Effective field theory interpretation for measurements of top quark pair-production in association with a W or Z boson

Thesis Defense

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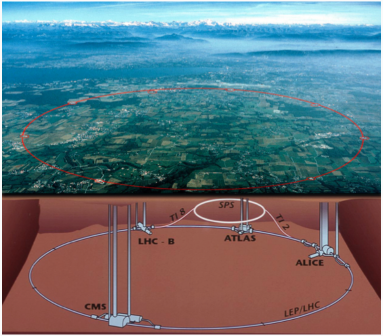
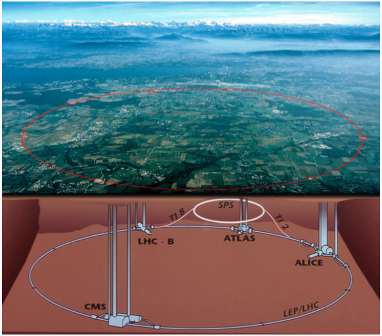
February 27, 2018

The Large Hadron Collider (LHC)



- 26.7 km tunnel
- 8 TeV center-of-mass energy, upgraded to 13 TeV starting in 2015
- Total beam energy: 260 MJ ($\approx$ kinetic energy of 750 Honda Civics each moving at 55 MPH)
- Superconducting magnet temperature is 2 K (colder than outer space)
- Colliding protons is like shooting two needles at each other from a distance of six miles and having them hit in the middle



Why did we build the LHC????

Outline

Theory

Experiment

Cross section measurements

Effective field theory interpretation

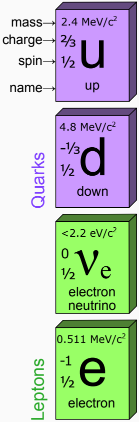
Future directions

Conclusions

The standard model (SM)

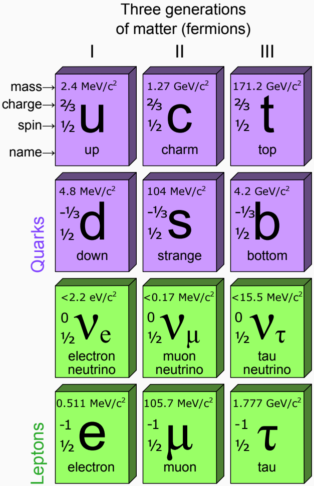
- Basic idea
  - Matter is made up of combinations of fundamental particles
    - Fundamental particles are excitations of quantum fields
  - Particles interact via several forces
    - Forces are associated with couplings between ‘matter’ fields and ‘gauge’ fields

The standard model (SM)



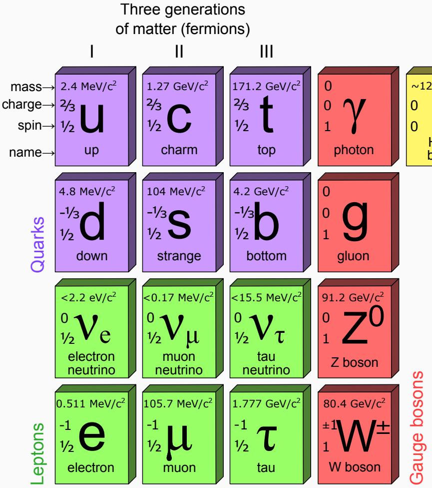
- Matter particles
  - Quarks:
    'up type'
    'down type'
  - Leptons:
    'neutrino type'
    'electron type'

The standard model (SM)



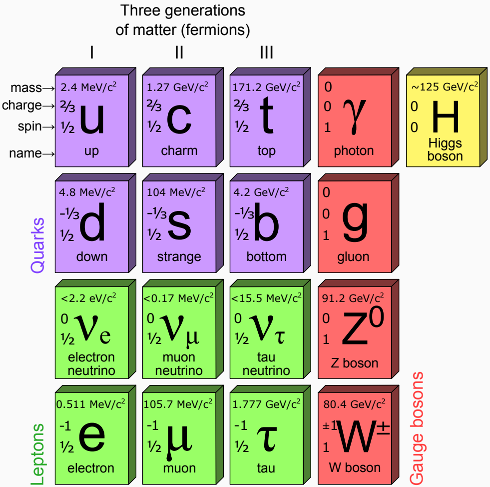
- Matter particles
  - Quarks:
    'up type' x 3
    'down type' x 3
  - Leptons:
    'neutrino type' x 3
    'electron type' x 3

The standard model (SM)



- Matter particles
  - Quarks:
    'up type' x 3
    'down type' x 3
  - Leptons:
    'neutrino type' x 3
    'electron type' x 3
- Forces
  - Electromagnetic (γ)
  - Weak (W/Z)
  - Strong (g)
  - Higgs (H)

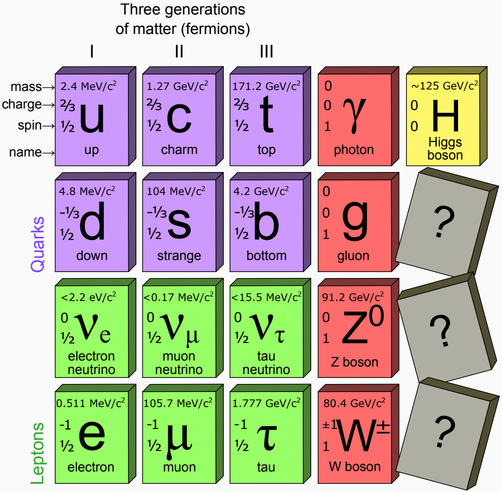
Physics beyond the SM



We know this picture is incomplete!

- Gravity
- Matter/anti-matter asymmetry
- Dark matter
- Dark energy
- etc etc

Physics beyond the SM



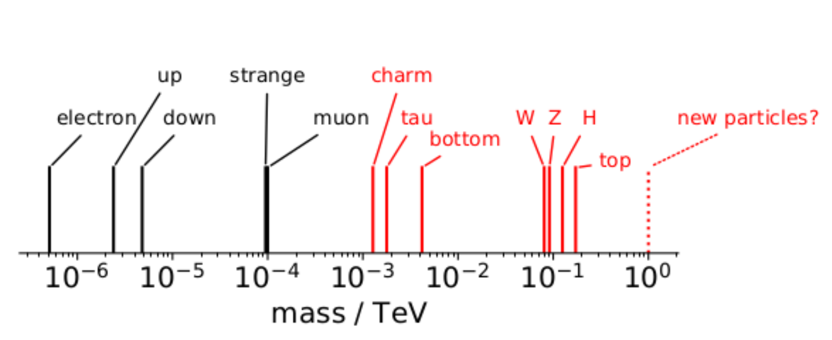
There must be particles we have not discovered yet!

How do we find new particles?

