Search for new physics in top quark production with additional leptons using effective field theory

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On behalf of the CMS collaboration

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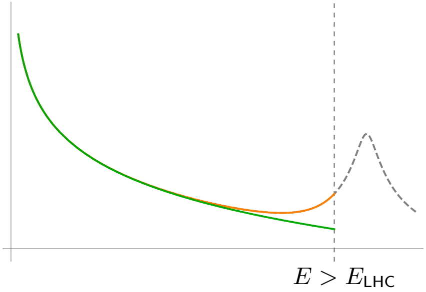
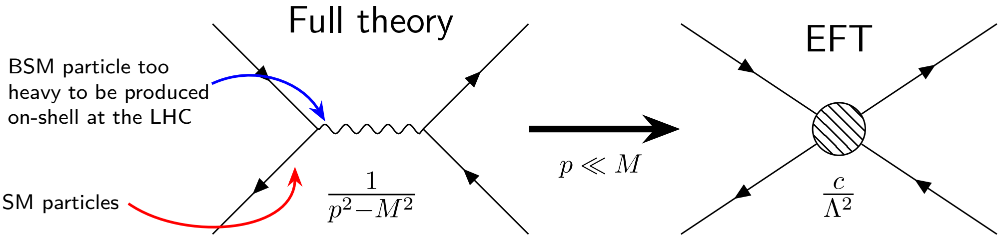
Motivation

- Search for 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 on-shell at the LHC
- Indirect searches are needed if we want to probe these regimes (or wait until someone builds a larger collider)
- Effective field theory provides a framework for probing these higher energy scales



Introduction to Effective Field Theory



Since we can't produce heavy particle on-shell at the LHC, it would be hard to find it via a direct search, but EFT can provide discovery potential

The interaction can be described by an EFT operator, with the strength of the interaction determined by a WC c

Important notes:

- EFT validity is only good for energy scales below the cutoff scale Λ
- Underlying low energy theory needs to be complete
- Provides systematic and mostly model independent search for BSM effects

Introduction to Effective Field Theory

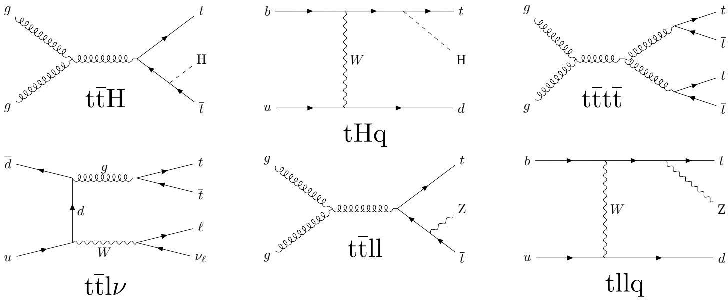
- SM is treated as the lowest order term in an expansion of higher dimensional ($d > 4$) operators, that describe physics above some cutoff scale Λ

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

- The strength of the interactions introduced by the EFT operators is controlled by a dimensionless parameter called a Wilson coefficient (WC)
- If all WCs are 0, the EFT Lagrangian reduces naturally to the SM
- Only one dimension 5 operator $\rightarrow$ Violates lepton number and is excluded
- Focus only on dimension 6 operators as the lowest order contributions

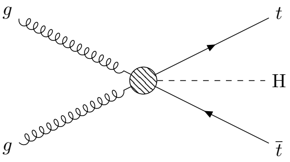
Analysis Overview

- Aim is to probe the effects of as many EFT operators across all relevant processes simultaneously
- Analysis focuses on operators that couple the top quark to leptons, bosons, and other heavy quarks
- Focus on associated top processes and model how EFT operators affect expected yields
  - Signal processes: $\mathrm{t\bar{t}H}$, tHq, $\mathrm{t\bar{t}t\bar{t}}$, $\mathrm{t\bar{t}l\nu}$, $\mathrm{t\bar{t}ll}$, tllq
  - Processes are relatively rare and provide for a clean well isolated signal region

