EFT Interpretations in Top Analyses

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On behalf of the CMS collaboration

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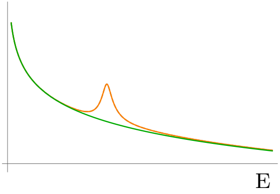
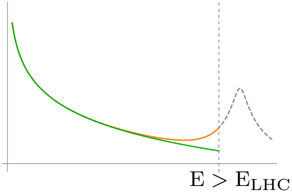
Searches for New Physics

- Searches for new physics typically fall into two categories: Bump and tail searches
- Bump searches look for sharp resonance peaks over some well understood background
- Tail searches look for indirect effects from particle states that may exist just beyond the energy reach of the LHC





EFT Approach

- Framework:
    - Extend SM lagrangian with new interactions preserving the SM gauge symmetries
    - Assume the new interactions decouple from SM below the mass scale of the new particles
    - New interaction terms are built from higher-dimensional operators of only SM fields
    - SM is recovered in a well defined way: $\Lambda \to \infty$

$$\mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}^D}{\Lambda^{D-4}}$$

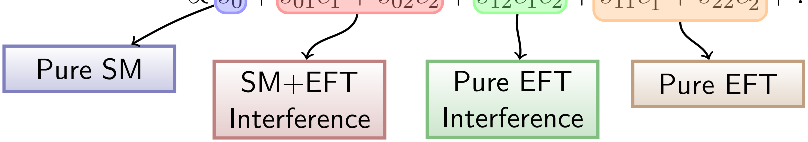
- Only one dimension five operator is possible and produces lepton number violation, so is excluded from most analyses
- Dimension six operators are therefore least suppressed terms

EFT Parameterizations

- Strength of NP contributions parameterized by dimensionless Wilson coefficient (WC) for each operator
- NP suppressed by powers of relevant energy scale Λ
- Matrix element is sum of SM+NP terms: $\mathcal{M} = \mathcal{M}_{\text{SM}} + \sum_i c_i \mathcal{M}_i$
- Cross section (proportional to ME squared) can be parameterized quadratically as a function of WCs

$$\sigma(c_1, c_2, \ldots) \propto |\mathcal{M}|^2$$

$$\propto s_0 + s_{01}c_1 + s_{02}c_2 + s_{12}c_1c_2 + s_{11}c_1^2 + s_{22}c_2^2 + \ldots$$



EFT in Top Physics

- The top quark is currently the most massive particle and 40 times more massive then the next heaviest quark
  - Large mass makes it difficult to produce in association with other massive particles
  - Decays before hadronization $\rightarrow$ avoids complications of non-perturbative effects
  - Able to directly study ‘bare’ quark couplings
- Large number of different EFT operators are able to modify top production
- Different production modes are affected differently $\rightarrow$ gives an avenue for disentangling contributions from multiple operators

Top Quark EFT Searches in CMS

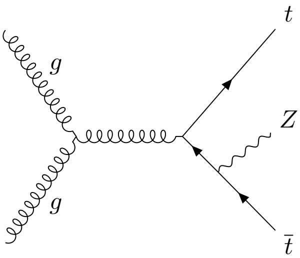
- A lot of activity in top analyses incorporating EFT interpretations
- Will focus here on the TOP-18-009 analysis

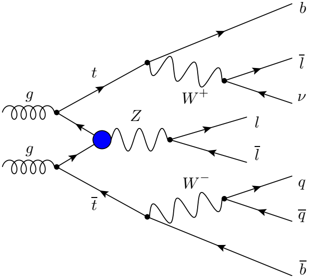
Analysis	Processes	Operators
TOP-17-005*	$t\bar{t}W, t\bar{t}Z$	$\bar{c}_{uW}$, $\bar{c}_{u}$, $\bar{c}_{uB}$, $\bar{c}_{Hu}$
TOP-17-014	$t\bar{t}$	c_{tG}
TOP-17-019	$t\bar{t}t\bar{t}$	c^{1}_{QQ}, c^{8}_{QQ}, c^{1}_{Qt}, c^{8}_{Qt}, c^{1}_{tt}
TOP-17-020	$t\bar{t}, tW$	c_{G}, $c^{3}_{\phi q}$, c_{tW}, c_{tG}, c_{uG}, c_{cG}
TOP-18-006	$t\bar{t}$	c_{tG}
TOP-18-009	$t\bar{t}Z$	c_{tZ}, $c^{[I]}_{tZ}$, $c^{-}_{\phi Q}$, $c_{\phi t}$