Turn kinetic energy into mass!

$$E \iff mc^2$$

In red: particles discovered at particle accelerators of higher and higher energy



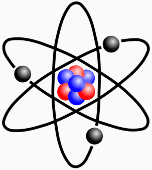
Bad news: finding new particles may require more energy than the LHC provides

Good news: we have tools for coping; one is effective field theory (EFT)

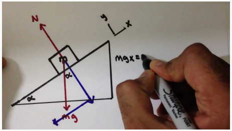
What is an effective theory?

An effective theory describes observations without claiming that the mechanism of the theory is the actual cause of observations (expect a more fundamental underlying theory)

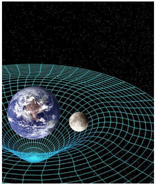
‘solid’ matter



atomic theory



newtonian mechanics



general relativity

Effective field theory

Extend SM by adding higher dimensional operators representing new physics associated with particles too heavy to produce at LHC

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

Operators: unique products of fields

Wilson coefficients: constants which characterize the strength of the NP effect (analysis goal is to constrain these)

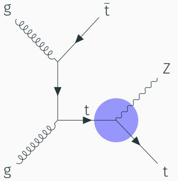
Top quark physics

Why study EFT in the top sector?

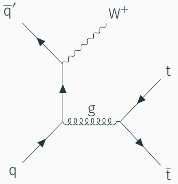
- Top's huge mass stands out— is it special?
- Top decays before hadronizing: our only chance to study a 'bare' quark

Top is so heavy that nothing decays to it: study associated production!

Tops + Z ($t\bar{t}Z$): Direct probe of t-Z coupling!



Tops + W ($t\bar{t}W$): Not sensitive to t-W coupling (can be measured via $t \to Wb$). But tops + Ws could be a sign of NP ($X \to tW$)!

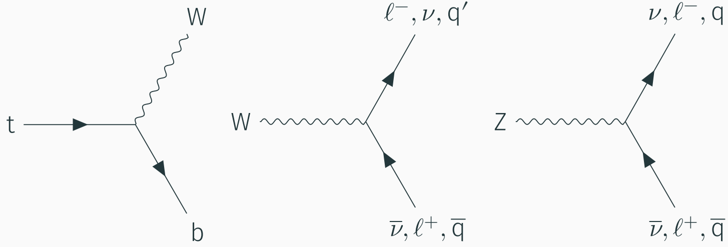


EFT is a useful tool for searching for NP

Some dimension-six operators would affect $t\bar{t}W$ and $t\bar{t}Z$ cross sections

Analysis goal: use $t\bar{t}W$ and $t\bar{t}Z$ cross section measurements to constrain their Wilson coefficient values

What does $t\bar{t}W$ and $t\bar{t}Z$ look like?



We do not see the tops, Zs, and Ws directly: they decay before they reach the detector. So we look for the stuff they decay to.

$\rightarrow$ Focus on **multilepton signatures:** at least one lepton ($\ell = \mu, e$) from the top and one from the W or Z. Fewer events, but cleaner signature!

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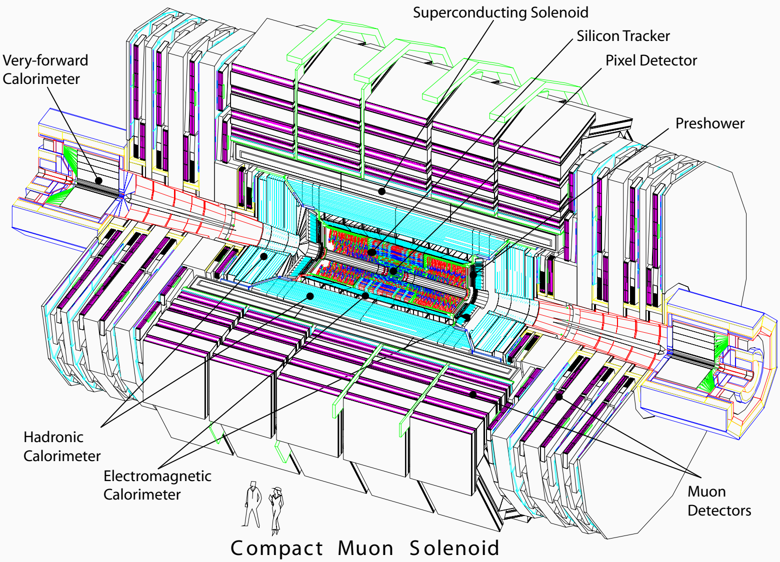
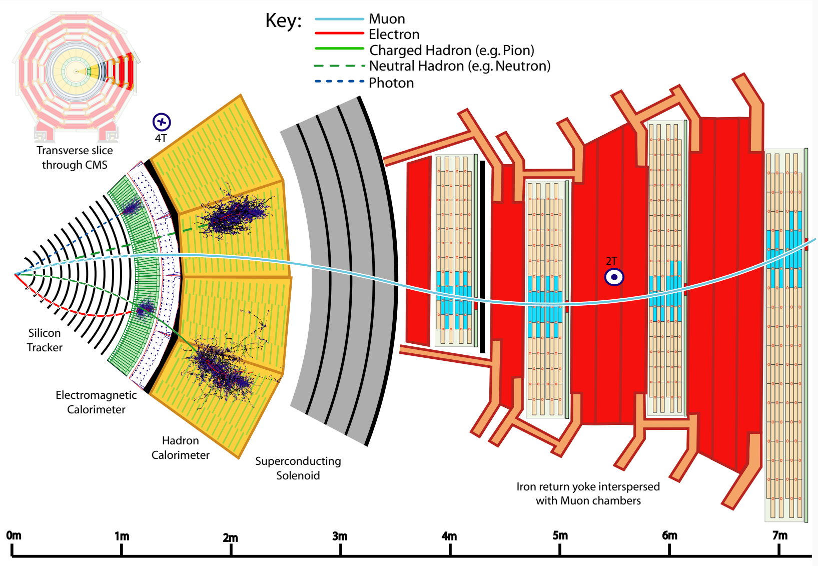
The Compact Muon Solenoid

