Probing EFT models using associated top quark production in multilepton final states

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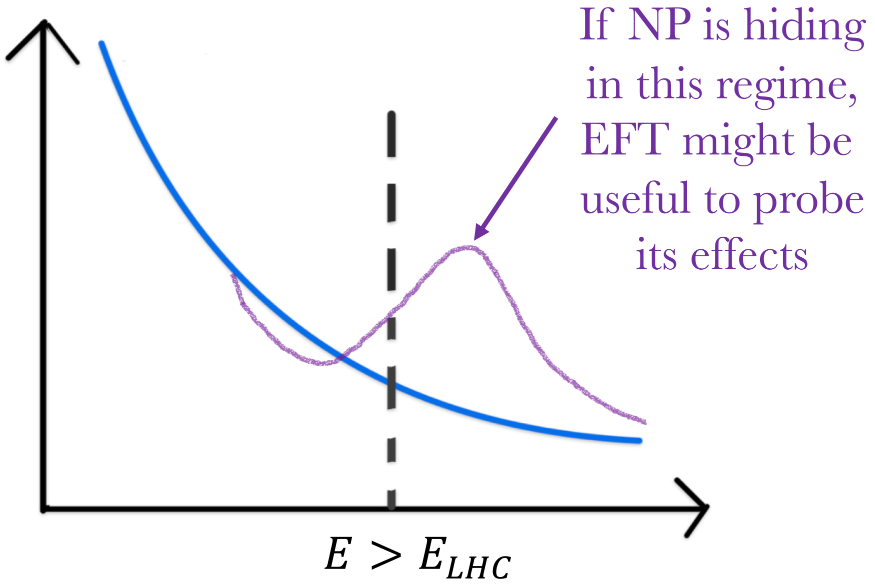
Motivation for searches for new physics

- Strong indications that the Standard Model (SM) is not the complete description of nature

- No clear evidence of new physics (NP) at the LHC

- What if new particles are too heavy to be produced on-shell at the LHC?
  - Indirect search strategies might be useful

- Effective Field Theory (EFT) is an indirect search probe, that allows a relatively model-independent way of exploring mass scales higher than what LHC is capable of achieving



Standard Model Effective Field Theory (SMEFT)

- In SMEFT, the SM is treated as the lowest order term and is extended by a set of higher dimensional operators that encode the effects of new heavy particles. These operators characterize the physics at energy scale Λ

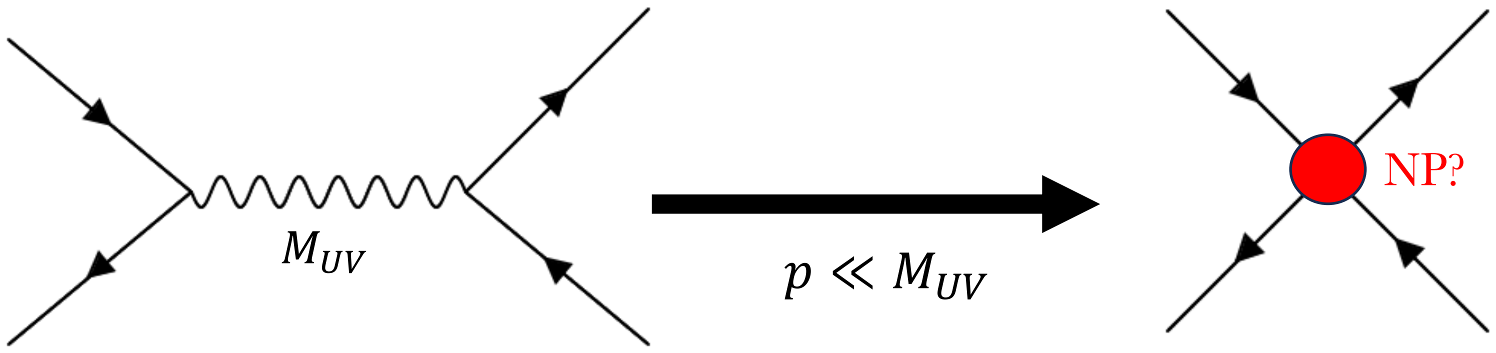
Wilson Coefficients (strength of NP interaction)
Setting all WCs = 0 gives us SM lagrangian back

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

Energy scale of new physics $\Lambda \gg \Lambda_{LHC}$

EFT operators made of SM fields and their derivatives. The numbers indicate mass dimension of the operators

We consider only dim-6 top EFT operators since they are the lowest non-LFV terms that contribute

