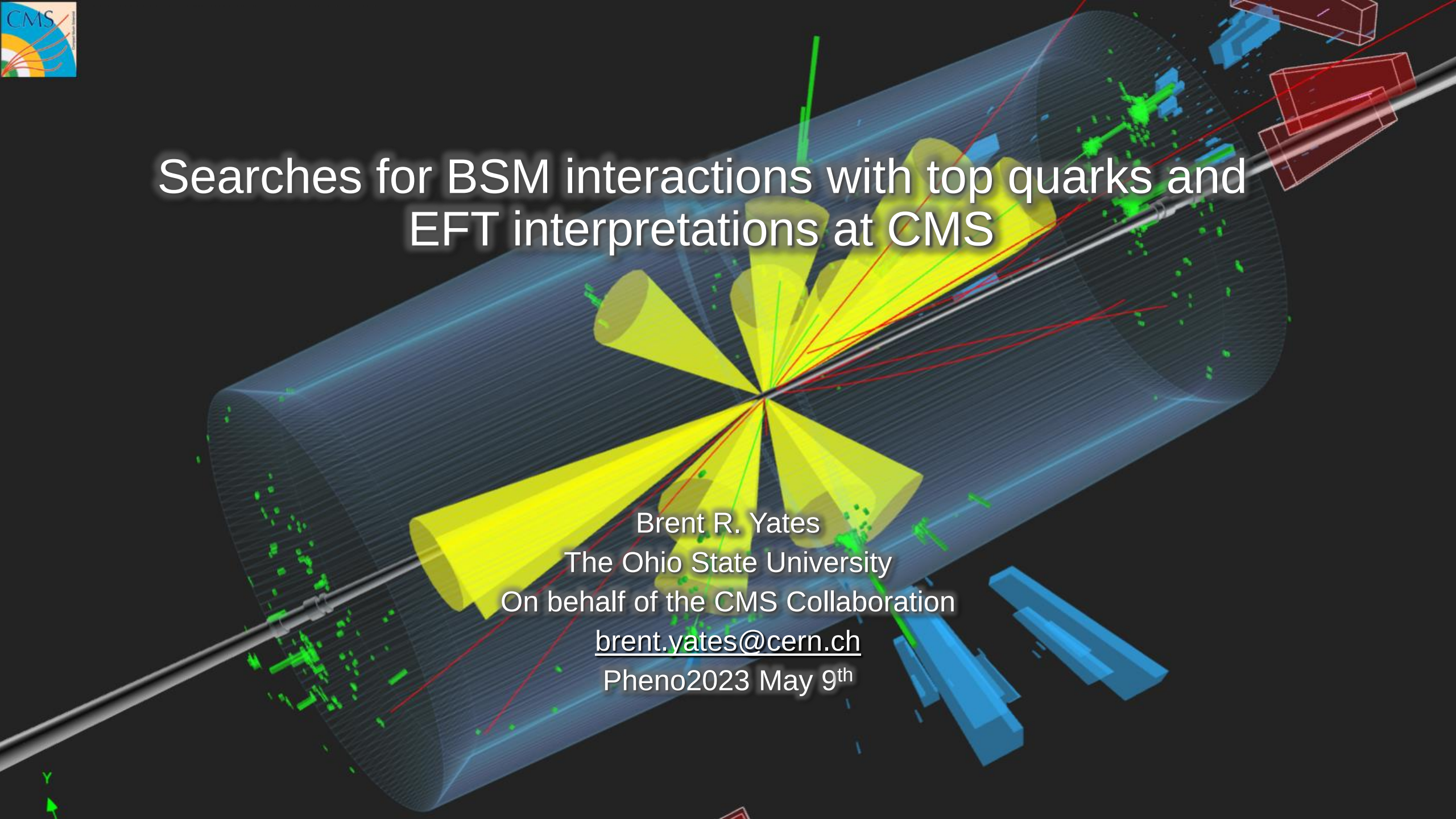

Searches for BSM interactions with top quarks and EFT interpretations at CMS

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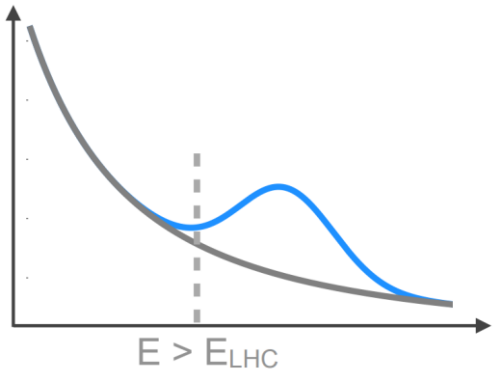
Pheno2023 May 9th

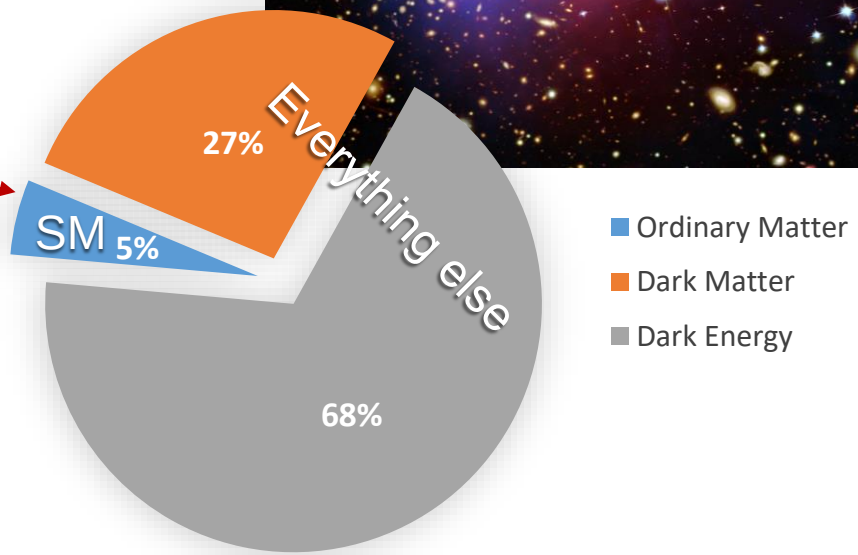
Motivation for new physics

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

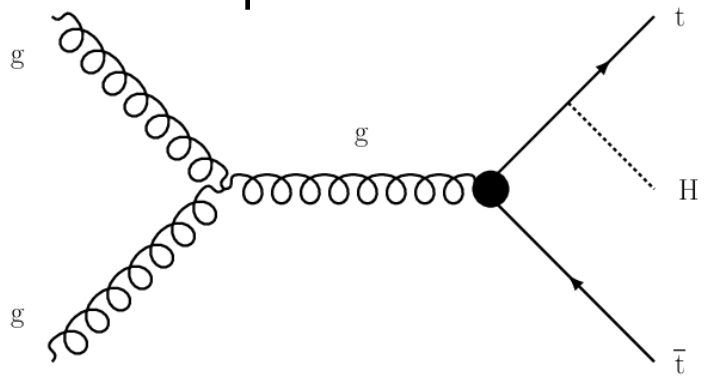
Operators are suppressed by powers of the energy scale Λ, and the strength is controlled by the Wilson coefficients (WCs) c_i

