LHC constraints on the SM Effective Field Theory

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SMEFT

Standard **M**odel **E**ffective **F**ield **T**heory:
The EFT constructed with **Standard Model** field & symmetries

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$

$$\mathcal{L}_d = \sum_i C_i \mathcal{O}_i^{(d)}$$

C_i = Wilson coefficients

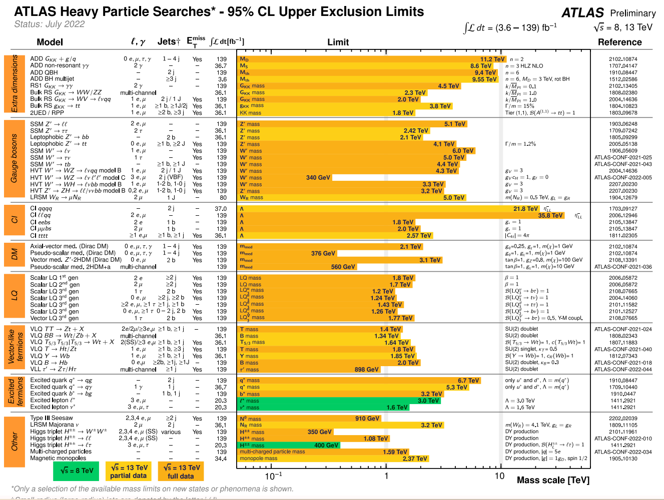
$\mathcal{O}_i^{(d)}$ = gauge-invariant operators

At each order, $\mathcal{O}_i^{(d)}$ form a complete, non-redundant **basis**

SMEFT describes **any nearly-decoupled ($\Lambda \gg v$) BSM physics**
with "good" analyticity/geometry properties in the scalar sector

SMEFT for indirect searches at LHC

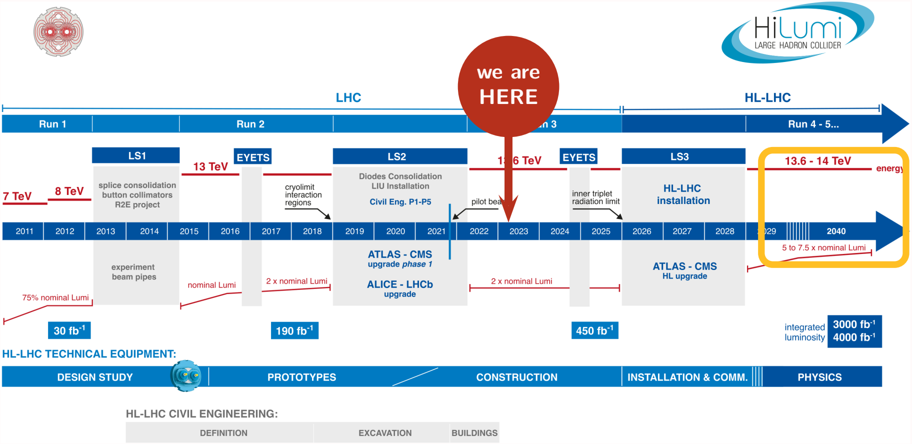
near decoupling seems a reasonable assumption



SMEFT for indirect searches at LHC

near decoupling seems a reasonable assumption

LHC becoming an increasingly **precise** machine



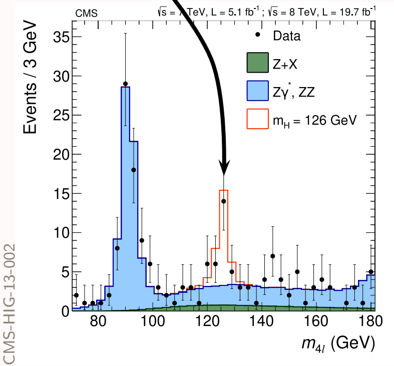
SMEFT for indirect searches at LHC

near decoupling seems a reasonable assumption

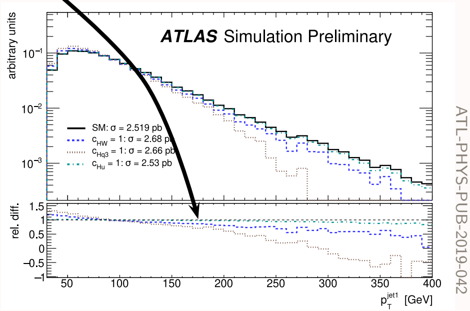
LHC becoming an increasingly **precise** machine

indirect searches
more and more competitive with direct ones

direct



indirect



SMEFT for indirect searches at LHC

near decoupling seems a reasonable assumption

LHC becoming an increasingly **precise** machine

indirect searches more and more competitive with direct ones

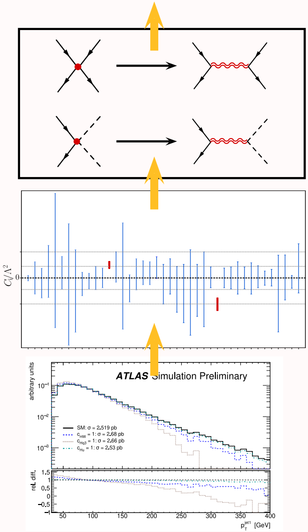
SMEFT-based searches at the LHC

+ a proper QFT : renormalizable order by order, systematically improvable in loops
+ minimal commitment to a specific UV
+ systematically includes all BSM effects, compatible with assumptions
+ universal framework for data interpretation: can connect to other experiments