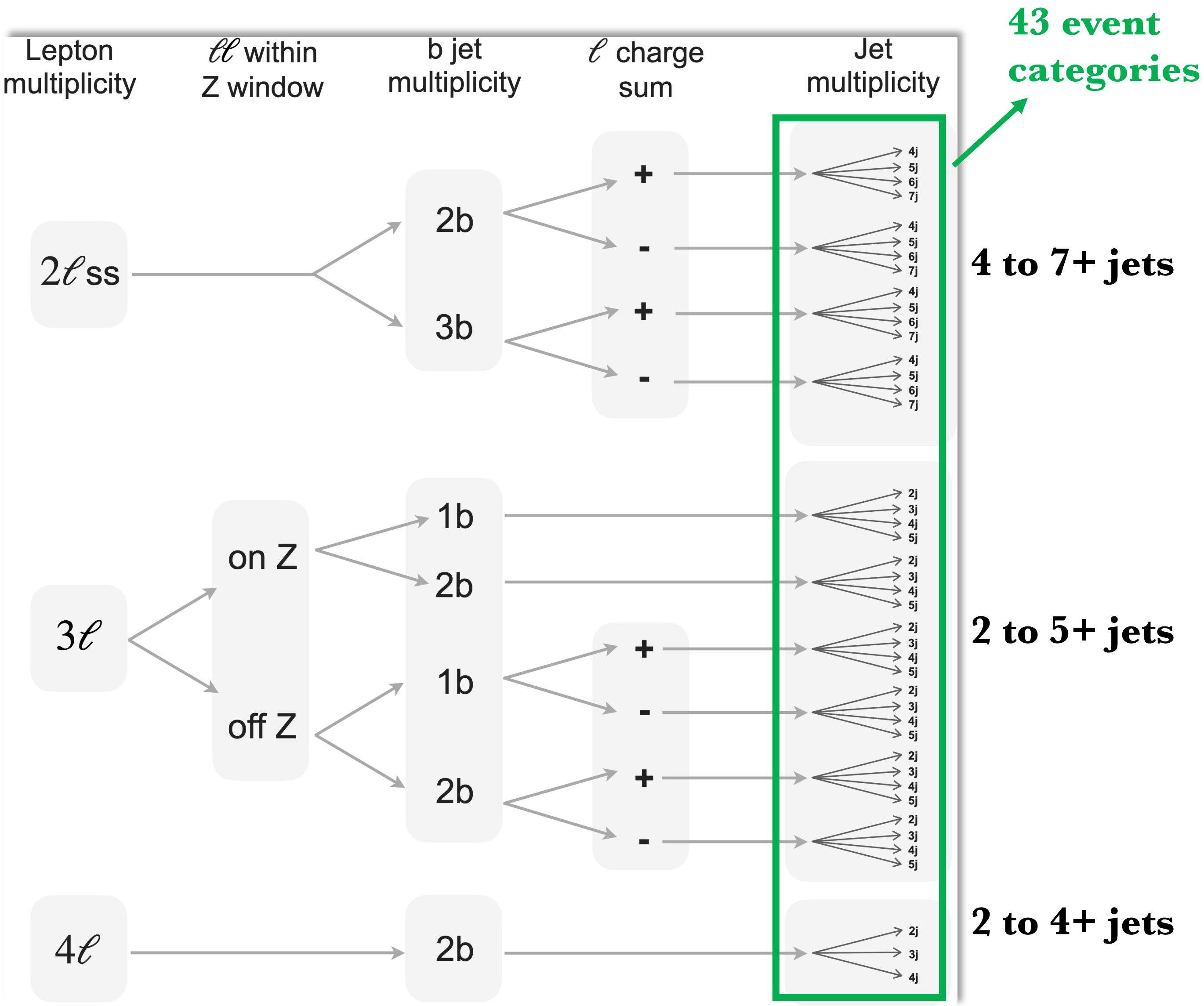


$$\sim \frac{1}{p^2 - M_{UV}^2}$$

$$\sim \frac{1}{M_{UV}^2}$$

Overview of the analysis

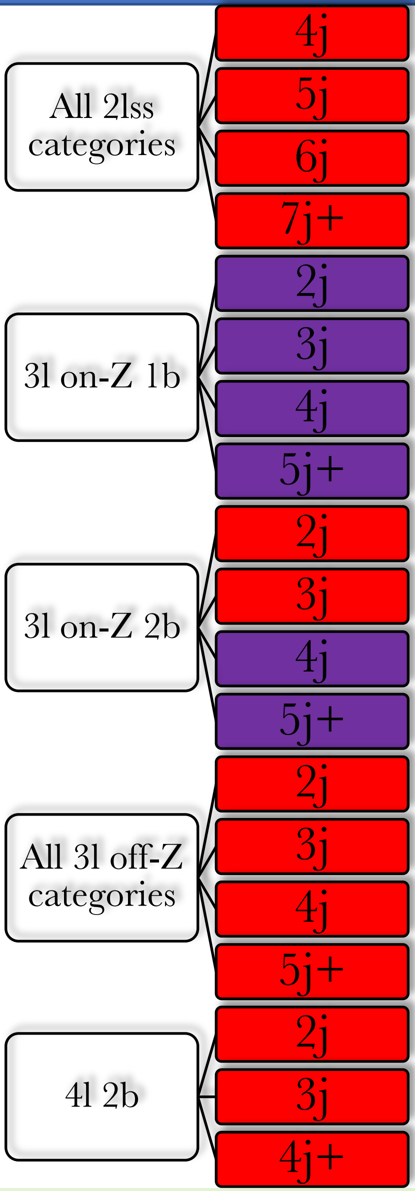
- Probes NP using global fitting approach by simultaneous fitting of the WCs to data
- **Unique aspects of the analysis**:
  - Models EFT effects directly at the detector level (see [Kelci's talk]() for more details)
  - Studies 6 relatively rare signal processes: $t\bar{t}H, t\bar{t}lv, t\bar{t}l\bar{l}, tl\bar{l}q, tHq, t\bar{t}t\bar{t}$
  - Considers all dim-6 EFT operators involving top quarks that strongly impact the signal processes ➜ 26 operators

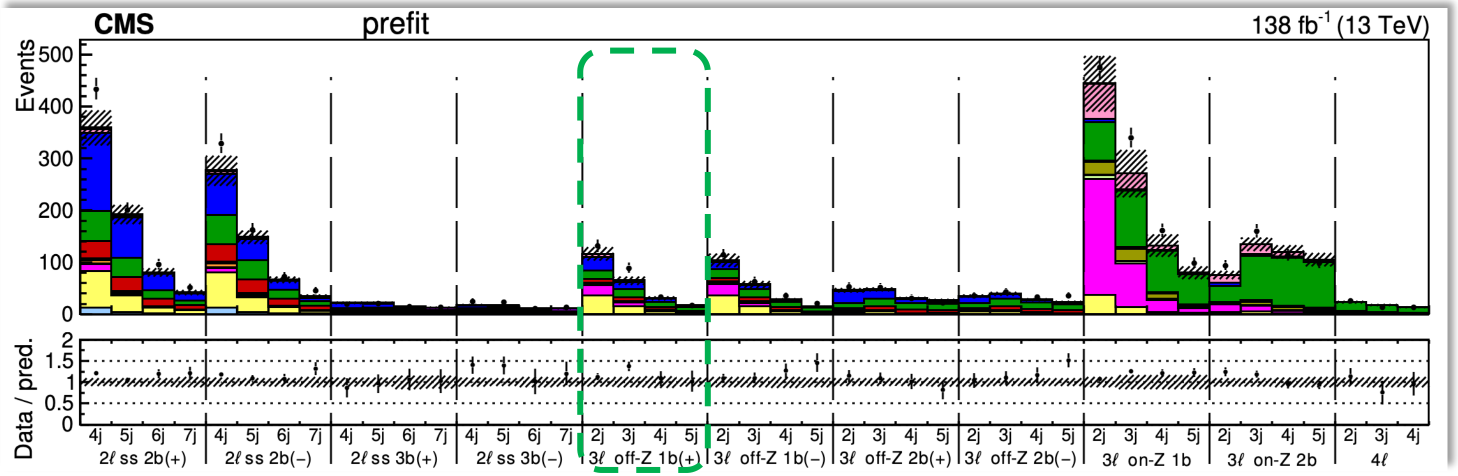


Going differential

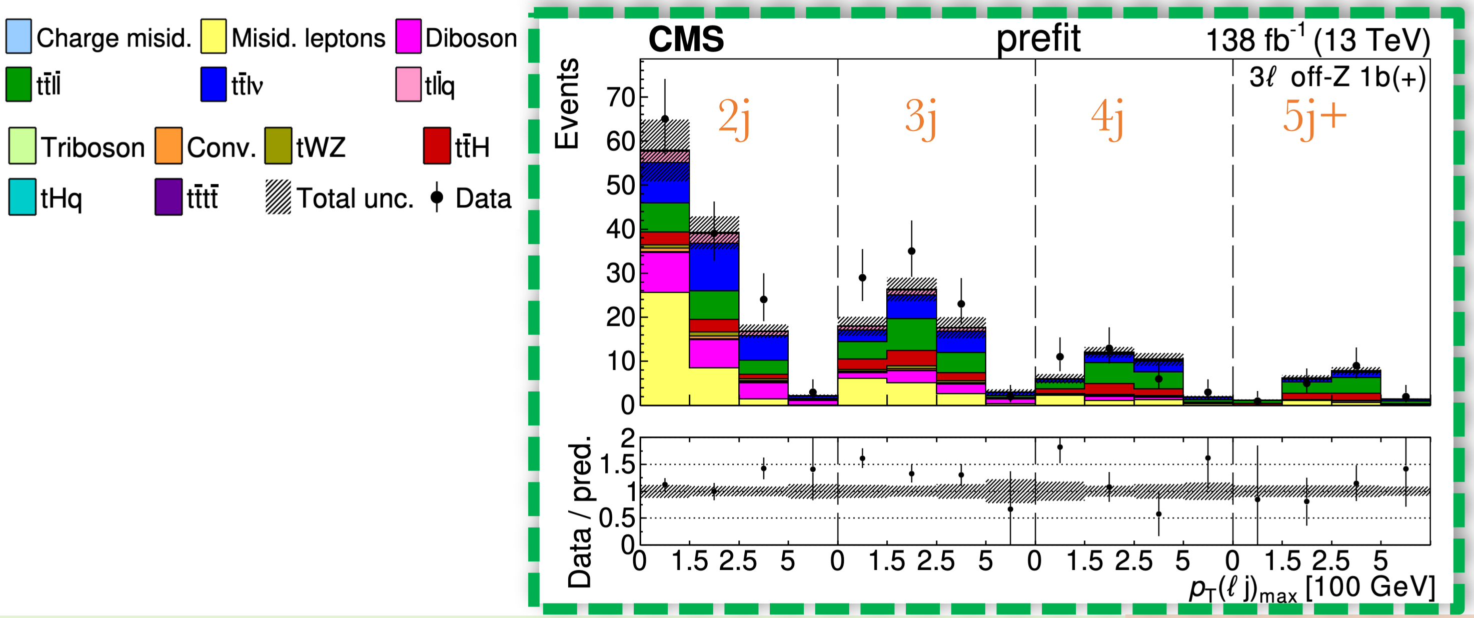
- Uses differential kinematic variables for fitting leading to 178 analysis bins:
  - $p_T(Z)$: p_T of on-shell Z boson for most 3ℓ on-shell categories
  - $p_T(\ell j)_{max}$: p_T of leading pair of leptons and/or jets for all other categories