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

Analyses presented

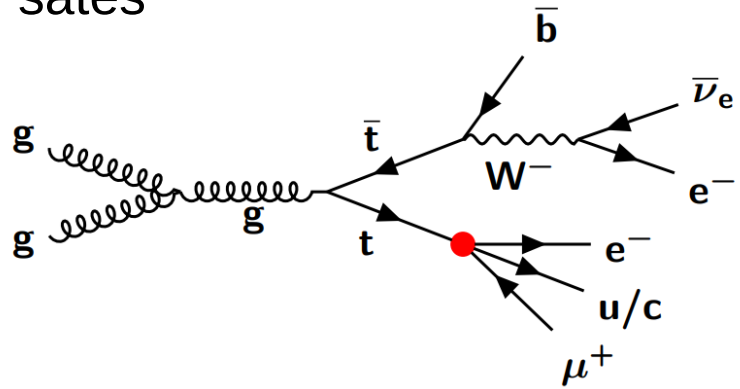
CMS PAS TOP-22-006 (CDS)

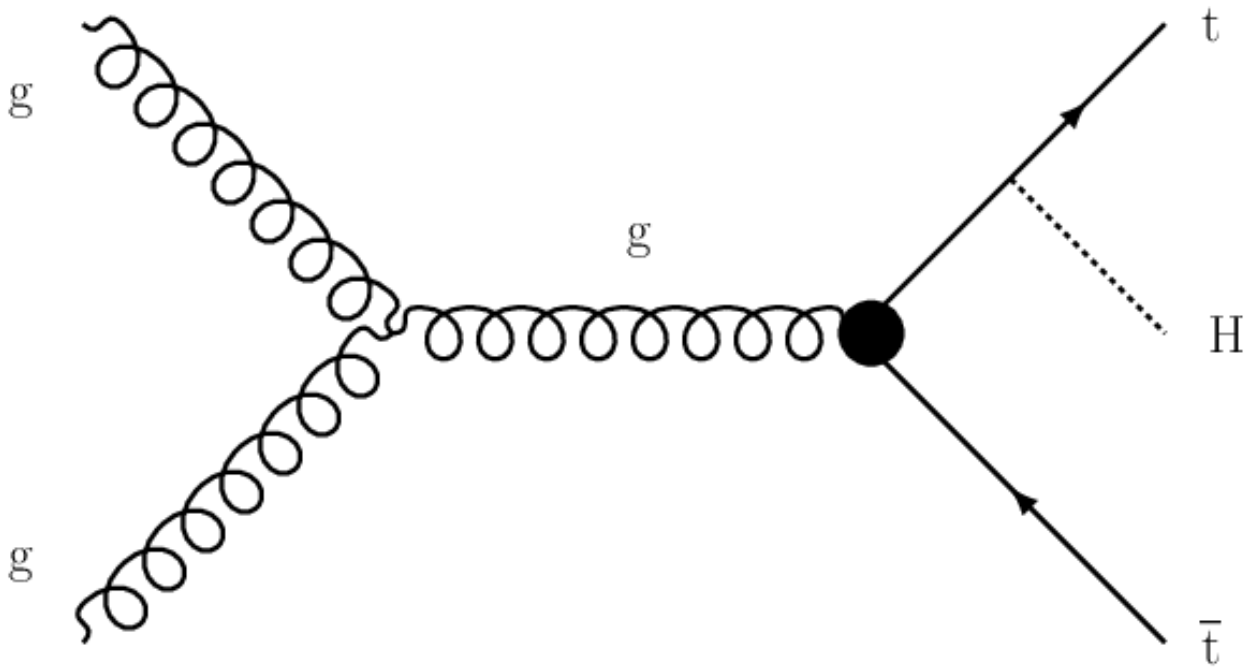
- Probing EFT using top quarks with additional final-state leptons



CMS PAS TOP-22-005 (CDS)

- Search for LFV using top quarks in trilepton final sates





Probing EFT using top quarks with additional final-state leptons

CMS PAS TOP-22-006

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 $(138\ \mathrm{fb}^{-1})$

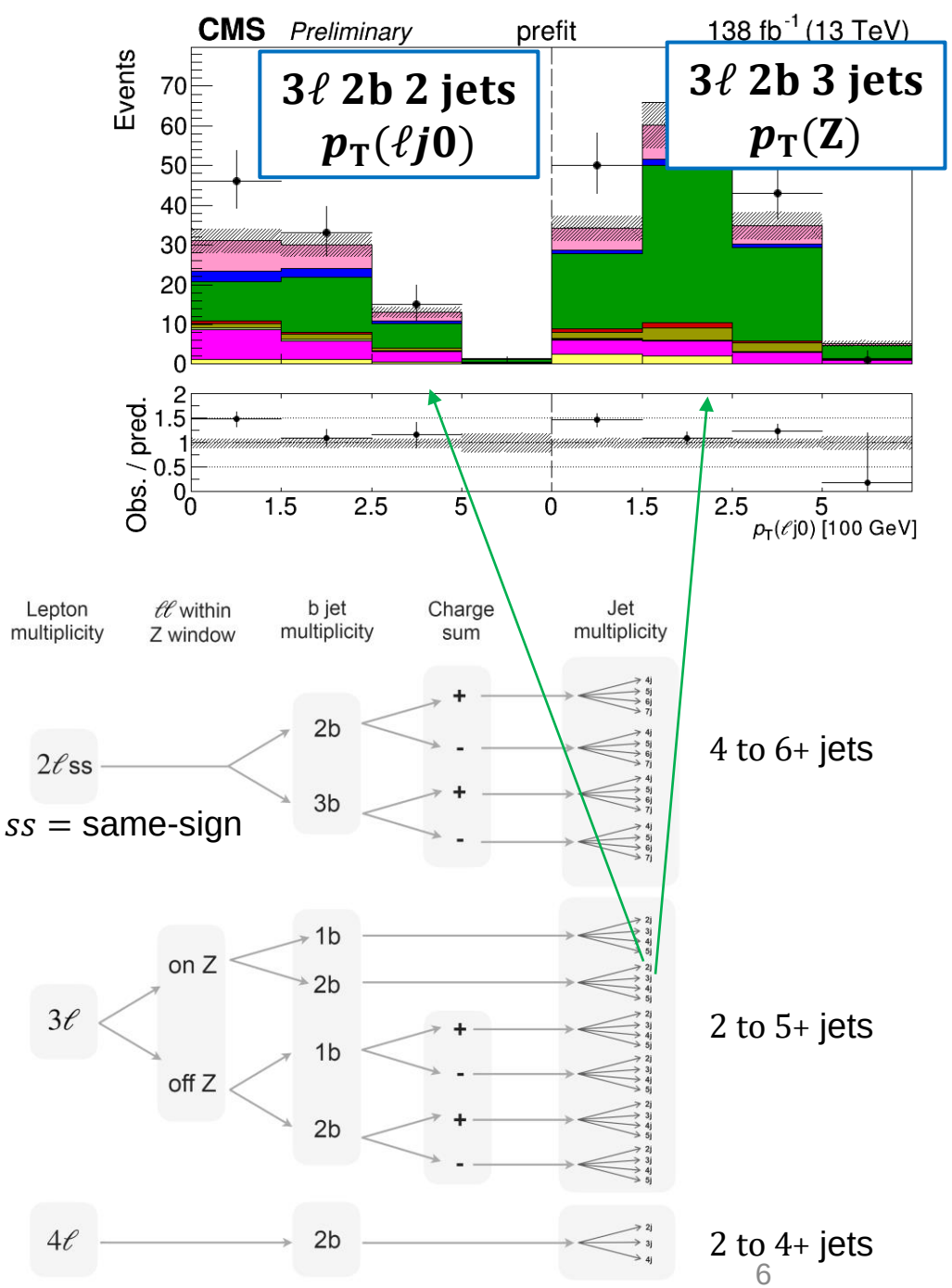
Probe EFT effects in multilepton final states

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 ($p_{\mathrm{T}}(\ell j0)$)