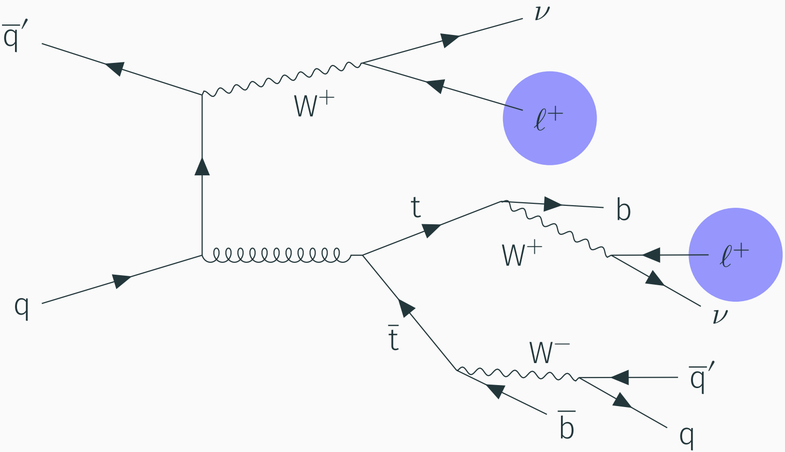


The Compact Muon Solenoid



Outline

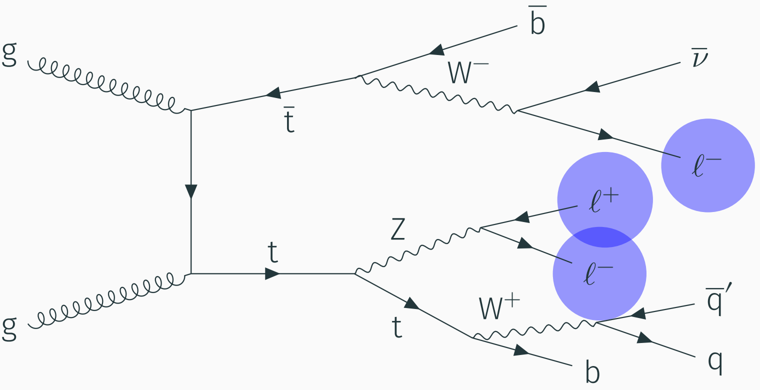
Analysis signatures



same-sign $t\bar{t}W$

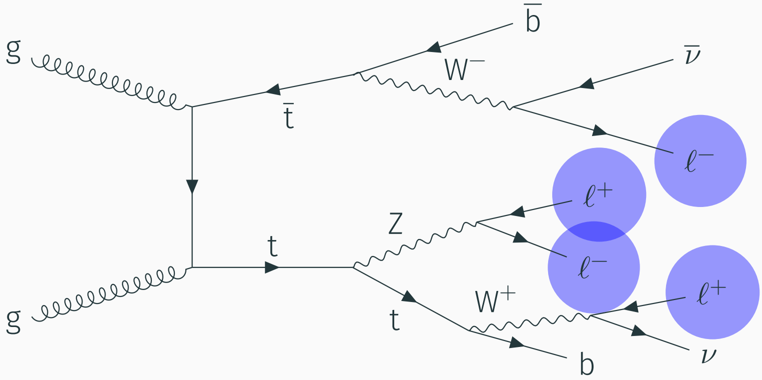
$$t\bar{t}W \to (b\ell\nu)(bjj)(\ell\nu)$$

Analysis signatures



3ℓ $t\bar{t}Z$

$t\bar{t}Z \rightarrow (b\ell\nu)(bjj)(\ell\ell)$



4ℓ $t\bar{t}Z$

$$t\bar{t}Z \to (b\ell\nu)(b\ell\nu)(\ell\ell)$$

Reducible Backgrounds

Nonprompt leptons (SS $t\bar{t}W$, 3ℓ $t\bar{t}Z$)

- Leptons from b decays, misidentified jets, photon conversions, etc (mostly from $t\bar{t}$ + jets)
- Estimated from data
  - Measure rate f_{TL} loose leptons pass tight criteria in **measurement region** enriched with nonprompt leptons
  - Weight **application region** events which pass full selection, except that at least one lepton passes loose selection but fails tight selection by f_{TL}

Charge misidentification (SS $t\bar{t}W$)

- Charge of one electron is misidentified
- Misidentification rate measured in simulation and validated in data $Z \to ee$ events

Irreducible Backgrounds

Diboson (SS $t\bar{t}W$, 3ℓ $t\bar{t}Z$, 4ℓ $t\bar{t}Z$)

- Estimated from simulation
- Measure data/MC correction factor in WZ enriched control region
- ZZ validated in enriched control region

Rare and $t(\bar{t})X$ (SS $t\bar{t}W$, 3ℓ $t\bar{t}Z$, 4ℓ $t\bar{t}Z$)

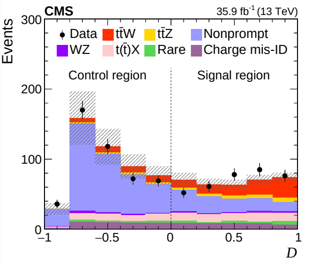
- Irreducible, but generally small contribution
- Estimated from simulation

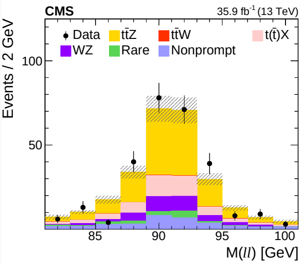
Event selection

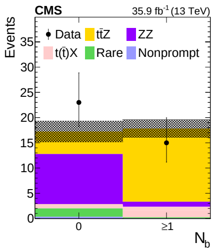
	SS $t\bar{t}W$	3ℓ $t\bar{t}Z$	4ℓ $t\bar{t}Z$
lepton p_T	$> \begin{cases} 27/40\,\text{GeV}(e) \\ 25\,\text{GeV}(\mu) \end{cases}$	$> 10/20/40$ GeV	$> 10/10/10/40$ GeV
jets[a]	$2, 3, > 3$	$2, 3, > 3$	≥ 2
b-tagged jets[a]	$1, > 1$	$0, 1, > 1$	$0, \geq 1$
Z window	$\lvert M_{ee} - M_Z \rvert > 15$ GeV	OSSF pair with $\lvert M_{\ell\ell} - M_Z \rvert < 10$ GeV	OSSF pair with $\lvert M_{\ell\ell} - M_Z \rvert < 20$ GeV and veto on additional OSSF pair
loose lepton veto			
charge[a]	$\ell^+\ell^+, \ell^-\ell^-$		
p_T^{miss}	> 30 GeV		
BDT[a]	$D > 0$, $D < 0$		

[a] Entries separated by commas indicate events are categorized according to each listed criteria.

