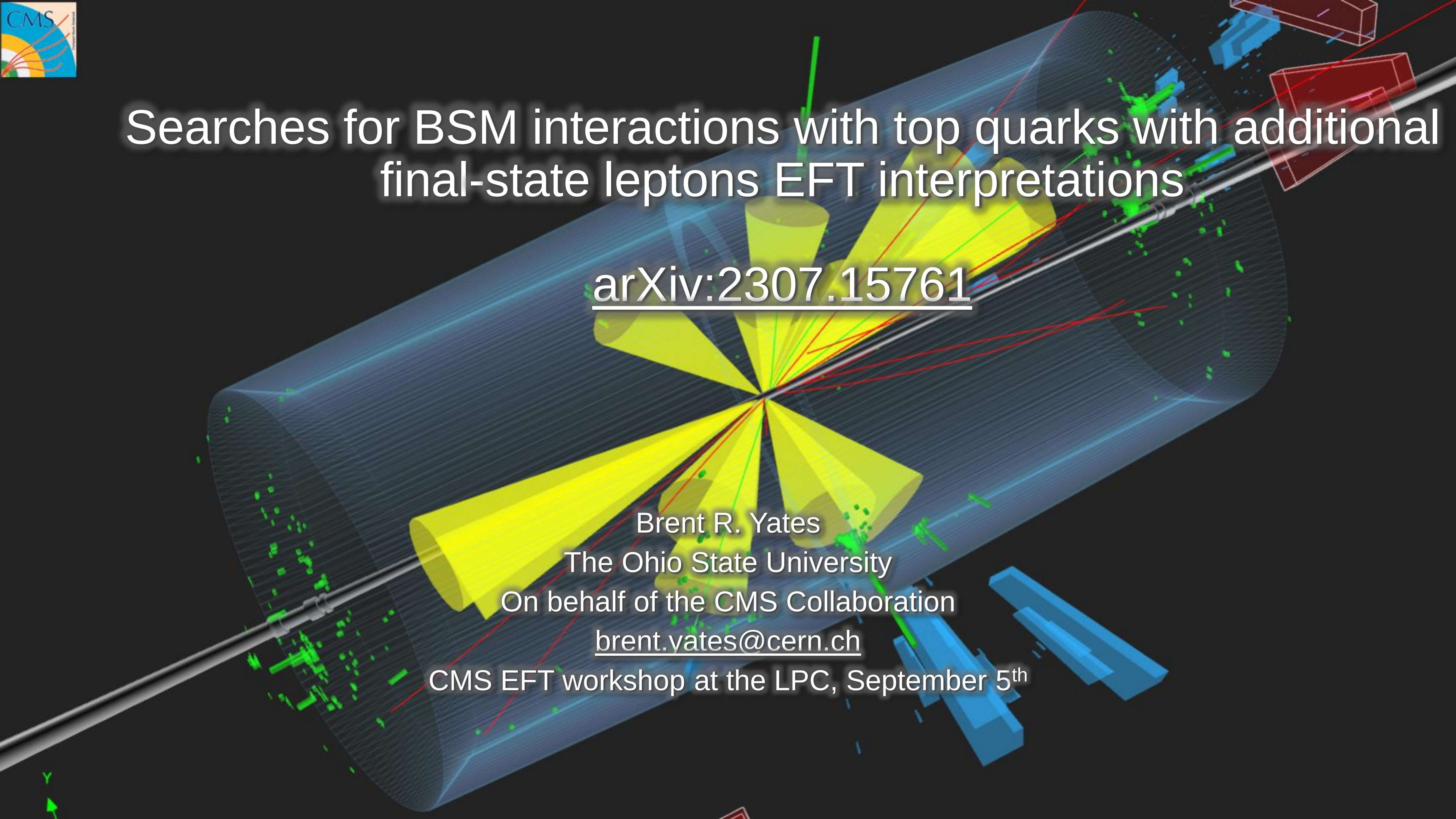

Searches for BSM interactions with top quarks with additional final-state leptons EFT interpretations

arXiv:2307.15761

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On behalf of the CMS Collaboration
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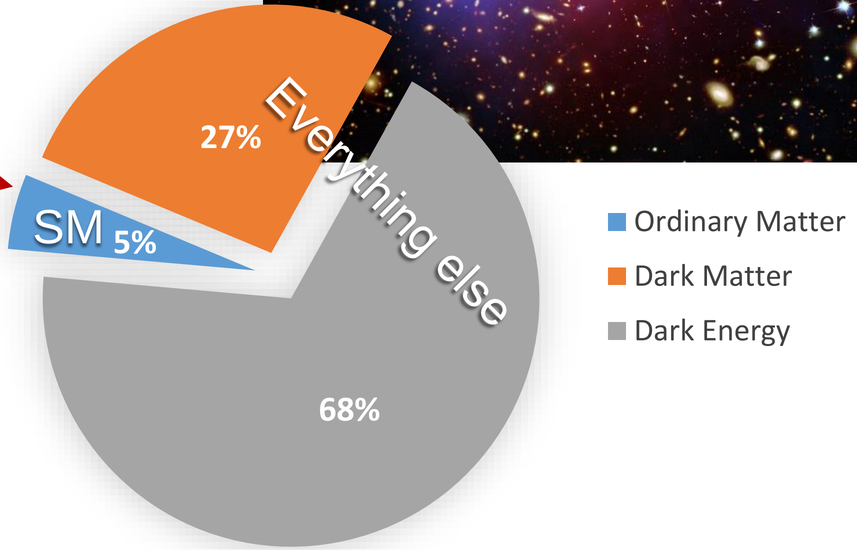
CMS EFT workshop at the LPC, September 5th

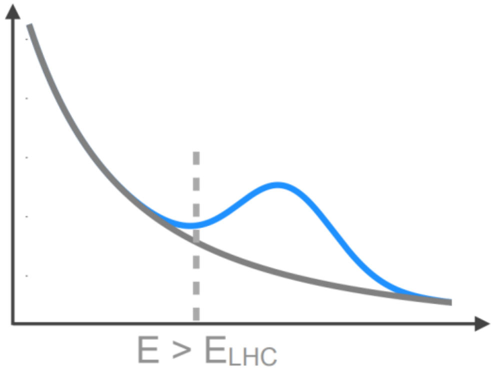
Motivation for new physics

The standard model of particle physics (SM) is a very precise theory, but only accounts for 5% of the energy content of the universe



The LHC has been running for 10 years with no clear signs of new physics

What if $\Lambda_{\text{New physics}} > \Lambda_{\text{LHC}}$?

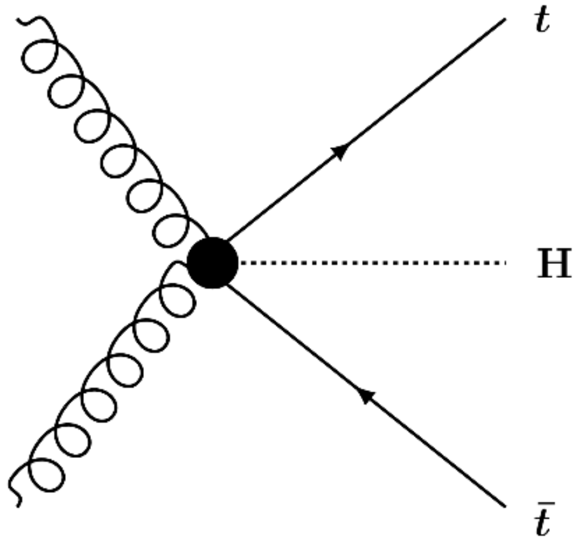


Introduction to SM effective field theory (SMEFT)

New physics at scales beyond what the LHC can directly probe can be approximated by expanding terms of higher dimensional (d) operators $\mathcal{O}$ consisting of SM fields

Operators are suppressed by powers of the energy scale Λ, and the strength is controlled by the Wilson coefficients (WCs) c_i

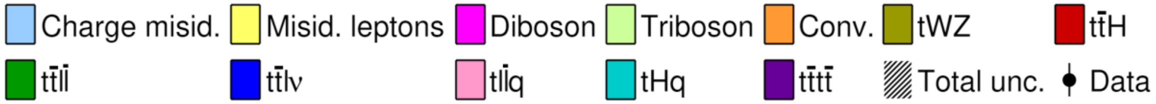
$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d,i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$