No assumptions made to the underlying correlations

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



EFT parametrization

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	$c^{1}_{QQ}, c^{1}_{Qt}, c^{8}_{Qt}, c^{1}_{tt}$

Matrix element is a function of WCs

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

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

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

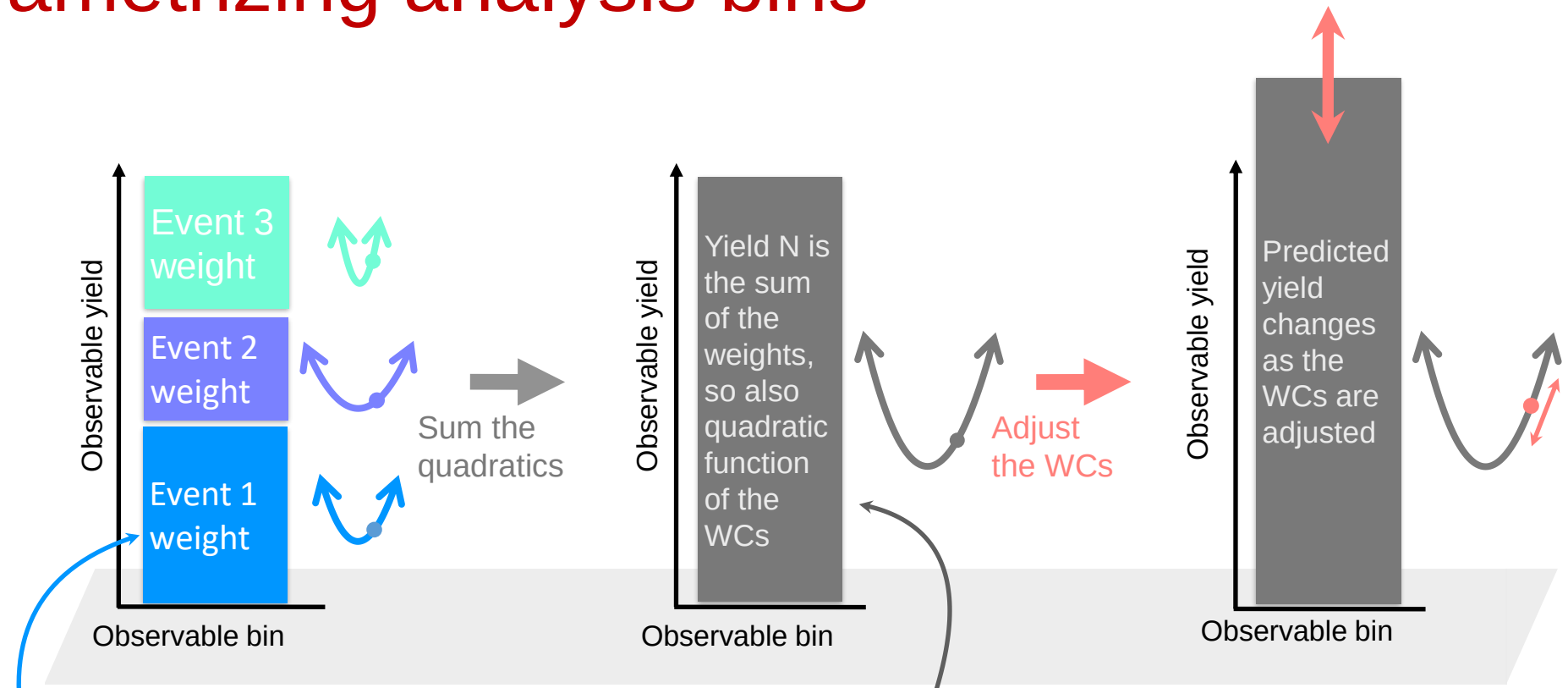
SM term

SM interference term

Pure EFT term

EFT interference term

Parametrizing analysis bins



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

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

Unique challenges overcome

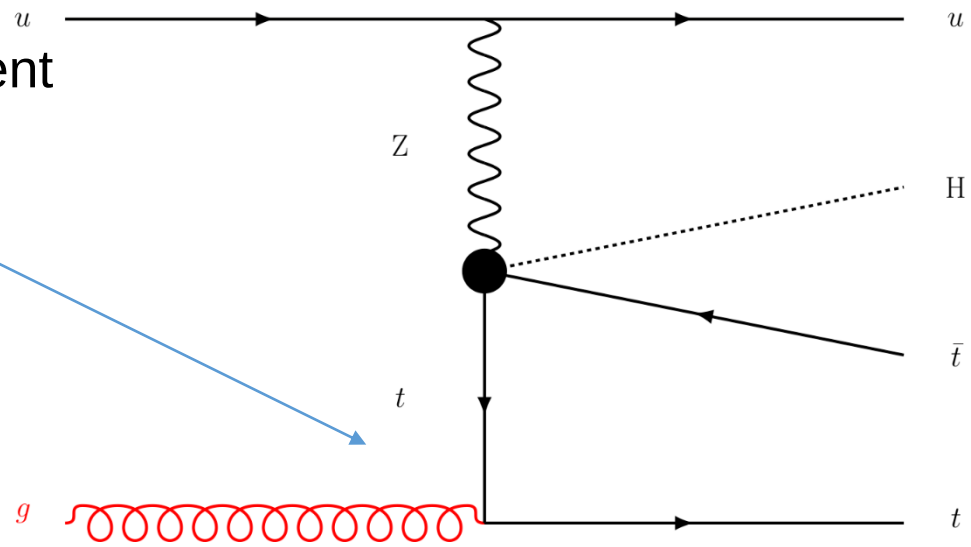
Simulation samples generated at non-SM point to form more complete phase space

- Optimized statistical power $\sigma^2_{\text{stat}} = \sum_j w_j^2(\vec{c})$

Extra partons are added when possible in matrix element

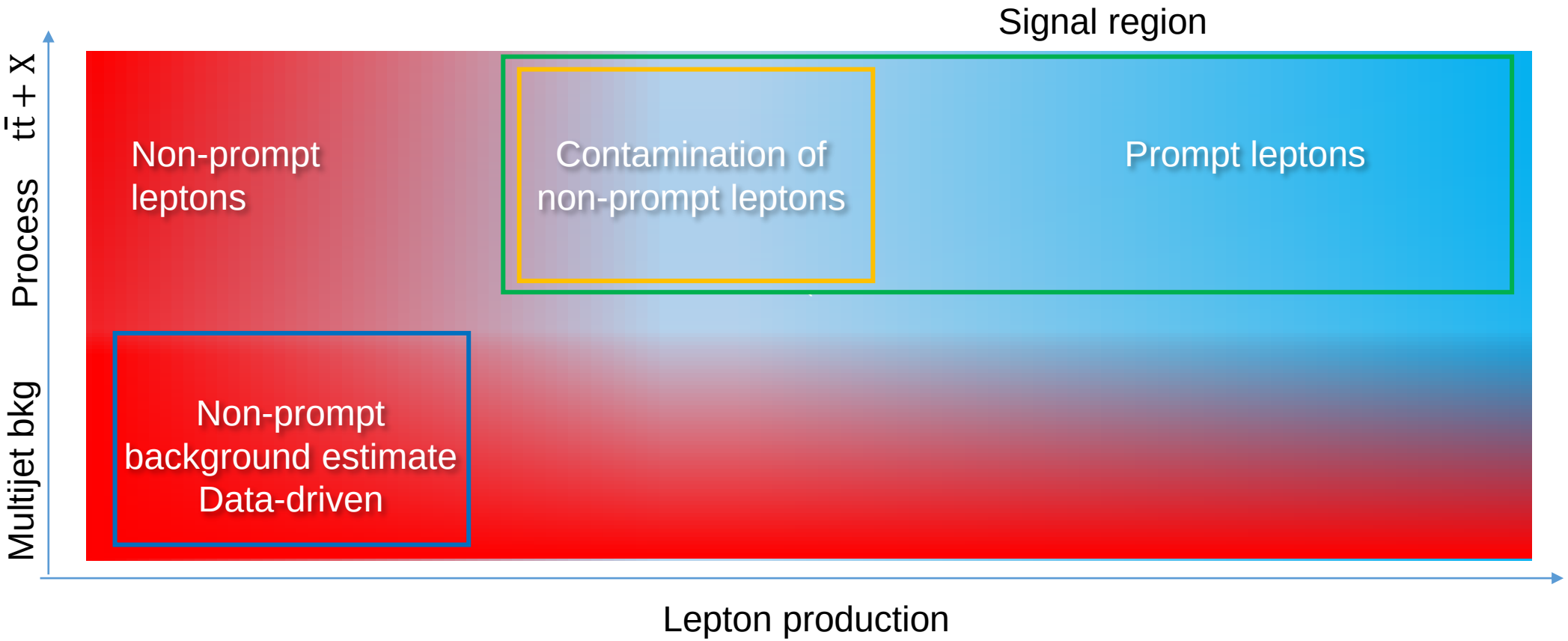
Generated enough simulations to over constrain structure constants in quadratic parameterization