Signal extraction







SS $t\bar{t}W$

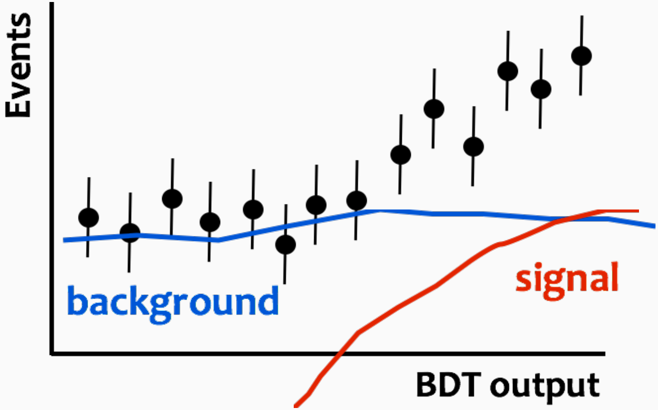
Categorize by charge to take advantage of W charge asymmetry; use BDT to enhance sensitivity

3ℓ $t\bar{t}Z$, 4ℓ $t\bar{t}Z$

Cut on Z mass window and b jets

Characterizing the data

signal strength $\mu = \frac{\sigma}{\sigma_{\text{SM}}}$



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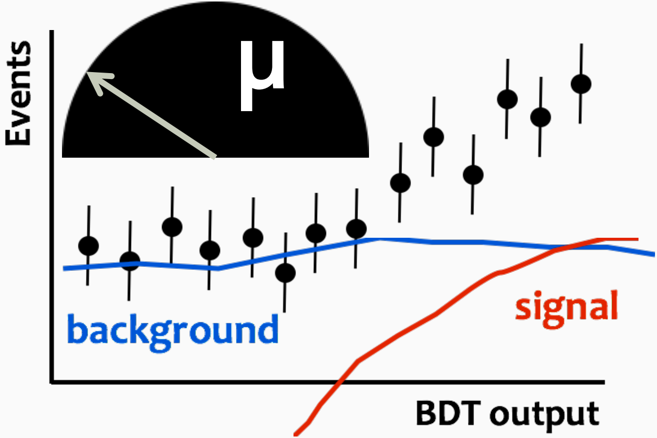

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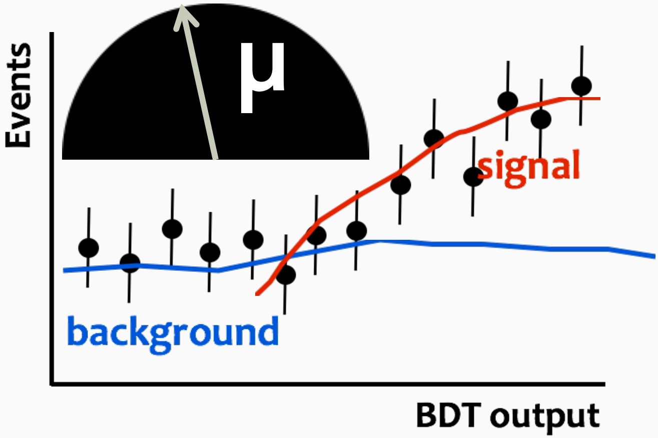

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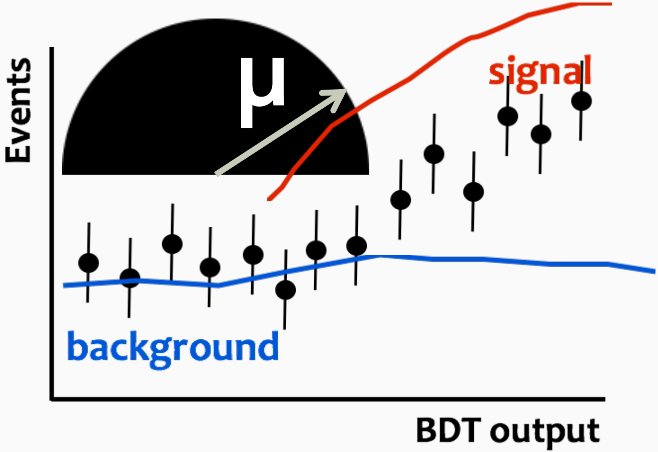

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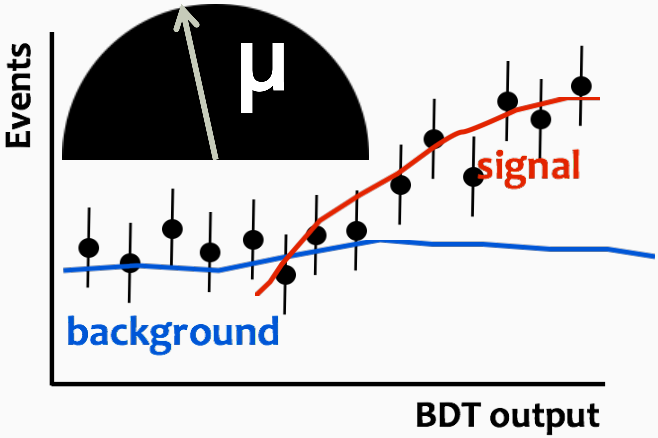
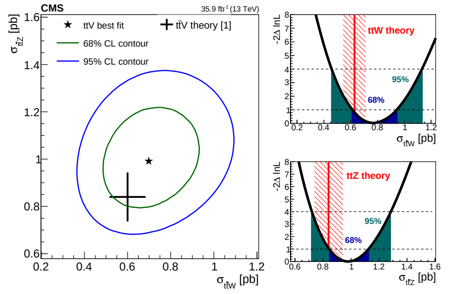


Results



$$\sigma(\mathrm{pp}\to\mathrm{t\bar{t}Z}) = 0.99^{+0.09}_{-0.08}(\mathrm{stat})^{+0.12}_{-0.10}(\mathrm{syst})\,\mathrm{pb}$$

$$\sigma(\mathrm{pp}\to\mathrm{t\bar{t}W}) = 0.77^{+0.12}_{-0.11}(\mathrm{stat})^{+0.13}_{-0.12}(\mathrm{syst})\,\mathrm{pb}$$

$$\sigma(\mathrm{pp}\to\mathrm{t\bar{t}W^{+}}) = 0.58 \pm 0.09\,(\mathrm{stat})\;^{+0.09}_{-0.08}\,(\mathrm{syst})\;\mathrm{pb}$$

$$\sigma(\mathrm{pp}\to\mathrm{t\bar{t}W^{-}}) = 0.19 \pm 0.07\,(\mathrm{stat})\;\pm 0.06\,(\mathrm{syst})\;\mathrm{pb}$$

Outline

Why is this hard?

1. There are 59 operators— multiple couplings may be enhanced, and operators may interfere with each other
2. EFT might affect $t\bar{t}W$ and $t\bar{t}Z$ kinematics

In this work[1], we make two simplifications:

1. Study couplings independently
2. Assume EFT only affects process rates

[1] *Most* of this work— later I will show preliminary steps toward relaxing assumption 1) and ideas for tackling 2)

General strategy

How to calculate scaling of $\sigma_{\mathrm{t\bar{t}W}}$ and $\sigma_{\mathrm{t\bar{t}Z}}$ as a function of the Wilson coefficients?

$$\mathcal{M} = \mathcal{M}_0 + \sum c_i \mathcal{M}_i$$

General strategy

How to calculate scaling of $\sigma_{\mathrm{t\bar{t}W}}$ and $\sigma_{\mathrm{t\bar{t}Z}}$ as a function of the Wilson coefficients?