*Uses different basis for the EFT operators

TOP-18-009 Analysis

- Inclusive $t\bar{t}Z$cross section measurement
- Differential cross section measurement at parton-level
- BSM/EFT reinterpretation placing limits on anomalous couplings and dim6 EFT operators that affect $t\bar{t}Z$ vertex
- Measured final states:
  - $3l$: $t\bar{t}Z \rightarrow (\mathrm{b}l\nu)(\mathrm{b}jj)(ll)$
  - $4l$: $t\bar{t}Z \rightarrow (\mathrm{b}l\nu)(\mathrm{b}l\nu)(ll)$





TOP-18-009: Event Selection

3-lepton final state

- exactly 3 leptons with $p_T > 10, 20, 40$ GeV
- one OSSF lepton pair with $|M_{ll} - M_Z| < 10$ GeV

4-lepton final state

- exactly 4 leptons with $p_T > 10, 10, 10, 40$ GeV
- exactly one OSSF lepton pair with $|M_{ll} - M_Z| < 20$ GeV

Categories in number of jets and b-jets

- BSM/EFT interpretation: Form regions in bins of Z boson observables

N_l	N_j	N_b	N_Z	$p_T(Z)$ (GeV)	$-1 \leq \cos\theta^* < -0.6$	$-0.6 \leq \cos\theta^* < 0.6$	$0.6 \leq \cos\theta^*$
3	≥ 3	≥ 1	1	0–100	SR1	SR2	SR3
				100–200	SR4	SR5	SR6
				200–400	SR7	SR8	SR9
				≥ 400	SR10	SR11	SR12
4	≥ 1	≥ 1	1	0–100		SR13	
				100–200		SR14	
				≥ 200		SR15	

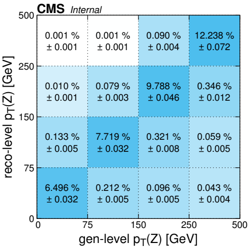
TOP-18-009: Observables

Observables

- $p_{\mathrm{T}}(Z)$: Transverse momentum of the Z boson/dilepton system
- $\cos\theta^{*}$: Cosine of angle of leptons in rest frame of the Z boson/dilepton system
- Sensitive to modified Lorentz structure of top quark-Z boson coupling
- Purely leptonic observables
  - Very good detector resolution
  - Diagonal detector response in the unfolding procedure

Unfolding

- Parton-level definition: $\sigma(pp \rightarrow t\bar{t}Z) \times \mathrm{BR}(Z \rightarrow l^{+}l^{-})$
- Reconstruction-level definition: $3l$ selection with $N_j \geq 3, N_b \geq 1$
- response matrix built from signal MC
- unregularized unfolding implemented with TUnfold



TOP-18-009: BSM/Anomalous Approach

- SM $t\bar{t}Z$ lagrangian with vector, axial-vector couplings and weak magnetic and electric dipole moments

$$\mathcal{L}_{t\bar{t}Z} = e\bar{u}(p_t)\left[\gamma^{\mu}(C_{1,V} + \gamma_5 C_{1,A}) + \frac{i\sigma^{\mu\nu}q_{\nu}}{M_Z}(C_{2,V} + C_{2,A})\right]v(p_{\bar{t}})Z_{\mu}$$

arXiv:1501.05939

- Z current couplings are predicted exactly by SM EWSB
- Dipole moments are generated only radiatively in the SM for Z

$$C_{1,V}^{SM} = \frac{T_t^3 - 2Q_t \sin^2\theta_W}{2\sin\theta_W\cos\theta_W} \approx 0.24 \qquad C_{1,A}^{SM} = \frac{-T_t^3}{2\sin\theta_W\cos\theta_W} \approx -0.60$$

- Model independent search for modified coupling coefficients ($C_{1/2,A/V}$) that can be mapped to dim6 EFT operators