Parameterization used to simultaneously fit all 26 WCs



Largest background (non-prompt lepton) is data driven

Misidentified lepton background



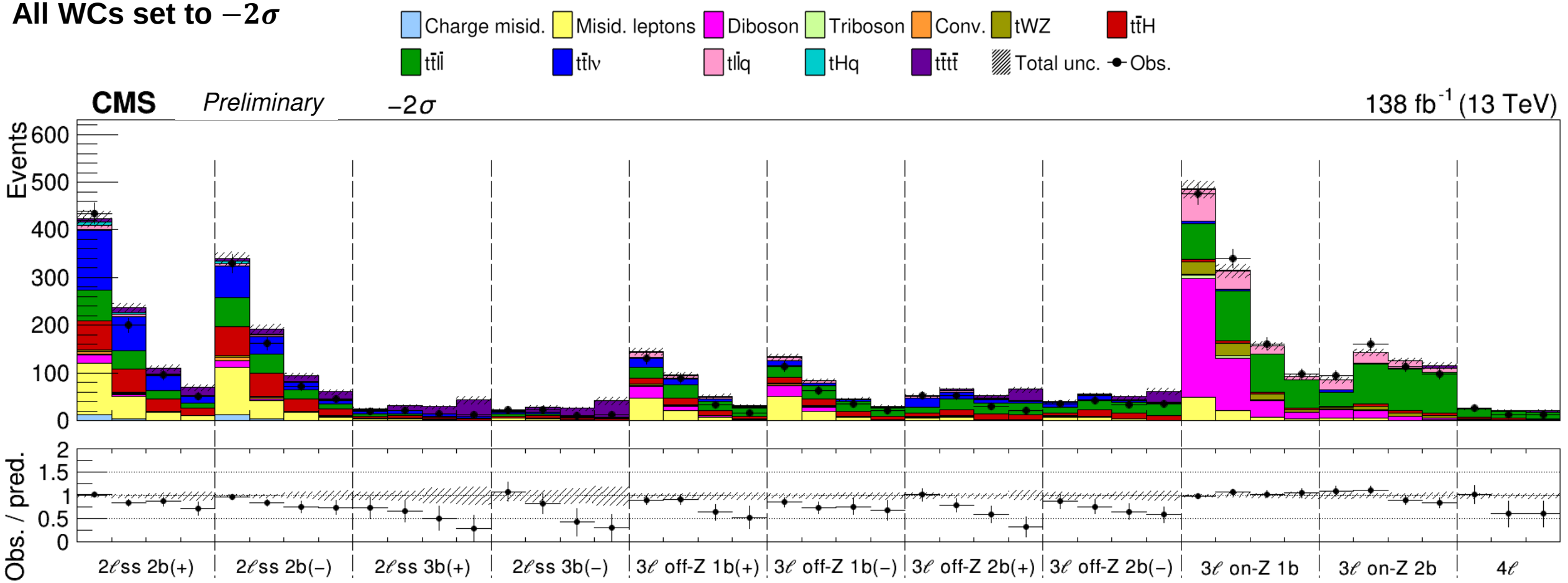
Probability of a non-prompt lepton passing prompt cuts is measured in a multijet enriched region

