

Searching for New Physics in SMEFT Global Analyses

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Theory Meets Experiment - SMEFT for Higgs and Top

June 26th, 2020



Netherlands Organisation
for Scientific Research

Overview

- Bottom-up approach to SMEFT allows us to extract potential new physics signals directly from experimental data

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4} \mathcal{O}_j^{(8)} + \dots$$

- Higher dimension operators in SMEFT modify SM predictions:

$$\sigma = \sigma_{\text{SM}} + \sum_i^{N_{d6}} \kappa_i \frac{c_i}{\Lambda^2} + \sum_{i,j}^{N_{d6}} \tilde{\kappa}_{ij} \frac{c_i c_j}{\Lambda^4}$$

- Predictions in SMEFT can be matched to experimental data to determine bounds on Wilson coefficients

e.g. $\sigma(c_1) < (\sigma_{\text{exp}} + 2\sigma_{\text{error}}) \rightarrow$ can determine c_1 bound analytically

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- Interference with SM diagrams
- Squared SMEFT diagrams
- Interference between SMEFT

- Predictions in SMEFT can be matched to experimental data to determine bounds on Wilson coefficients

e.g. $\sigma(c_1) < (\sigma_{\text{exp}} + 2\sigma_{\text{error}}) \rightarrow$ can determine c_1 bound analytically

Bottom-Up Approach

- Best-fit parameters (Wilson coefficients) obtained by minimizing cost function:

$$\chi^2 (\{c_l\}) \equiv \frac{1}{n_{\text{dat}}} \sum_{i,j=1}^{n_{\text{dat}}} \left(\mathcal{O}_i^{(\text{th})} (\{c_l\}) - \mathcal{O}_i^{(\text{exp})} \right) (\text{cov}^{-1})_{ij} \left(\mathcal{O}_j^{(\text{th})} (\{c_l\}) - \mathcal{O}_j^{(\text{exp})} \right)$$

-Theoretical predictions (functions of SMEFT coefficients)

-Experimental data (central value)

-Covariance matrix: encodes all experimental and theoretical uncertainties

$$\text{cov}_{ij} = \text{cov}_{ij}^{(\text{exp})} + \text{cov}_{ij}^{(\text{th})}$$



Statistical and systematic
errors (uncorrelated and
correlated)

Errors from: PDFs,
Scale variation,
SMEFT truncation,
etc.

- How can we obtain reliable bounds on the fitted SMEFT coefficients?

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Errors from: PDFs, ✓
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~~SMEFT truncation,~~
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Single Parameter Fits

- One operator at a time is varied: $\sigma(c) = \sigma_{\text{SM}} + \frac{c}{\Lambda^2} \sigma_1 + \frac{c^2}{\Lambda^4} \sigma_2$
- Resulting chi-squared will have quartic form:

$$\chi^2(c) = \chi_0^2 + r_2(c - c_0)^2 + r_3(c - c_0)^3 + r_4(c - c_0)^4$$

$$\chi_0^2 = \chi^2(c_0) \text{ (minimum)}$$

- Sample chi-squared for fixed points in c , and fit r parameters
- Resulting 95% CL range:

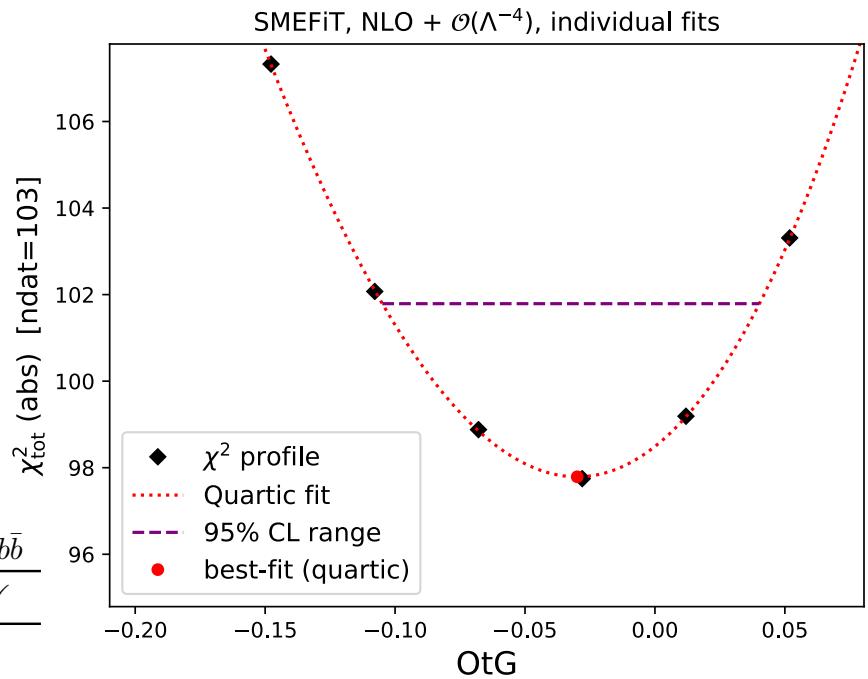
$$\chi^2 - \chi^2(c_0) \equiv \Delta\chi^2 \leq 4$$

Example:

$$\mathcal{O}_{tG} = ig_S (\bar{Q} \tau^{\mu\nu} T_A t) \tilde{\varphi} G_{\mu\nu}^A + \text{h.c.}$$

Top Production Processes:

	$t\bar{t}$	single- t	tW	tZ	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}h$	$t\bar{t}t\bar{t}$	$t\bar{t}b\bar{b}$
0tG	✓		✓		✓	✓	✓	✓	✓



Top Quark Sector

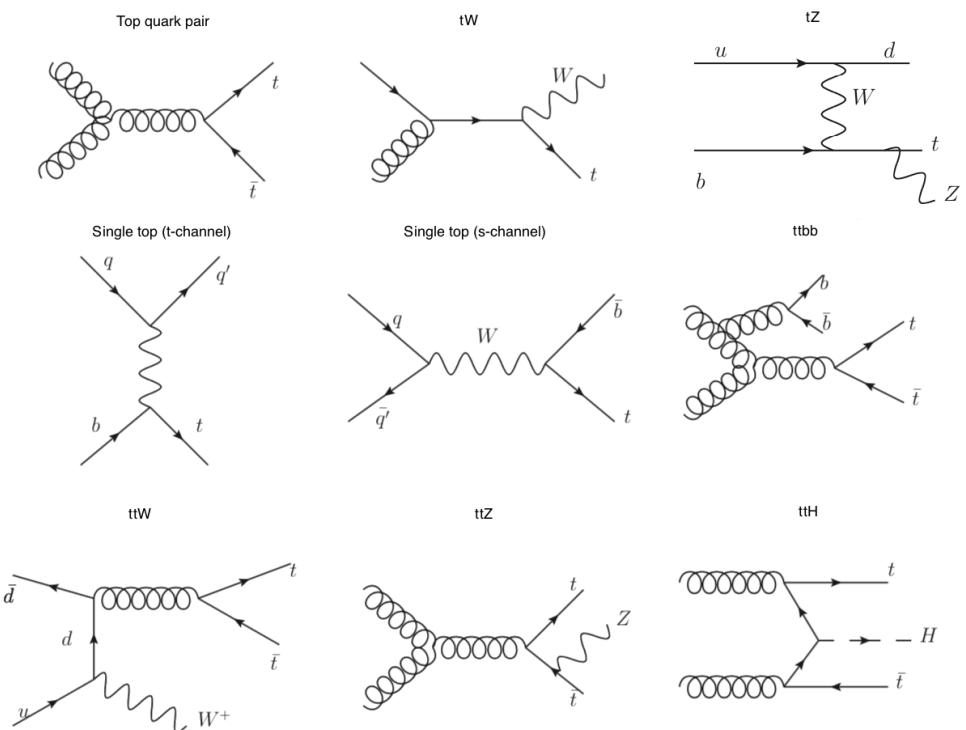
- Single parameter fits do not provide the full picture!
- Consider $d = 6$ operators associated with top production and decay at LHC
- Experimental measurements from ATLAS and CMS: Based on analysis by N. Hartland et. al.
JHEP 04 (2019) 100
arXiv: 1901.05965

→ Top pair production (+ VB / Higgs)

→ Single-top production (+ VB / Higgs)

→ Double pair production

- Many different SMEFT operators enter the same types of process — significant correlations across different channels



Top Quark Sector

Operators enter various processes at different orders in the SMEFT (and pQCD) expansion

