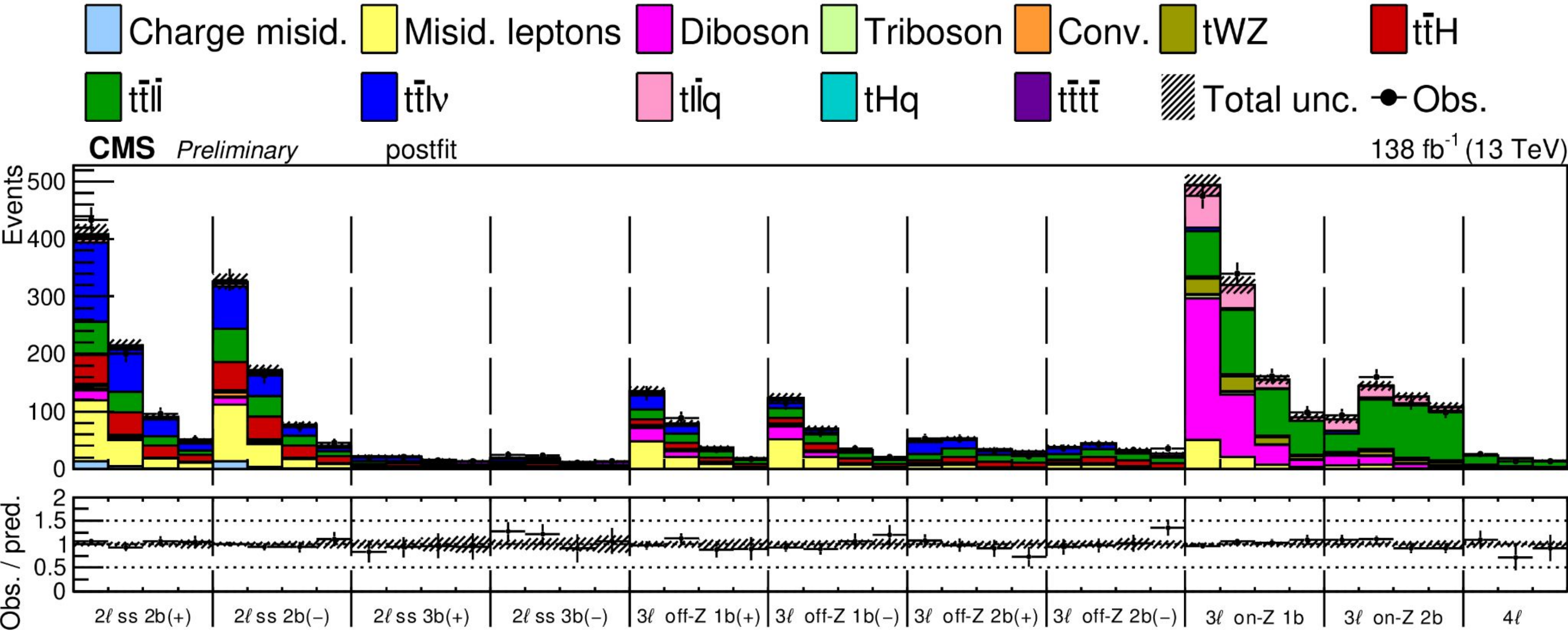
Aim to include all operators that **significantly impact** processes in which one or more top quarks are produced in association with charged leptons

Event Selection

- Aims to discriminate between signal processes as much as possible:
  - **2lss:** ttH and ttW (split by charge)
  - **3l on Z:** ttll (2b), tllq (1b)
  - **3l off Z:** non-resonant ttll and tllq (2-quark 2-lepton EFT contributions)
  - **≥ 4l:** ttH and ttll
- Use different variables to optimize sensitivity to EFT effects
  - **p_T(lj0):** p_T of the leading lepton plus jet pairs **(39 categories)**
  - **p_T(Z):** p_T of the opposite sign lepton pair **(6 categories)**