Odd dimensions violate lepton and baryon numbers

Focusing on dimension-6

dim-8+ suppressed by additional powers of Λ



Analysis overview

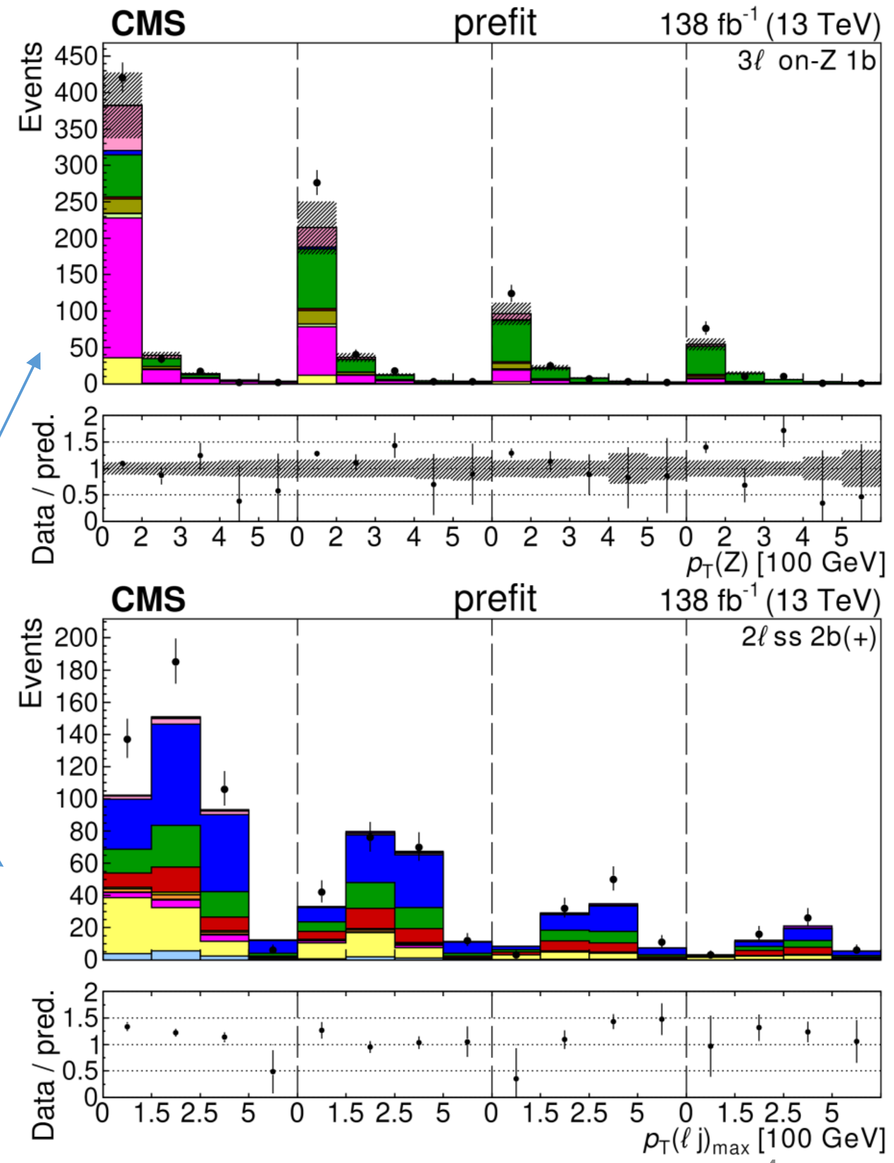
Dimension-six is the lowest order **non-LFV** SMEFT term

Global fit for 26 dimension-six WCs using data collected in 2016-2018 $(138\ \mathrm{fb}^{-1})$

Probe EFT effects in multilepton final states

Fitting kinematic variables (178 bins)

- p_{T} of Z-boson for most 3ℓ on-shell Z production ($p_{\mathrm{T}}(\mathrm{Z})$)
- p_{T} of the leading pair of leptons and/or jets ($p_{\mathrm{T}}(\ell j)_{\mathrm{max}}$)

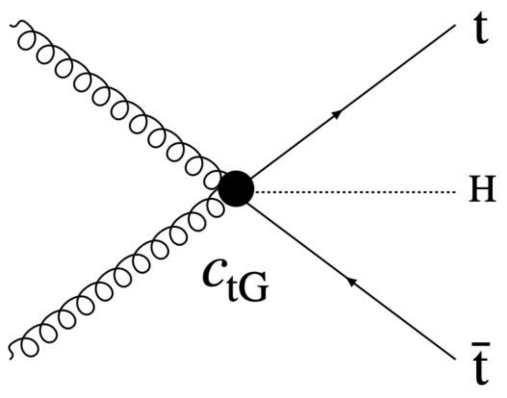


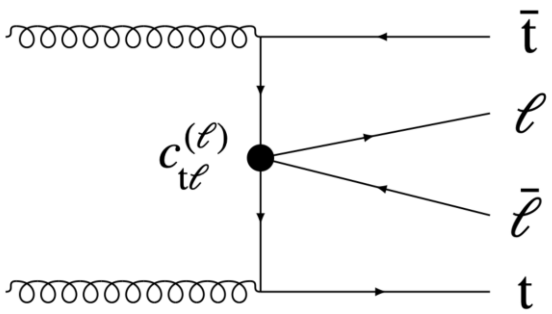
No assumptions made to the underlying correlations

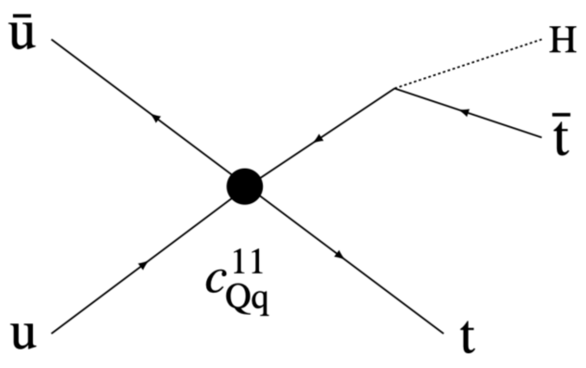
Production modes: $t\bar{t}l\nu$, $t\bar{t}ll$, $tllq$, $t\bar{t}H$, tHq, and $t\bar{t}t\bar{t}$

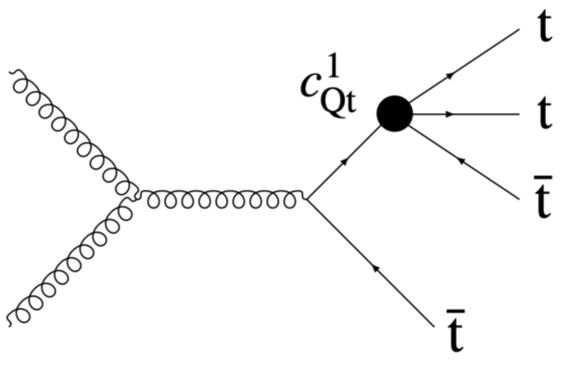
Model operators

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}









EFT parametrization

Matrix element is a function of WCs

$$\mathcal{M} = \mathcal{M}_{\text{SM}} + \sum_j \frac{c_j}{\Lambda^2} \mathcal{M}_j$$

Events are weighted depending on simulated cross section ($\propto \mathcal{M}^2$)