Data-driven

Visualizing parameterization

Kinematic variables integrated out

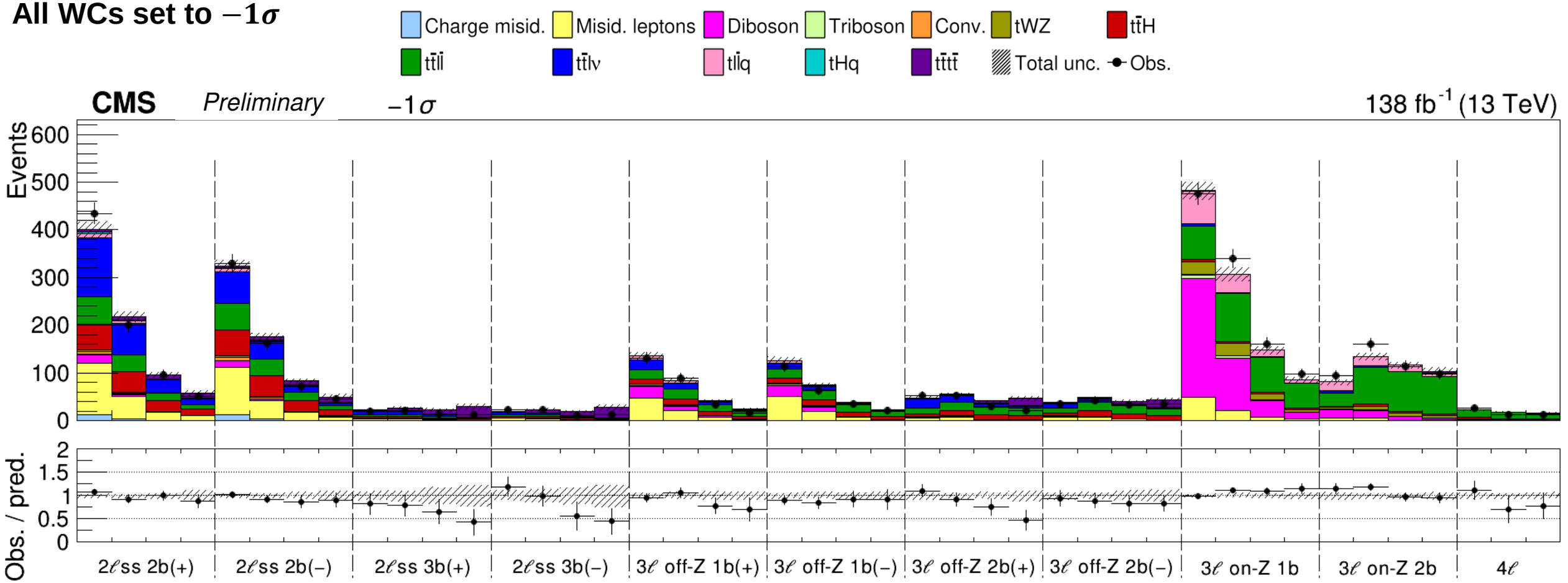
All WCs set to -2σ



Visualizing parameterization

Kinematic variables integrated out

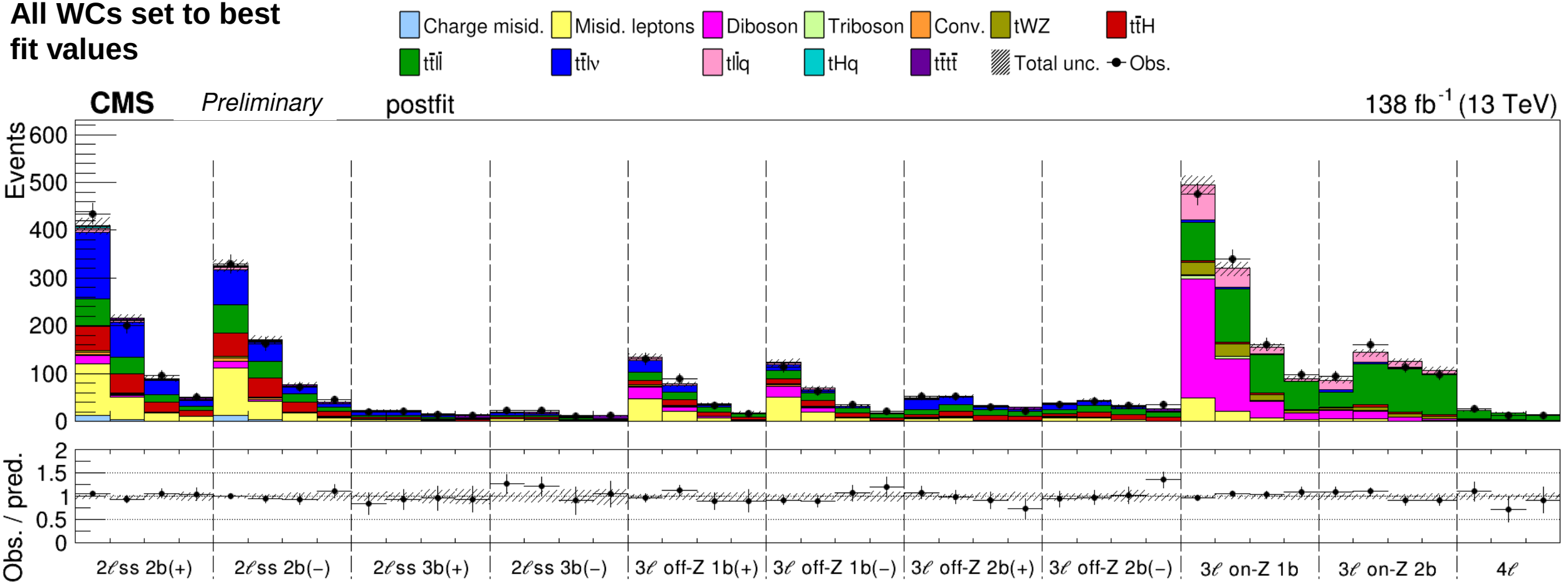
All WCs set to -1σ



Visualizing parameterization

Kinematic variables integrated out

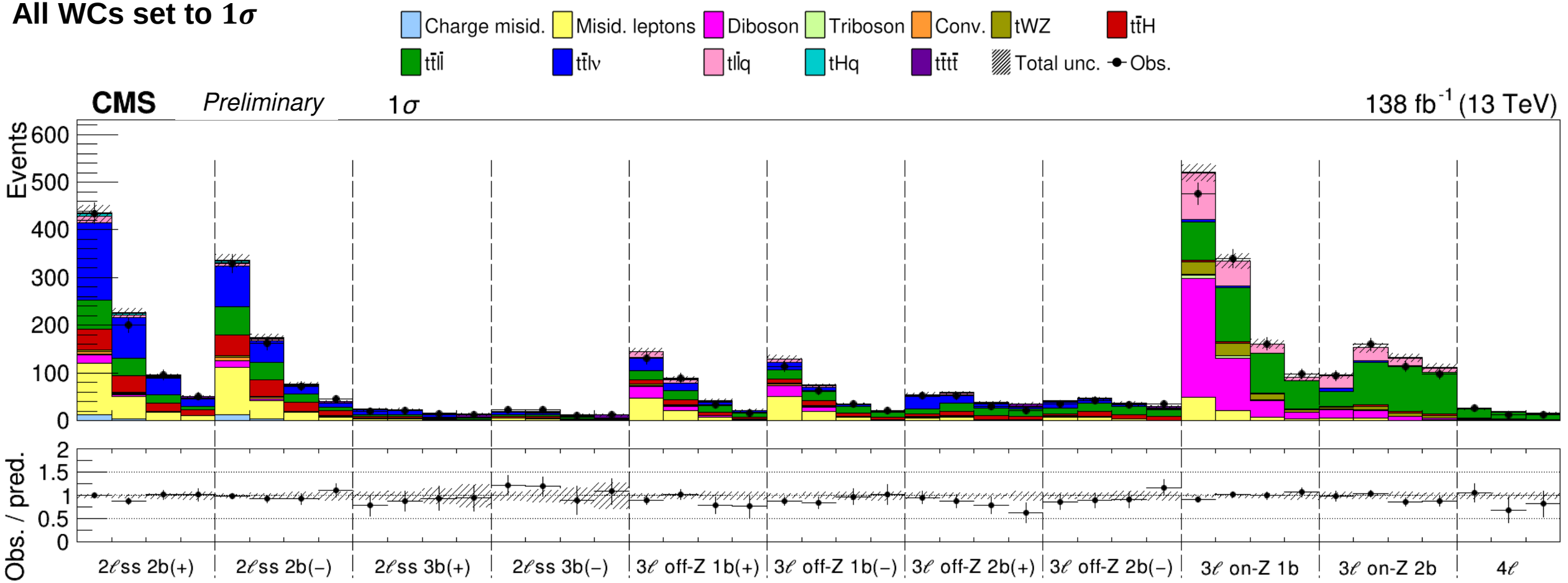
All WCs set to best fit values



Visualizing parameterization

Kinematic variables integrated out

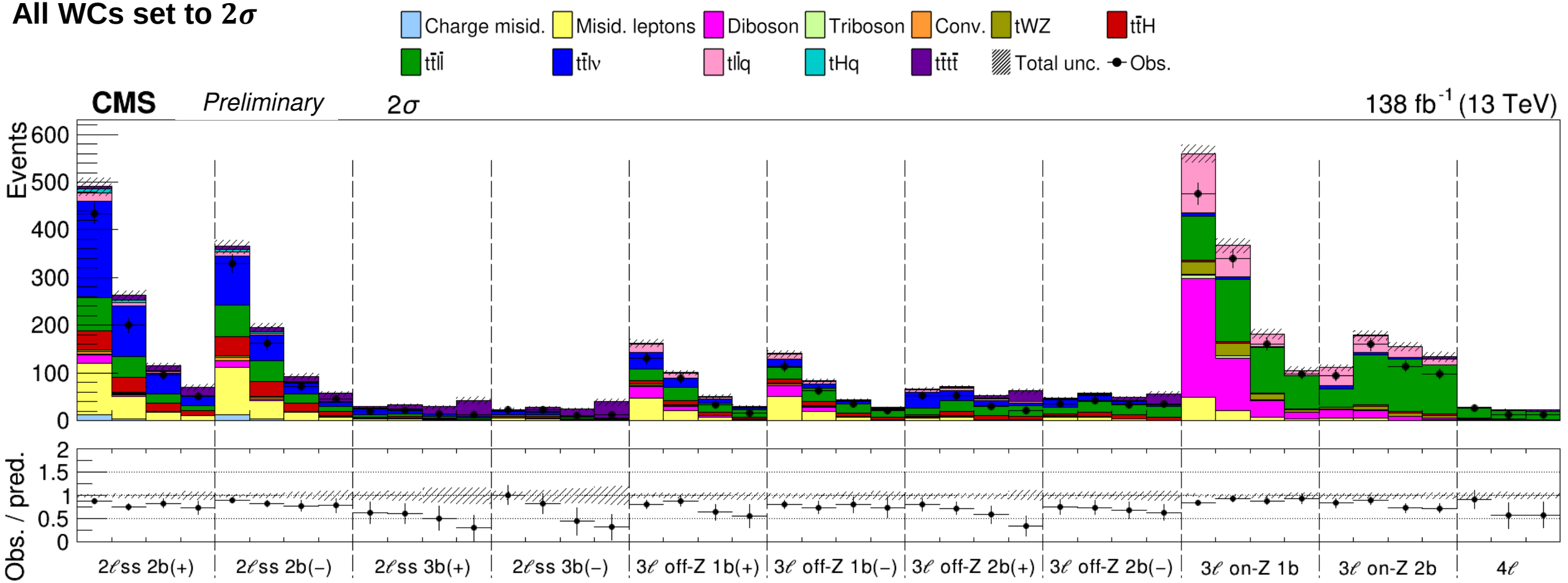