$$(\) = \mathcal{O}(\lambda^{-4})$$

$$[] = \text{NLO}$$

Can provide insight *a priori* to level of constraint

Table from analysis by
N. Hartland et. al.
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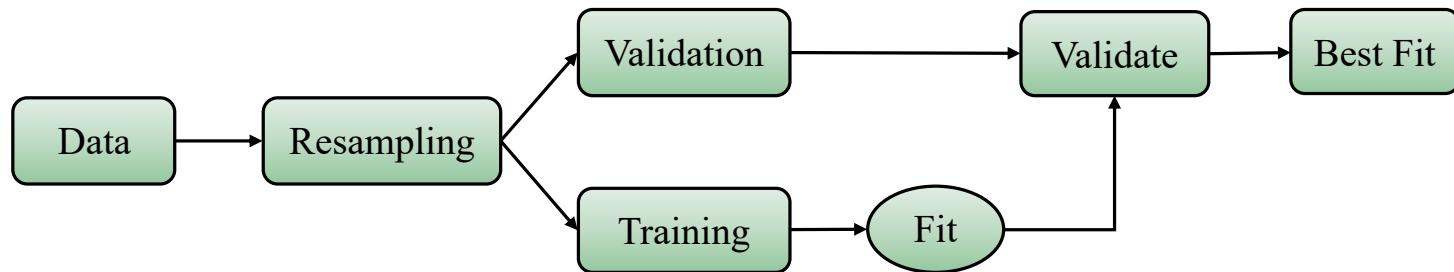
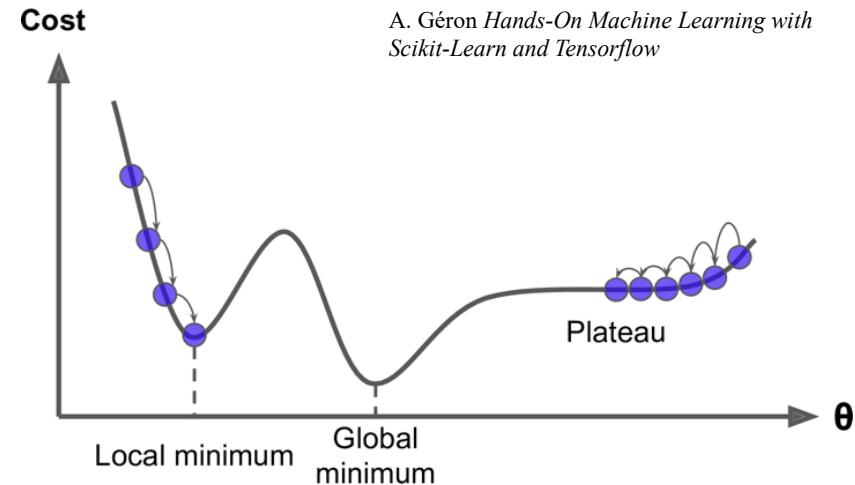
Notation	Sensitivity at $\mathcal{O}(\Lambda^{-2})$ ($\mathcal{O}(\Lambda^{-4})$)								
	$t\bar{t}$	single-top	tW	tZ	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$t\bar{t}t\bar{t}$	$t\bar{t}b\bar{b}$
OQQ1								✓	✓
OQQ8								✓	✓
OQt1								✓	✓
OQt8								✓	✓
OQb1									✓
OQb8									✓
Ott1							✓		
Otb1								✓	
Otb8								✓	
OQtQb1								(✓)	
OQtQb8								(✓)	
081qq	✓					✓	✓	✓	✓
011qq	[✓]					[✓]	[✓]	[✓]	✓
083qq	✓		[✓]			✓	✓	✓	✓
013qq	[✓]		✓			[✓]	[✓]	[✓]	✓
08qt	✓					✓	✓	✓	✓
01qt	[✓]					[✓]	[✓]	[✓]	✓
08ut	✓						✓	✓	✓
01ut	[✓]						[✓]	[✓]	✓
08qu	✓						✓	✓	✓
01qu	[✓]						[✓]	[✓]	✓
08dt	✓						✓	✓	✓
01dt	[✓]						[✓]	[✓]	✓
08qd	✓						✓	✓	✓
01qd	[✓]						[✓]	[✓]	✓
OtG	✓					✓	✓	✓	✓
OtW		✓				✓	✓	✓	✓
ObW		(✓)	(✓)	(✓)	(✓)				
OtZ						✓			
Off		(✓)	(✓)	(✓)	(✓)				
Ofq3		✓				✓			
OpqM						✓			
Opt						✓			
Otp							✓		

Global Analyses

- Analyzing experimental data (from multiple types of physics processes) to determine all relevant SMEFT parameters simultaneously
 - High-dimensional regression: 59 non-redundant $d = 6$ operators for one generation of fermions (2499 for three generations)
 - Correlations among operators from different physics sectors (top, Higgs, gauge, etc.)
- Significant advantage over single fits: provides more realistic SMEFT bounds
 - Readily available optimization techniques and tools that can reliably explore large parameter spaces
 - Monte Carlo (MC) methods for robust uncertainty estimation:
- Two approaches:
 1. MC fitting
 2. Nested Sampling

Monte Carlo Fitting (MCFit)

- Cost function minimized via gradient descent based algorithms
- Data resampling (i.e. bootstrap) to generate artificial data replicas
- Sampling of initial starting parameters from (flat) prior
- Cross validation to prevent over-fitting



- Many fits are performed to obtain a sample probability distribution:

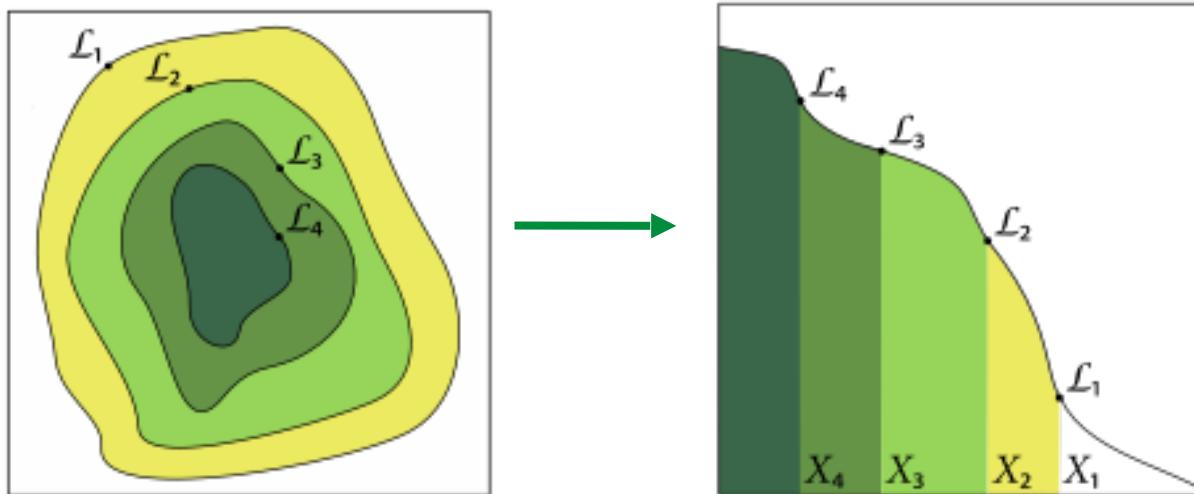
$$E[\mathcal{O}] = \frac{1}{n_{\text{rep}}} \sum_k^{n_{\text{rep}}} \mathcal{O}(\mathbf{a}_{0,k}) \quad V[\mathcal{O}] = \frac{1}{n_{\text{rep}}} \sum_k^{n_{\text{rep}}} (\mathcal{O}(\mathbf{a}_{0,k}) - E[\mathcal{O}])^2$$

Nested Sampling (NS)

- Statistical mapping of multidimensional integral to 1-D

$$Z = \int d^n a \mathcal{L}(\text{data} | \vec{a}) \pi(\vec{a}) = \int_0^1 dX \mathcal{L}(X) \quad \mathcal{L} \propto e^{-\frac{1}{2} \chi^2}$$

where the *prior volume* $dX = \pi(\vec{a}) d^n a$



$$Z_i \sim \sum_i \mathcal{L}_i w_i$$

$$w_i = \frac{1}{2} (X_{i-1} - X_{i+1})$$

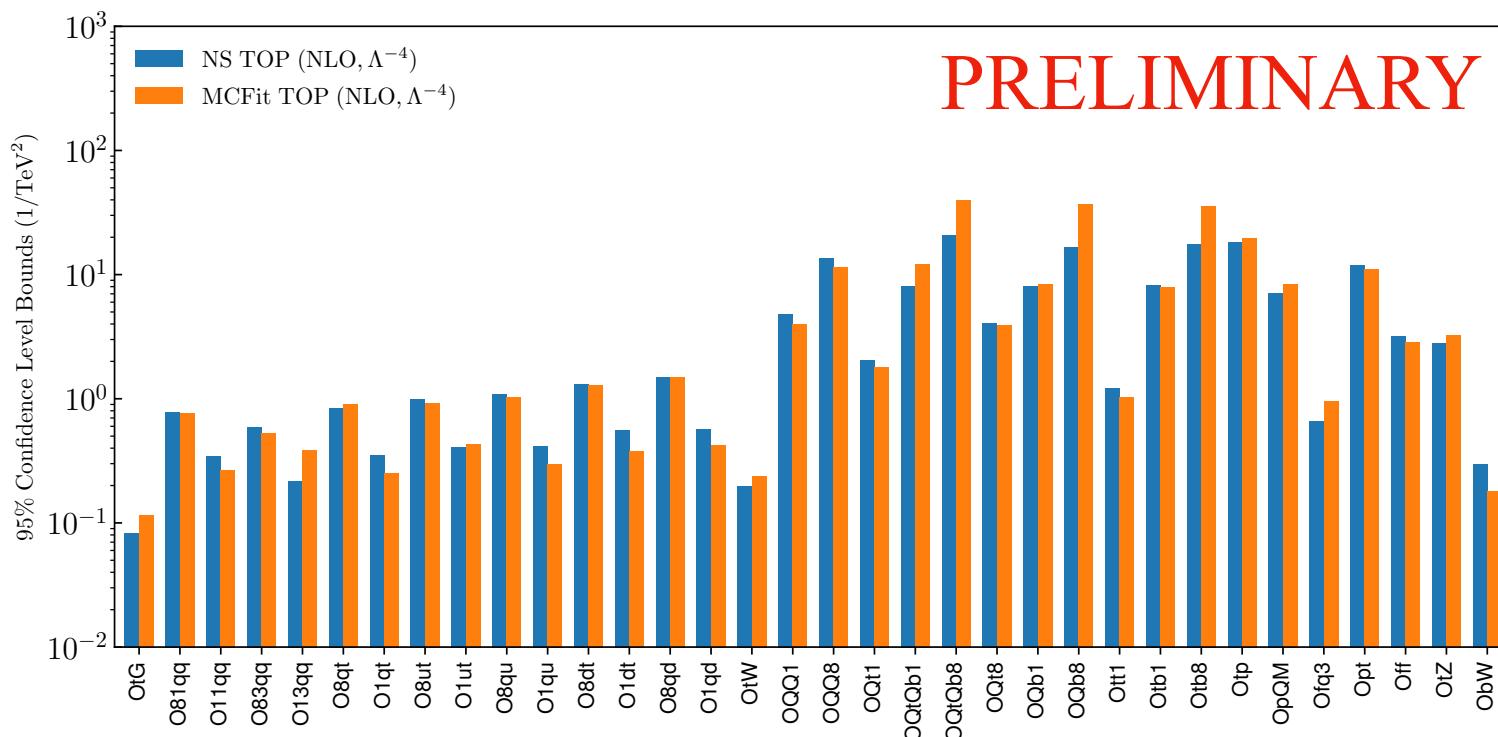
Feroz et al. arXiv:1306.2144
[astro-ph]

- Algorithm samples the prior volume to locate region of maximum likelihood
- Posterior samples obtained as a by-product of computing evidence Z

$$E[\mathcal{O}(\vec{a})] = \sum_k w_k \mathcal{O}(\vec{a}_k) \quad V[\mathcal{O}(\vec{a})] = \sum_k w_k (\mathcal{O}(\vec{a}_k) - E[\mathcal{O}])^2$$

Top Quark Sector (revisited)

- 103 data points from top quark production at LHC (top pair, single top, double pair)
- 34 degrees of freedom (SMEFT operator coefficients)
- SM theory: NNLO QCD for top pair + single top (s-channel), NLO for others
- SMEFT theory: NLO QCD where available, LO + (SM) K-factors for remaining