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

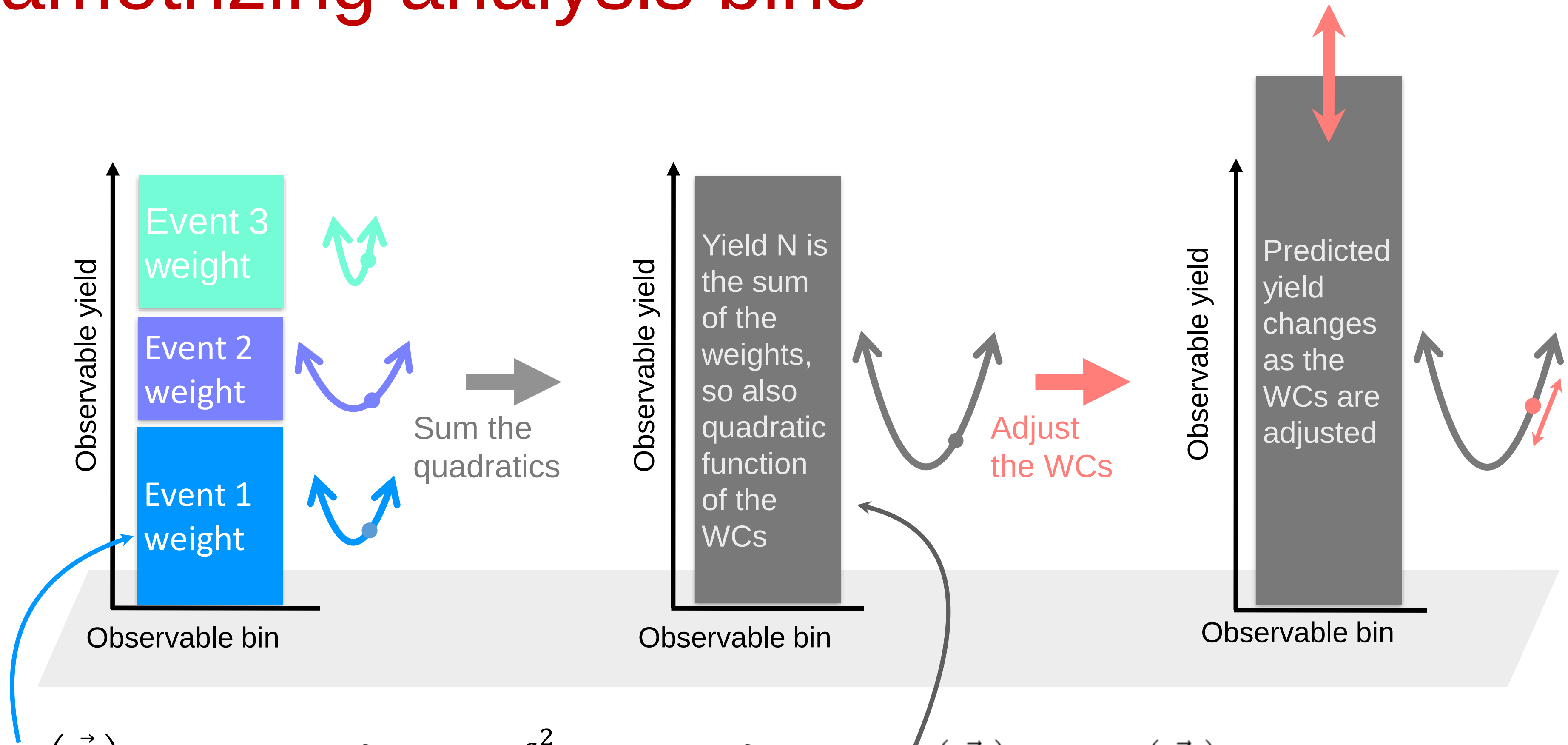
SM term

SM interference term

Pure EFT term

EFT interference term

Parametrizing analysis bins



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

$$N\left(\frac{\vec{c}}{\Lambda^2}\right) = \sum_i w_i\left(\frac{\vec{c}}{\Lambda^2}\right)$$

Unique challenges overcome

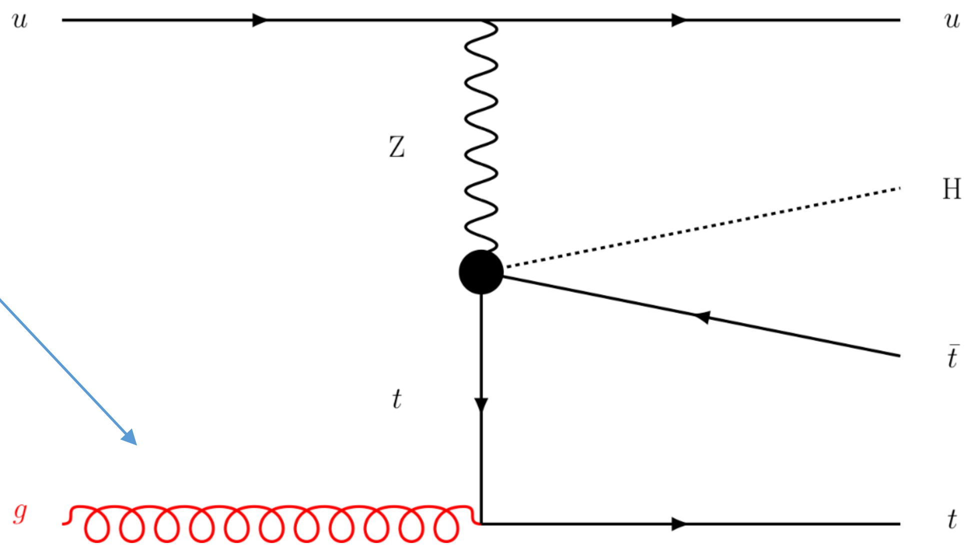
Simulation samples generated at non-SM point to cover more complete phase space

Extra partons are added when possible in matrix element

Generated enough simulations to over constrain structure constants in quadratic parameterization

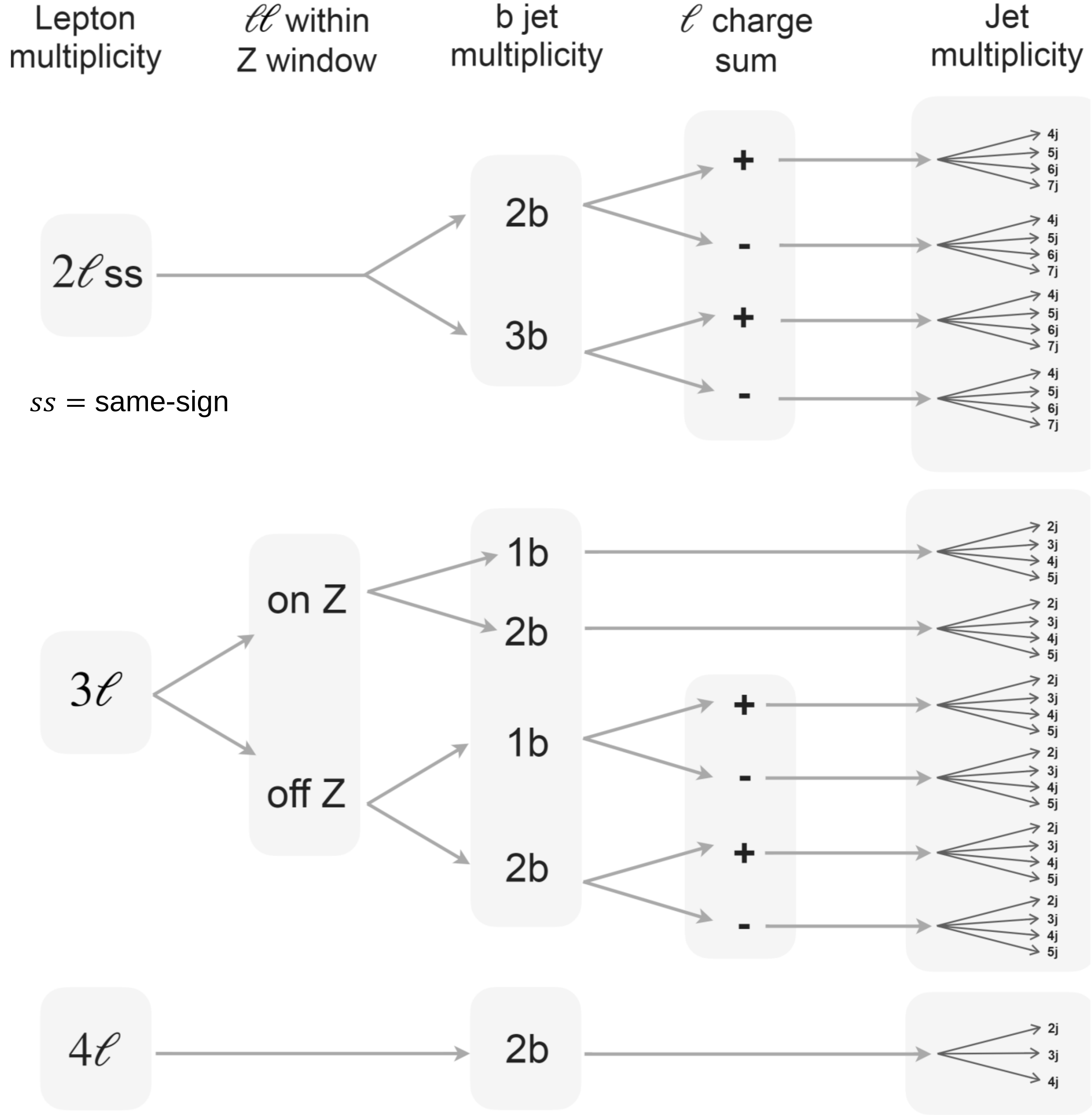
Parameterization used to simultaneously fit all 26 WCs