- Up to a factor of ~2 improvement in sensitivity through kinematic variable binning





Kinematic bins integrated out



EFT operators

Operator category	Wilson coefficients
Two-heavy (2hqV)	$c_{t\varphi}, c^{-}_{\varphi Q}, c^{3}_{\varphi Q}, c_{\varphi t}, c_{\varphi tb}, c_{tW}, c_{tZ}, c_{bW}, c_{tG}$
Two-heavy-two-lepton (2hq2ℓ)	$c^{3(\ell)}_{Q\ell}, c^{-(\ell)}_{Q\ell}, c^{(\ell)}_{Qe}, c^{(\ell)}_{t\ell}, c^{(\ell)}_{te}, c^{S(\ell)}_{t}, c^{T(\ell)}_{t}$
Two-heavy-two-light (2hq2lq)	$c^{31}_{Qq}, c^{38}_{Qq}, c^{11}_{Qq}, c^{18}_{Qq}, c^{1}_{tq}, c^{8}_{tq}$
Four-heavy (4hq)	$c^{1}_{QQ}, c^{1}_{Qt}, c^{8}_{Qt}, c^{1}_{tt}$

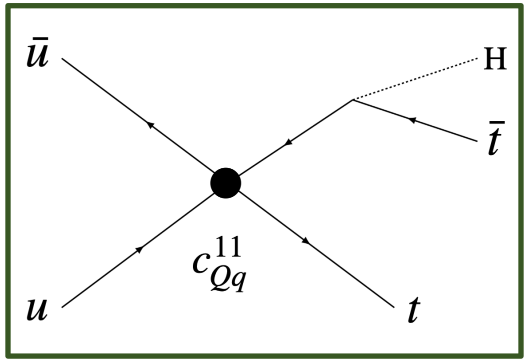
more or less all signal processes → Two-heavy (2hqV)

$t\bar{t}l\bar{l}$, $tl\bar{l}q$ and $t\bar{t}l\nu$ → Two-heavy-two-lepton (2hq2ℓ)

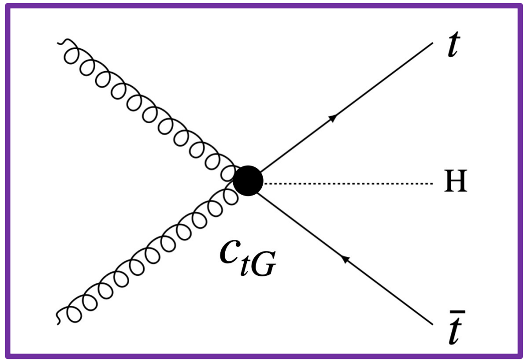
Only $t\bar{t}t\bar{t}$ → Four-heavy (4hq)

All signal processes → c^{31}_{Qq}, c^{38}_{Qq}

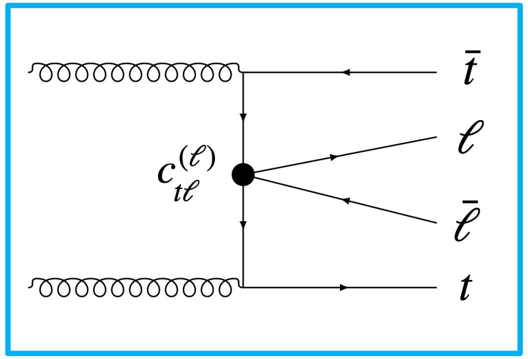
$t\bar{t}+X$, $t\bar{t}t\bar{t}$ → $c^{11}_{Qq}, c^{18}_{Qq}, c^{1}_{tq}, c^{8}_{tq}$



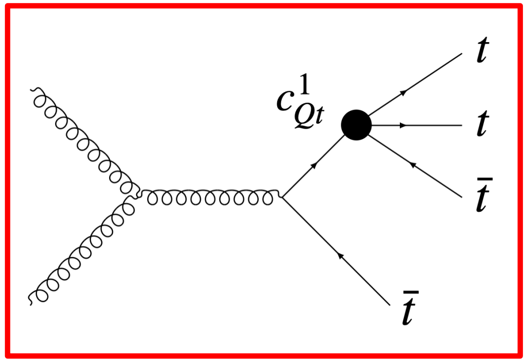
A 2hq2lq operator impacting $t\bar{t}H$ process



A 2hqV operator impacting $t\bar{t}H$ process



A 2hq2ℓ operator impacting $t\bar{t}l\bar{l}$ process

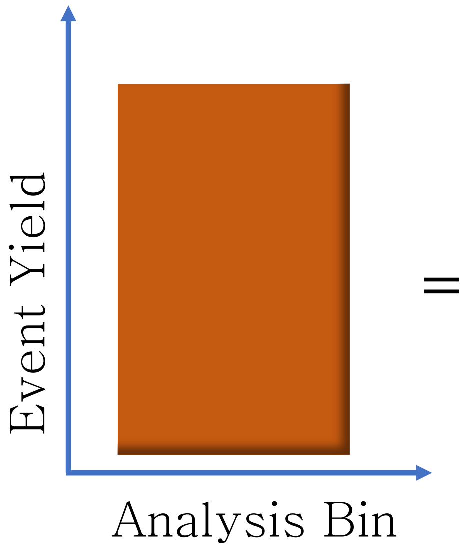


A 4hq operator impacting $t\bar{t}t\bar{t}$ process

Parametrization of EFT effects

- We incorporate EFT effects directly at detector level.
- At amplitude level: $\mathcal{M}_{SM} + \sum_i c_i \mathcal{M}_i$ ← New Physics Component
- Cross-section: $\sigma(c_i) \propto |\mathcal{M}_{SM} + \sum_i c_i \mathcal{M}_i|^2 = S_{0i} + \sum_j S_{1ij} c_j + \sum_j S_{2ij}\, c_j^2 + \sum_{j \neq k} S_{3ijk} c_j c_k$
  - S_{0i}: pure SM
  - S_{1ij}: Interference with SM
  - S_{2ij}: pure NP
  - S_{3ijk}: Interference between NP terms

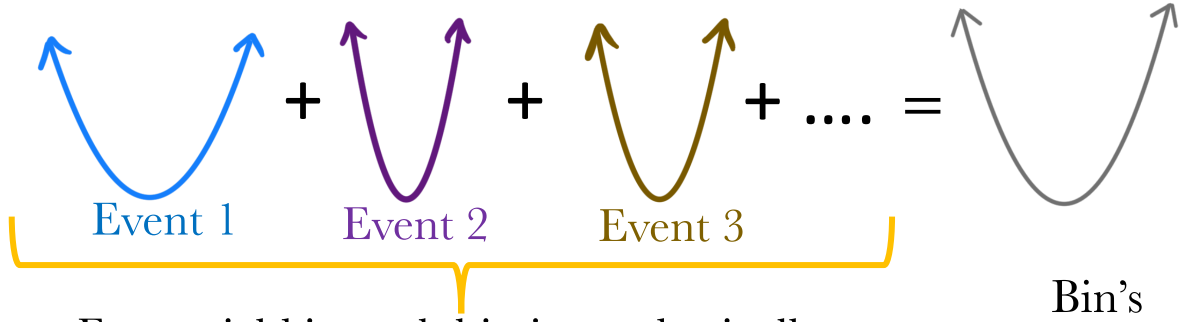
More details in [Kelci's talk]



$$= f(c_1, c_2, c_3, \ldots\ldots\ldots) = \sum_i w_i =$$

Weight of each simulated event passing selection criteria (w_i)