All WCs set to 1σ



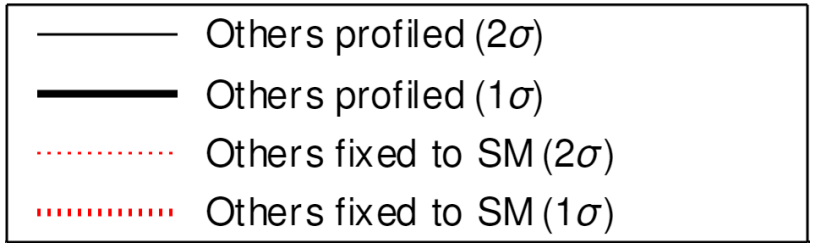
Visualizing parameterization

Kinematic variables integrated out

All WCs set to 2σ



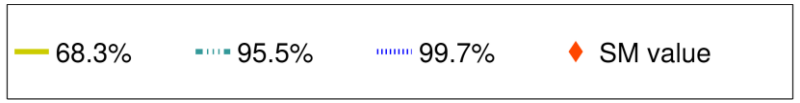
Results

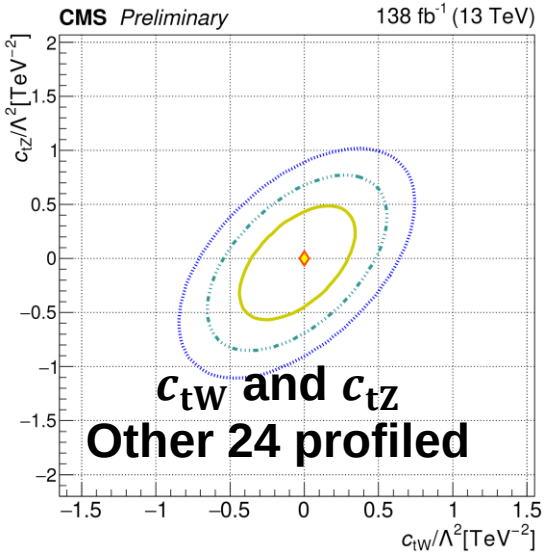


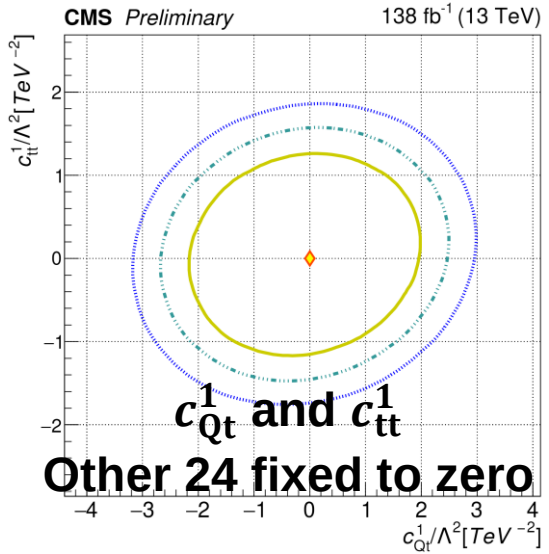
95% CIs for WCs extracted under two scenarios

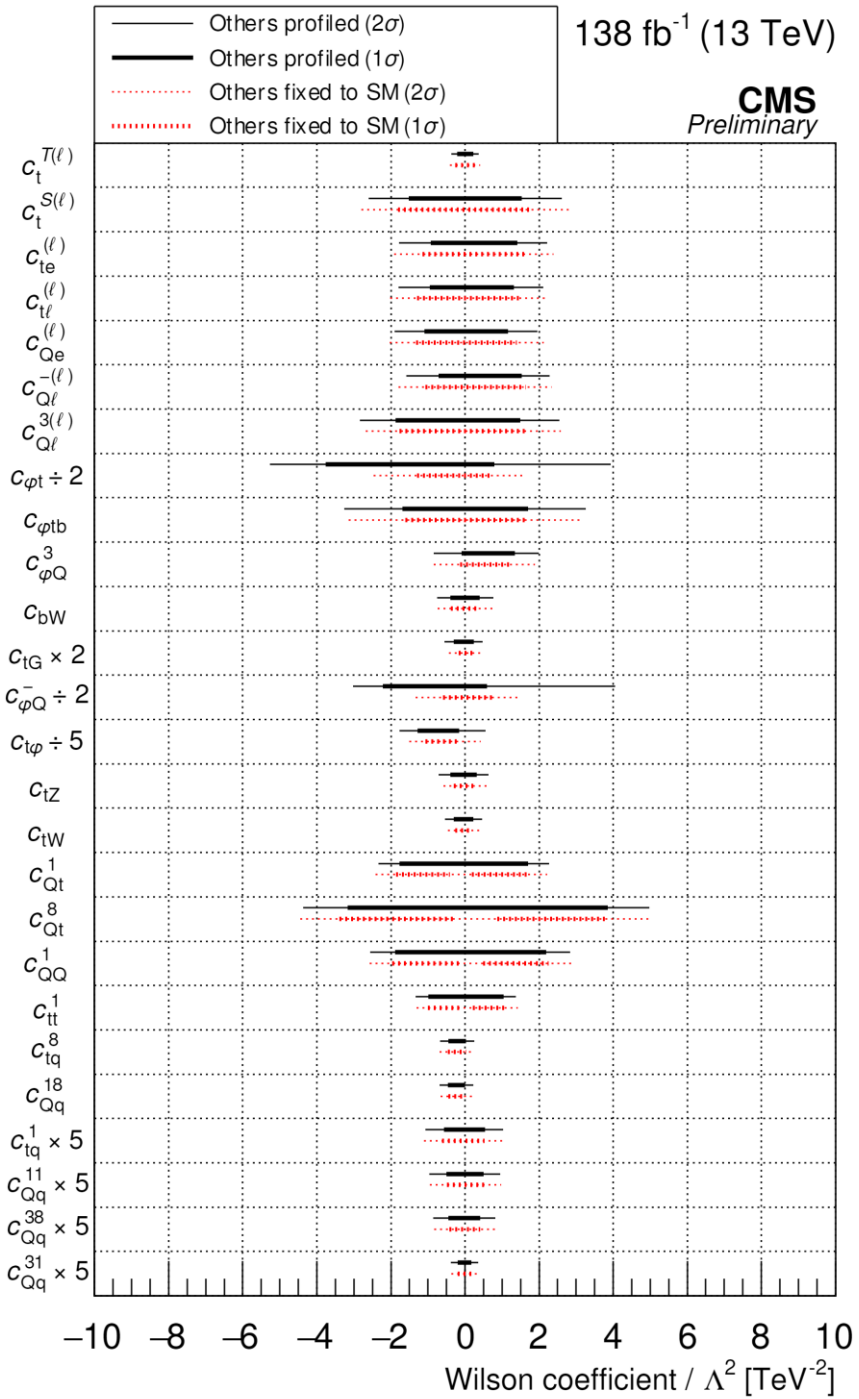
- Scan over 1 while **profiling** the other 25
- Scan over 1 while **fixing** the other 25 to their SM value of zero