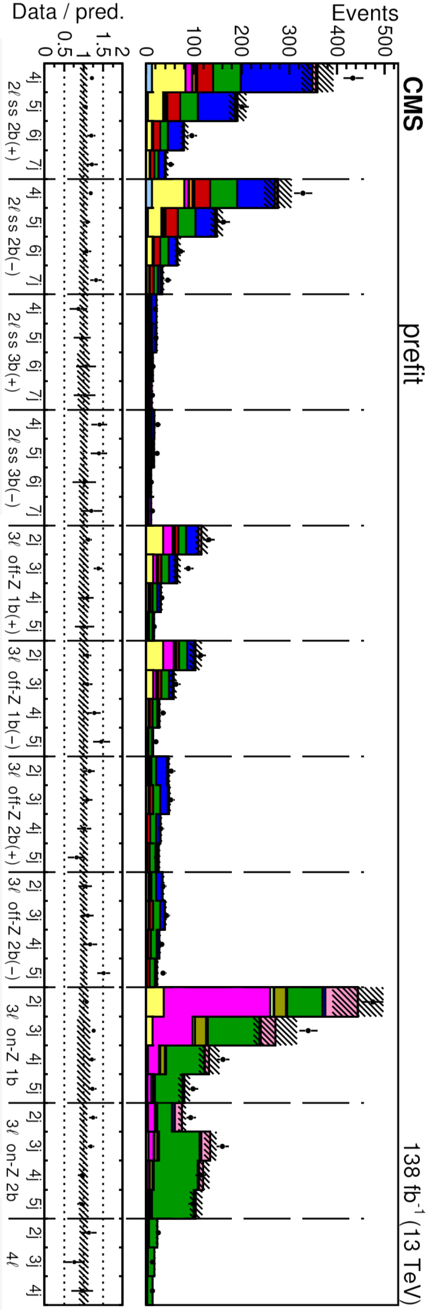
Largest backgrounds:
non-prompt lepton (data driven) and diboson background



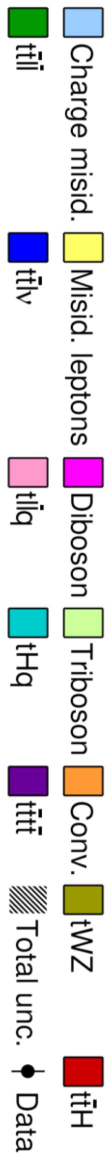
Computationally intensive framework – 210 NPs, ~ 2.7M templates

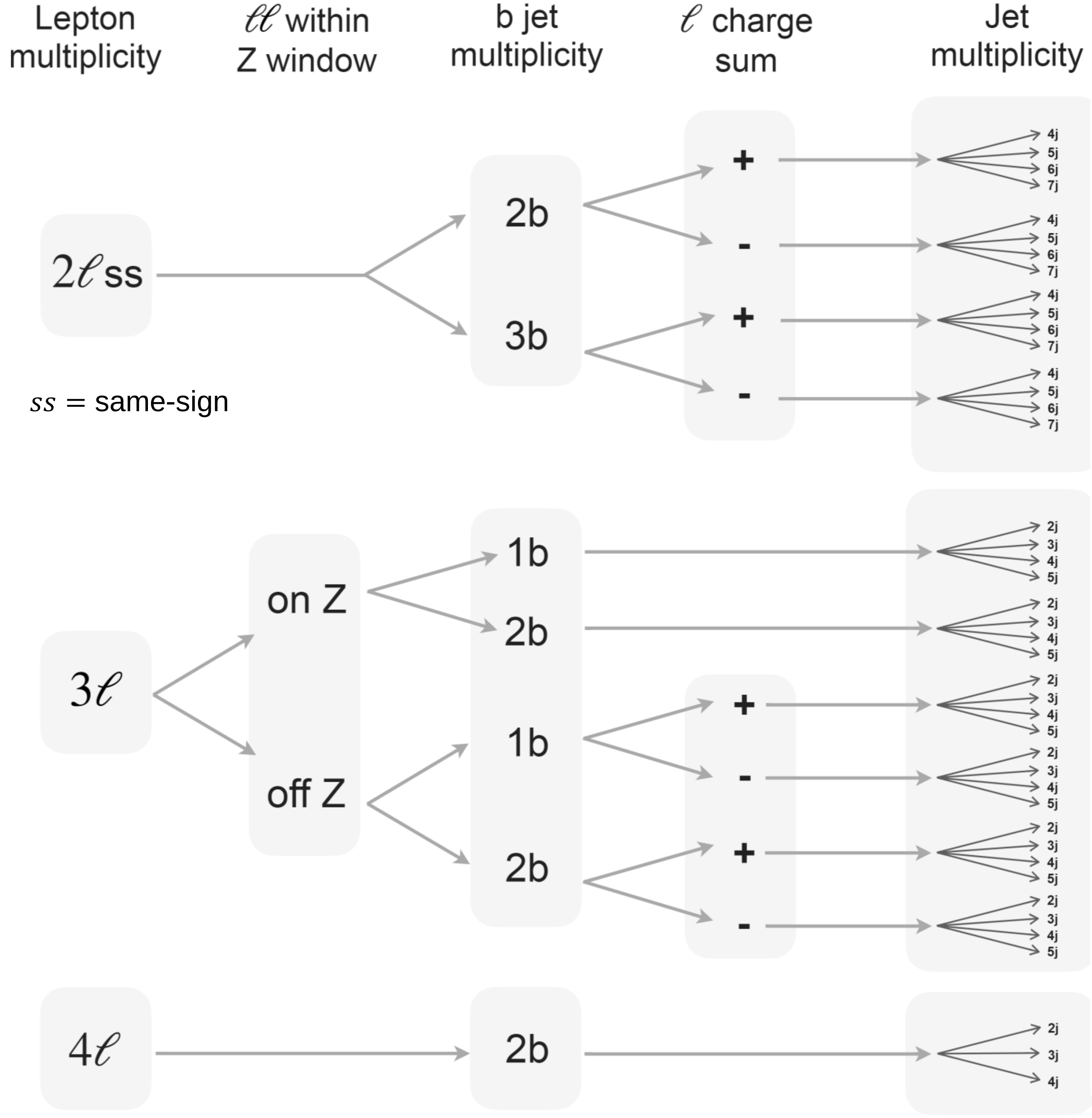
Goal of 10-minute histogram time in sight