The predicted event yield in a given bin is a function of the WCs

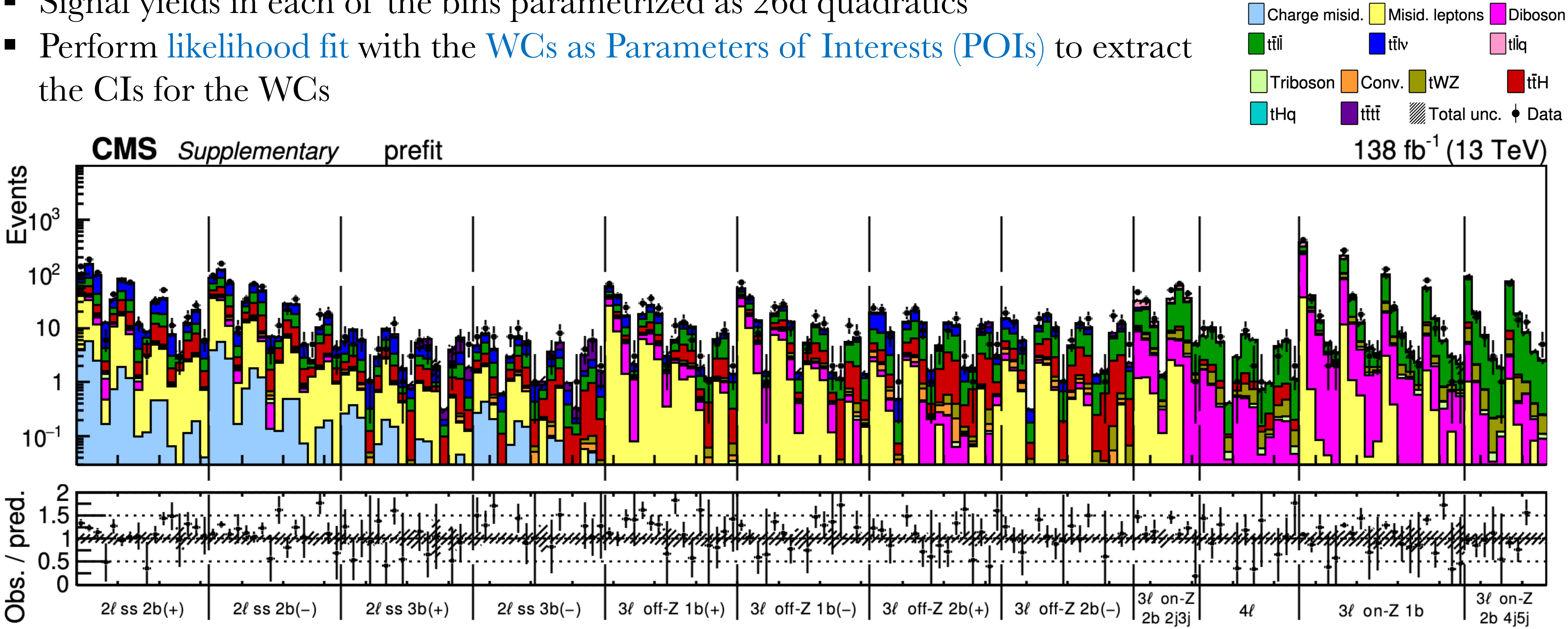


Event yield in each bin is quadratically dependent on the WCs. 26d quadratic for this analysis

Bin's parametrization

Event categorization and binning overview

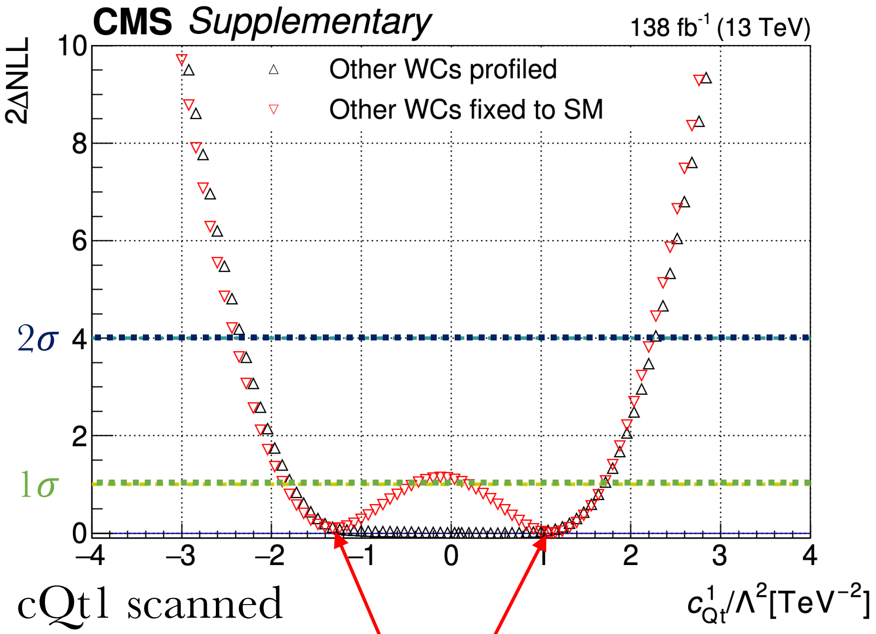
- 43 event categories binned using kinematic variables ➜ 178 analysis bins
- Signal yields in each of the bins parametrized as 26d quadratics
- Perform likelihood fit with the WCs as Parameters of Interests (POIs) to extract the CIs for the WCs



Results

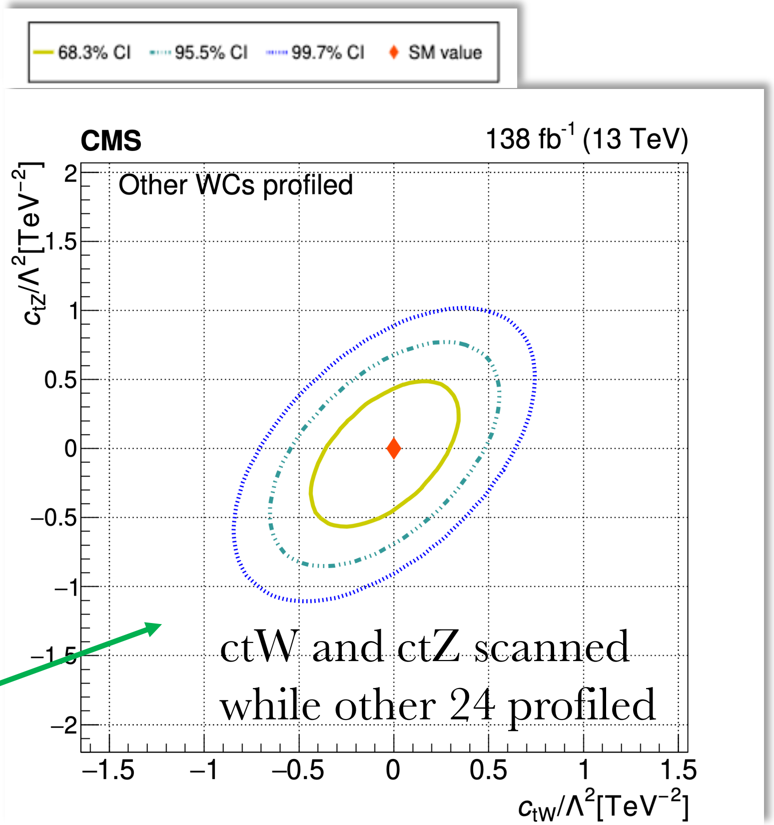
- Extracted 95% CIs for the WCs under two scenarios:
  - Scanning 1 WC while **freezing** other 25 to SM value of 0
  - Scanning 1 WC while **profiling** other 25 WCs