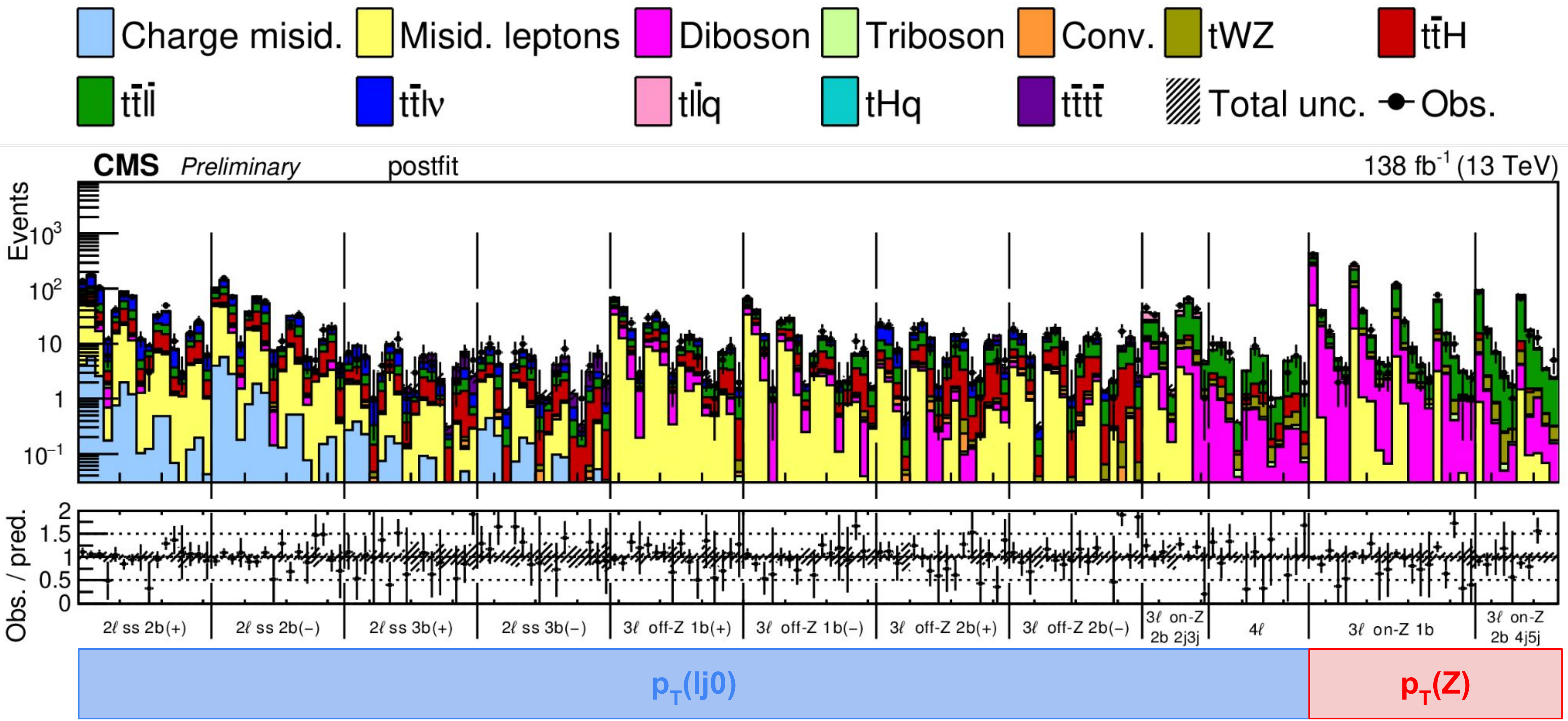


Event yields per category



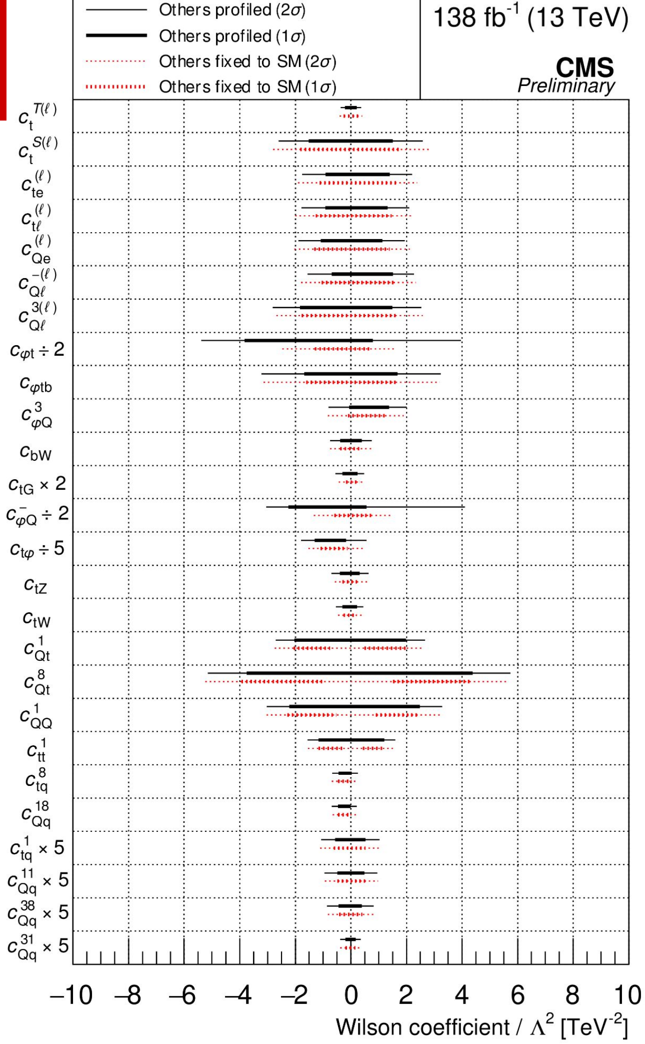
4j 5j 6j 7j | 4j 5j 6j 7j | 4j 5j 6j 7j | 4j 5j 6j 7j | 2j 3j 4j 5j| 2j 3j 4j 5j | 2j 3j 4j 5j | 2j 3j 4j 5j| 2j 3j 4j 5j | 2j 3j 4j 5j | 2j 3j 4j

Kinematic variables per category



Results

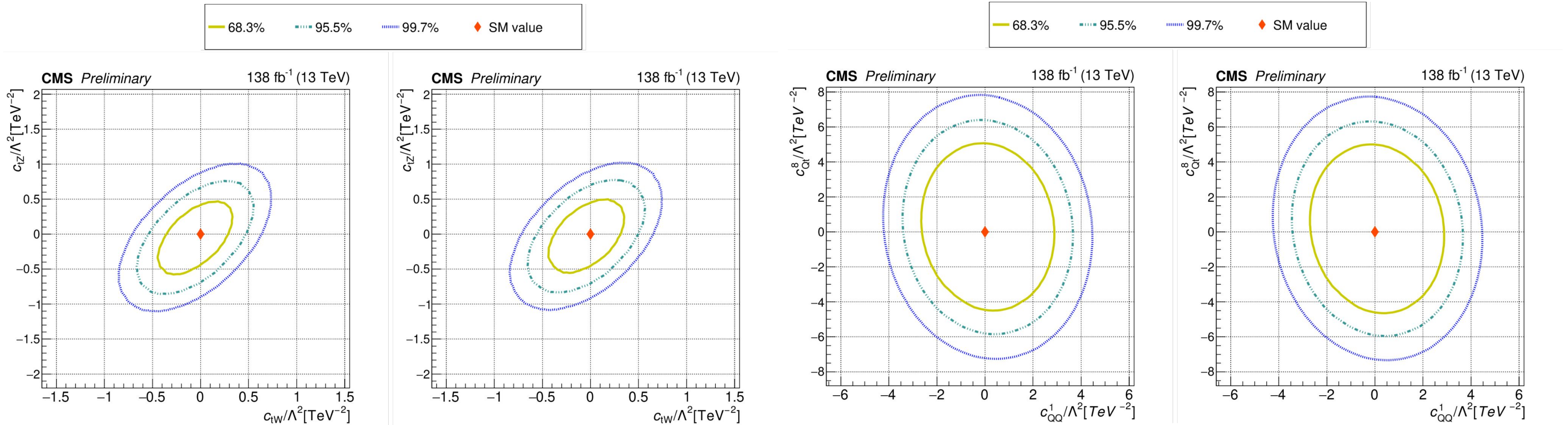
- The postfit values are obtained by **simultaneously fitting** all 26 WCs and the NPs
- Summary of confidence intervals extracted from the likelihood fits
- In red where the other WCs are fixed to their SM values of zero
- **In black where the other WCs are also profiled**
- To make the figure more readable some the intervals were scaled (*values shown on back-up slides*)
- Most results dominated by **statistical uncertainties**, the main syst. unc. is NLO norm