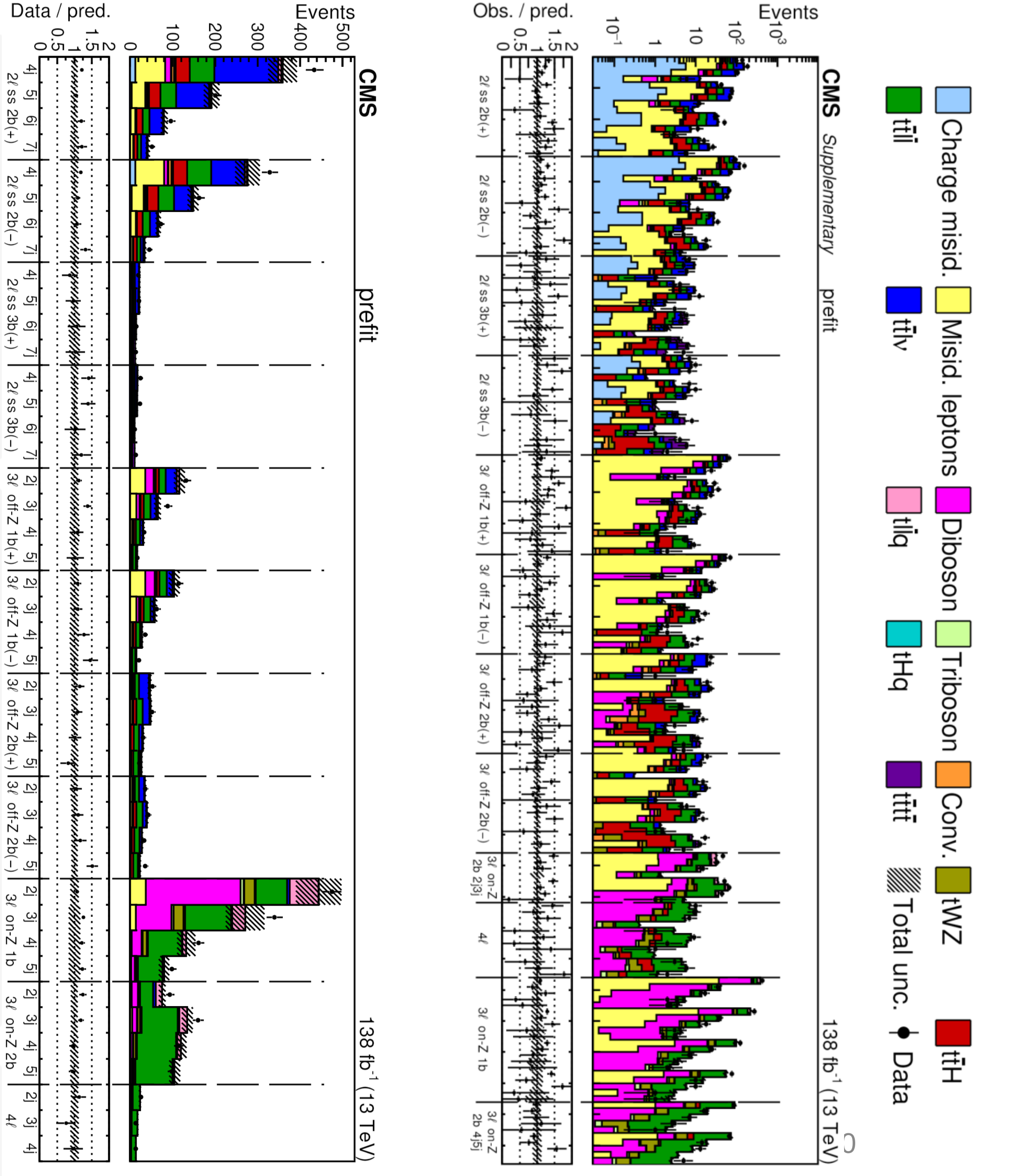




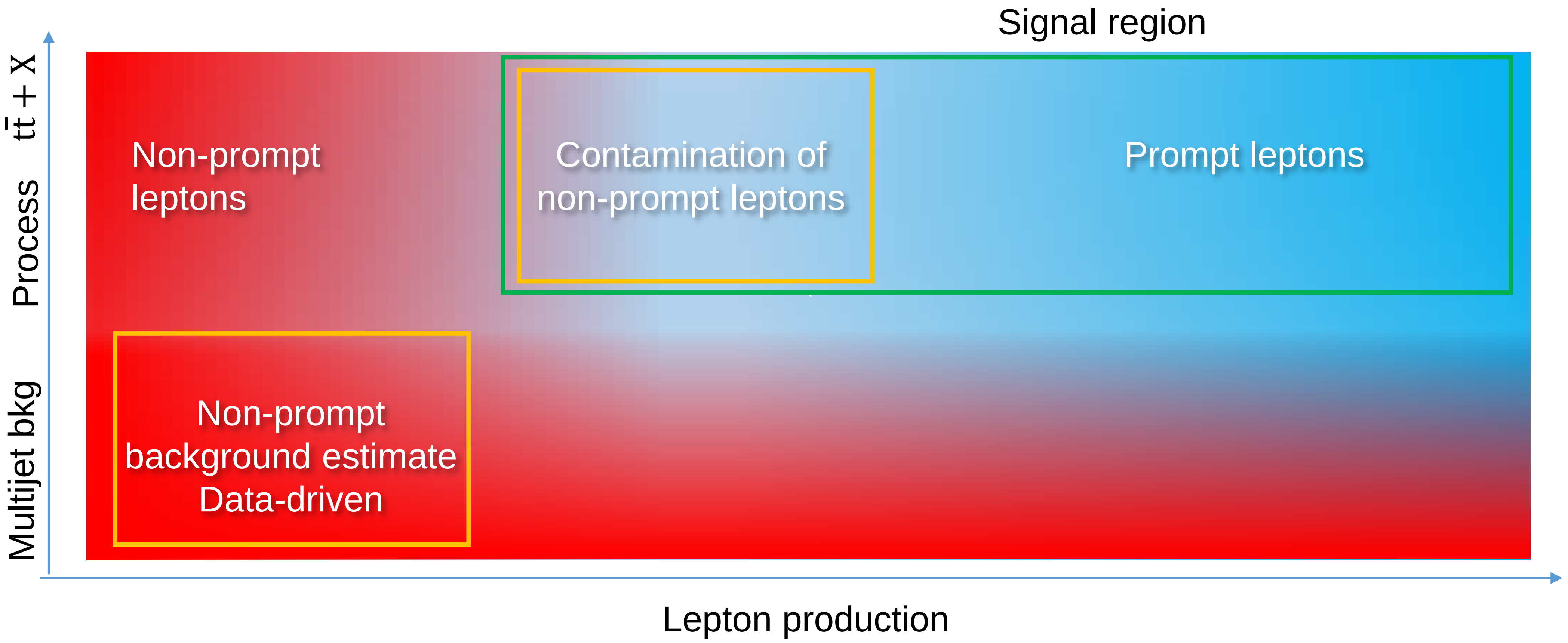
*differential distributions integrated out in plot




Lepton multiplicity
ℓℓ within Z window
b jet multiplicity
ℓ charge sum
Jet multiplicity
2ℓss
ss = same-sign
3ℓ
4ℓ
on Z
off Z
1b
2b
3b
+
-
2j
3j
4j
5j
6j
7j


CMS
CMS Supplementary
prefit
138 fb-1 (13 TeV)
Events
Data / pred.
Obs. / pred.
Charge misid.
Misid. leptons
Diboson
Triboson
Conv.
tWZ
ttH
ttl
ttν
tlq
tHq
tttt
Total unc.
Data

Misidentified lepton background



Probability of a non-prompt lepton passing prompt cuts is measured in a multijet enriched region

Data-driven

Fitting procedure

Each bin is treated as a Poisson experiment with a probability of obtaining the observed data

Profiled likelihood simultaneously fits all bins; extract the 95% confidence intervals of the various WCs

Two fitting procedures are used:

Scan single WC, other 25 are unconstrained nuisance parameters

- More physical of the two, no reason for new physics to only favor one WC

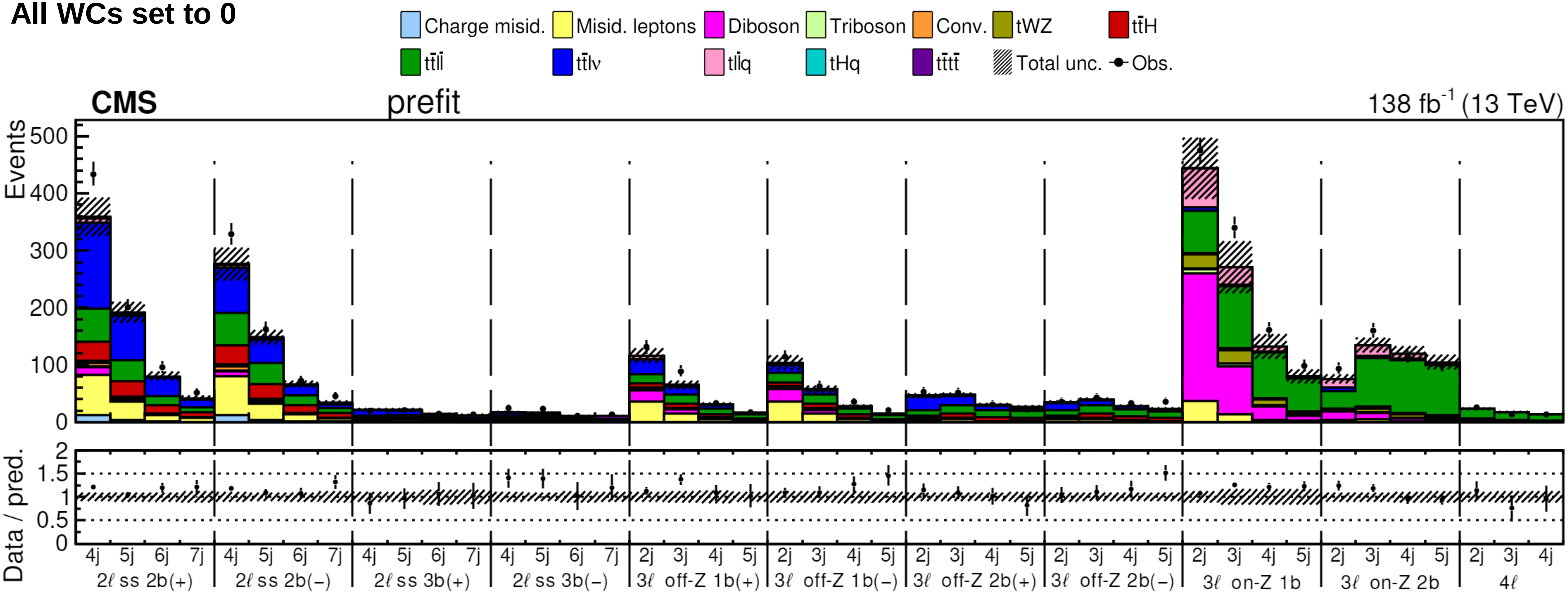
Scan a single WC, other 25 are fixed to their SM value of zero