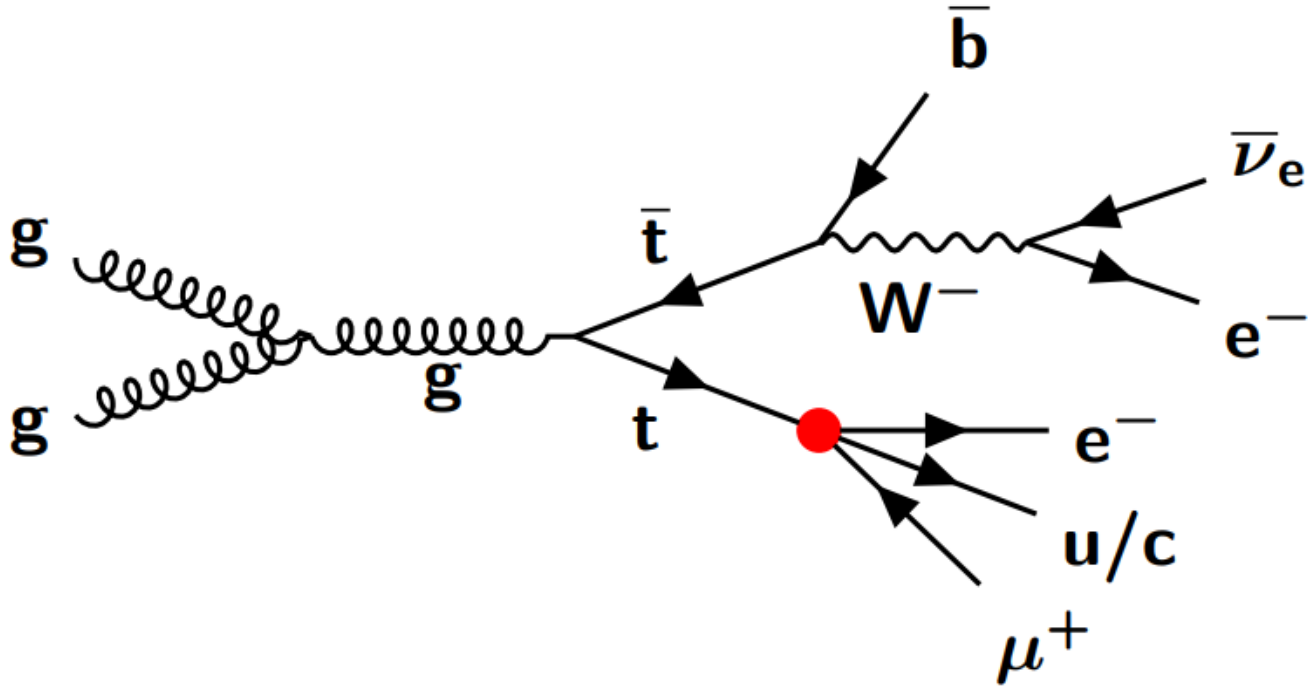
Subset of pairs of WCs are also explored







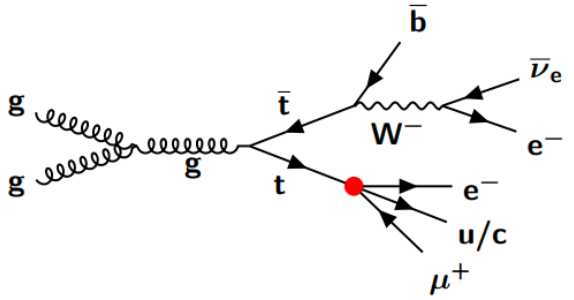




Search for charged lepton flavor violation using top quarks in trilepton final states

CMS PAS TOP-22-005

Analysis overview



Require $e^{\pm}\mu^{\mp}$ + e/μ from t quark leptonic decay ($\tau \to e/\mu$ included)

One or more jets and at most one b-jet

BDT to separate signal and background

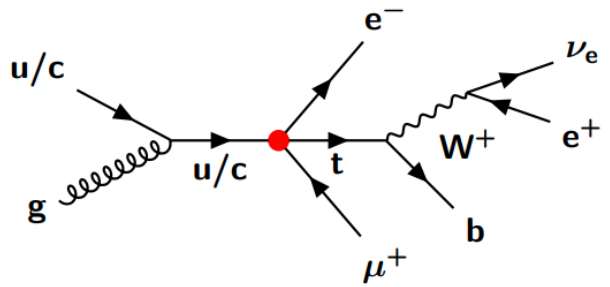
Data-driven non-prompt estimation

Data collected in 2016-2018 (138 fb^{-1})

Assuming LFV includes e/μ, t, and u/c at tree level

Signal-free regions: $eee/\mu\mu\mu$

vector	$O_{lq}^{(1)ijkl}$	$(\bar{l}_i\gamma^\mu l_j)(\bar{q}_k\gamma^\mu q_l)$
	O_{lu}^{ijkl}	$(\bar{l}_i\gamma^\mu l_j)(\bar{u}_k\gamma^\mu u_l)$
	O_{eq}^{ijkl}	$(\bar{e}_i\gamma^\mu e_j)(\bar{q}_k\gamma^\mu q_l)$
	O_{eu}^{ijkl}	$(\bar{e}_i\gamma^\mu e_j)(\bar{u}_k\gamma^\mu u_l)$
scalar	$O_{lequ}^{(1)ijkl}$	$(\bar{l}_i e_j)\ \varepsilon\ (\bar{q}_k u_l)$
tensor	$O_{lequ}^{(3)ijkl}$	$(\bar{l}_i\sigma^{\mu\nu} e_j)\ \varepsilon\ (\bar{q}_k\sigma_{\mu\nu} u_l)$



Event categorization

Signal region (SR)

- $m(e\mu) < 150\text{GeV}$ top decay enriched
- $m(e\mu) > 150\text{GeV}$ top production enriched