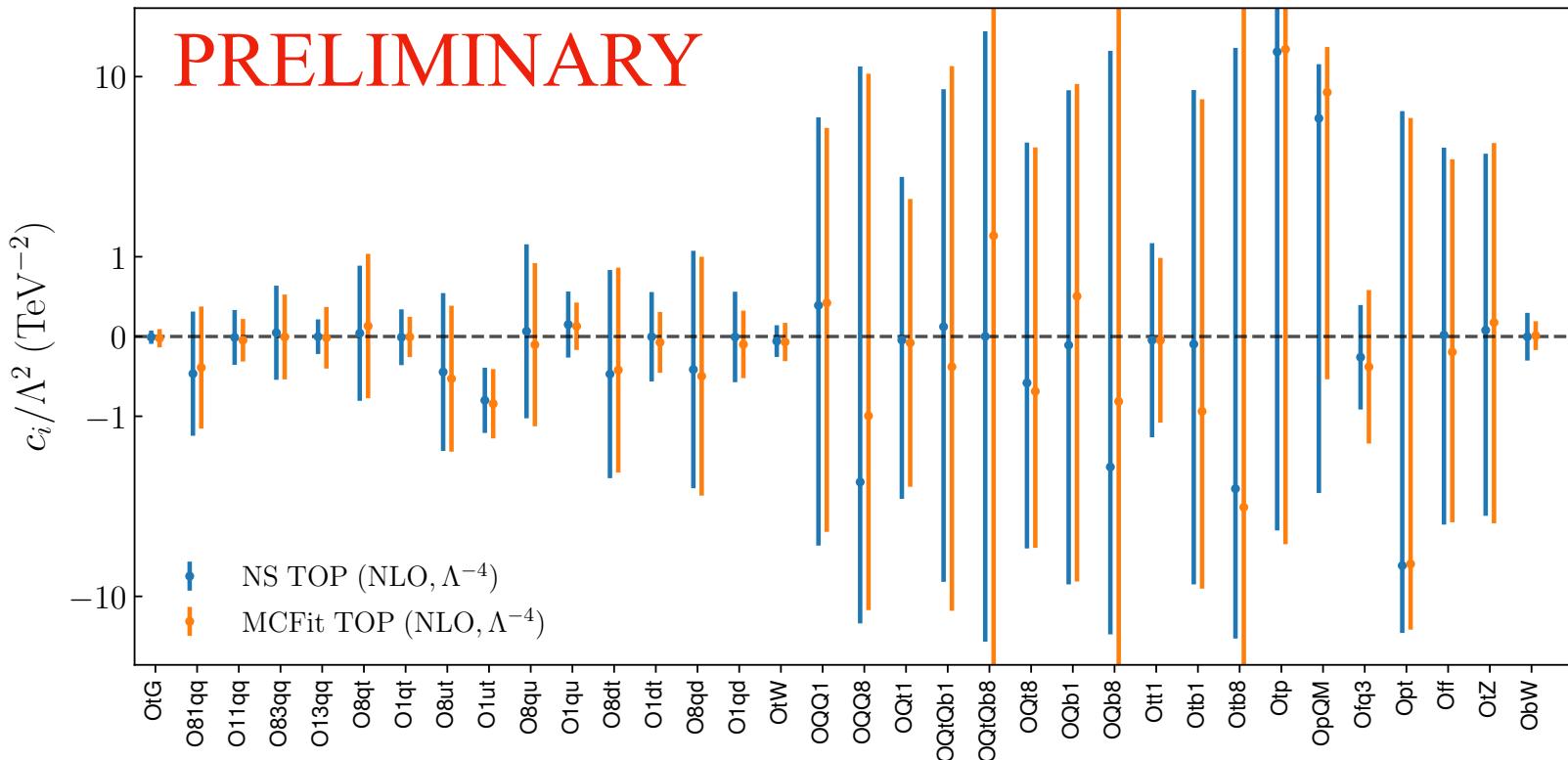
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JHEP 04 (2019) 100

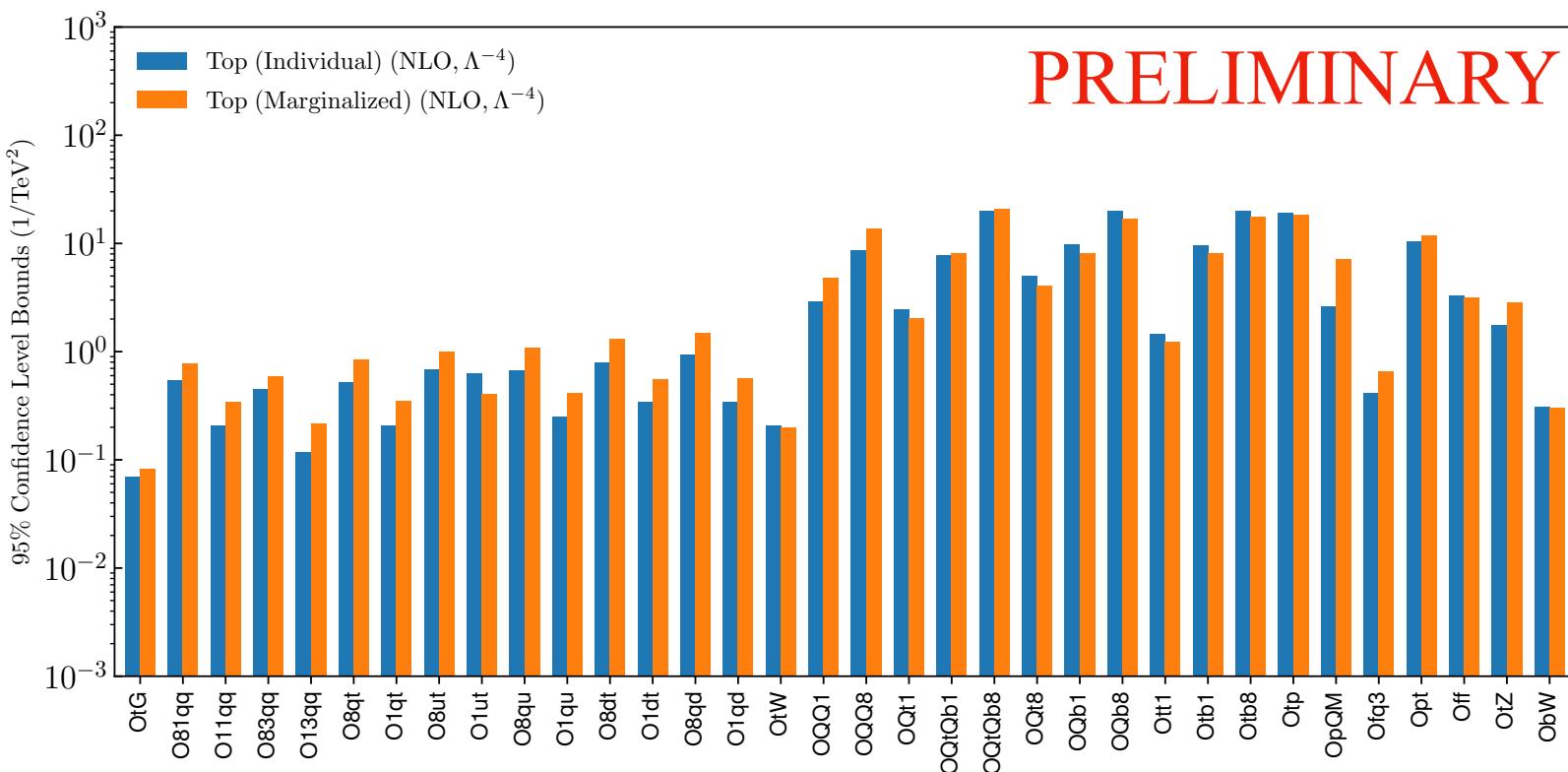
arXiv:1901.05965

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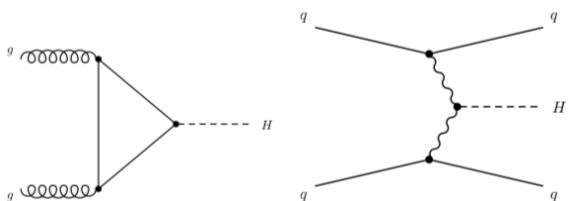
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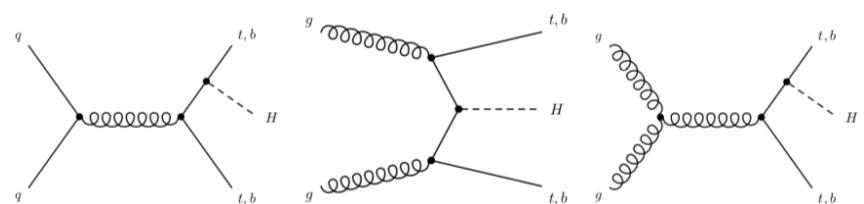
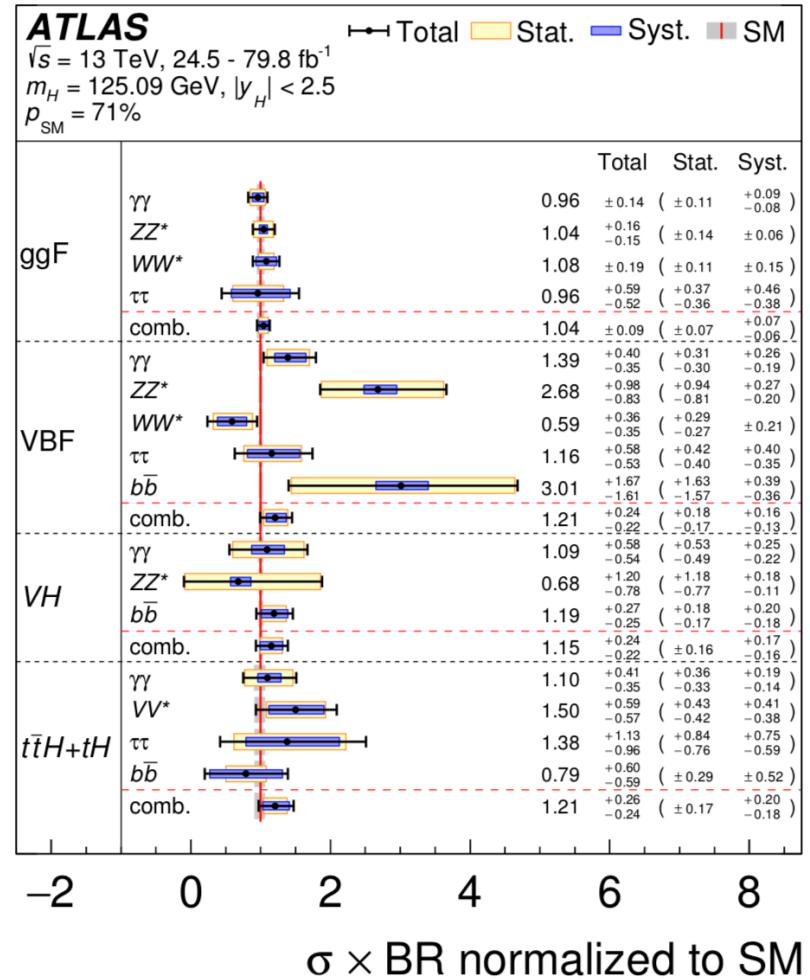
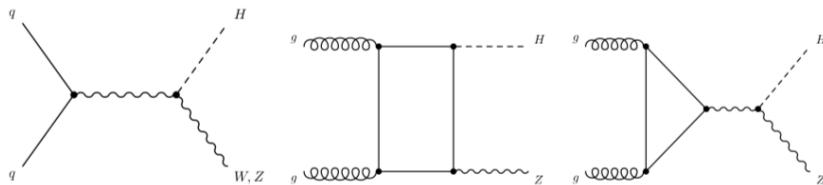
Adding the Higgs Sector