$$\cancel{\mathcal{M} = \mathcal{M}_0 + \sum c_i \mathcal{M}_i}$$

$$\mathcal{M} = \mathcal{M}_0 + c_1 \mathcal{M}_1$$

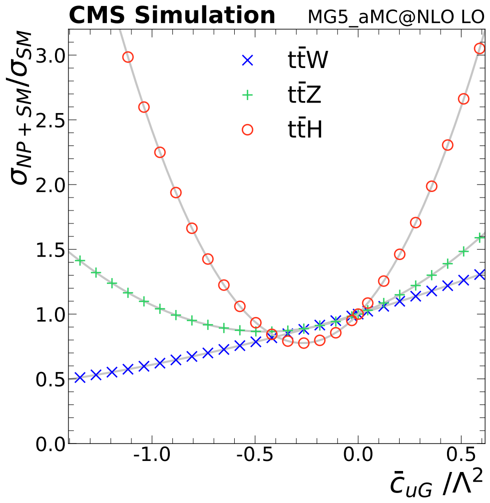
$$\begin{aligned}
\mu(c_1) = \frac{\sigma_{\text{SM+NP}}(c_1)}{\sigma_{\text{SM}}} = \frac{\sigma_{\text{SM+NP}}(c_1)}{\sigma_{\text{SM+NP}}(0)} &= \propto \frac{|\mathcal{M}|^2}{|\mathcal{M}_0|^2} \\
&\propto \frac{|\mathcal{M}_0 + c_1 \mathcal{M}_1|^2}{|\mathcal{M}_0|^2} \\
&\propto s_0 + s_1 c_1 + s_2 c_1^2
\end{aligned}$$

!!!!!!!!!!!!!!!!

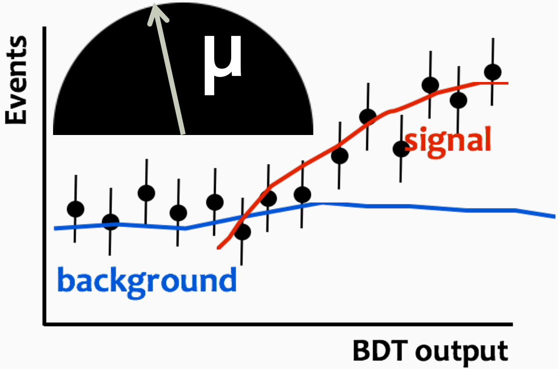
We do not need to calculate $\mu(c_1)$ at each possible c_1: we can calculate $\mu(c_1)$ for three values of c_1 and solve the system of equations to determine s_0, s_1, and s_2!

General strategy

What does $\mu(c_1)$ look like?



General strategy



Find best-fit c_1 (constrained by $\mu(c_1) = s_0 + s_1 c_1 + s_2 c_1^2$)

Eight TeV analysis[2]

Select five operators because they have a small effect on inclusive Higgs boson and $t\bar{t}$, and a large effect on $t\bar{t}Z$, $t\bar{t}W$, or both

Coefficient	Best fit point(s)	68 % CL	95 % CL
$\bar{c}_{\mathrm{uB}}$	-0.07 and 0.07	$[-0.11, 0.11]$	$[-0.14, 0.14]$
$\bar{c}_{\mathrm{3W}}$	-0.28 and 0.28	$[-0.36, -0.18]$ and $[0.18, 0.36]$	$[-0.43, 0.43]$
$\bar{c}_{\mathrm{Hu}}$	-0.47 and 0.13	$[-0.60, -0.23]$ and $[-0.11, 0.26]$	$[-0.71, 0.37]$
$\bar{c}_{\mathrm{HQ}}$	-0.09 and 0.41	$[-0.22, 0.08]$ and $[0.24, 0.54]$	$[-0.31, 0.63]$
$\bar{c}'_{\mathrm{HQ}}$	0.12	$[-0.07, 0.18]$	$[-0.33, -0.24]$ and $[-0.02, 0.23]$

[2] V. Khachatryan et al. "Observation of top quark pairs produced in association with a vector boson in pp collisions at $\sqrt{s}$ = 8 TeV". In: JHEP 01 (2016), p. 096. doi:10.1007/JHEP01(2016)096.

Thirteen TeV analysis: improvements

- Removed NP couplings to light quarks[3]: makes it harder to set limits because we are only sensitive to 3rd-gen couplings, but those are exactly what we want to probe
- Added scaling for $t\bar{t}H$
- Improved range-finding for parameterization
- More sophisticated operator selection

[3] Big thanks to Adam Martin for providing the new Feynrules implementation and a great deal of additional help

Thirteen TeV analysis: what operators do we care about?

We can eliminate:

- Operators which do not affect $t\bar{t}W$, $t\bar{t}Z$, or $t\bar{t}H$
- Operators which have a large effect on already precisely measured processes ($t\bar{t}$ etc)
- Operators which produce a large effect on background yields

Operators with large effect on precisely measured processes

Define extreme signal scaling $\mu_{\text{e}}(c_1)$ to be $\mu(c_1)$ evaluated at the c_1 which maximizes $|\mu(c_1) - 1|$ within the range of c_1 corresponding to 2σ sensitivity

Exclude operators producing $|\mu_{\text{e}} - 1| > 0.7$ for any of $\text{t}\bar{\text{t}}$, inclusive Higgs, WW, and WZ

	$\mu_{\text{e,t}\bar{\text{t}}}$	$\mu_{\text{e,H}}$	$\mu_{\text{e,DY}}$	$\mu_{\text{e,ZZ}}$	$\mu_{\text{e,WZ}}$	$\mu_{\text{e,WW}}$
$\tilde{c}_{HB}$	1.0	1.0	1.0	1.1	5.0	4.6
$\bar{c}_{G}$	0.6	1610.7	1.1	5.2	1.0	2.5
$\tilde{c}_{G}$	1.0	739.4	1.0	2.9	1.0	1.7
$\bar{c}_{Hd}$	1.0	1.0	1.3	1.1	1.0	2.8
$\bar{c}_{HW}$	1.0	1.0	1.0	1.0	1.7	1.1
$\tilde{c}_{3W}$	1.0	1.0	1.0	1.0	7.9	2.6
$\bar{c}_{3W}$	1.0	1.0	1.0	1.0	7.9	2.6
$\bar{c}_{WW}$	1.0	1.0	1.0	1.0	2.0	1.2

Operators with large effect on background yields

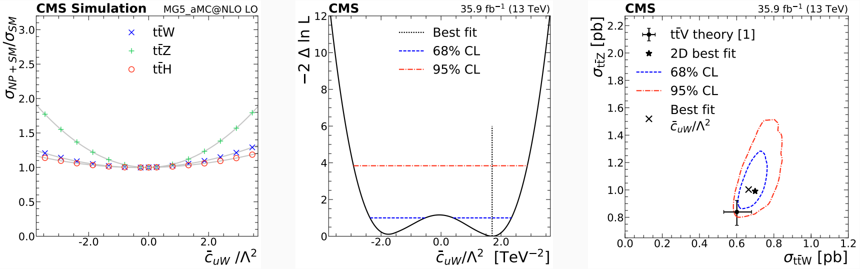
Worst offenders: triboson, VH, $t(\bar{t})X$. Eliminate them for now, but promising direction for future work!