In SM scenario, all WCs = 0

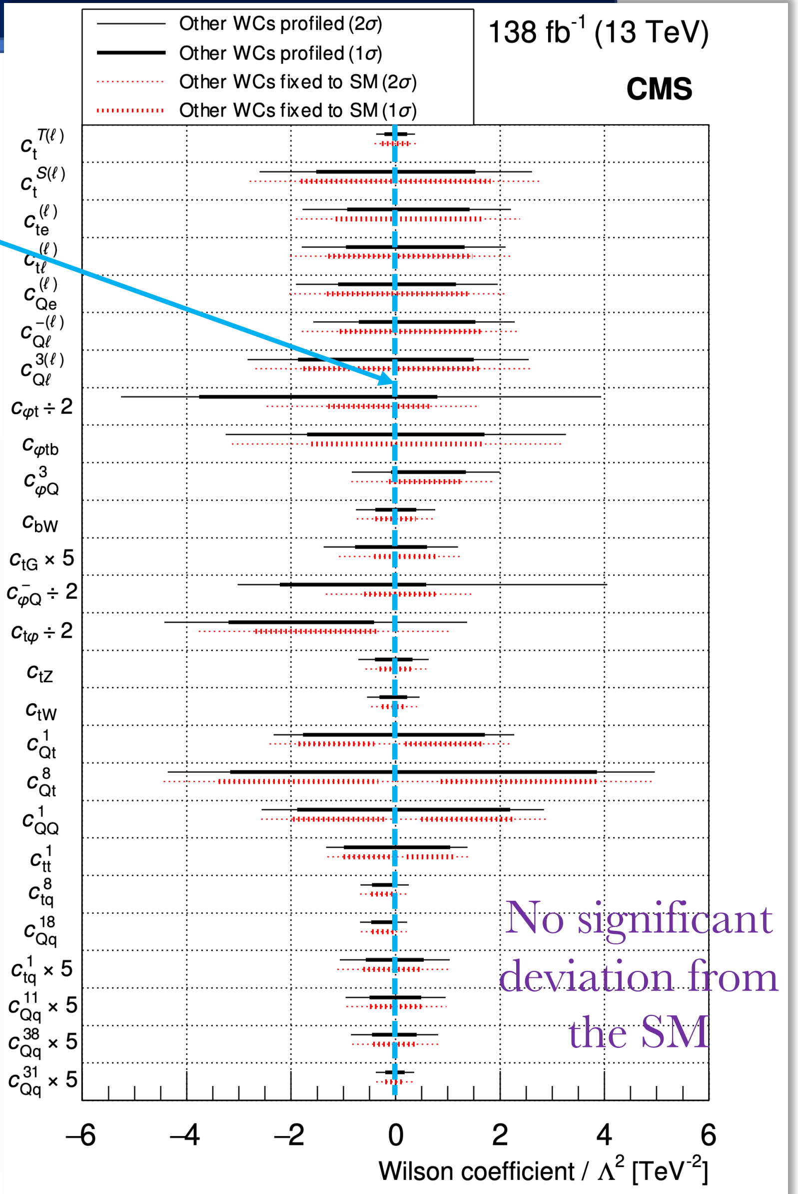


cQt1 scanned

Double minima broadens NLL curve



ctW and ctZ scanned while other 24 profiled



No significant deviation from the SM

- Also scanned pairs of WCs

Interpretation of sensitivity

- Studied the relative contribution of bins (or group of bins) to the sensitivity to each WC
- Important to emphasize that the sensitivity to a WC comes from a diverse combination of bins from several categories
- Interference and correlations among WCs are also important factors in driving yields for a given bin

Grouping of WCs	WCs	Lead categories
2hq2ℓ	$c_{Q\ell}^{3(\ell)}$, $c_{Q\ell}^{-(\ell)}$, $c_{Qe}^{(\ell)}$, $c_{t\ell}^{(\ell)}$, $c_{te}^{(\ell)}$, $c_{t}^{S(\ell)}$, $c_{t}^{T(\ell)}$	3ℓ off-Z
4hq	c_{QQ}^{1}, c_{Qt}^{1}, c_{Qt}^{8}, c_{tt}^{1}	2ℓss
2hq2lq "$t\bar{t}\ell\nu$-like"	c_{Qq}^{11}, c_{Qq}^{18}, c_{tq}^{1}, c_{tq}^{8}	2ℓss
2hq2lq "$t\ell\bar{\ell}q$-like"	c_{Qq}^{31}, c_{Qq}^{38}	3ℓ on-Z
2hqV "$t\bar{t}\ell\bar{\ell}$-like"	c_{tZ}, $c_{\varphi t}$, $c_{\varphi Q}^{-}$	3ℓ on-Z and 2ℓss
2hqV "tXq-like"	$c_{\varphi Q}^{3}$, $c_{\varphi tb}$, c_{bW}	3ℓ on-Z
2hqV (significant impacts on many processes)	c_{tG}, $c_{t\varphi}$, c_{tW}	3ℓ and 2ℓss

Summary and outlook

- SMEFT is a relatively model-independent and systematic framework to characterize NP effects
- We search for NP impacting associated top production in multilepton final states using SMEFT framework
  - Modeled EFT effects at detector level and performed global fitting of 26 EFT operators that strongly impact 6 relatively rare signal processes
  - Results consistent with the SM
  - For more details: arXiv:2307.15761 (Submitted to JHEP)
- Many improvements in progress for the analysis:
  - More statistics
  - Optimizations of event categorizations and kinematic variables used for fitting
  - Including more signal processes and other final states
  - Combinations with other Top EFT analyses (paving path towards combination between different CMS EFT groups like Higgs and Electroweak sectors)

Exciting times ahead!