- Extreme scenario where nature has a single WC; lack of correlations → single WC must account for all discrepancies between data and simulation

Initial expected yields

Kinematic variables integrated out

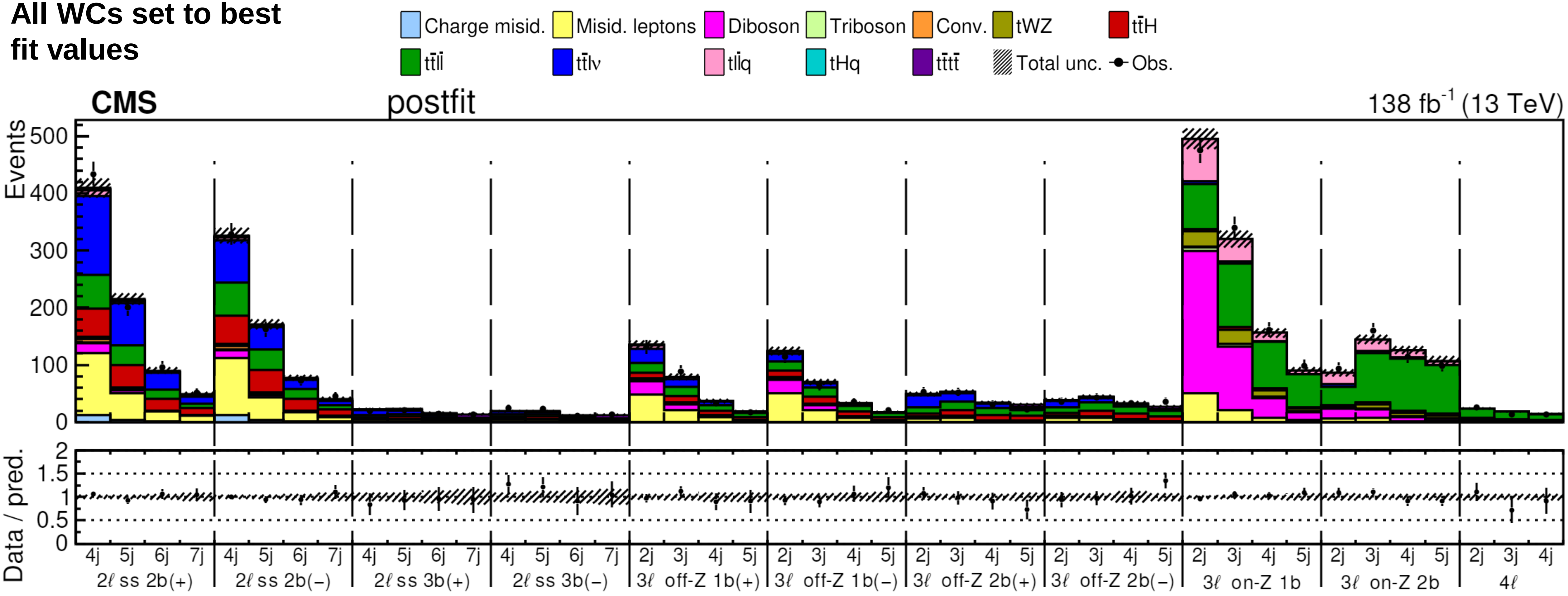
All WCs set to 0



Fitted expected yields

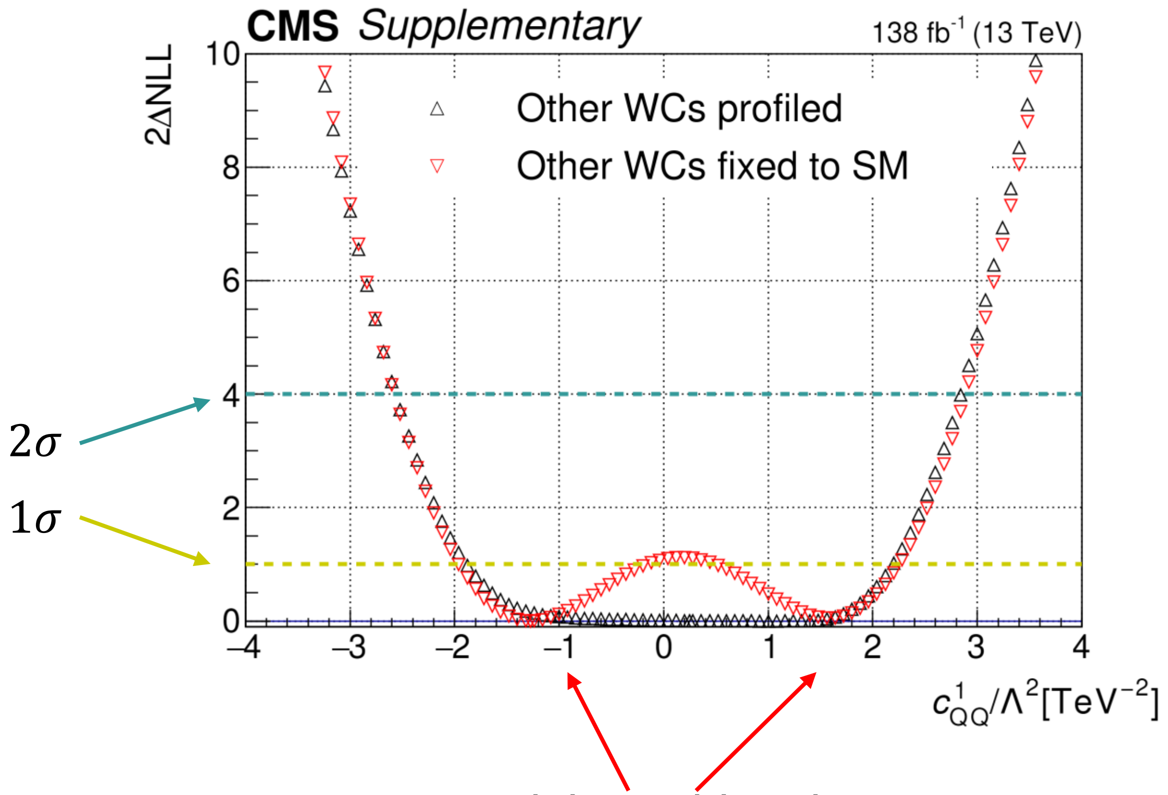
Kinematic variables integrated out

All WCs set to best fit values



Visualizing likelihood: single WC scan

Scanning c_{QQ}^{1} while the other 25 are **profiled** or **fixed to the SM** value of zero



Degenerate minima widen the NLL curve

Visualizing likelihood: two-dimensional WC scans

Pairs of WCs are also scanned to help investigate the correlations between WCs, as visualizing the full 26-dimensional hypersurface in not feasible