	$T^{3}_{SM} = 443$			$T_{SM} = 218$					$T_{SM} = 175$						$T_{SM} = 1176$	
	$\Delta_{t\bar{t}Z}$	$\Delta_{t\bar{t}W}$	$\Delta_{t\bar{t}H}$	Δ_{WWW}	Δ_{WZZ}	Δ_{ZZZ}	Δ_{WWZ}	Δ_{VH}	Δ_{tZq}	Δ_{tHq}	Δ_{tHW}	$\Delta_{t\bar{t}t\bar{t}}$	Δ_{tWZ}	Δ_{tG}	Δ_{WZ}	Δ_{ZZ}
$\bar{c}_{HB}$	135.2	0.3	36.5	59.5	8.6	272.8	1079.5	3355.3	47.8	0.0	0.0	1.0	0.3	0.0	113.3	1.3
$\tilde{c}_{HW}$	75.1	103.5	2.1	2052.7	950.4	416.7	1017.2	36709.2	37.0	804.6	47.3	0.0	0.4	0.0	260.2	8.6
$\bar{c}_{Hud}$	135.5	0.0	35.6	0.0	0.0	0.0	42.7	0.0	1818.3	1676.5	339.6	0.5	19.5	0.0	0.0	0.0
$\bar{c}_{HQ}$	−175.1	2.7	3.3	0.0	0.0	41.2	224.7	1280.5	257.7	0.0	0.0	3.4	4.2	0.0	0.0	90.1
$\bar{c}_{B}$	135.8	0.0	35.1	0.0	0.6	304.2	1750.1	4177.8	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.8
$\tilde{c}_{A}$	145.9	0.0	8.2	0.0	8.8	835.2	1958.5	20517.7	0.0	0.0	0.0	0.1	0.0	0.0	0.0	9.3
$\bar{c}'_{HQ}$	−149.6	2.5	47.5	0.0	0.0	24.4	81.3	772.0	1687.7	1503.6	269.0	2.5	15.8	0.0	0.0	17.8
$\bar{c}_{u}$	0.9	0.1	81.0	0.0	0.0	0.0	0.0	0.0	0.0	292.0	44.7	4.1	0.0	0.0	0.0	0.0

[1] Yields differences are calculated as $\Delta = \sum_i N^{i}_{SM}(\mu_e - 1)$, where N^{i}_{SM} refers to the expected SM yield in a particular channel, and the sum is over i channels.

[3] T_{SM} is the sum of expected SM yields over channels and the given process group: $T_{SM} = \sum_{i,p} N^{i,p}_{SM}$.

Eight survivors: $\bar{c}_{\mathrm{H}}$, $\tilde{c}_{3\mathrm{G}}$, $\bar{c}_{3\mathrm{G}}$, $\bar{c}_{\mathrm{uG}}$, $\bar{c}_{\mathrm{uB}}$, $\bar{c}_{\mathrm{Hu}}$, and $\bar{c}_{2\mathrm{G}}$



Wilson coefficient	Best fit [TeV^{-2}]	68 % CL [TeV^{-2}]	95 % CL [TeV^{-2}]
$\bar{c}_{\mathrm{uW}}/\Lambda^2$	1.7	$[-2.4, -0.5] \cup [0.4, 2.4]$	$[-2.9, 2.9]$
$\lvert\bar{c}_{\mathrm{H}}/\Lambda^2 - 16.8\ \mathrm{TeV}^{-2}\rvert$	15.6	$[0, 23.0]$	$[0, 28.5]$
$\lvert\tilde{c}_{3\mathrm{G}}/\Lambda^2\rvert$	0.5	$[0, 0.7]$	$[0, 0.9]$
$\bar{c}_{3\mathrm{G}}/\Lambda^2$	-0.4	$[-0.6, 0.1] \cup [0.4, 0.7]$	$[-0.7, 1.0]$
$\bar{c}_{\mathrm{uG}}/\Lambda^2$	0.2	$[0, 0.3]$	$[-1.0, -0.9] \cup [-0.3, 0.4]$
$\lvert\bar{c}_{\mathrm{uB}}/\Lambda^2\rvert$	1.6	$[0, 2.2]$	$[0, 2.7]$
$\bar{c}_{\mathrm{Hu}}/\Lambda^2$	-9.3	$[-10.3, -8.0] \cup [0, 2.1]$	$[-11.1, -6.5] \cup [-1.6, 3.0]$
$\bar{c}_{2\mathrm{G}}/\Lambda^2$	0.4	$[-0.9, -0.3] \cup [-0.1, 0.6]$	$[-1.1, 0.8]$

$\mu(c_i)$ parameterization in multiple dimensions

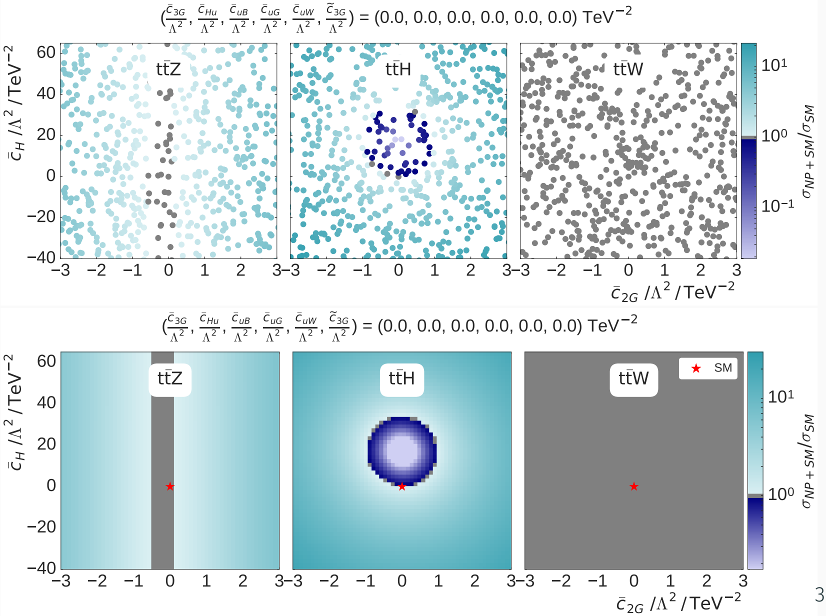
Considering the effects of operators simultaneously is more physically meaningful. Example for three:

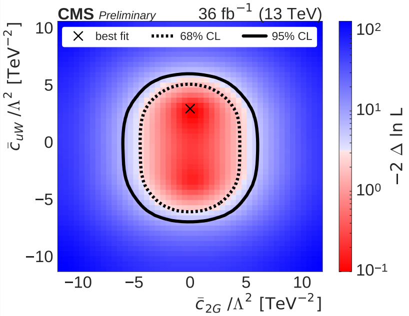
$$\begin{aligned}\sigma(c_1, c_2, c_3) &\propto |\mathcal{M}_0 + c_1\mathcal{M}_1 + c_2\mathcal{M}_2 + c_3\mathcal{M}_3|^2 \\ &\propto \underbrace{s_0}_{\text{constant}} + \underbrace{s_1c_1 + s_2c_2 + s_3c_3}_{\text{linear}} \\ &\quad + \underbrace{s_4c_1^2 + s_5c_2^2 + s_6c_3^2}_{\text{quadratic}} + \underbrace{s_7c_1c_2 + s_8c_1c_3 + s_9c_2c_3}_{\text{mixed}}\end{aligned}$$

If there are d operators, there will be N_s structure constants, where

$$N_s = 1 + 2d + \frac{d}{2}(d-1)$$

$\mu(c_i)$ parameterization in two dimensions





CL surface 'bounding box' for 8D simultaneous fit

	0.68 % CL / TeV^{-2}	0.95 % CL / TeV^{-2}
$\bar{c}_{2G}/\Lambda^2$	[-10.4, 10.0]	[-12, 12]
$\bar{c}_{3G}/\Lambda^2$	[-9.2, 8.6]	[-10.4, 9.9]
$\bar{c}_{H}/\Lambda^2$	[-25, 52]	[-31, 57]
$\bar{c}_{Hu}/\Lambda^2$	[-13, 6.2]	[-14, 7.3]
$\bar{c}_{uB}/\Lambda^2$	[-7.8, 7.3]	[-8.5, 7.9]
$\bar{c}_{uG}/\Lambda^2$	[-1.4, 1.0]	[-1.6, 1.1]
$\bar{c}_{uW}/\Lambda^2$	[-7.5, 6.8]	[-8.2, 7.4]
$\tilde{c}_{3G}/\Lambda^2$	[-1.3, 1.3]	[-1.4, 1.4]

Outline

Parameterized matrix element reweighting

Matrix element reweighting: 'recycle' simulated events to model different hypothesis by weighting events:

$$w_{\text{new}} = w_{\text{orig}} \frac{|\mathcal{M}_{\text{new}}|^2}{|\mathcal{M}_{\text{orig}}|^2}$$

Bad news: 'combinatoric explosion' still a problem! Assuming 32 bits of memory per weight: weights for one event evaluated at just 10 values per parameter in a 15 dimensional parameter space would require 10^{15} x 32 bits = 4000 TB!

Parameterized matrix element reweighting

Luckily, we have a lot of practice parameterizing second-order polynomials!

$$\begin{aligned} w_{\text{new}}(c_1) &= w_{\text{orig}} \frac{|\mathcal{M}_0 + c_1 \mathcal{M}|^2}{|\mathcal{M}_{\text{orig}}|^2} \\ &= w_{\text{orig}} \frac{s_0 + s_1 c_1 + s_2 c_1^2}{|\mathcal{M}_{\text{orig}}|^2}. \end{aligned}$$

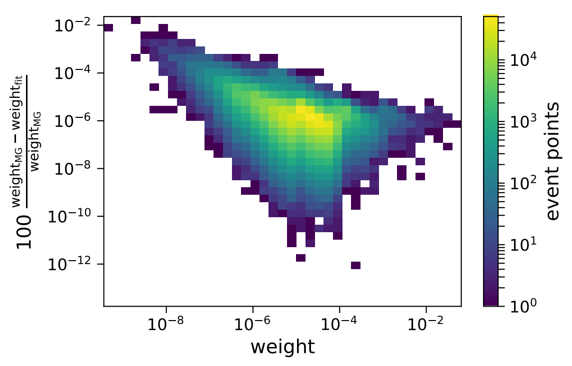
Before: parameterized $\mu(c_i)$ per-process

Now: parameterize $w(c_i)$ per-event

Need more, but they are cheap: 50 000 parameterizations in 8D (one for each event) to 200 points: $\approx 100\,$seconds

Parameterized matrix element reweighting

Preliminary parameterizations look promising!



Future work: how to choose reference model, properly handle uncertainties, etc... If these problems can be addressed satisfactorily, could perform ‘traditional’ analysis, then apply reweighting to final discriminant histograms

Outline

Conclusion

- Used $t\bar{t}W$ and $t\bar{t}Z$ cross section measurements to constrain Wilson coefficients of dimension-six operators (results consistent with SM)
- Challenging because of large phase space; we (mostly) studied operators independently, and assumed only rates are affected
- Different combos of Wilson coefficient values can correspond to identical cross section scaling; this degeneracy is a challenge
- Identified large NP effects on triboson, $t(\bar{t})X$, and VH processes– hints at interesting direction for future work (fitting effects on more signal regions simultaneously helps break degeneracies)
- Building on experience parameterizing NP effects in one dimension, we:
    - Presented preliminary results in higher dimensions
    - Demonstrated how approach can be extended to 'recycle' simulation; this could be used in detector-level analyses, benefit from kinematic handles to further break degeneracies

The end: THANK YOU!

LHC accelerator team, CMS Collaboration

Kevin Lannon, committee members, ND HEP group, Jason Slaunwhite, Andrew Brinkerhoff, all the students who have helped me

Theorists who put up with many questions: Adam Martin, Fatimah Elahi, Landon Lehman, Ayan Paul, Joe Bramante, Brian Ostdiek