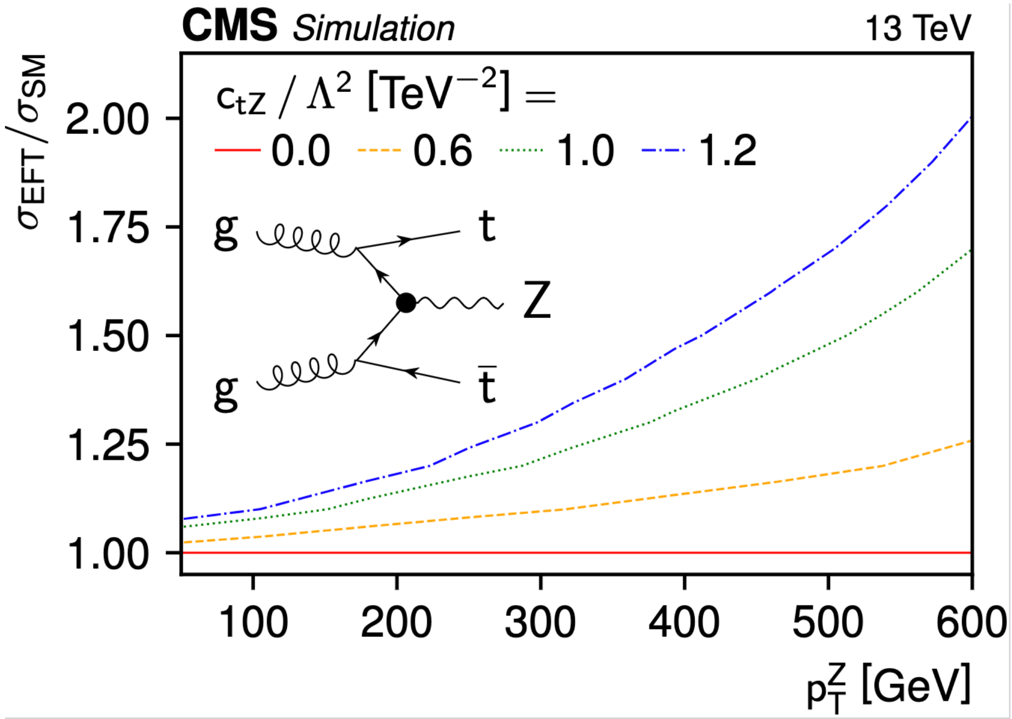
Thank you!

CMS

The Ohio State University

BACKUP

Sensitivity to EFT effects

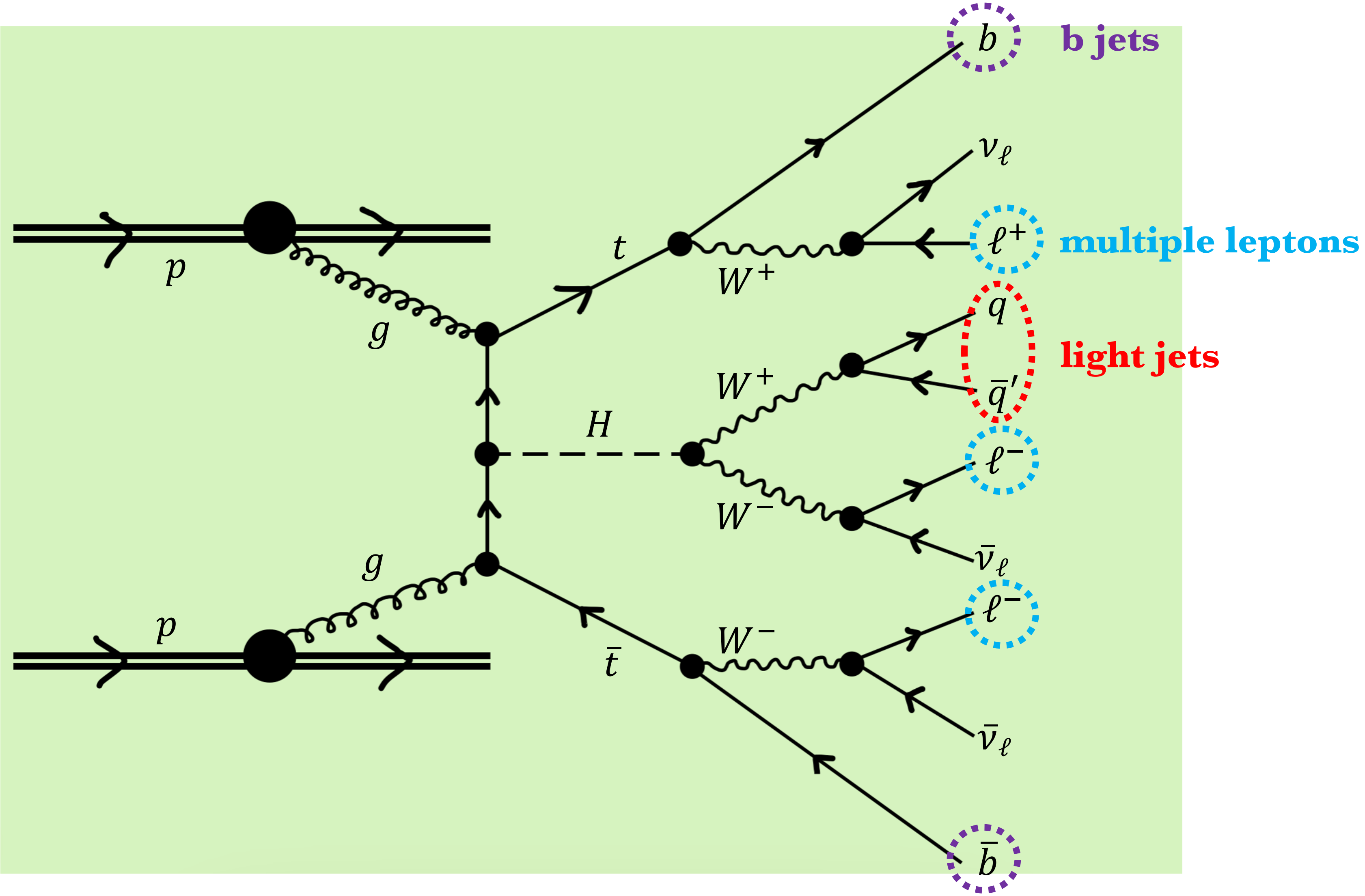


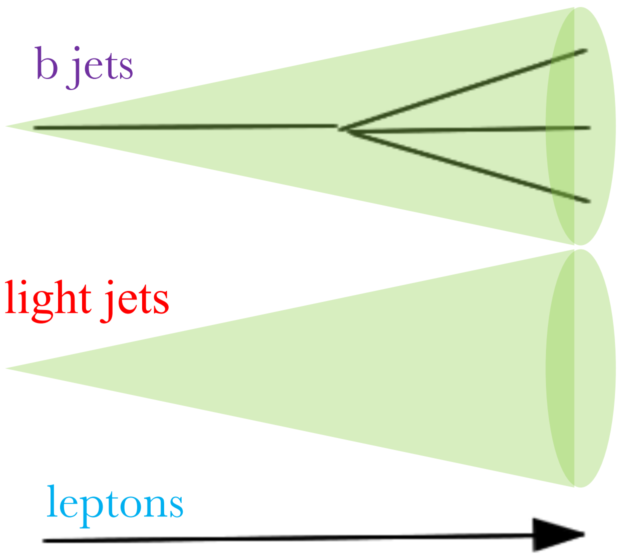
Ratio of ttZ cross-section in SMEFT scenario vs. SM scenario as a function of ctZ and Z-boson pT.
Taken from Fig. 2a) PhysRevD.108.032008

Event selection overview

Event category	Leptons	$m_{\ell\ell}$	b tags	Lepton charge sum	Jets	Kinematical variable
2ℓss 2b	2	No requirement	2	$>0, <0$	4, 5, 6, $\geq$7	$p_T(\ell j)_{max}$
2ℓss 3b	2	No requirement	$\geq$3	$>0, <0$	4, 5, 6, $\geq$7	$p_T(\ell j)_{max}$
3ℓ off-Z 1b	3	$\|m_Z - m_{\ell\ell}\| > 10\,GeV$	1	$>0, <0$	2, 3, 4, $\geq$5	$p_T(\ell j)_{max}$
3ℓ off-Z 2b	3	$\|m_Z - m_{\ell\ell}\| > 10\,GeV$	$\geq$2	$>0, <0$	2, 3, 4, $\geq$5	$p_T(\ell j)_{max}$
3ℓ on-Z 1b	3	$\|m_Z - m_{\ell\ell}\| < 10\,GeV$	1	No requirement	2, 3, 4, $\geq$5	$p_T(Z)$
3ℓ on-Z 2b	3	$\|m_Z - m_{\ell\ell}\| < 10\,GeV$	$\geq$2	No requirement	2, 3, 4, $\geq$5	$p_T(Z)$ or $p_T(\ell j)_{max}$
4ℓ	$\geq$4	No requirement	$\geq$2	No requirement	2, 3, $\geq$4	$p_T(\ell j)_{max}$