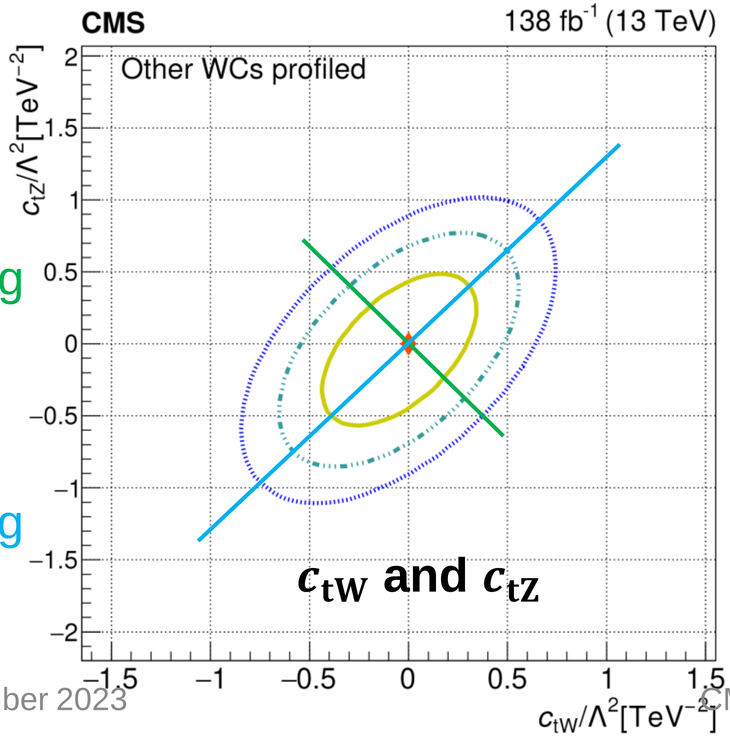
Other 24 WCs **profiled**

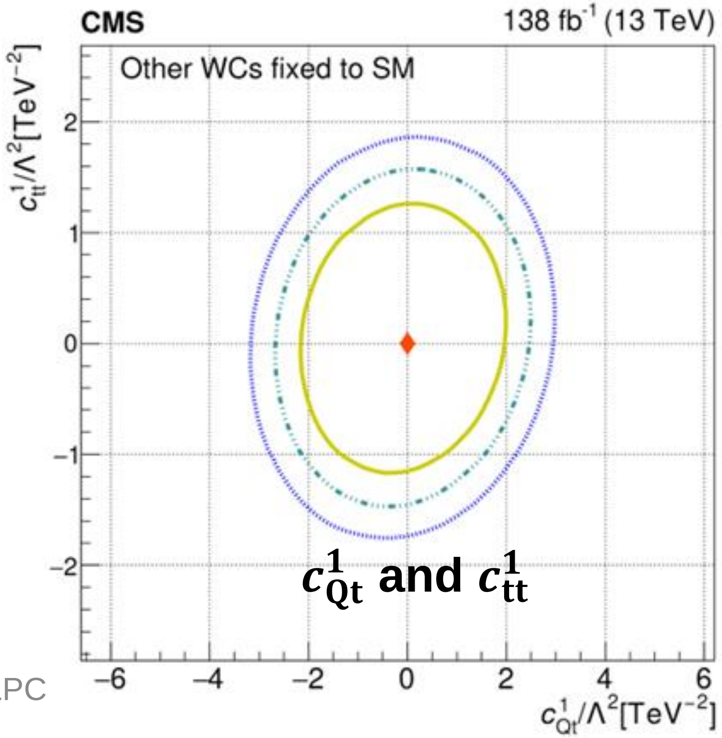
68.3% CI   95.5% CI   99.7% CI   ♦ SM value

Other 24 WCs are **fixed to SM**

Better constraints along the negative vertical axis

Looser constraints along the positive vertical axis





2 WCs must compensate for other 24 → less correlation

Important/unique systematic uncertainties

Monte Carlo simulation modeling

- **Scale uncertainties** – QCD and PDF cross section uncertainties (normalization)
- **Diboson jet multiplicity** – Diboson jet rate scale derived from control regions