Doug Thain and his Cooperative Computing Lab team

Serguei Federov, Paul Brenner, Scott Hampton, and the CRC team

13 TeV ttV team: Didar Dobur, Illia Khvastunov, Mirena Paneva, and Deniz Poyraz

backup

Summary of selection

Requirement	Eliminated
No effect on $t\bar{t}H$, $t\bar{t}Z$, $t\bar{t}W$	$\bar{c}_{\mathrm{l}}$, $\bar{c}_{\mathrm{lB}}$, $\bar{c}_{\mathrm{d}}$, $\bar{c}_{\mathrm{2B}}$, $\bar{c}_{\mathrm{lW}}$, $\bar{c}_{\mathrm{dB}}$, $\bar{c}_{\mathrm{dW}}$, $\bar{c}'_{\mathrm{HL}}$, $\bar{c}_{\mathrm{He}}$, $\bar{c}_{\mathrm{dG}}$, $\bar{c}_{6}$, $\bar{c}_{\mathrm{HL}}$
$\lvert\mu_{WZ} - 1\rvert > 0.7$	$\tilde{c}_{\mathrm{HB}}$, $\bar{c}_{\mathrm{T}}$, $\tilde{c}_{\mathrm{3W}}$, $\bar{c}_{\mathrm{3W}}$, $\bar{c}_{\mathrm{WW}}$, $\bar{c}_{\mathrm{HW}}$
$\lvert\mu_{ZZ} - 1\rvert > 0.7$	$\bar{c}_{\mathrm{G}}$, $\tilde{c}_{\mathrm{G}}$, $\bar{c}_{\mathrm{T}}$
$\lvert\mu_{WW} - 1\rvert > 0.7$	$\tilde{c}_{\mathrm{HB}}$, $\bar{c}_{\mathrm{G}}$, $\tilde{c}_{\mathrm{G}}$, $\bar{c}_{\mathrm{T}}$, $\bar{c}_{\mathrm{Hd}}$, $\tilde{c}_{\mathrm{3W}}$, $\bar{c}_{\mathrm{3W}}$
$\lvert\mu_{tt} - 1\rvert > 0.7$	$\bar{c}_{\mathrm{uG}}$, $\bar{c}_{\mathrm{G}}$
$\lvert\mu_{H} - 1\rvert > 0.7$	$\bar{c}_{\mathrm{G}}$, $\tilde{c}_{\mathrm{G}}$
Large effect on backgrounds	$\bar{c}_{\mathrm{HB}}$, $\tilde{c}_{\mathrm{HW}}$, $\bar{c}_{\mathrm{Hud}}$, $\bar{c}_{\mathrm{HQ}}$, $\bar{c}_{\mathrm{B}}$, $\tilde{c}_{\mathrm{A}}$, $\bar{c}'_{\mathrm{HQ}}$, $\bar{c}_{\mathrm{u}}$

Eight survivors: $\bar{c}_{\mathrm{H}}$, $\tilde{c}_{\mathrm{3G}}$, $\bar{c}_{\mathrm{3G}}$, $\bar{c}_{\mathrm{uG}}$, $\bar{c}_{\mathrm{uB}}$, $\bar{c}_{\mathrm{Hu}}$, and $\bar{c}_{\mathrm{2G}}$

$\mu(c_i)$ parameterization in multiple dimensions

Considering the effects of operators simultaneously is more physically meaningful. For two:

$$\begin{aligned}
\sigma(c_1, c_2) &\propto |\mathcal{M}_0 + c_1\mathcal{M}_1 + c_2\mathcal{M}_2|^2 \\
&\propto \underbrace{s_0}_{\text{constant}} + \underbrace{s_1c_1 + s_2c_2}_{\text{linear}} + \underbrace{s_3c_1^2 + s_4c_2^2}_{\text{quadratic}} + \underbrace{s_5c_1c_2}_{\text{mixed}}.
\end{aligned}$$

And for three:

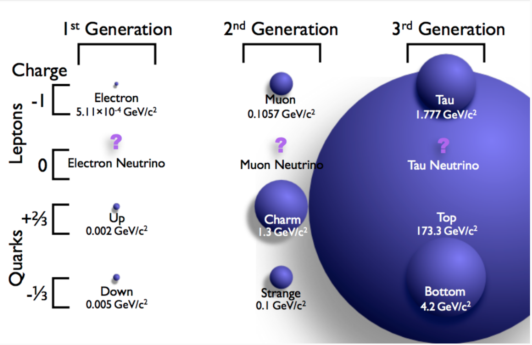
$$\begin{aligned}
\sigma(c_1, c_2, c_3) &\propto |\mathcal{M}_0 + c_1\mathcal{M}_1 + c_2\mathcal{M}_2 + c_3\mathcal{M}_3|^2 \\
&\propto \underbrace{s_0}_{\text{constant}} + \underbrace{s_1c_1 + s_2c_2 + s_3c_3}_{\text{linear}} \\
&+ \underbrace{s_4c_1^2 + s_5c_2^2 + s_6c_3^2}_{\text{quadratic}} + \underbrace{s_7c_1c_2 + s_8c_1c_3 + s_9c_2c_3}_{\text{mixed}}
\end{aligned}$$

$\mu(c_i)$ parameterization in multiple dimensions

There are only constant, linear, quadratic, and mixed terms with two parameters! If there are d operators, there will be N_s structure constants, where

$$N_s = 1 + 2d + \frac{d}{2}(d-1)$$

Top quark physics

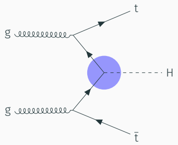


Why study EFT in the top sector?

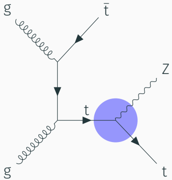
- Top's huge mass stands out— is it special?
- Top decays before hadronizing: our only chance to study a 'bare' quark

Top is so heavy that nothing decays to it $\rightarrow$ study associated production!

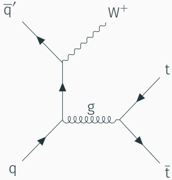
Top quark + what?



Tops + Higgs ($t\bar{t}H$): Obviously! Source of mass and most massive particle. Sign me up!



Tops + Z ($t\bar{t}Z$): Also very interesting! Direct probe of t-Z coupling!



Tops + W ($t\bar{t}W$): Not sensitive to t-W coupling in SM (can be measured via $t \to Wb$). But tops + Ws could be a sign of new physics ($X \to tW$).

Thirteen TeV analysis

We received feedback on 8 TeV paper:

- D6 operators were flavor-independent (equal coupling to all flavors) in 8 TeV analysis: this is a simplifying assumption
- Z coupling to light quarks is highly constrained by other measurements $\rightarrow$ we removed 1st and 2nd gen quark couplings in the MadGraph implementation[4]
- Makes it harder to set limits because we are only sensitive to 3rd-gen couplings, but those are exactly what we want to probe

[4]Big thanks to Adam Martin For providing the new Feynrules implementation and a great deal of additional help

Thirteen TeV results

Wilson coefficient	Best fit [TeV^{-2}]	68 % CL [TeV^{-2}]
$\bar{c}_{\mathsf{uW}}/\Lambda^2$	1.7	$[-2.4, -0.5] \cup [0.4, 2.4]$
$\lvert\bar{c}_{\mathsf{H}}/\Lambda^2 - 16.8\ \mathrm{TeV}^{-2}\rvert$	15.6	$[0, 23.0]$
$\lvert\tilde{c}_{\mathsf{3G}}/\Lambda^2\rvert$	0.5	$[0, 0.7]$
$\bar{c}_{\mathsf{3G}}/\Lambda^2$	-0.4	$[-0.6, 0.1] \cup [0.4, 0.7]$
$\bar{c}_{\mathsf{uG}}/\Lambda^2$	0.2	$[0, 0.3]$
$\lvert\bar{c}_{\mathsf{uB}}/\Lambda^2\rvert$	1.6	$[0, 2.2]$
$\bar{c}_{\mathsf{Hu}}/\Lambda^2$	-9.3	$[-10.3, -8.0] \cup [0, 2.1]$
$\bar{c}_{\mathsf{2G}}/\Lambda^2$	0.4	$[-0.9, -0.3] \cup [-0.1, 0.6]$

[1] In some cases the profile likelihood shows another local minimum the number reported here is the global minimum.