- All Run I and Run II signal strengths from ATLAS and CMS
- p_T and y_H differential distributions from Run II ATLAS and CMS

ggF and VBF:

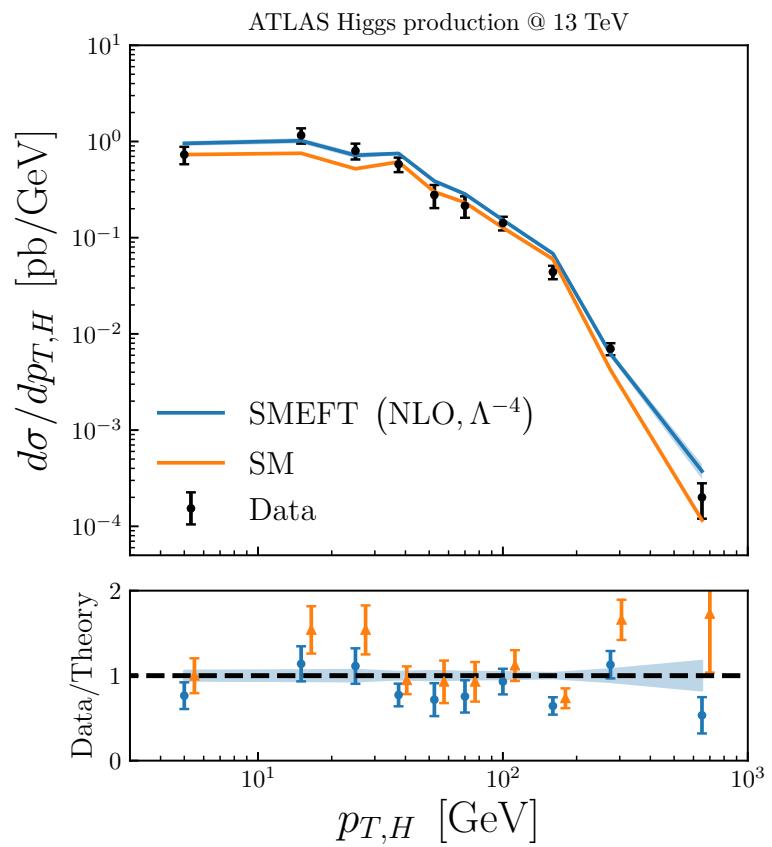
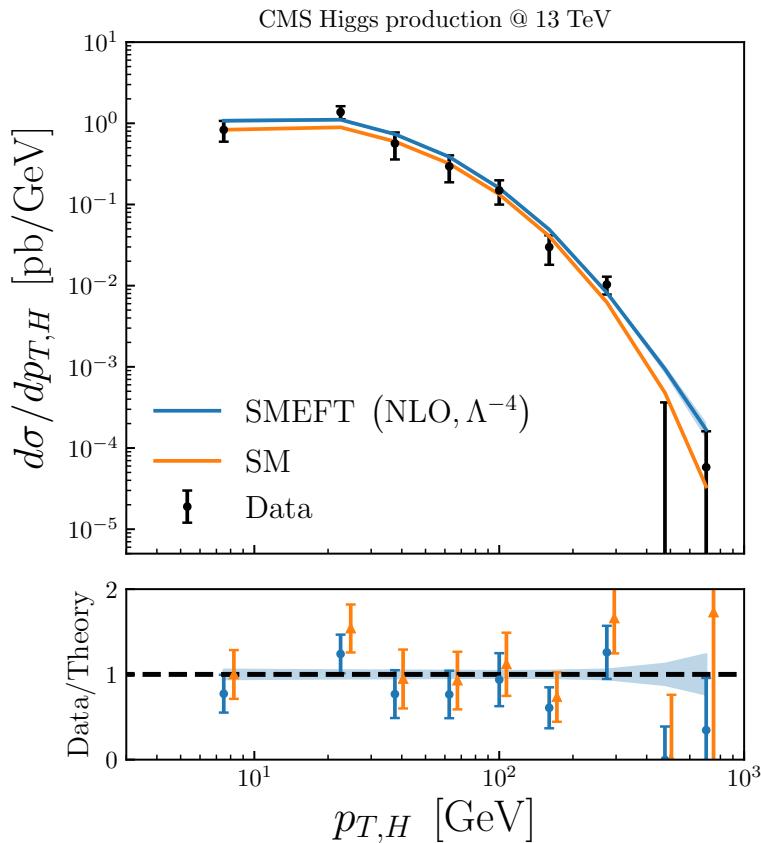


VH and ttH:



Adding the Higgs Sector

- All Run I and Run II signal strengths from ATLAS and CMS
- p_T and y_H differential distributions from Run II ATLAS and CMS



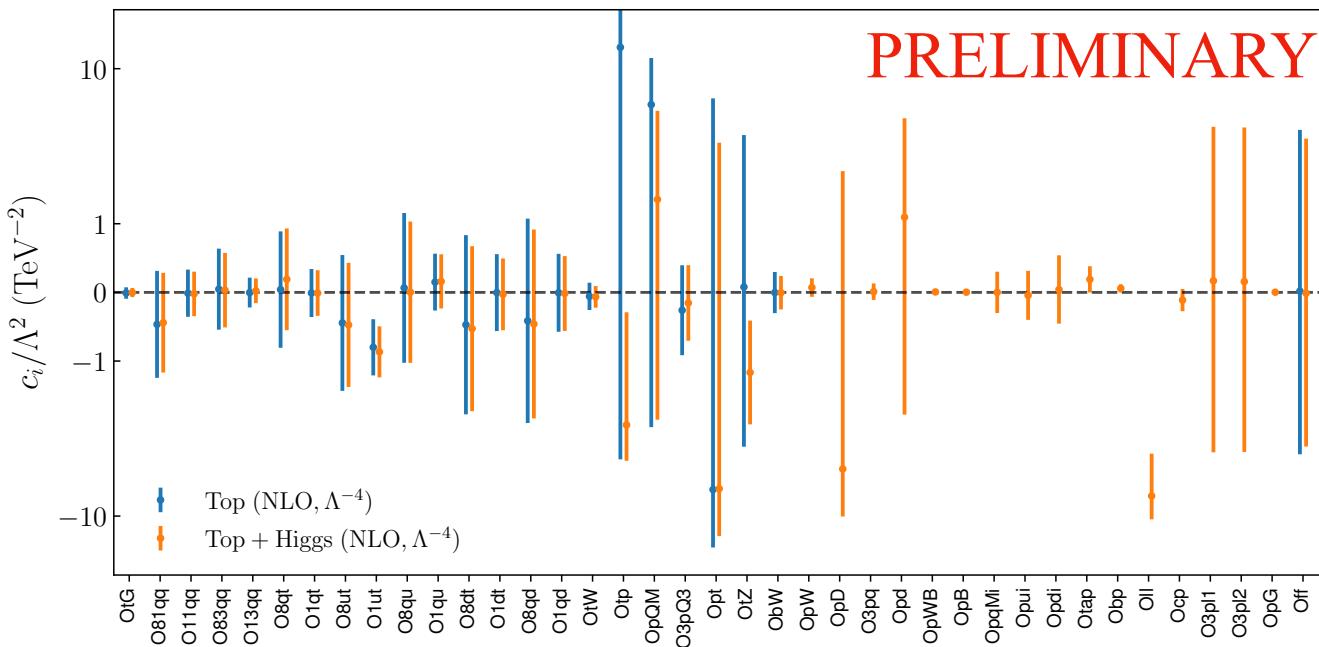
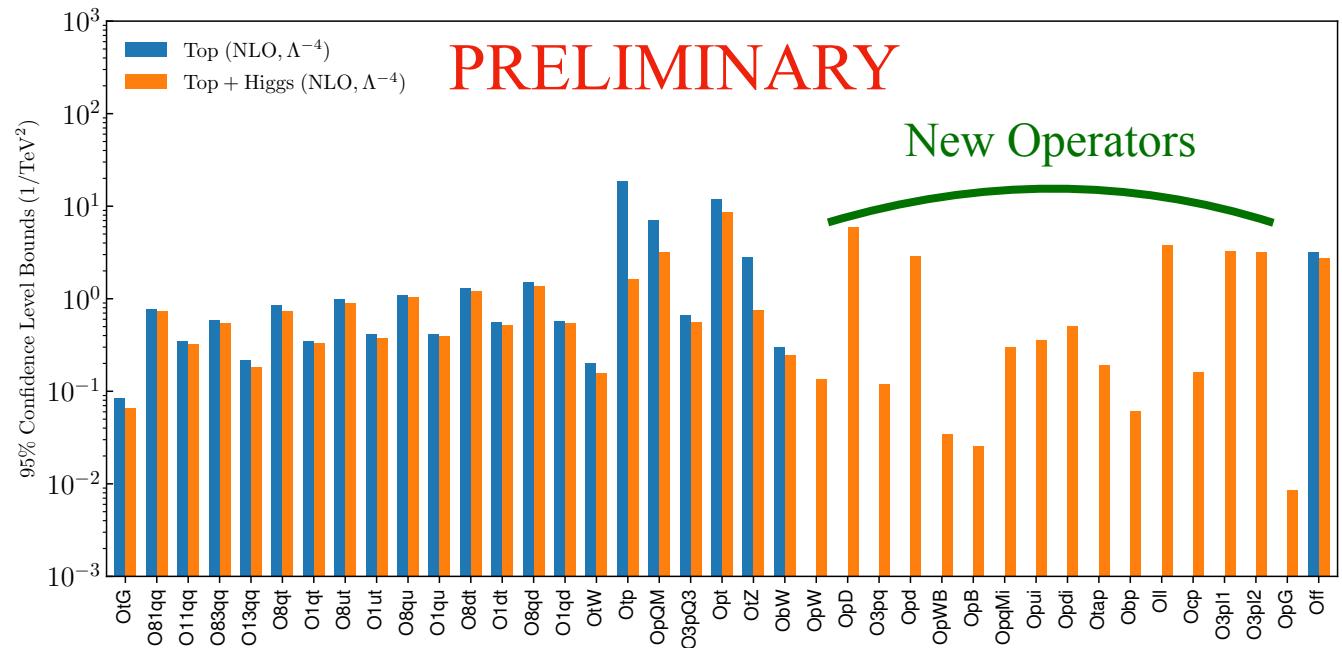
$\chi^2/N_{\text{data}} = 2.19$ (SM) $\rightarrow 0.76$ (SMEFT)