Experimental signatures





Challenges faced

- Even though multilepton signatures are relatively cleaner, thus providing several advantages, there are also many challenges:
  - Multiple signal processes and WCs can contribute to the same final states
  - Analysis needs dedicated private EFT samples generation
    - Computationally expensive
  - No reinterpretation in terms of cross section measurement possible

EFT parametrization details

- Matrix Element ($\mathcal{M}$) is a function of WCs:

$$\mathcal{M} = \mathcal{M}_{SM} + \sum_i c_i \mathcal{M}_i$$

- Cross-section $\sigma \propto \mathcal{M}^2 \Longrightarrow \sigma \propto c_i{}^2$ and event weights depend on σ:

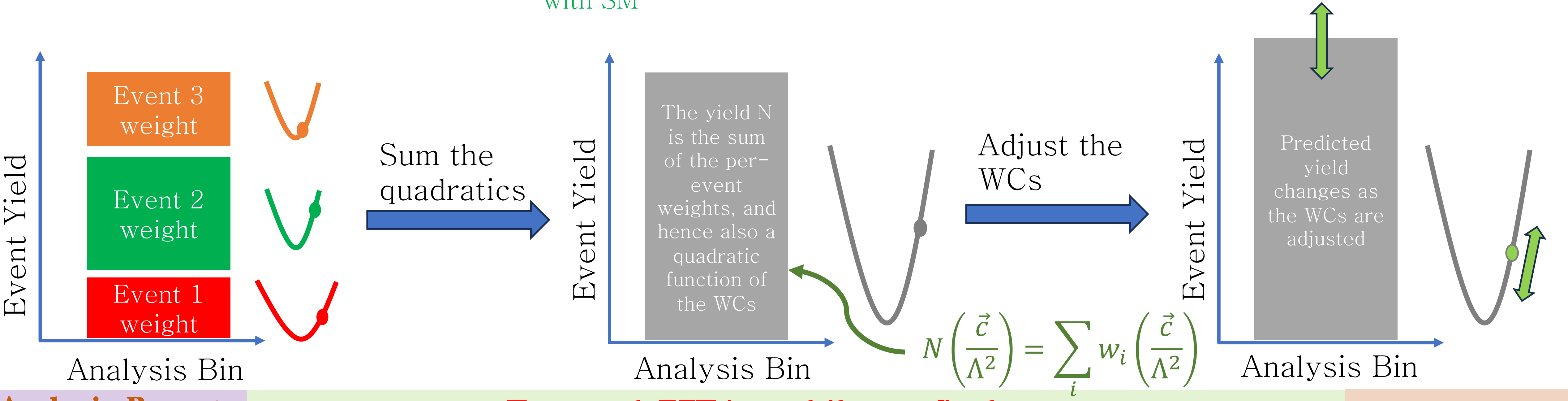
$$w_i\left(\frac{\vec{c}}{\Lambda^2}\right) = S_{0i} + \sum_j S_{1ij}\frac{c_j}{\Lambda^2} + \sum_j S_{2ij}\frac{c_j^2}{\Lambda^4} + \sum_{j\neq k} S_{3ijk}\frac{c_j}{\Lambda^2}\frac{c_k}{\Lambda^2}$$

pure SM

Interference with SM

pure NP

Interference between NP terms



EFT parametrization details (II)

- Number of structure constants (K) required to describe an N-dimensional quadratic is:

$$K = \frac{(N+1).(N+1)-(N+1)}{2} + (N+1)$$

- Example: N = 1 → K = 3:

$$\sigma \propto s_0 + s_1 c_1 + s_2 c_1^2$$

Interference with SM

Pure EFT

Pure SM

- For N = 26, K = 378
- In theory, we could extract these 378 structure constants if we knew the xsec at 378 points in the 26d WC space.
    - Requires generating 378 unique simulated samples. Not feasible
- Instead use MG reweighting technique.
    - Generate event under a certain theoretical scenario corresponding to a particular point in 26d WC space. Call it "starting point"
    - Compute event weights at alternative points in the WC space. We need event weights at least 378 such points
    - Extract 378 structure constants. We know full parametrization of the event weight in terms of the WCs!

Background estimation details

- Background contribution dominated by diboson production (WZ and ZZ)
  - Subleading contribution from triboson and tWZ processes
  - Estimated using simulations
- Nonprompt leptons (e.g., from b hadrons decay) also another important background
  - Estimated using data-driven methods
- Other sources of background:
  - charge flips
  - photon conversion

Systematic uncertainties

Systematic uncertainty	Average change in the yields
Integrated luminosity	1.6%
Jet energy scale and resolution	1%
b jet tagging scale factors	1%
Theoretical cross section	1–4% (QCD) 1% (PDF)
Renormalization and factorization scales	3%
Parton shower	1–2%
Additional radiation	7%
Electron and muon identification and isolation	2% (electron) 1% (muon)
Trigger efficiency	$\leq$1%
Pileup	1%
L1 prefiring	1%
Misidentified-lepton rate	3%
Charge misreconstruction rate	1%
Jet mismodeling	7%