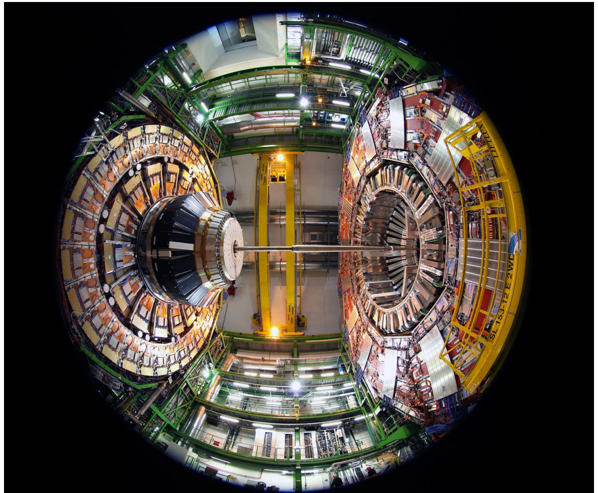
CMS-PAS-TOP-22-006

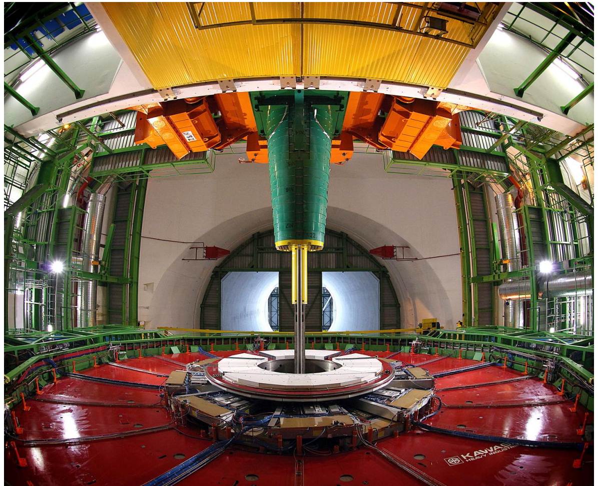
Summary

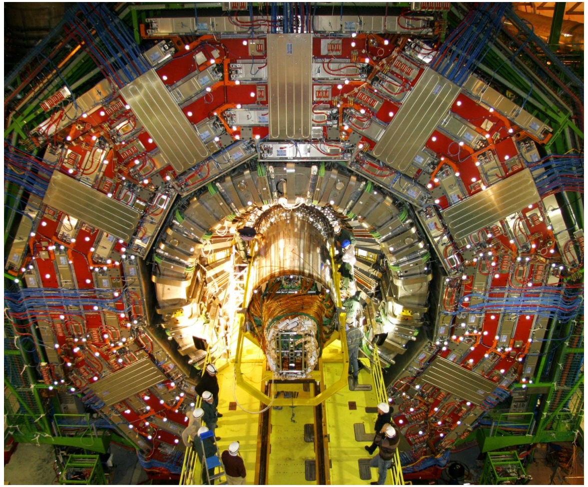
- Presented **a search for new physics** in associated top production processes using **EFT** with 138 fb^{-1} of data collected by CMS during Run-2 [CMS-PAS-TOP-22-006]
- Set simultaneous confidence interval limits on **26 WCs** associated with top quarks
- The results are **consistent** with SM expectations
- EFT is a **powerful technique** for indirect searches of **BSM** physics at the LHC
- In the future, EFT approaches will benefit greatly from increased statistics of the current LHC and HL-LHC



BACK-UP SLIDES







Ideal EFT Parametrization

- Model the EFT contributions
- Matrix element can be written as the sum of SM and new physics components

$$\mathcal{M} = \mathcal{M}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{M}_i$$