CMS

$\chi^2/N_{\text{data}} = 0.80$ (SM) $\rightarrow 1.00$ (SMEFT)

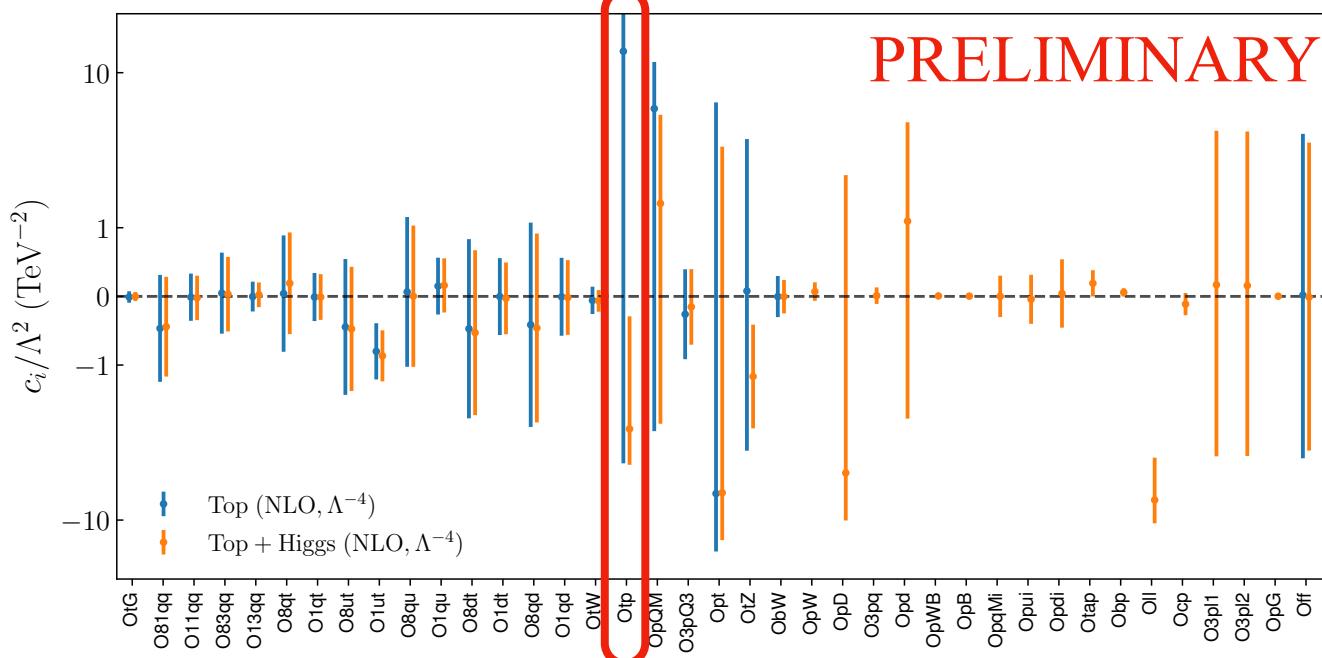
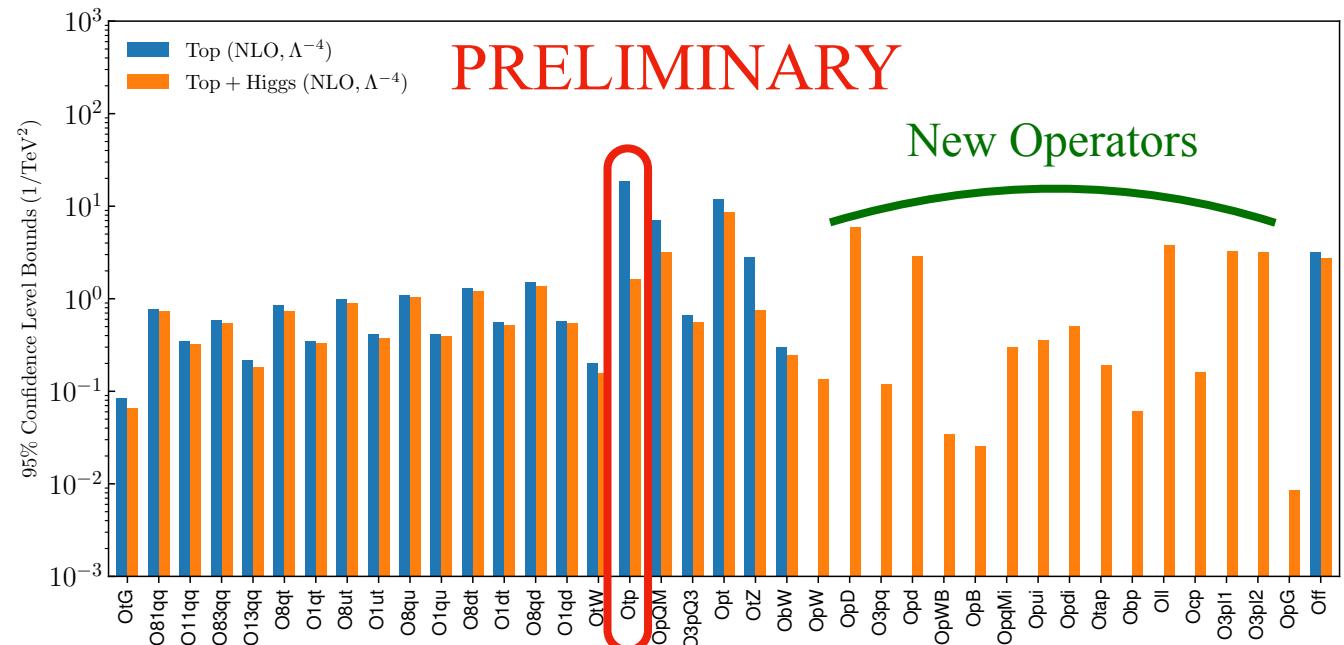
Global Fits

Top Only
vs
Top + Higgs



Global Fits

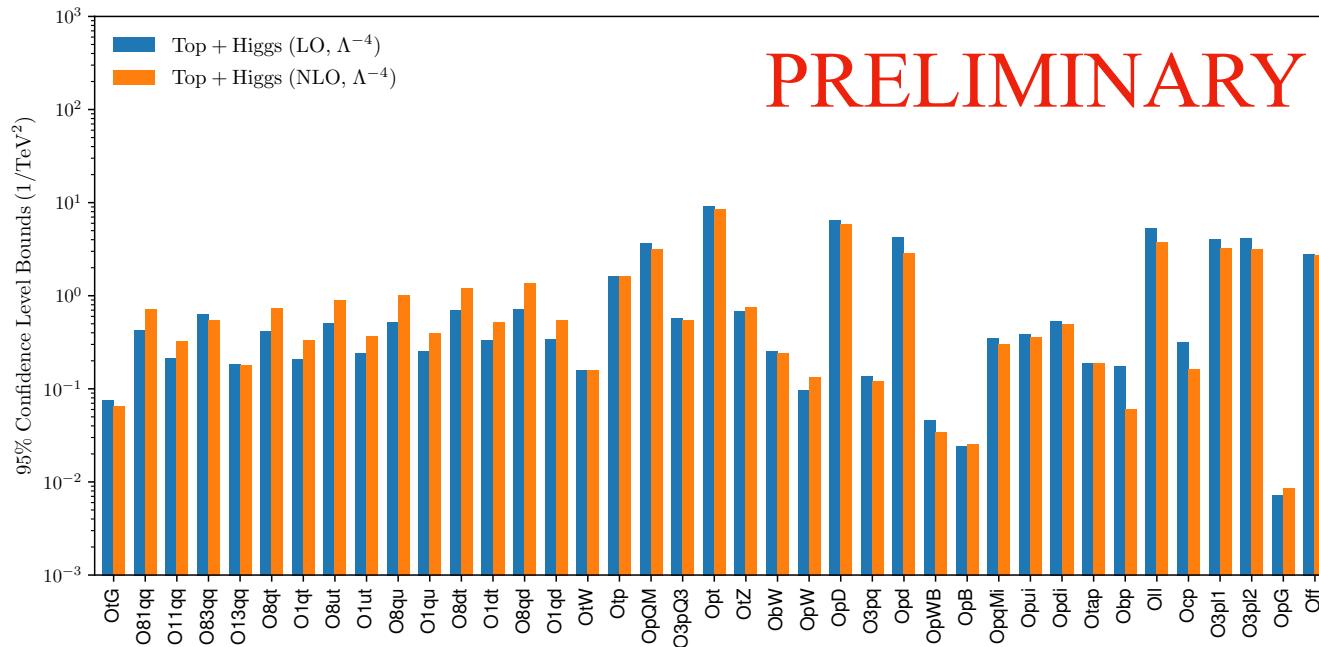
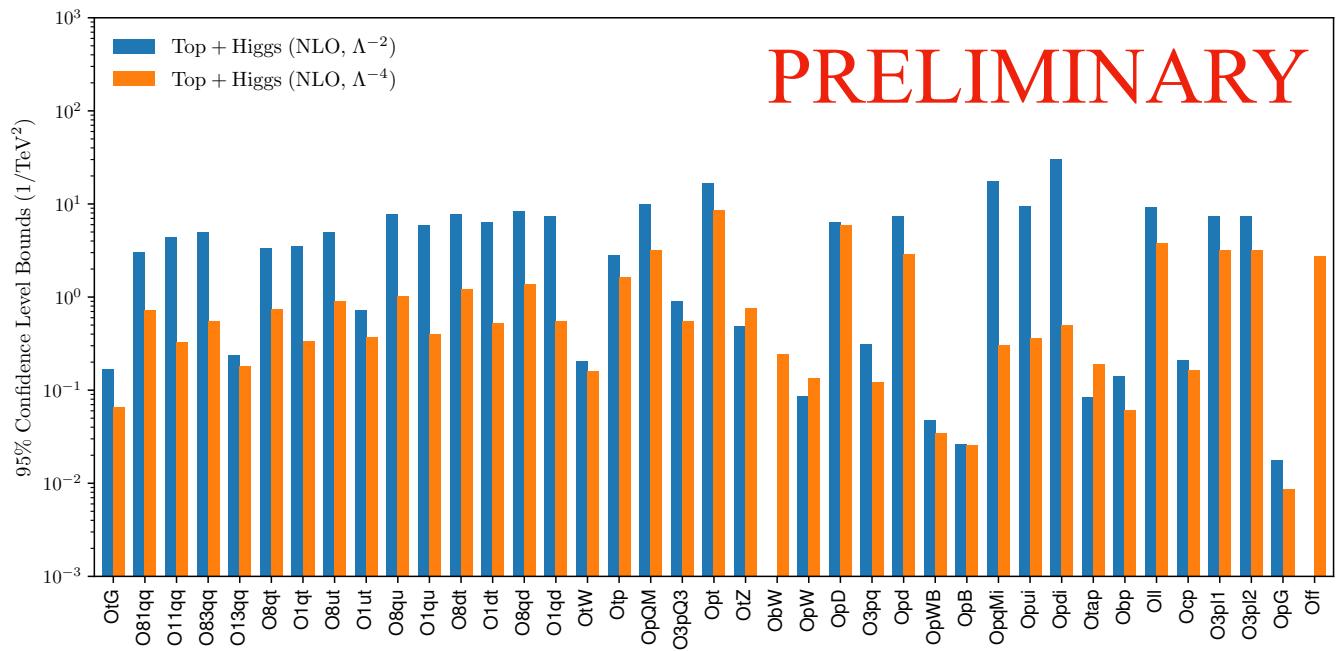
Top Only
vs
Top + Higgs