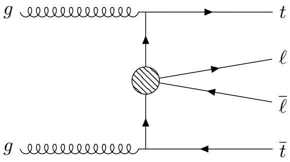


Analysis Overview

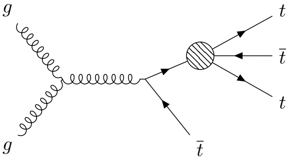
- Focus on 26 operators, which can be grouped together into 4 different categories



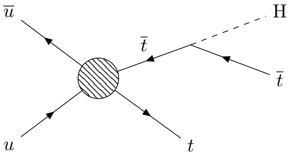
Operators involving heavy quarks and bosons



Operators involving 2 heavy quarks and 2 leptons



Operators involving 4 heavy quarks



Operators involving 2 heavy quarks and 2 light quarks

EFT Parameterization

- Need some way to model EFT contributions
- Matrix element can be written as the sum of SM and new physics components

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

→ c_i are the Wilson coefficients

- Since $\sigma \propto \mathcal{M}^2 \rightarrow$ the cross section will have a quadratic dependence on the WCs

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

s_0 → Pure SM

s_j → Interference with SM

s_{jk} → Pure NP

- Could solve for s_0, s_j, s_{jk} by generating samples at distinct points in the WC phase space
- Far too computationally intensive. Would need $\mathcal{O}(100)$ MC samples per signal process!

EFT Event Weights

- Instead can calculate the dependence on a per event basis
- Parameterization extends to the event level where each event will then have a **weight function**:

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

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

Pure SM — Interference with SM — Pure NP

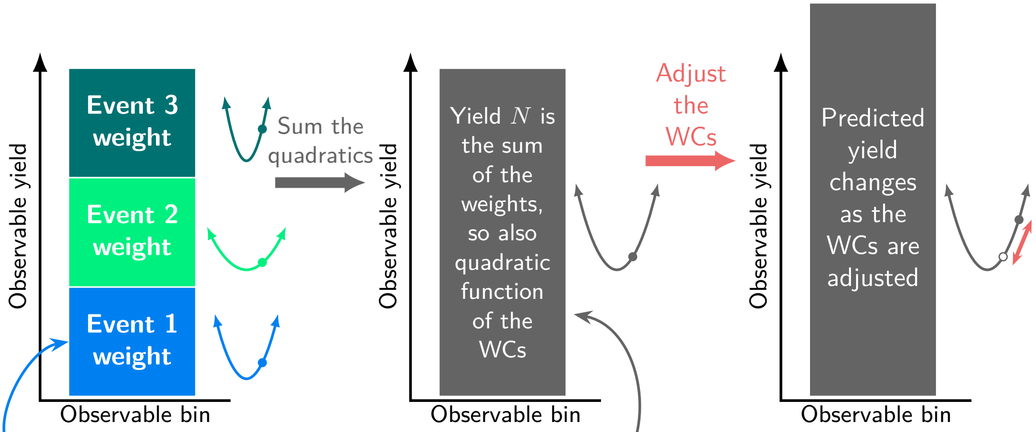
- Can sum individual weight functions for events passing a given selection ($\mathcal{S}$):

$$N(\vec{c}) = \sum_{i\in\mathcal{S}} w_i(\vec{c})$$

N is a function of the WCs, so can predict the yield for this selection for any arbitrary values of the WCs

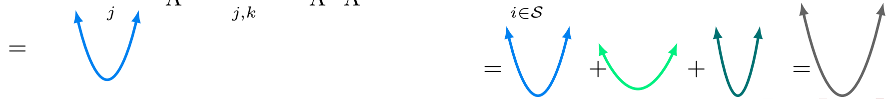
N is the sum of a bunch of quadratics, so it is also a quadratic