→ c_i are the Wilson coefficients

- Since σ ∝ M^2 → the cross section will have a quadratic dependence on the WCs

$$d\sigma(\vec{c}) \propto \left| \mathcal{M}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{M}_i \right|^2 \propto s_0 + \sum_j s_j \frac{c_j}{\Lambda^2} + \sum_{j,k} s_{jk} \frac{c_j}{\Lambda^2}\frac{c_k}{\Lambda^2}$$

s_0 → Pure SM; s_j → Interference with SM; s_{jk} → Pure NP

- Far too computationally intensive. Would need O(100) MC samples per signal process

Real EFT Parametrization

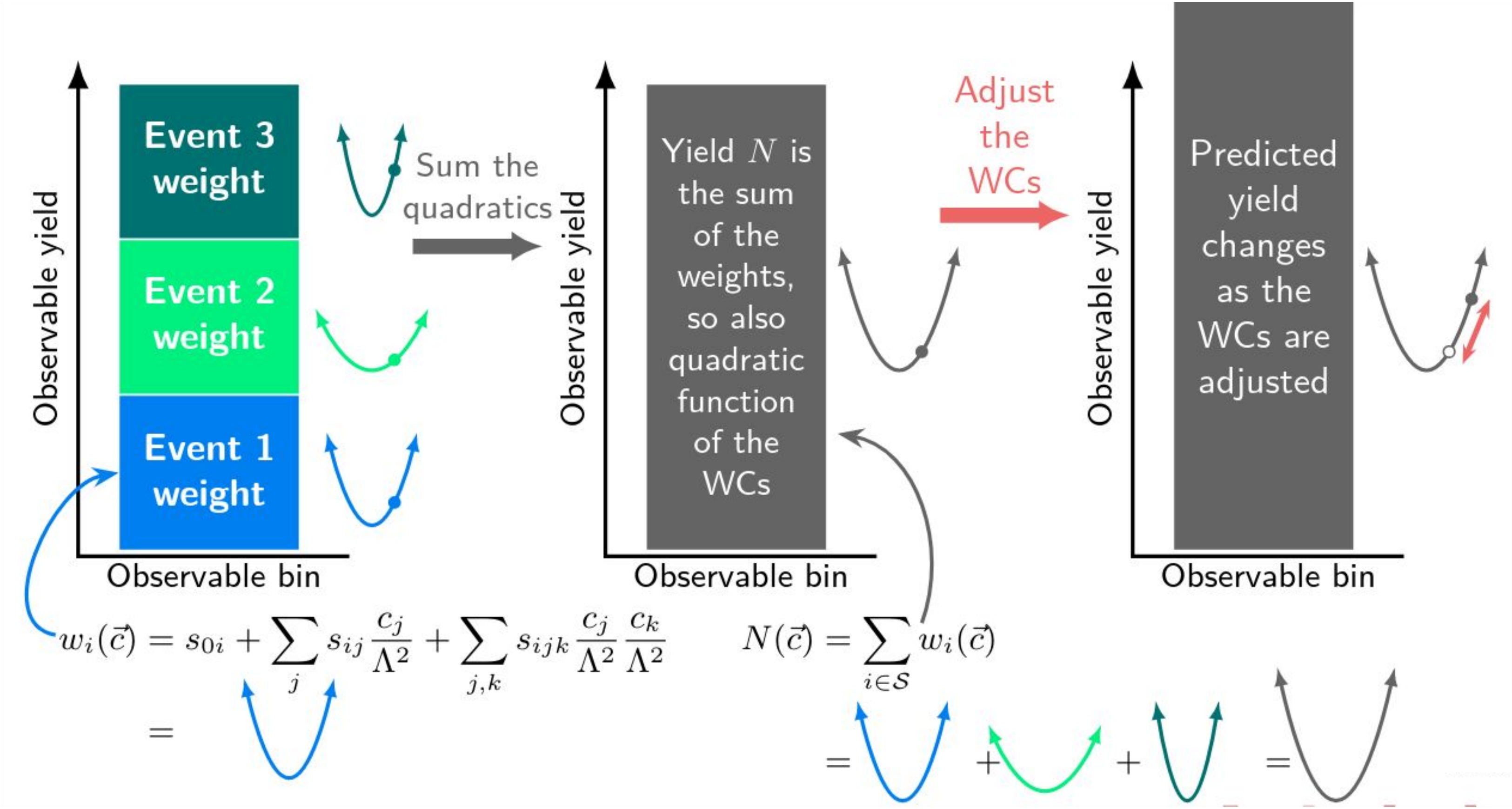
- Model the EFT contributions event by event
- Build a **weight function per event** based on a 26-dimensional quadratic parametrization using the Madgraph event reweighting technique:

The parameterization is similar to the one from before, but is now done per event!

$$w_i(\vec{c}) = s_{0i} + \sum_j s_{ij} \frac{c_j}{\Lambda^2} + \sum_{j,k} s_{ijk} \frac{c_j}{\Lambda^2} \frac{c_k}{\Lambda^2}$$

- s_{0i}: Pure SM
- s_{ij}: Interference with SM
- s_{ijk}: Pure NP

Real EFT Parametrization



Real EFT Parametrization

- Signal contribution is modeled at leading order, **LO**, using *MadGraph5_aMC@NLO* with **dim6top** model
- Using **Warsaw basis** of gauge invariant dimension-6 operators providing **tree-level modeling** for the effects
- In the analysis, it is assumed that the EFT effects impact each lepton generation on the same way

Object Requirements

Object requirements for the 43 event selection categories. Requirements separated by commas indicate a division into subcategories. The kinematical variable that is used in the event category is also listed

Event category	Leptons	$m_{\ell\ell}$	b tags	Lepton charge sum	Jets	Differential variable
2ℓss 2b	2	No requirement	2	> 0, <0	4,5,6,$\geq$7	$p_{\mathrm{T}}(\ell j0)$
2ℓss 3b	2	No requirement	≥ 3	> 0, <0	4,5,6,$\geq$7	$p_{\mathrm{T}}(\ell j0)$
3ℓ off-Z 1b	3	$\lvert m_{\mathrm{Z}} - m_{\ell\ell}\rvert > 10\,\mathrm{GeV}$	1	> 0, <0	2,3,4,$\geq$5	$p_{\mathrm{T}}(\ell j0)$
3ℓ off-Z 2b	3	$\lvert m_{\mathrm{Z}} - m_{\ell\ell}\rvert > 10\,\mathrm{GeV}$	≥ 2	> 0, <0	2,3,4,$\geq$5	$p_{\mathrm{T}}(\ell j0)$
3ℓ on-Z 1b	3	$\lvert m_{\mathrm{Z}} - m_{\ell\ell}\rvert \leq 10\,\mathrm{GeV}$	1	No requirement	2,3,4,$\geq$5	$p_{\mathrm{T}}(\mathrm{Z})$
3ℓ on-Z 2b	3	$\lvert m_{\mathrm{Z}} - m_{\ell\ell}\rvert \leq 10\,\mathrm{GeV}$	≥ 2	No requirement	2,3,4,$\geq$5	$p_{\mathrm{T}}(\mathrm{Z})$ or $p_{\mathrm{T}}(\ell j0)$
4ℓ	$\geq$4	No requirement	≥ 2	No requirement	2,3,$\geq$4	$p_{\mathrm{T}}(\ell j0)$

NLO theoretical cross sections used for normalizing the signal simulation samples