Important constraints on top Yukawa coupling

Variations

Linear vs Quadratic



LO vs NLO QCD

Summary and Outlook

- Global analyses of SMEFT parameters will play a major role in the search of BSM signals in experimental data
 - Monte Carlo methods needed to explore multidimensional parameter space and obtain reliable bounds on operator coefficients
- Future improvements in theory and experiment will allow more robust analyses:
 - Theory: higher order pQCD calculations in SMEFT, errors from missing h.o.
 - Experiment: precision measurements, full breakdown of correlated errors (also including correlations between bins of different distributions...?)
- SMEFiT collaboration quickly progressing towards a full combined top+Higgs analysis
 - Towards modern machine learning tools, new and improved Monte Carlo methods
- Can extend SMEFiT framework to account for low-energy measurements in a fully consistent way

Extra Slides

Monte Carlo Methods

- Based on Bayesian principles:

$$E[\mathcal{O}] = \int d^n a \mathcal{P}(\mathbf{a}|D) \mathcal{O}(\mathbf{a}) \quad V[\mathcal{O}] = \int d^n a \mathcal{P}(\mathbf{a}|D) (\mathcal{O}(\mathbf{a}) - E[\mathcal{O}])^2$$

- Bayes' theorem:

$$\mathcal{P}(\vec{a}|data) = \frac{1}{Z} \mathcal{L}(data|\vec{a}) \pi(\vec{a})$$

Monte Carlo Methods

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- Bayes' theorem:

$$\mathcal{P}(\vec{a}|data) = \frac{1}{Z} \mathcal{L}(data|\vec{a}) \pi(\vec{a})$$

“Evidence” $Z = \int d^n a \mathcal{L}(data|\vec{a}) \pi(\vec{a})$

Monte Carlo Methods

- Based on Bayesian principles:

$$E[\mathcal{O}] = \int d^n a \mathcal{P}(\mathbf{a}|D) \mathcal{O}(\mathbf{a}) \quad V[\mathcal{O}] = \int d^n a \mathcal{P}(\mathbf{a}|D) (\mathcal{O}(\mathbf{a}) - E[\mathcal{O}])^2$$

- Bayes' theorem:

$$\mathcal{P}(\vec{a}|data) = \frac{1}{Z} \mathcal{L}(data|\vec{a}) \pi(\vec{a})$$

- Monte Carlo approximation:

$$E[\mathcal{O}(\vec{a})] = \sum_k w_k \mathcal{O}(\vec{a}_k) \quad V[\mathcal{O}(\vec{a})] = \sum_k w_k (\mathcal{O}(\vec{a}_k) - E[\mathcal{O}])^2$$

SMEFiT Analysis: Top Sector

- Analysis of $d = 6$ operators associated with top production and decay at LHC
- Includes measurements from ATLAS and CMS:

Process	Dataset	\sqrt{s}	Info	Observables	N_{dat}
$t\bar{t}$	ATLAS_tt_8TeV_1jets	8 TeV	lepton+jets	$d\sigma/d y_t , d\sigma/dp_t^T, d\sigma/dm_{t\bar{t}}, d\sigma/d y_{t\bar{t}} $	5, 8, 7, 5
$t\bar{t}$	CMS_tt_8TeV_1jets	8 TeV	lepton+jets	$d\sigma/dy_t, d\sigma/dp_t^T, d\sigma/dm_{t\bar{t}}, d\sigma/dy_{t\bar{t}}$	10, 8, 7, 10
$t\bar{t}$	CMS_tt2D_8TeV_dilep	8 TeV	dileptons	$d^2\sigma/dy_t dp_t^T, d^2\sigma/dy_t dm_{t\bar{t}}, d^2\sigma/dp_{t\bar{t}}^T dm_{t\bar{t}}, d^2\sigma/dy_{t\bar{t}} dm_{t\bar{t}}$	16, 16, 16, 16
$t\bar{t}$	CMS_tt_13TeV_1jets	13 TeV	lepton+jets	$d\sigma/d y_t , d\sigma/dp_t^T, d\sigma/dm_{t\bar{t}}, d\sigma/d y_{t\bar{t}} $	7, 9, 8, 6
$t\bar{t}$	CMS_tt_13TeV_1jets2	13 TeV	lepton+jets	$d\sigma/d y_t , d\sigma/dp_t^T, d\sigma/dm_{t\bar{t}}, d\sigma/d y_{t\bar{t}} $	11, 12, 10, 10
$t\bar{t}$	CMS_tt_13TeV_dilep	13 TeV	dileptons	$d\sigma/dy_t, d\sigma/dp_t^T, d\sigma/dm_{t\bar{t}}, d\sigma/dy_{t\bar{t}}$	8, 6, 6, 8
$t\bar{t}$	ATLAS_WhelF_8TeV	8 TeV	W helicity fract	F_0, F_L, F_R	3
$t\bar{t}$	CMS_WhelF_8TeV	8 TeV	W helicity fract	F_0, F_L, F_R	3

SMEFiT Analysis: Top Sector

- Analysis of $d = 6$ operators associated with top production and decay at LHC
- Includes measurements from ATLAS and CMS:

Process	Dataset	\sqrt{s}	Info	Observables	N_{dat}
$t\bar{t}b\bar{b}$	CMS_ttbb_13TeV	13 TeV	total xsec	$\sigma_{\text{tot}}(t\bar{t}b\bar{b})$	1
$t\bar{t}t\bar{t}$	CMS_tttt_13TeV	13 TeV	total xsec	$\sigma_{\text{tot}}(t\bar{t}t\bar{t})$	1
$t\bar{t}Z$	CMS_ttZ_8_13TeV	8+13 TeV	total xsec	$\sigma_{\text{tot}}(t\bar{t}Z)$	2
$t\bar{t}Z$	ATLAS_ttZ_8_13TeV	8+13 TeV	total xsec	$\sigma_{\text{tot}}(t\bar{t}Z)$	2
$t\bar{t}W$	CMS_ttW_8_13TeV	8+13 TeV	total xsec	$\sigma_{\text{tot}}(t\bar{t}W)$	2
$t\bar{t}W$	ATLAS_ttW_8_13TeV	8+13 TeV	total xsec	$\sigma_{\text{tot}}(t\bar{t}W)$	2
$t\bar{t}H$	CMS_tth_13TeV	13 TeV	signal strength	$\mu_{t\bar{t}H}$	1
$t\bar{t}H$	ATLAS_tth_13TeV	13 TeV	total xsec	$\sigma_{\text{tot}}(t\bar{t}H)$	1

SMEFiT Analysis: Top Sector

- Analysis of $d = 6$ operators associated with top production and decay at LHC
- Includes measurements from ATLAS and CMS:

Process	Dataset	\sqrt{s}	Info	Observables	N_{dat}
Single t	CMS_t_tch_8TeV_inc	8 TeV	t -channel	$\sigma_{\text{tot}}(t), \sigma_{\text{tot}}(\bar{t}) (R_t)$	2 (1)
Single t	CMS_t_sch_8TeV	8 TeV	s -channel	$\sigma_{\text{tot}}(t + \bar{t})$	1
Single t	ATLAS_t_sch_8TeV	8 TeV	s -channel	$\sigma_{\text{tot}}(t + \bar{t})$	1
Single t	ATLAS_t_tch_8TeV	8 TeV	t -channel	$d\sigma(tq)/dp_T^t, d\sigma(\bar{t}q)/dp_T^{\bar{t}}, d\sigma(tq)/dy_t, d\sigma(\bar{t}q)/dy_t$	5, 4 4, 4
Single t	ATLAS_t_tch_13TeV	13 TeV	t -channel	$\sigma_{\text{tot}}(t), \sigma_{\text{tot}}(\bar{t}) (R_t)$	2 (1)
Single t	CMS_t_tch_13TeV_inc	13 TeV	t -channel	$\sigma_{\text{tot}}(t + \bar{t}) (R_t)$	1 (1)
Single t	CMS_t_tch_8TeV_dif	8 TeV	t -channel	$d\sigma/dp_T^{(t+\bar{t})}, d\sigma/d y^{(t+\bar{t})} $	6 6
Single t	CMS_t_tch_13TeV_dif	13 TeV	t -channel	$d\sigma/dp_T^{(t+\bar{t})}, d\sigma/d y^{(t+\bar{t})} $	4 4
tW	ATLAS_tW_inc_8TeV	8 TeV	inclusive	$\sigma_{\text{tot}}(tW)$	1
tW	CMS_tW_inc_8TeV	8 TeV	inclusive	$\sigma_{\text{tot}}(tW)$	1
tW	ATLAS_tW_inc_13TeV	13 TeV	inclusive	$\sigma_{\text{tot}}(tW)$	1
tW	CMS_tW_inc_13TeV	13 TeV	inclusive	$\sigma_{\text{tot}}(tW)$	1
tZ	CMS_tZ_inc_13TeV	13 TeV	inclusive	$\sigma_{\text{fid}}(Wbl^+l^-q)$	1
tZ	ATLAS_tZ_inc_13TeV	13 TeV	inclusive	$\sigma_{\text{tot}}(tZq)$	1