Validation region (VR) for checking non-prompt background subtraction

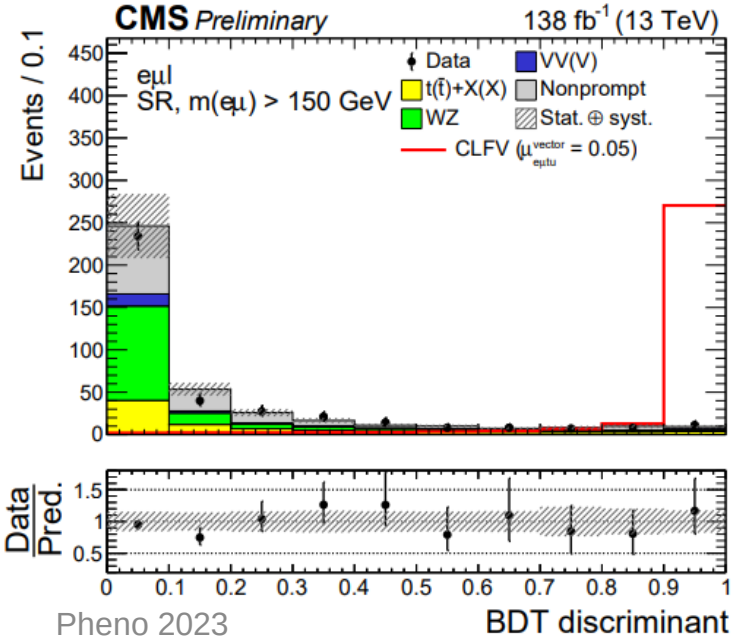
Control region (CR) for on-shell $Z \to ee/\mu\mu$ decays

Diboson CR (N_{jets} inclusive, 1 + b-jets)

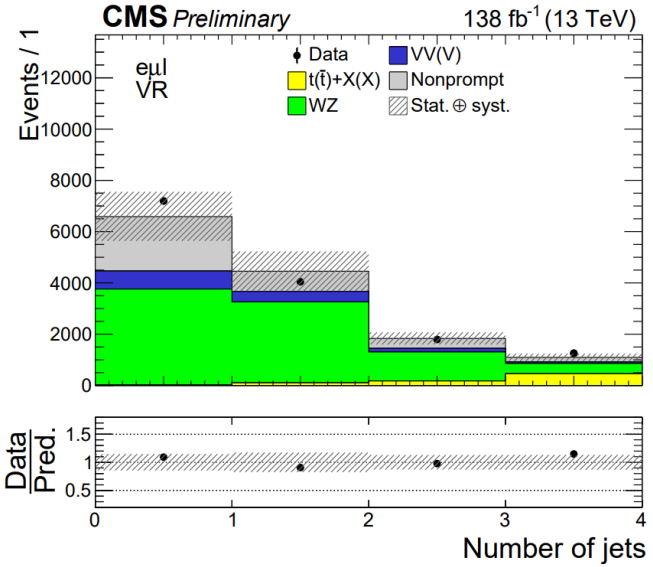
Table 2: Summary of the selection criteria used to define different event regions.

Channel	Region	OnZ	OffZ	$p_{\text{T}}^{\text{miss}} > 20\,\text{GeV}$	# jets ≥ 1	# b jets ≤ 1
$eee/\mu\mu\mu$	VR	-	-	-	-	-
	WZ CR	✓	-	✓	✓	✓
$e\mu l$	SR	-	✓	✓	✓	✓
	VR	✓	-	-	-	-
	WZ CR	✓	-	✓	✓	✓

SR $m(e\mu) > 150$ GeV BDT score



VR $e\mu\ell$ N_{jets}



Results

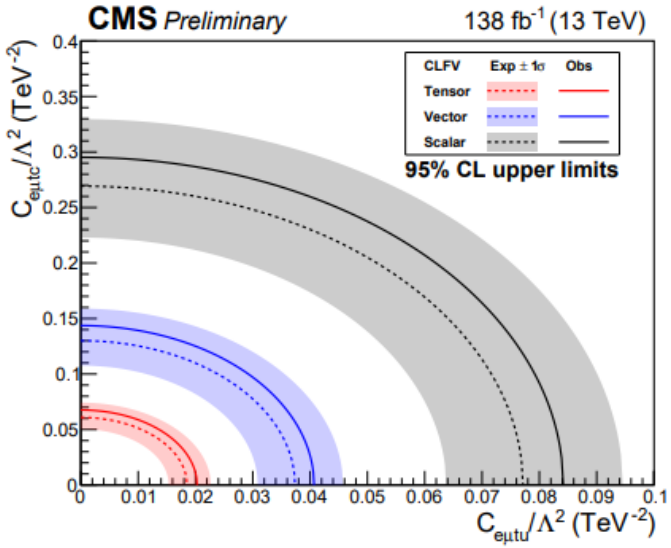
Binned likelihood

CLFV coupling	Lorentz structure	$C_{e\mu tq}/\Lambda^2$ (TeV^{-2}) exp $(-\sigma, +\sigma)$	obs	$\mathcal{B}(t \to e\mu q) \times 10^{-6}$ exp $(-\sigma, +\sigma)$	obs
$e\mu tu$	tensor	0.019 (0.015, 0.023)	**0.020**	0.019 (0.013, 0.029)	**0.023**
	vector	0.037 (0.031, 0.046)	**0.041**	0.013 (0.009, 0.020)	**0.016**
	scalar	0.077 (0.064, 0.095)	**0.084**	0.007 (0.005, 0.011)	**0.009**
$e\mu tc$	tensor	0.061 (0.050, 0.074)	**0.068**	0.209 (0.143, 0.311)	**0.258**
	vector	0.130 (0.108, 0.159)	**0.144**	0.163 (0.111, 0.243)	**0.199**
	scalar	0.269 (0.223, 0.330)	**0.295**	0.087 (0.060, 0.130)	**0.105**

95% upper limit for each WC (setting others to zero)

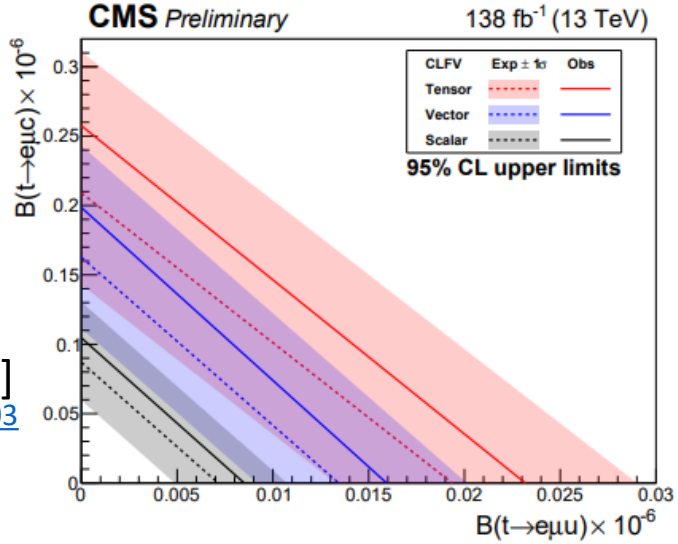
$$\mu(C/\Lambda^2) = \frac{\sigma_{\mathrm{CLFV}}(C/\Lambda^2)}{\sigma_{\mathrm{CLFV}}(1\ \mathrm{TeV}^{-2})} \propto (C/\Lambda^2)^2$$

$$C/\Lambda^2 = \sqrt{\mu_a}$$



$\mathcal{B}$ assuming $m_t = 172.5$ GeV [1]

[1] https://journals.aps.org/prd/abstract/10.1103/PhysRevD.78.094008



Summary

TOP-22-006

EFT in t quark + additional lepton final states

95% confidence intervals extracted for 26 WCs

Consistent with SM

TOP-22-005

LFV in t quark trilepton final states

95% CL upper limits on WCs $\mathcal{O}(0.01 - 0.1)$

95% CL upper limits on $\mathcal{B}(\mathrm{t} \to \mathrm{e}\mu\mathrm{u})$ $\mathcal{O}(10^{-8})$, $\mathcal{B}(\mathrm{t} \to \mathrm{e}\mu c)$ $\mathcal{O}(10^{-7})$

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
- $\mathrm{u}, \mathrm{d}, \mathrm{s}, \mathrm{c}, \mathrm{e}, \mu$ 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