Scaling EFT Contributions



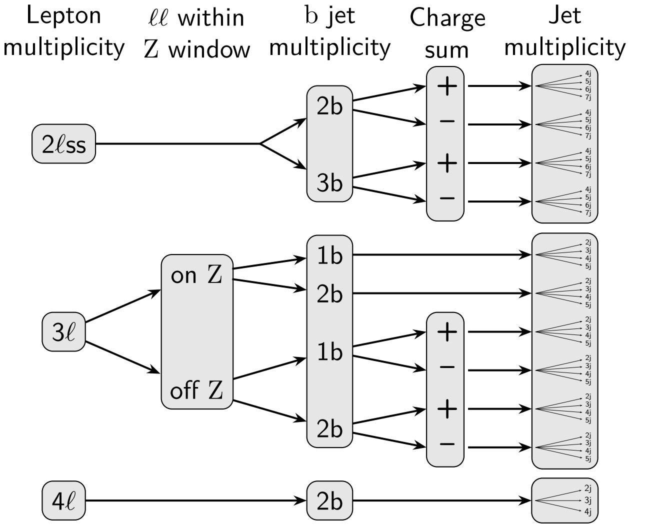
$$w_i(\vec{c}) = s_{0i} + \sum_j s_{ij}\frac{c_j}{\Lambda^2} + \sum_{j,k} s_{ijk}\frac{c_j}{\Lambda^2}\frac{c_k}{\Lambda^2}$$

$$N(\vec{c}) = \sum_{i\in\mathcal{S}} w_i(\vec{c})$$

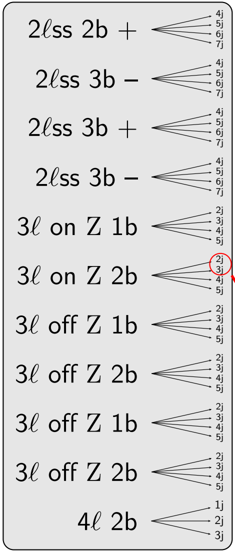


Event Selection

- The event selection targets prompt well isolated leptons produced with b jets and additional other jets
- Aims to discriminate between signal processes as much as possible
  - 2ℓss: $\mathrm{t\bar{t}H}$ and $\mathrm{t\bar{t}W}$ (split by charge)
  - 3ℓ on Z: $\mathrm{t\bar{t}ll}$ (2b), tllq (1b)
  - 3ℓ off Z: non-resonant $\mathrm{t\bar{t}ll}$ and tllq (2-quark 2-lepton EFT contributions)
  - $\geq 4\ell$: $\mathrm{t\bar{t}H}$ and $\mathrm{t\bar{t}ll}$

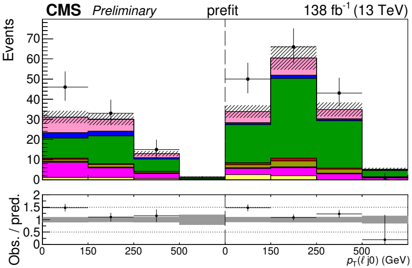


Event Selection

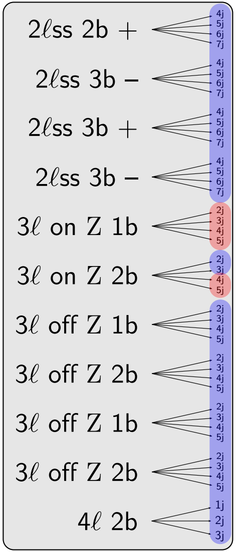


- We use a differential kinematic distribution for each of the 43 jet categories
- Kinematic variable for each jet category is chosen to optimize sensitivity to EFT effects