SMEFiT Analysis: Top Sector

- Analysis of $d = 6$ operators associated with top production and decay at LHC
- Theoretical calculations:

Process	SM	Code	SMEFT	Code
$t\bar{t}$	NNLO QCD	MCFM/SHERPA NLO + NNLO K -factors	NLO QCD	MG5_aMC
single- t (t -ch)	NNLO QCD	MCFM NLO + NNLO K -factors	NLO QCD	MG5_aMC
single- t (s -ch)	NLO QCD	MCFM	NLO QCD	MG5_aMC
tW	NLO QCD	MG5_aMC	NLO QCD	MG5_aMC
tZ	NLO QCD	MG5_aMC	LO QCD + NLO SM K -factors	MG5_aMC
$t\bar{t}W(Z)$	NLO QCD	MG5_aMC	LO QCD + NLO SM K -factors	MG5_aMC
$t\bar{t}h$	NLO QCD	MG5_aMC	LO QCD + NLO SM K -factors	MG5_aMC
$t\bar{t}\bar{t}\bar{t}$	NLO QCD	MG5_aMC	LO QCD + NLO SM K -factors	MG5_aMC
$t\bar{t}b\bar{b}$	NLO QCD	MG5_aMC	LO QCD + NLO SM K -factors	MG5_aMC

SMEFiT Analysis: Top Sector

- Analysis of d = 6 operators associated with top production and decay at LHC

Degrees of freedom: 4-heavy

$$c_{QQ}^1 \equiv 2C_{qq}^{1(3333)} - \frac{2}{3}C_{qq}^{3(3333)}$$

$$c_{QQ}^8 \equiv 8C_{qq}^{3(3333)}$$

$$c_{Qt}^1 \equiv C_{qu}^{1(3333)}$$

$$c_{Qt}^8 \equiv C_{qu}^{8(3333)}$$

$$c_{Qb}^1 \equiv C_{qd}^{1(3333)}$$

$$c_{Qb}^8 \equiv C_{qd}^{8(3333)}$$

$$c_{tt}^1 \equiv C_{uu}^{1(3333)}$$

$$c_{tb}^1 \equiv C_{ud}^{1(3333)}$$

$$c_{tb}^8 \equiv C_{ud}^{8(3333)}$$

$$c_{QtQb}^1 \equiv \text{Re}\{C_{quqd}^{1(3333)}\}$$

$$c_{QtQb}^8 \equiv \text{Re}\{C_{quqd}^{8(3333)}\}$$

4-fermion operators in Warsaw basis

$$O_{qq}^{1(ijkl)} = (\bar{q}_i \gamma^\mu q_j)(\bar{q}_k \gamma_\mu q_l)$$

$$O_{qq}^{3(ijkl)} = (\bar{q}_i \gamma^\mu \tau^I q_j)(\bar{q}_k \gamma_\mu \tau^I q_l)$$

$$O_{qu}^{1(ijkl)} = (\bar{q}_i \gamma^\mu q_j)(\bar{u}_k \gamma_\mu u_l)$$

$$O_{qu}^{8(ijkl)} = (\bar{q}_i \gamma^\mu T^A q_j)(\bar{u}_k \gamma_\mu T^A u_l)$$

$$O_{qd}^{1(ijkl)} = (\bar{q}_i \gamma^\mu q_j)(\bar{d}_k \gamma_\mu d_l)$$

$$O_{qd}^{8(ijkl)} = (\bar{q}_i \gamma^\mu T^A q_j)(\bar{d}_k \gamma_\mu T^A d_l)$$

$$O_{uu}^{(ijkl)} = (\bar{u}_i \gamma^\mu u_j)(\bar{u}_k \gamma_\mu u_l)$$

$$O_{ud}^{1(ijkl)} = (\bar{u}_i \gamma^\mu u_j)(\bar{d}_k \gamma_\mu d_l)$$

$$O_{ud}^{8(ijkl)} = (\bar{u}_i \gamma^\mu T^A u_j)(\bar{d}_k \gamma_\mu T^A d_l)$$

$$\dagger O_{quqd}^{1(ijkl)} = (\bar{q}_i u_j) \varepsilon (\bar{q}_k d_l)$$

$$\dagger O_{quqd}^{8(ijkl)} = (\bar{q}_i T^A u_j) \varepsilon (\bar{q}_k T^A d_l)$$

SMEFiT Analysis: Top Sector

- Analysis of d = 6 operators associated with top production and decay at LHC

Degrees of freedom: 2-heavy-2-light

$$c_{Qq}^{1,1} \equiv C_{qq}^{1(ii33)} + \frac{1}{6}C_{qq}^{1(i33i)} + \frac{1}{2}C_{qq}^{3(i33i)}$$

$$c_{Qq}^{3,1} \equiv C_{qq}^{3(ii33)} + \frac{1}{6}(C_{qq}^{1(i33i)} - C_{qq}^{3(i33i)})$$

$$c_{Qq}^{1,8} \equiv C_{qq}^{1(i33i)} + 3C_{qq}^{3(i33i)}$$

$$c_{Qq}^{3,8} \equiv C_{qq}^{1(i33i)} - C_{qq}^{3(i33i)}$$

$$c_{tu}^1 \equiv C_{uu}^{(ii33)} + \frac{1}{3}C_{uu}^{(i33i)}$$

$$c_{tu}^8 \equiv 2C_{uu}^{(i33i)}$$

$$c_{td}^1 \equiv C_{ud}^{1(33ii)}$$

$$c_{td}^8 \equiv C_{ud}^{8(33ii)}$$

$$c_{tq}^1 \equiv C_{qu}^{1(ii33)}$$

$$c_{Qu}^1 \equiv C_{qu}^{1(33ii)}$$

$$c_{Qd}^1 \equiv C_{qd}^{1(33ii)}$$

$$c_{tq}^8 \equiv C_{qu}^{8(ii33)}$$

$$c_{Qu}^8 \equiv C_{qu}^{8(33ii)}$$

$$c_{Qd}^8 \equiv C_{qd}^{8(33ii)}$$

4-fermion operators in Warsaw basis

$$O_{qq}^{1(ijkl)} = (\bar{q}_i \gamma^\mu q_j)(\bar{q}_k \gamma_\mu q_l)$$

$$O_{qq}^{3(ijkl)} = (\bar{q}_i \gamma^\mu \tau^I q_j)(\bar{q}_k \gamma_\mu \tau^I q_l)$$

$$O_{qu}^{1(ijkl)} = (\bar{q}_i \gamma^\mu q_j)(\bar{u}_k \gamma_\mu u_l)$$

$$O_{qu}^{8(ijkl)} = (\bar{q}_i \gamma^\mu T^A q_j)(\bar{u}_k \gamma_\mu T^A u_l)$$

$$O_{qd}^{1(ijkl)} = (\bar{q}_i \gamma^\mu q_j)(\bar{d}_k \gamma_\mu d_l)$$

$$O_{qd}^{8(ijkl)} = (\bar{q}_i \gamma^\mu T^A q_j)(\bar{d}_k \gamma_\mu T^A d_l)$$

$$O_{uu}^{(ijkl)} = (\bar{u}_i \gamma^\mu u_j)(\bar{u}_k \gamma_\mu u_l)$$

$$O_{ud}^{1(ijkl)} = (\bar{u}_i \gamma^\mu u_j)(\bar{d}_k \gamma_\mu d_l)$$

$$O_{ud}^{8(ijkl)} = (\bar{u}_i \gamma^\mu T^A u_j)(\bar{d}_k \gamma_\mu T^A d_l)$$

$$\ddagger O_{quqd}^{1(ijkl)} = (\bar{q}_i u_j) \varepsilon (\bar{q}_k d_l)$$

$$\ddagger O_{quqd}^{8(ijkl)} = (\bar{q}_i T^A u_j) \varepsilon (\bar{q}_k T^A d_l)$$

SMEFiT Analysis: Top Sector

- Analysis of d = 6 operators associated with top production and decay at LHC

Degrees of freedom: 2-heavy + gauge/Higgs

$$c_{t\varphi} \equiv \text{Re}\{C_{u\varphi}^{(33)}\}$$

$$c_{\varphi Q}^- \equiv C_{\varphi q}^{1(33)} - C_{\varphi q}^{3(33)}$$

$$c_{\varphi Q}^3 \equiv C_{\varphi q}^{3(33)}$$

$$c_{\varphi t} \equiv C_{\varphi u}^{(33)}$$

$$c_{\varphi tb} \equiv \text{Re}\{C_{\varphi ud}^{(33)}\}$$

$$c_{tW} \equiv \text{Re}\{C_{uW}^{(33)}\}$$

$$c_{tZ} \equiv \text{Re}\{-s_W C_{uB}^{(33)} + c_W C_{uW}^{(33)}\}$$

$$c_{bW} \equiv \text{Re}\{C_{dW}^{(33)}\}$$

$$c_{tG} \equiv \text{Re}\{C_{uG}^{(33)}\}$$

Gauge/Higgs operators in Warsaw basis

$$\dagger O_{u\varphi}^{(ij)} = \bar{q}_i u_j \tilde{\varphi} (\varphi^\dagger \varphi)$$

$$O_{\varphi q}^{1(ij)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{q}_i \gamma^\mu q_j)$$

$$O_{\varphi q}^{3(ij)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi) (\bar{q}_i \gamma^\mu \tau^I q_j)$$

$$O_{\varphi u}^{(ij)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{u}_i \gamma^\mu u_j)$$

$$\dagger O_{\varphi ud}^{(ij)} = (\tilde{\varphi}^\dagger i D_\mu \varphi) (\bar{u}_i \gamma^\mu d_j)$$

$$\dagger O_{uW}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} \tau^I u_j) \tilde{\varphi} W_{\mu\nu}^I$$

$$\dagger O_{dW}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} \tau^I d_j) \varphi W_{\mu\nu}^I$$

$$\dagger O_{uB}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} u_j) \tilde{\varphi} B_{\mu\nu}$$

$$\dagger O_{uG}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} T^A u_j) \tilde{\varphi} G_{\mu\nu}^A$$