TOP-18-009: Connection to EFT

- Deviations from SM vector and axial-vector couplings can be related to EFT operators as:

$$\Delta C_{1,V} = \frac{-1}{\cos\theta_W \sin\theta_W} \left(\frac{\nu}{2\Lambda}\right)^2 (c^{-}_{\phi Q} + c_{\phi t})$$
$$\Delta C_{1,A} = \frac{1}{\cos\theta_W \sin\theta_W} \left(\frac{\nu}{2\Lambda}\right)^2 (c^{-}_{\phi Q} - c_{\phi t})$$

- The weak magnetic and electric dipole moment couplings can be related simply as:

$$C_{2,V} = \frac{\sqrt{2}\nu M_Z}{e\Lambda^2} c_{tZ} \qquad C_{2,A} = \frac{\sqrt{2}\nu M_Z}{e\Lambda^2} c^{[I]}_{tZ}$$

TOP-18-009: BSM reweighting

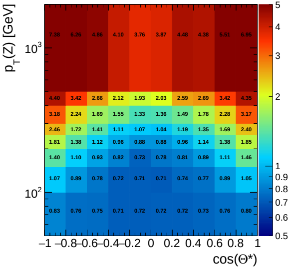
- Running the full MC production chain with multidimensional scans of coupling values is very CPU intensive
- Instead produce gridpacks for each BSM configuration and only perform the GEN step
  - Cuts short detector sim, digi, reco, and processing steps
  - Drastically reduces CPU hours

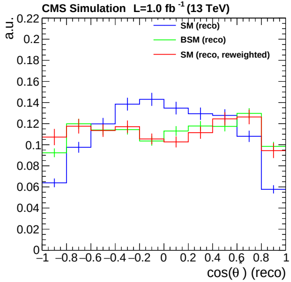
TOP-18-009: BSM reweighting

- Use generator truth information to calculate weights and use reweighted SM sample
- Calculate weights in bins of $p_{\mathrm{T}}(Z)$ and $\cos\theta^*$

$$w_i = \frac{w(\mathrm{BSM})_i}{w(\mathrm{SM})_i}$$

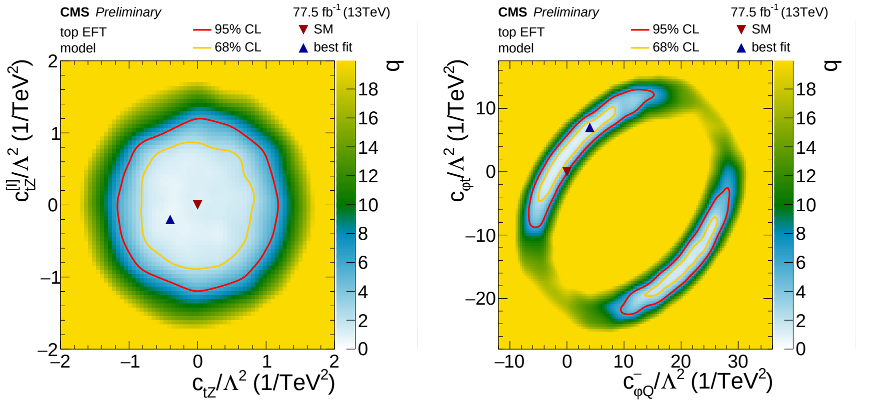
where $w(\mathrm{BSM})_i$ and $w(\mathrm{SM})_i$ correspond to the normalized event count in the i-th $p_{\mathrm{T}}(Z)$ and $\cos\theta^*$ bin