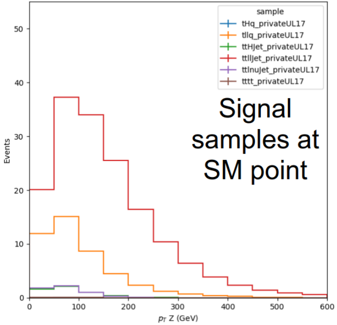
Differential distribution

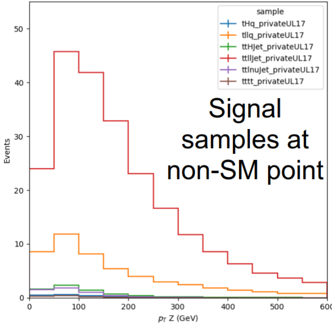


Event Selection



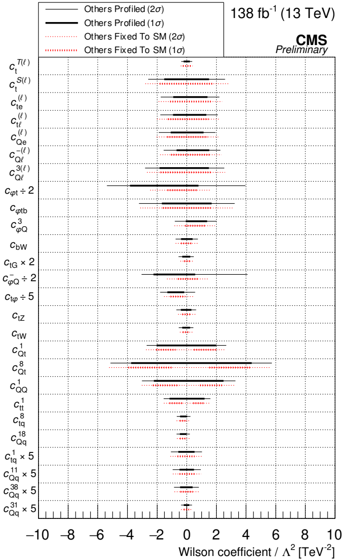
- Use different variables for different categories to optimize sensitivity to EFT effects
  - $p_{\mathrm{T}}(\ell j0) \rightarrow p_{\mathrm{T}}$ of the leading lepton plus jet pairs
  - $p_{\mathrm{T}}(\mathrm{Z}) \rightarrow p_{\mathrm{T}}$ of the opposite sign lepton pair





Results

- The solid black bars show the limits for each WC where the other WCs are **profiled**
- The dashed red bars show the limits when the other WCs are **frozen to the SM**
- Results are consistent with the SM
- Disjoint 1σ intervals for the 4-heavy quark operators is due to the quadratic nature of the EFT parameterization
    - In principle this is true for all WCs
    - Varied signal processes and kinematic distributions help resolve these double minima



Summary

- EFT can be a powerful technique for indirect searches of BSM physics at the LHC
- EFT approaches stand to benefit greatly from increased statistics of the current LHC and future HL-LHC runs
- Showcased a search by CMS for new physics in associated top production processes using EFT
  - Data corresponds to $138\ \mathrm{fb}^{-1}$ of pp collisions collected by CMS
  - Set simultaneous confidence interval limits on 26 WCs associated with top quarks
  - All limits found to be consistent with SM expectations
- There are a number of potential future directions for expanding and improving the analysis:
  - More data!
  - Optimization of the categorization and kinematic variable choices
  - Adding additional signal processes and final states
  - Translate the limits back into constraints on potential BSM models

Backup

Modeling EFT Contributions

- The EFT MC samples for the six signal processes ($\mathrm{t\bar{t}H}$, $\mathrm{t\bar{t}l\nu}$, $\mathrm{t\bar{t}ll}$, tllq, tHq, $\mathrm{t\bar{t}t\bar{t}}$) are generated using the dim6top model (1802.07237) to estimate relevant EFT effects
  - Uses the Warsaw basis
  - LO calculation, so include an extra jet in the matrix element (when possible) to improve modeling at high jet-multiplicities
  - Include 26 WCs which were found to significantly impact the signal processes

Operator category	WCs
Two heavy quarks	$c_{\mathrm{t}\varphi}, c^{-}_{\varphi\mathrm{Q}}, c^{3}_{\varphi\mathrm{Q}}, c_{\varphi\mathrm{t}}, c_{\varphi\mathrm{tb}}, c_{\mathrm{tW}}, c_{\mathrm{tZ}}, c_{\mathrm{bW}}, c_{\mathrm{t}G}$
Two heavy quarks two leptons	$c^{3(\ell)}_{\mathrm{Q}l}, c^{-(\ell)}_{\mathrm{Q}l}, c^{(\ell)}_{\mathrm{Q}e}, c^{(\ell)}_{\mathrm{t}l}, c^{(\ell)}_{\mathrm{t}e}, c^{S(\ell)}_{\mathrm{t}}, c^{T(\ell)}_{\mathrm{t}}$
Two light quarks two heavy quarks	$c^{31}_{\mathrm{Qq}}, c^{38}_{\mathrm{Qq}}, c^{11}_{\mathrm{Qq}}, c^{18}_{\mathrm{Qq}}, c^{1}_{\mathrm{tq}}, c^{8}_{\mathrm{tq}}$
Four heavy quarks	$c^{1}_{\mathrm{QQ}}, c^{1}_{\mathrm{Qt}}, c^{8}_{\mathrm{Qt}}, c^{1}_{\mathrm{tt}}$