SMEFiT Analysis: Top Sector

Class	Notation	Degree of Freedom	Operator Definition
QQQQ	0QQ1	c_{QQ}^1	$2C_{qq}^{1(3333)} - \frac{2}{3}C_{qq}^{3(3333)}$
	0QQ8	c_{QQ}^8	$8C_{qq}^{3(3333)}$
	0Qt1	c_{Qt}^1	$C_{qu}^{1(3333)}$
	0Qt8	c_{Qt}^8	$C_{qu}^{8(3333)}$
	0Qb1	c_{Qb}^1	$C_{qd}^{1(3333)}$
	0Qb8	c_{Qb}^8	$C_{qd}^{8(3333)}$
	0tt1	c_{tt}^1	$C_{uu}^{(3333)}$
	0tb1	c_{tb}^1	$C_{ud}^{1(3333)}$
	0tb8	c_{tb}^8	$C_{ud}^{8(3333)}$
	0QtQb1	c_{QtQb}^1	$C_{quqd}^{1(3333)}$
	0QtQb8	c_{QtQb}^8	$C_{quqd}^{8(3333)}$
QQqq	081qq	$c_{Qq}^{1,8}$	$C_{qq}^{1(ii33i)} + 3C_{qq}^{3(ii33i)}$
	011qq	$c_{Qq}^{1,1}$	$C_{qq}^{1(ii33)} + \frac{1}{6}C_{qq}^{1(iii3)} + \frac{1}{2}C_{qq}^{3(ii33i)}$
	083qq	$c_{Qq}^{3,8}$	$C_{qq}^{1(ii33i)} - C_{qq}^{3(ii33i)}$
	013qq	$c_{Qq}^{3,1}$	$C_{qq}^{3(ii33)} + \frac{1}{6}(C_{qq}^{1(iii3)} - C_{qq}^{3(ii33i)})$
	08qt	c_{tq}^8	$C_{qu}^{8(ii33)}$
	01qt	c_{tq}^1	$C_{qu}^{1(ii33)}$
	08ut	c_{tu}^8	$2C_{uu}^{(ii33i)}$
	01ut	c_{tu}^1	$C_{uu}^{(ii33)} + \frac{1}{3}C_{uu}^{(i33i)}$
	08qu	c_{Qu}^8	$C_{qu}^{8(33ii)}$
	01qu	c_{Qu}^1	$C_{qu}^{1(33ii)}$
	08dt	c_{td}^8	$C_{ud}^{8(33ii)}$
	01dt	c_{td}^1	$C_{ud}^{1(33ii)}$
	08qd	c_{Qd}^8	$C_{qd}^{8(33ii)}$
	01qd	c_{Qd}^1	$C_{qd}^{1(33ii)}$
$QQ + V, G, \varphi$	0tG	c_{tG}	$\text{Re}\{C_{uG}^{(33)}\}$
	0tW	c_{tW}	$\text{Re}\{C_{uW}^{(33)}\}$
	0bW	c_{bW}	$\text{Re}\{C_{dW}^{(33)}\}$
	0tZ	c_{tZ}	$\text{Re}\{-s_W C_{uB}^{(33)} + c_W C_{uW}^{(33)}\}$
	Off	$c_{\varphi tb}$	$\text{Re}\{C_{\varphi ud}^{(33)}\}$
	Ofq3	$c_{\varphi Q}^3$	$C_{\varphi q}^{3(33)}$
	OpQM	$c_{\varphi Q}^-$	$C_{\varphi q}^{1(33)} - C_{\varphi q}^{3(33)}$
	Opt	$c_{\varphi t}$	$C_{\varphi u}^{(33)}$
	Otp	$c_{t\varphi}$	$\text{Re}\{C_{u\varphi}^{(33)}\}$

- Total of 34 free parameters:

→ 11 from 4-heavy operators

→ 14 from 2-heavy-2-light operators

→ 9 from 2-heavy with boson/Higgs interaction

Higgs Operators

Operator	Notation	Definition
$\mathcal{O}_{\varphi G}$	OpG (cpG , $c_{\varphi G}$)	$(\varphi^\dagger \varphi - \frac{v^2}{2}) G_A^{\mu\nu} G_{\mu\nu}^A$
$\mathcal{O}_{\varphi B}$	OpB (cpB , $c_{\varphi B}$)	$(\varphi^\dagger \varphi - \frac{v^2}{2}) B^{\mu\nu} B_{\mu\nu}$
$\mathcal{O}_{\varphi W}$	OpW (cpW , $c_{\varphi W}$)	$(\varphi^\dagger \varphi - \frac{v^2}{2}) W_I^{\mu\nu} W_{I\mu\nu}^I$
$\mathcal{O}_{\varphi WB}$	OpWB (cpWB , $c_{\varphi WB}$)	$(\varphi^\dagger \tau_I \varphi) B^{\mu\nu} W_{\mu\nu}^I$
$\mathcal{O}_{\varphi d}$	Opd (cpd , $c_{\varphi d}$)	$\partial_\mu (\varphi^\dagger \varphi) \partial^\mu (\varphi^\dagger \varphi)$
$\mathcal{O}_{\varphi D}$	OpD (cpD , $c_{\varphi D}$)	$(\varphi^\dagger D^\mu \varphi)^\dagger (\varphi^\dagger D_\mu \varphi)$
\mathcal{O}_W	OW (cWWW , c_{WWW})	$\epsilon_{IJK} W_{\mu\nu}^I W^{J,\nu\rho} W_\rho^{K,\mu}$

Operator	Notation	Definition
$\mathcal{O}_{t\varphi}$	0tp (0tp , $c_{t\varphi}$)	$(\varphi^\dagger \varphi - \frac{v^2}{2}) \bar{Q} t \tilde{\varphi} + \text{h.c.}$
\mathcal{O}_{tG}	0tG (0tG , c_{tG})	$i g_S (\bar{Q} \tau^{\mu\nu} T_A t) \tilde{\varphi} G_{\mu\nu}^A + \text{h.c.}$
$\mathcal{O}_{b\varphi}$	0bp (0bp , $c_{b\varphi}$)	$(\varphi^\dagger \varphi - \frac{v^2}{2}) \bar{Q} b \varphi + \text{h.c.}$
$\mathcal{O}_{c\varphi}$	0cp (0cp , $c_{c\varphi}$)	$(\varphi^\dagger \varphi - \frac{v^2}{2}) \bar{Q} c \varphi + \text{h.c.}$
$\mathcal{O}_{\tau\varphi}$	0tap (0tap , $c_{\tau\varphi}$)	$(\varphi^\dagger \varphi - \frac{v^2}{2}) \bar{Q} \tau \tilde{\varphi} + \text{h.c.}$
\mathcal{O}_{tW}	0tW (0tW , c_{tW})	$i (\bar{Q} \tau^{\mu\nu} \tau_I t) \tilde{\varphi} W_{\mu\nu}^I + \text{h.c.}$
\mathcal{O}_{tB}	-	$i (\bar{Q} \tau^{\mu\nu} t) \tilde{\varphi} B_{\mu\nu} + \text{h.c.}$
\mathcal{O}_{tZ}	0tZ (0tZ , c_{tZ})	$-\sin \theta_W c_{tB} + \cos \theta_W c_{tW}$
$\mathcal{O}_{\varphi l_1}^{(1)}$	0pl1 (cp11 , $c_{\varphi l_1}^{(1)}$)	$i (\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi) (\bar{l}_1 \gamma^\mu l_1)$
$\mathcal{O}_{\varphi l_1}^{(3)}$	03pl1 (c3pl1 , $c_{\varphi l_1}^{(3)}$)	$i (\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \tau_I \varphi) (\bar{l}_1 \gamma^\mu \tau^I l_1)$
$\mathcal{O}_{\varphi l_2}^{(1)}$	0pl2 (cp12 , $c_{\varphi l_2}^{(1)}$)	$i (\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi) (\bar{l}_2 \gamma^\mu l_2)$
$\mathcal{O}_{\varphi l_2}^{(3)}$	03pl2 (c3pl2 , $c_{\varphi l_2}^{(3)}$)	$i (\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \tau_I \varphi) (\bar{l}_2 \gamma^\mu \tau^I l_2)$
$\mathcal{O}_{\varphi l_3}^{(1)}$	0pl3 (cp13 , $c_{\varphi l_3}^{(1)}$)	$i (\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi) (\bar{l}_3 \gamma^\mu l_3)$
$\mathcal{O}_{\varphi l_3}^{(3)}$	03pl3 (c3pl3 , $c_{\varphi l_3}^{(3)}$)	$i (\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \tau_I \varphi) (\bar{l}_3 \gamma^\mu \tau^I l_3)$
$\mathcal{O}_{\varphi e}$	0pe (cpe , $c_{\varphi e}$)	$i (\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi) (\bar{e} \gamma^\mu e)$
$\mathcal{O}_{\varphi \mu}$	0pmu (cpmu , $c_{\varphi \mu}$)	$i (\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi) (\bar{\mu} \gamma^\mu \mu)$
$\mathcal{O}_{\varphi \tau}$	0pta ($\text{cpt}\alpha$, $c_{\varphi \tau}$)	$i (\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi) (\bar{\tau} \gamma^\mu \tau)$
$\mathcal{O}_{\varphi q_i}^{(1)}$	-	$\sum_{i=1,2} i (\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi) (\bar{q}_i \gamma^\mu q_i)$
$\mathcal{O}_{\varphi q_i}^{(3)}$	03pq (c3pq , $c_{\varphi q_i}^{(3)}$)	$\sum_{i=1,2} i (\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \tau_I \varphi) (\bar{q}_i \gamma^\mu \tau^I q_i)$
$\mathcal{O}_{\varphi Q}^{(1)}$	-	$i (\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi) (\bar{Q} \gamma^\mu Q)$
$\mathcal{O}_{\varphi Q}^{(3)}$	03pQ3 (c3pQ3 , $c_{\varphi Q}^{(3)}$)	$i (\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \tau_I \varphi) (\bar{Q} \gamma^\mu \tau^I Q)$
$\mathcal{O}_{\varphi q_i}^{(-)}$	0pqMi (cpqMi , $c_{\varphi q_i}^{(-)}$)	$c_{\varphi q_i}^{(1)} - c_{\varphi q_i}^{(3)}$
$\mathcal{O}_{\varphi Q}^{(-)}$	0pQM (cpQM , $c_{\varphi Q}^{(-)}$)	$c_{\varphi Q}^{(1)} - c_{\varphi Q}^{(3)}$
$\mathcal{O}_{\varphi u_i}$	0pui ($\text{cpu}\bar{u}_i$, $c_{\varphi u_i}$)	$\sum_{i=1,2} i (\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi) (\bar{u}_i \gamma^\mu u_i)$
$\mathcal{O}_{\varphi d_i}$	0pdi ($\text{cpd}\bar{d}_i$, $c_{\varphi d_i}$)	$\sum_{i=1,2} i (\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi) (\bar{d}_i \gamma^\mu d_i)$
$\mathcal{O}_{\varphi t}$	0pt (cpt , $c_{\varphi t}$)	$i (\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi) (\bar{t} \gamma^\mu t)$
\mathcal{O}_u	0ll (cll , c_{ll})	$(l \gamma_\mu l) (l \gamma^\mu l)$