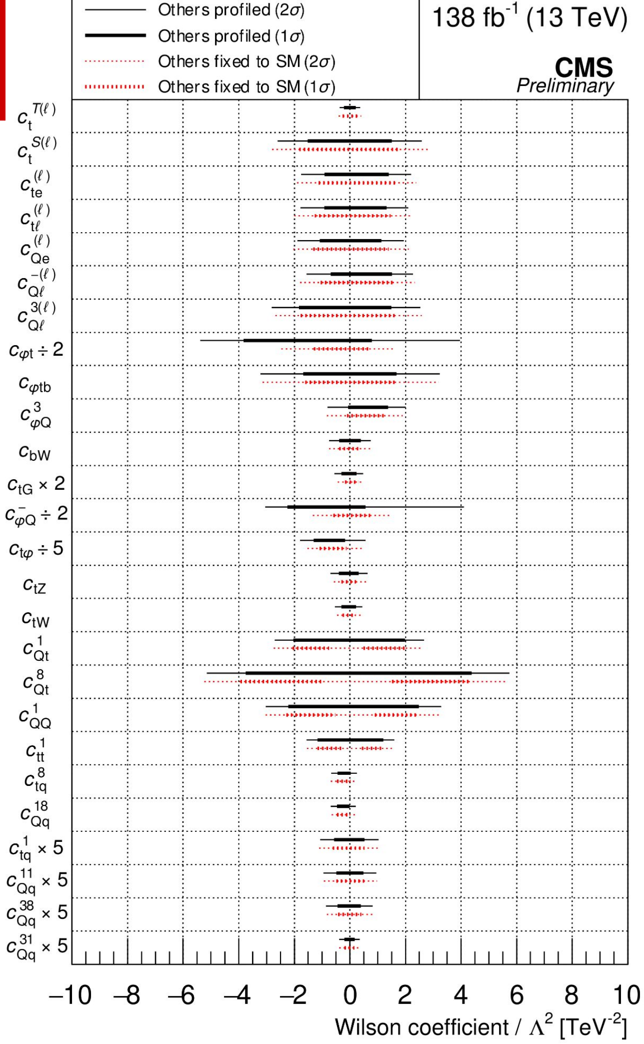
Process	Cross section (pb)
$t\bar{t}H$	0.215 [20]
$t\bar{t}l\bar{l}$	0.281 [20]
$t\bar{t}l\nu$	0.235 [21]
$tl\bar{l}q$	0.076 [15]
tHq	0.071 [20]
$t\bar{t}t\bar{t}$	0.012 [22]

Results

Summary of CIs extracted from the likelihood fits

To make the figure more readable, the intervals for:

- $c_{t\varphi}$ were scaled by ⅕
- $c_{\varphi t}$ and $c^{-}_{\varphi Q}$ were scaled by ½
- c_{tG} were scaled by 2,
- c_{tq}^{1}, c_{Qq}^{11}, c_{Qq}^{38} and C_{Qq}^{31} were all scaled by 5



The 1 and 2 σ uncertainty intervals extracted from the likelihood fits

WC/Λ^2 [TeV^{-2}]	2σ Interval (others profiled)	2σ Interval (others fixed to SM)
$c_{t}^{T(\ell)}$	[-0.37, 0.37]	[-0.40, 0.40]
$c_{t}^{S(\ell)}$	[-2.60, 2.59]	[-2.80, 2.80]
$c_{te}^{(\ell)}$	[-1.76, 2.20]	[-1.90, 2.39]
$c_{t\ell}^{(\ell)}$	[-1.78, 2.10]	[-2.01, 2.20]
$c_{Qe}^{(\ell)}$	[-1.89, 1.94]	[-2.04, 2.12]
$c_{Q\ell}^{-(\ell)}$	[-1.56, 2.27]	[-1.80, 2.33]
$c_{Q\ell}^{3(\ell)}$	[-2.81, 2.54]	[-2.68, 2.58]
$c_{\varphi t}$	[-10.76, 7.91]	[-4.95, 3.19]
$c_{\varphi tb}$	[-3.23, 3.23]	[-3.15, 3.19]
$c_{\varphi Q}^{3}$	[-0.81, 2.01]	[-0.84, 1.91]
c_{bW}	[-0.75, 0.76]	[-0.75, 0.75]
c_{tG}	[-0.27, 0.24]	[-0.22, 0.25]
$c_{\varphi Q}^{-}$	[-6.09, 8.20]	[-2.66, 2.95]
$c_{t\varphi}$	[-8.98, 2.85]	[-7.68, 2.15]
c_{tZ}	[-0.70, 0.63]	[-0.58, 0.59]
c_{tW}	[-0.54, 0.45]	[-0.47, 0.41]
c_{Qt}^{1}	[-2.71, 2.66]	[-2.75, 2.62]
c_{Qt}^{8}	[-5.15, 5.74]	[-5.24, 5.66]
c_{QQ}^{1}	[-3.03, 3.28]	[-3.04, 3.28]
c_{tt}^{1}	[-1.56, 1.60]	[-1.54, 1.63]
c_{tq}^{8}	[-0.67, 0.25]	[-0.68, 0.24]
c_{Qq}^{18}	[-0.68, 0.21]	[-0.67, 0.21]
c_{tq}^{1}	[-0.21, 0.21]	[-0.22, 0.20]
c_{Qq}^{11}	[-0.19, 0.19]	[-0.19, 0.19]
c_{Qq}^{38}	[-0.17, 0.16]	[-0.17, 0.16]
c_{Qq}^{31}	[-0.08, 0.07]	[-0.08, 0.07]