- Generated ~ 300M private MC events in total using the same configurations as central CMS samples

Event Selection Cuts

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	$p_{\mathrm{T}}(\ell\mathrm{j}0)$
2ℓss 3b	2	No requirement	≥ 3	>0, <0	4,5,6,$\geq$7	$p_{\mathrm{T}}(\ell\mathrm{j}0)$
3ℓ off-Z 1b	3	$\lvert m_{\mathrm{Z}} - m_{\ell\ell}\rvert > 10$ GeV	1	>0, <0	2,3,4,$\geq$5	$p_{\mathrm{T}}(\ell\mathrm{j}0)$
3ℓ off-Z 2b	3	$\lvert m_{\mathrm{Z}} - m_{\ell\ell}\rvert > 10$ GeV	≥ 2	>0, <0	2,3,4,$\geq$5	$p_{\mathrm{T}}(\ell\mathrm{j}0)$
3ℓ on-Z 1b	3	$\lvert m_{\mathrm{Z}} - m_{\ell\ell}\rvert \leq 10$ GeV	1	No requirement	2,3,4,$\geq$5	$p_{\mathrm{T}}(\mathrm{Z})$
3ℓ on-Z 2b	3	$\lvert m_{\mathrm{Z}} - m_{\ell\ell}\rvert \leq 10$ GeV	≥ 2	No requirement	2,3,4,$\geq$5	$p_{\mathrm{T}}(\mathrm{Z})$ or $p_{\mathrm{T}}(\ell\mathrm{j}0)$
4ℓ	$\geq$4	No requirement	≥ 2	No requirement	2,3,$\geq$4	$p_{\mathrm{T}}(\ell\mathrm{j}0)$

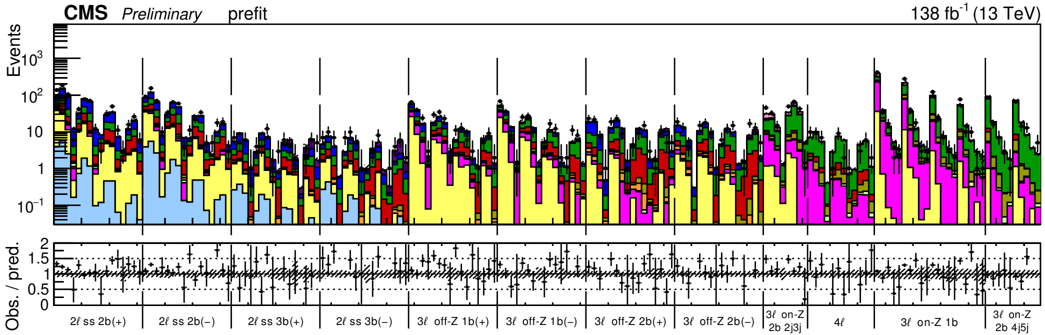
- All jets required to have $|\eta| < 2.4$ and $p_{\mathrm{T}} > 30$ GeV
- All electrons require $|\eta| < 2.5$ and all muons require $|\eta| < 2.4$
- Lepton p_{T} cuts (GeV):
  - 2ℓss: $p_{\mathrm{T}} > 25, 15$
  - 3ℓ for e (μ): $p_{\mathrm{T}} > 25, 15, 15\ (10)$
  - 4ℓ for e (μ): $p_{\mathrm{T}} > 25, 15, 15\ (10), 15\ (10)$

Interpretation of Sensitivity

- Sensitivity to most WCs comes from a wide range of bins over all selection categories

Grouping of WCs	WCs	Lead categories
Two heavy two leptons	$c_{Ql}^{3(\ell)}$, $c_{Ql}^{-(\ell)}$, $c_{Qe}^{(\ell)}$, $c_{tl}^{(\ell)}$, $c_{te}^{(\ell)}$, $c_{t}^{S(\ell)}$, $c_{t}^{T(\ell)}$	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 "tllq-like"	c_{Qq}^{31}, c_{Qq}^{38}	3ℓ on-Z
Two heavy with bosons "$t\bar{t}ll$-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

Signal Region Yields



Signal Region Yields