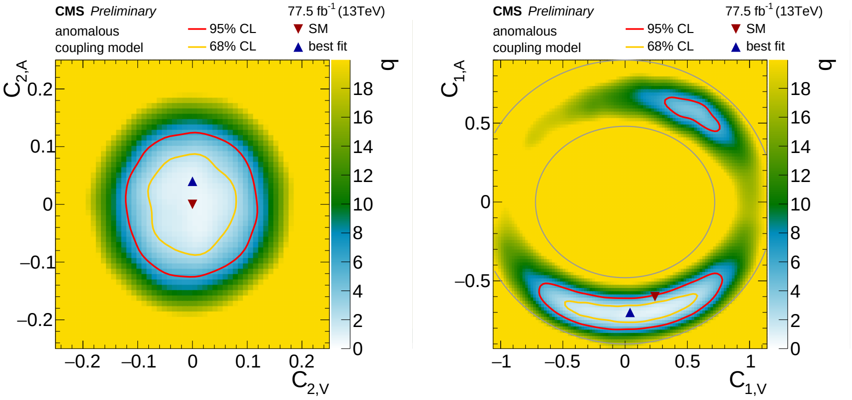
TOP-18-009: EFT Operators

- Scans in 2D planes of the EFT operators
- Disjointed 68/95% CL in $c^{-}_{\phi Q}/c_{\phi t}$plot is due to interference effects between SM and EFT diagrams



TOP-18-009: Anomalous Couplings

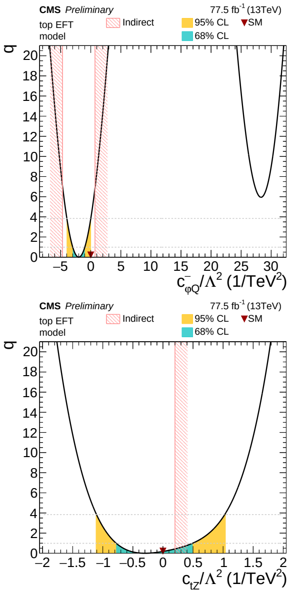
- Scans of EW dipole moment plane and axial-vector and vector plane

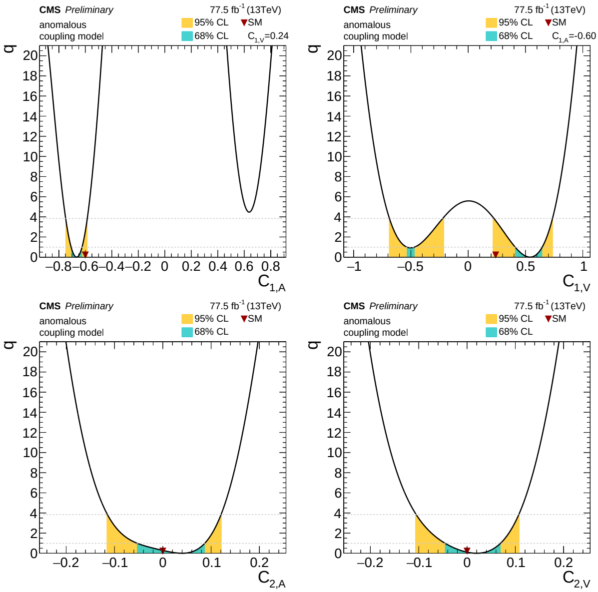


Summary

- EFT provides a flexible framework for probing and placing constraints on BSM physics
- EFT operators can be related to anomalous couplings when comparing results from different analyses
- Many top analyses are incorporating EFT interpretations of their results
  - Top quark provides access to a wide range of interactions that can be modified by dim6 EFT operators
  - Contributions from different EFT operators can be disentangled by considering the effects on multiple production modes, as well as using differential distributions in order to place stronger limits on potential areas of NP
- Still a lot of room for improvement and new measurements
- On track towards a global experimental analysis of dim6 EFT operators
- **stay tuned...**