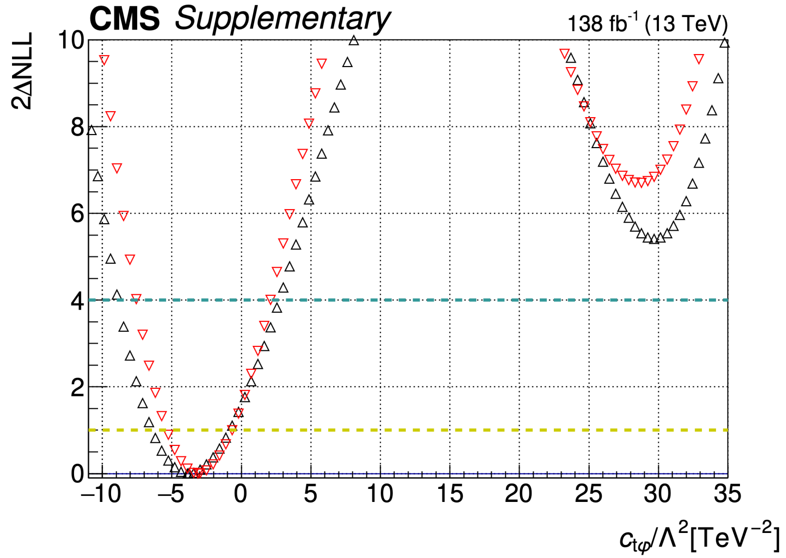
Observed 2σ CIs

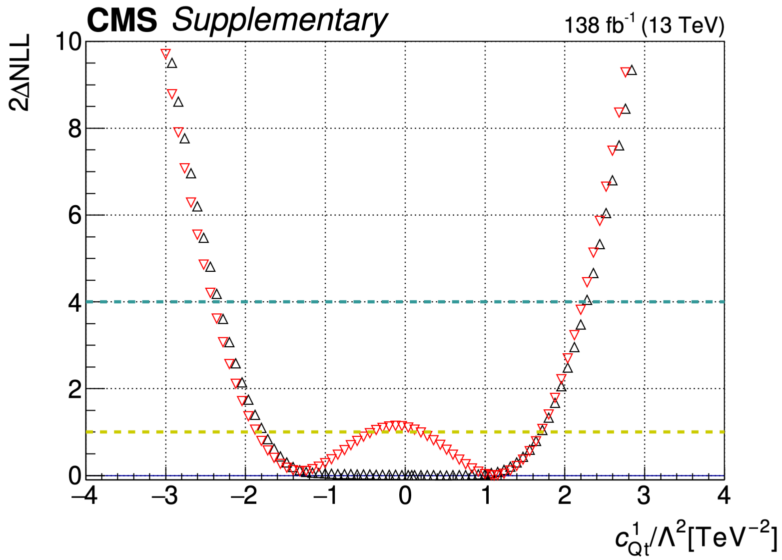
WC/Λ^2 [TeV^{-2}]	2σ CI (other WCs profiled)	2σ CI (other WCs fixed to SM)
WC category 2hq2ℓ		
$c_{t}^{T(\ell)}$	[−0.37, 0.37]	[−0.40, 0.40]
$c_{t}^{S(\ell)}$	[−2.60, 2.62]	[−2.80, 2.80]
$c_{te}^{(\ell)}$	[−1.78, 2.21]	[−1.91, 2.39]
$c_{t\ell}^{(\ell)}$	[−1.80, 2.11]	[−2.02, 2.20]
$c_{Qe}^{(\ell)}$	[−1.91, 1.96]	[−2.04, 2.12]
WC category 2hqV		
$c_{Q\ell}^{-(\ell)}$	[−1.58, 2.28]	[−1.80, 2.33]
$c_{Q\ell}^{3(\ell)}$	[−2.84, 2.55]	[−2.69, 2.58]
$c_{\varphi t}$	[−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]

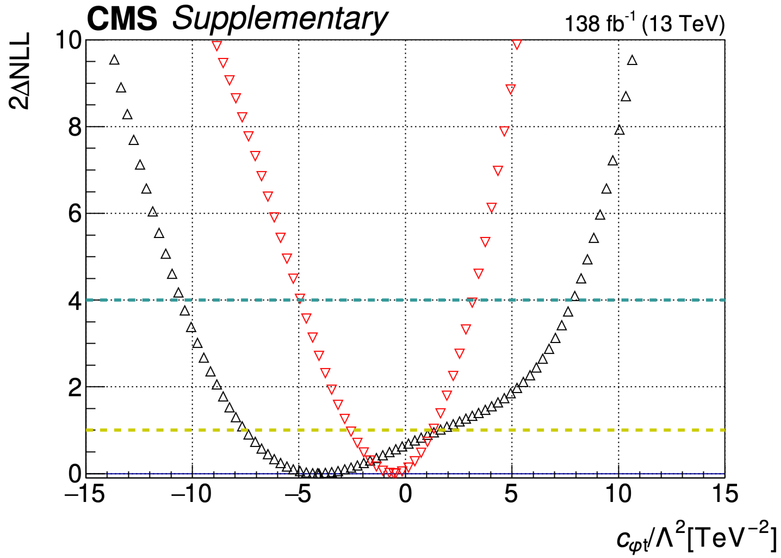
Selected 1D Scans

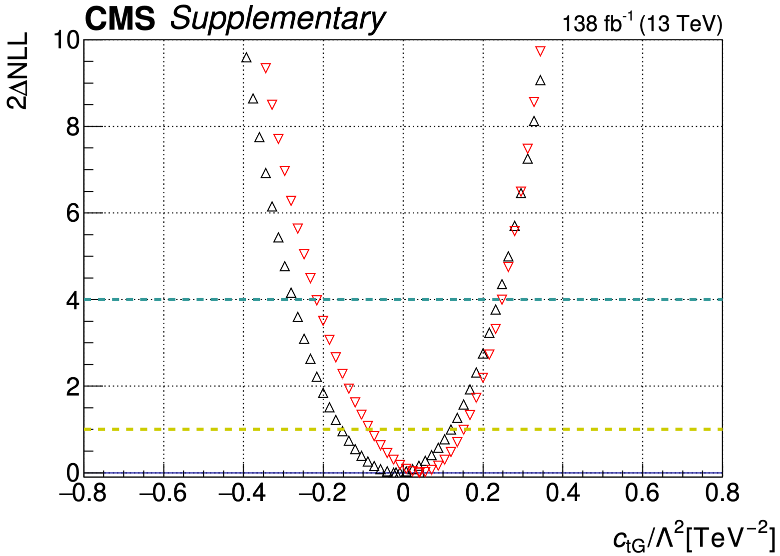
△ Other WCs profiled

▽ Other WCs fixed to SM

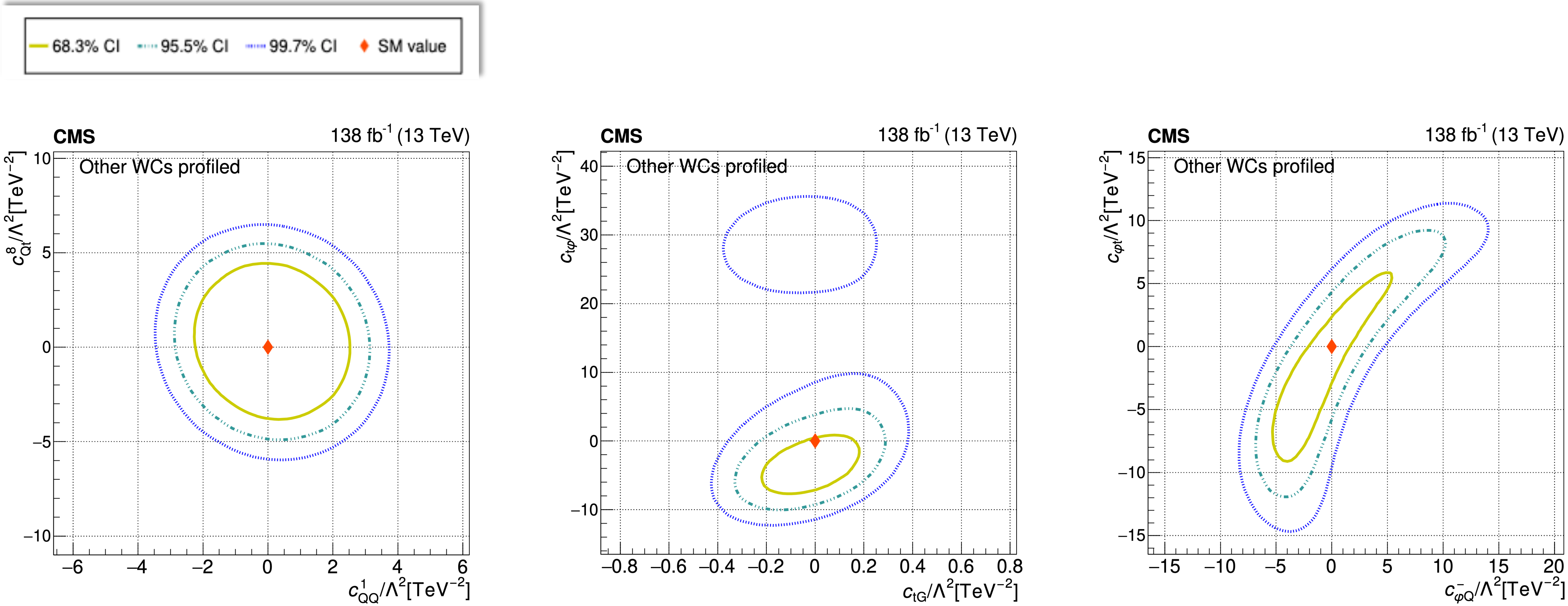








Selected 2D scans (others profiled)



Selected 2D scans (others frozen to SM)