Analysis specific

- **Misidentified lepton rate estimate** – Contamination from non-prompt leptons

  Overcome by examining the analysis side-bands

  Data-driven → statistically limited

Important in limits

- **Missing parton** – LO to NLO corrections for single-t samples

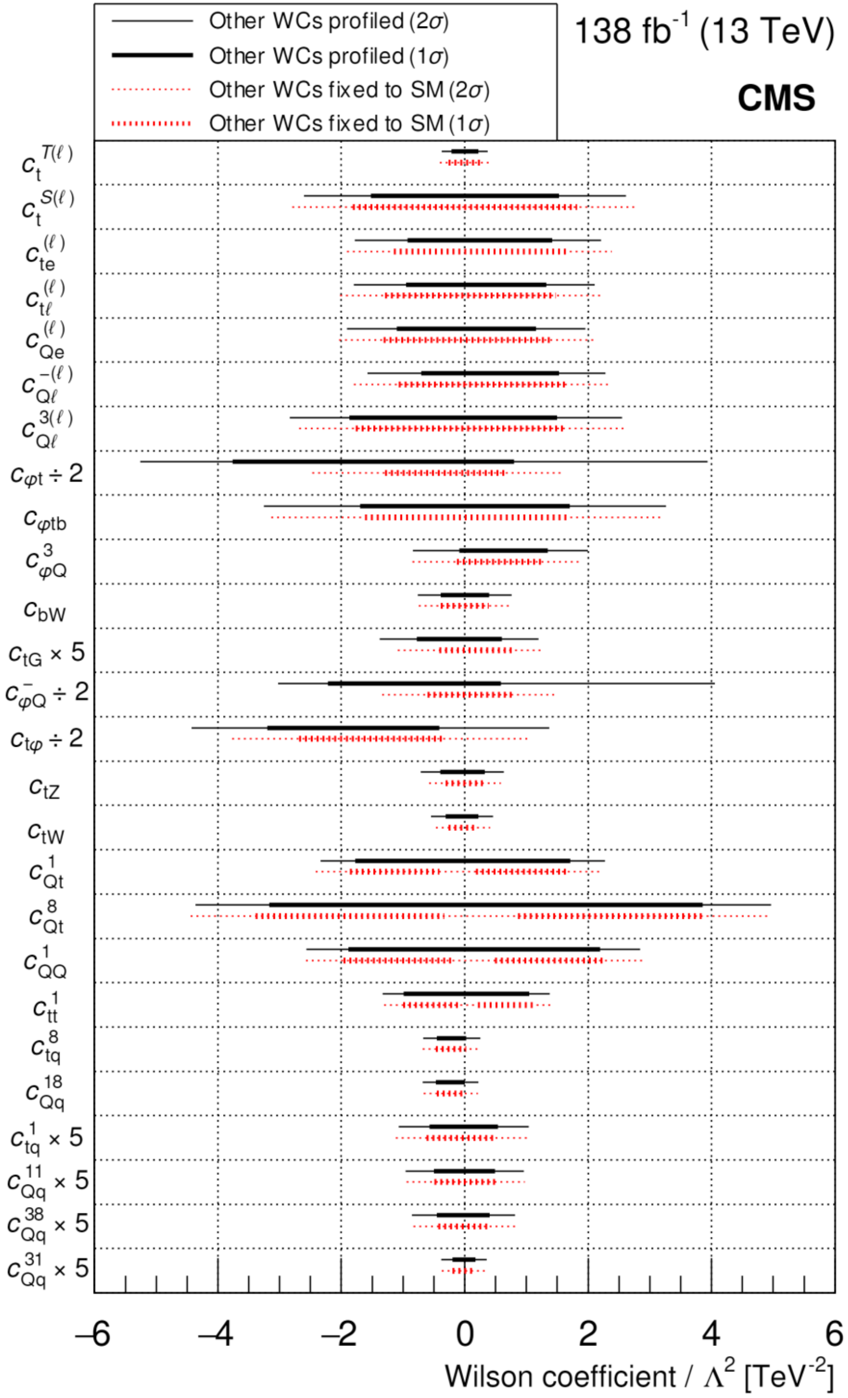
Unique to analysis

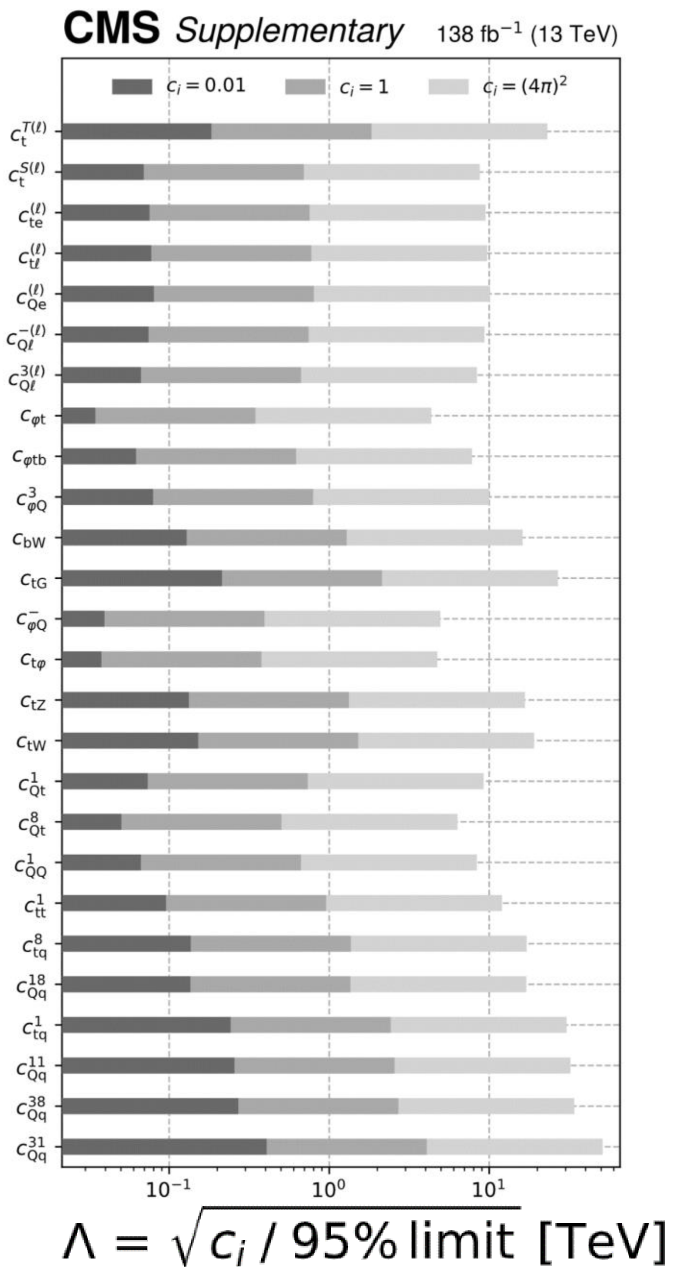
Results

Extracted 68 and 95% CIs

Some WCs have double minima due to quadratic parametrization

Use 95% CIs to extract energy scale Λ





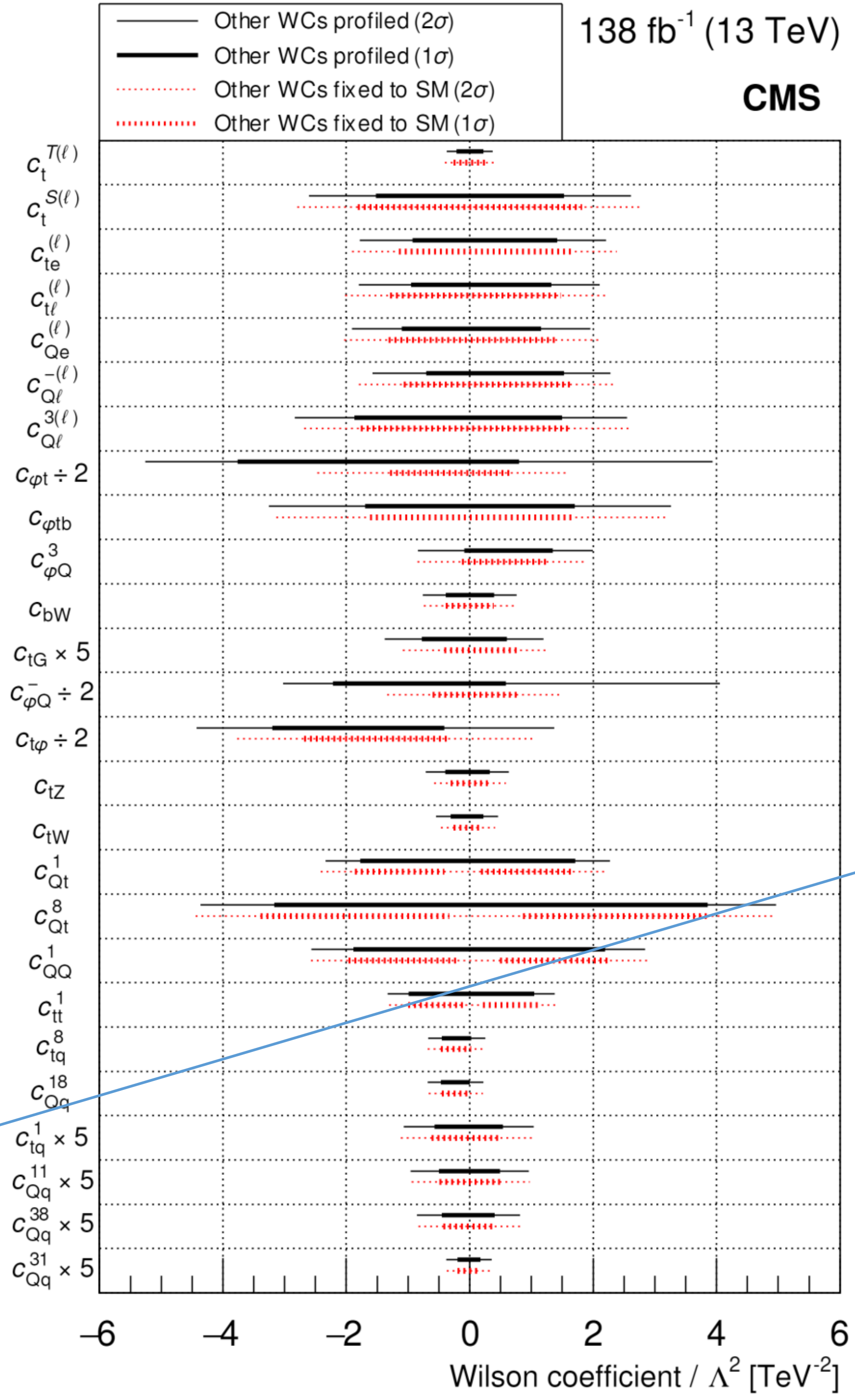
Results

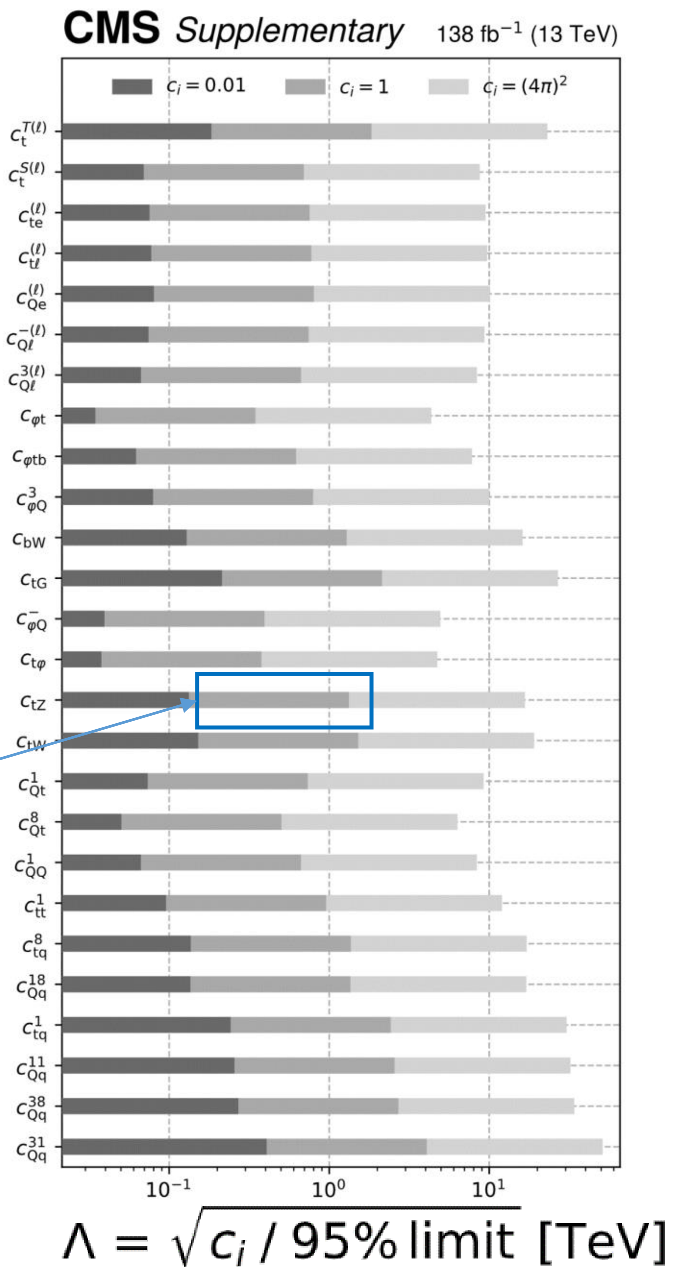
Extracted 68 and 95% CIs

Some WCs have double minima due to quadratic parametrization

Use 95% CIs to extract energy scale Λ

- Range at which we can probe new physics
- E.g., if nature set $c_{tZ} = 1$ we would measure $\Lambda \approx 1$ TeV





Summary

EFT in t quark + additional lepton final states

- Run 2 data ($138\ \mathrm{fb}^{-1}$)
- Kinematic distributions – $p_{\mathrm{T}}(lj)_{\mathrm{max}}$ and $p_{\mathrm{T}}(\mathrm{Z})$
- 95% confidence intervals extracted for 26 WCs

Very technical analysis with many moving parts

- Statistical inference computationally intensive

All WCs consistent with SM

Backup

Dim6TopEFT Model

EFT simulations are generated by MadGraph_aMC@NLO using the dim6TopEFT[1] model

- Warsaw basis of dimension six operators
- $\Lambda = 1\ \mathrm{TeV}$
- CKM matrix is assumed to be a unit matrix
- $\mathrm{u}, \mathrm{d}, s, \mathrm{c}, \mathrm{e}, \mu$ masses all set to zero
- The unitary gauge is used and Goldstone bosons are removed
- Baryon and lepton number violating operators are not included
- Only tree-level simulation is possible

[1] https://arxiv.org/abs/1802.07237