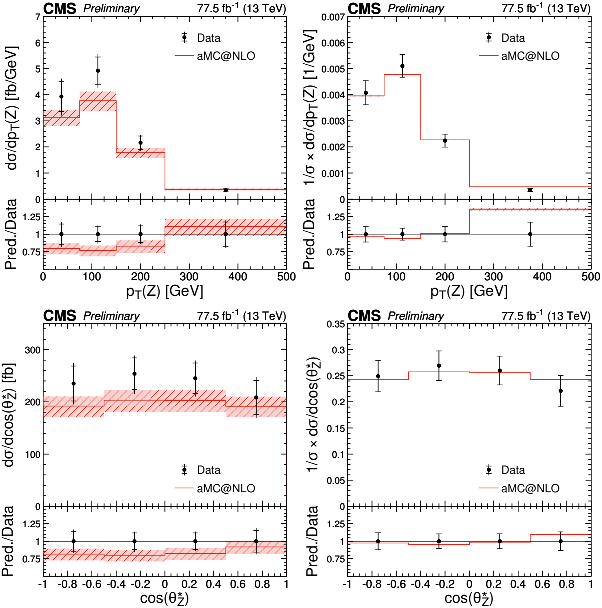
Backup

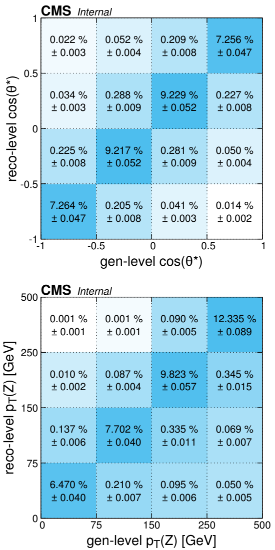

CMS Preliminary
77.5 fb-1 (13TeV)
top EFT model
Indirect
Prev. CMS
95% CL
68% CL
SM
q
c_φQ^-/Λ^2 (1/TeV^2)
c_φt/Λ^2 (1/TeV^2)
c_tZ/Λ^2 (1/TeV^2)
c_tZ^[I]/Λ^2 (1/TeV^2)


CMS Preliminary
77.5 fb^-1 (13TeV)
anomalous coupling model
95% CL
68% CL
SM
C_1,V=0.24
C_1,A=-0.60
q
C_1,A
C_1,V
C_2,A
C_2,V

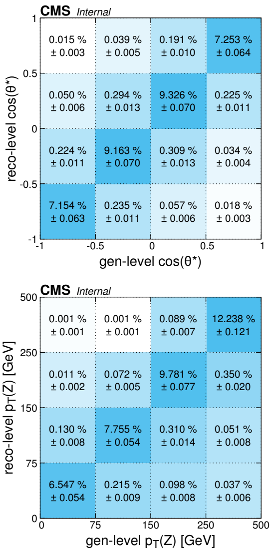
TOP-18-009: CL Intervals

Coefficient	Expected		Observed		Previous CMS constraints		Indirect constraints
	68% CL	95% CL	68% CL	95% CL	Exp, 95% CL	Obs, 95% CL	68% CL
c_{tZ}/Λ^2	$[-0.7, 0.7]$	$[-1.1, 1.1]$	$[-0.8, 0.5]$	$[-1.1, 1.1]$	$[-2.0, 2.0]$	$[-2.6, 2.6]$	$[-4.7, 0.2]$
$c_{tZ}^{[I]}/\Lambda^2$	$[-0.7, 0.7]$	$[-1.1, 1.1]$	$[-0.8, 1.0]$	$[-1.2, 1.2]$	–	–	–
$c_{\phi t}/\Lambda^2$	$[-1.6, 1.4]$	$[-3.4, 2.8]$	$[2.2, 4.7]$	$[0.7, 5.9]$	$[-20.2, 4.0]$	$[-22.2, -13.0]$ $[-3.2, 6.0]$	$[-0.1, 3.7]$
$c_{\phi Q}^{-}/\Lambda^2$	$[-1.1, 1.1]$	$[-2.1, 2.2]$	$[-3.0, -1.0]$	$[-4.0, 0.0]$	–	–	$[-4.7, 0.7]$

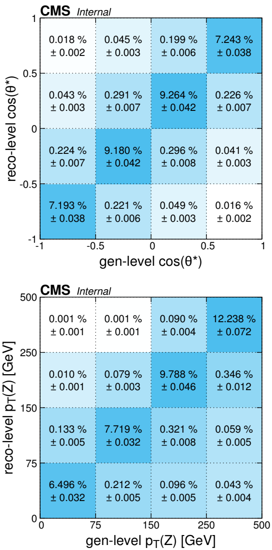

CMS Preliminary 77.5 fb-1 (13 TeV)
Data
aMC@NLO
dσ/dpT(Z) [fb/GeV]
Pred./Data
pT(Z) [GeV]
1/σ × dσ/dpT(Z) [1/GeV]
dσ/dcos(θ*Z) [fb]
1/σ × dσ/dcos(θ*Z)
cos(θ*Z)



2016 Data



2017 Data



Combined