WC/Λ^2 [TeV^{-2}]	1σ Interval (others profiled)	1σ Interval (others fixed to SM)
$c_{t}^{T(\ell)}$	[-0.21, 0.21]	[-0.26, 0.26]
$c_{t}^{S(\ell)}$	[-1.52, 1.50]	[-1.82, 1.82]
$c_{te}^{(\ell)}$	[-0.91, 1.40]	[-1.13, 1.68]
$c_{t\ell}^{(\ell)}$	[-0.92, 1.31]	[-1.27, 1.47]
$c_{Qe}^{(\ell)}$	[-1.08, 1.14]	[-1.32, 1.40]
$c_{Q\ell}^{-(\ell)}$	[-0.68, 1.52]	[-1.06, 1.64]
$c_{Q\ell}^{3(\ell)}$	[-1.84, 1.49]	[-1.76, 1.63]
$c_{\varphi t}$	[-7.66, 1.59]	[-2.59, 1.34]
$c_{\varphi tb}$	[-1.67, 1.68]	[-1.62, 1.67]
$c_{\varphi Q}^{3}$	[-0.06, 1.37]	[-0.11, 1.27]
c_{bW}	[-0.39, 0.39]	[-0.39, 0.39]
c_{tG}	[-0.16, 0.12]	[-0.09, 0.15]
$c_{\varphi Q}^{-}$	[-4.50, 1.12]	[-1.19, 1.58]
$c_{t\varphi}$	[-6.53, -0.84]	[-5.50, -0.63]
c_{tZ}	[-0.39, 0.32]	[-0.31, 0.32]
c_{tW}	[-0.31, 0.22]	[-0.26, 0.21]
c_{Qt}^{1}	[-2.03, 1.98]	[-2.05, -0.75] and [0.49, 1.97]
c_{Qt}^{8}	[-3.75, 4.38]	[-3.93, -0.95] and [1.51, 4.30]
c_{QQ}^{1}	[-2.21, 2.49]	[-2.28, -0.53] and [0.90, 2.47]
c_{tt}^{1}	[-1.16, 1.20]	[-1.16, -0.28] and [0.43, 1.22]
c_{tq}^{8}	[-0.45, 0.03]	[-0.47, 0.02]
c_{Qq}^{18}	[-0.47, -0.01]	[-0.46, -0.00]
c_{tq}^{1}	[-0.11, 0.11]	[-0.12, 0.10]
c_{Qq}^{11}	[-0.10, 0.10]	[-0.10, 0.10]
c_{Qq}^{38}	[-0.09, 0.08]	[-0.09, 0.08]
c_{Qq}^{31}	[-0.04, 0.03]	[-0.04, 0.03]

Leading Categories

Grouping of WCs	WCs	Lead categories
Two heavy two leptons	$c_{Q\ell}^{3(\ell)}$, $c_{Q\ell}^{-(\ell)}$, $c_{Qe}^{(\ell)}$, $c_{t\ell}^{(\ell)}$, $c_{te}^{(\ell)}$, $c_{t}^{S(\ell)}$, $c_{t}^{T(\ell)}$	3ℓ off-Z
Four heavy	c_{QQ}^{1}, c_{Qt}^{1}, c_{Qt}^{8}, c_{tt}^{1}	2ℓss
Two heavy two light "$t\bar{t}l\nu$-like"	c_{Qq}^{11}, c_{Qq}^{18}, c_{tq}^{1}, c_{tq}^{8}	2ℓss
Two heavy two light "$tl\bar{l}q$-like"	c_{Qq}^{31}, c_{Qq}^{38}	3ℓ on-Z
Two heavy with bosons "$t\bar{t}l\bar{l}$-like"	c_{tZ}, $c_{\varphi t}$, $c_{\varphi Q}^{-}$	3ℓ on-Z and 2ℓss
Two heavy with bosons "tXq-like"	$c_{\varphi Q}^{3}$, $c_{\varphi tb}$, c_{bW}	3ℓ on-Z
Two heavy with bosons with significant impacts on many processes	c_{tG}, $c_{t\varphi}$, c_{tW}	3ℓ and 2ℓss