The SMEFT program

agnostic approach: let data tell us what NP looks like

$\mathcal{L}_{UV}$



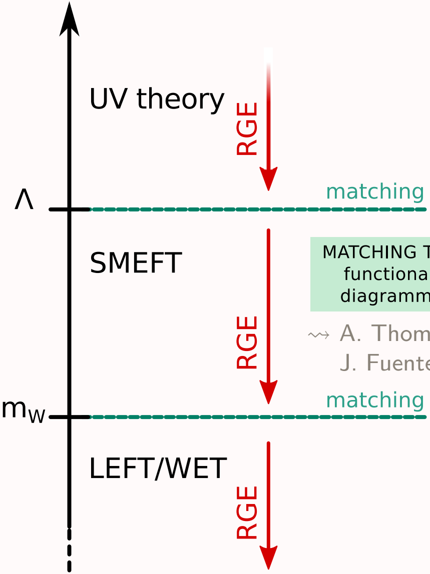
Embed in UV-complete model

Identify compatible simplified models

Global analysis → measure $C_i \neq 0$

general parameterization:
allow *all* SMEFT effects to be present at the same time

SMEFT program: broader theory perspective



MATCHING TECHNIQUES
functional methods,
diagrammatic match.

⇝ A. Thomsen, J. Santiago,
J. Fuentes-Martín

EXPLORING EFT PROPERTIES
parameters, bases,
unitarity, positivity,
geoSMEFT formulation..

⇝ T. Corbett

OBSERVABLE PREDICTIONS
MC, analytic calc.,
SMEFT beyond ME ...

⇝ C. Severi

STATISTICAL ANALYSIS
fitting tools,
infomation geometry...

SMEFT corrections to LHC processes

$$\int d\Phi \quad \int \text{PDFs} \quad |A_{SMEFT}|^2 \longrightarrow \text{shower/hadr.} \longrightarrow \text{detector} \longrightarrow \text{obs.}$$

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$$\int d\Phi \quad \int \text{PDFs} \quad |A_{SMEFT}|^2 \longrightarrow \text{shower/hadr.} \longrightarrow \text{detector} \longrightarrow \text{obs.}$$

could PDF fits absorb SMEFT away?

- SMEFT effects within unc. for Run I-II
- can be sizeable for HL-LHC pred.

Carrazza et al 1905.05215
Greljo et al. 2104.02723
Iranipour,Ubiali 2201.07240

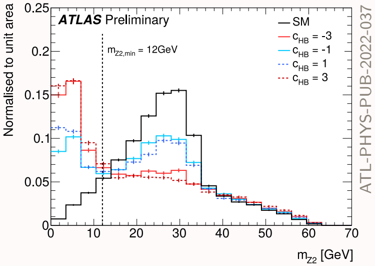
$\varepsilon \cdot A$

acceptances for SM and SMEFT differ if Lorentz structure changes

ATLAS 2004.03447
ATLAS-CONF-2020-053
ATL-PHYS-PUB-2022-037

EFT impact can depend on jet def.

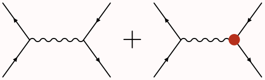
Haisch et al 2204.00663



SMEFT corrections to LHC processes

$$\int d\Phi \quad \int \mathrm{PDFs} \quad |A_{SMEFT}|^2 \longrightarrow \text{shower/hadr.} \longrightarrow \text{detector} \longrightarrow \text{obs.}$$

$$A_{SMEFT} = A_{SM} + \sum_i \left(C_i^{(6)}/\Lambda^2 \right) A_i$$



$$|A_{SMEFT}|^2 = |A_{SM}|^2 + \underbrace{\sum_i \frac{C_i^{(6)}}{\Lambda^2} 2Re\left(A_{SM} A_i^\dagger\right)}_{\text{interference/linear}} + \underbrace{\sum_{i,j} \frac{C_i^{(6)} C_j^{(6)}}{\Lambda^4} |A_i A_j^\dagger|}_{\text{quadratics}}$$

$\times$ (SM K-factor)

- A_{SMEFT} typically computed up to 1-loop in QCD / EW
- $\int d\Phi \int \mathrm{PDFs}\, |A_{SMEFT}|^2$ computed with **Monte Carlo generators**
  most used: MadGraph5 + `SMEFTsim` (LO)/ `SMEFT@NLO` (NLO QCD)

IB,Jiang,Trott 1709.06492, IB 2012.11343
Degrande,Durieux,Maltoni,Mimasu,Vryonidou,Zhang 2008.11743

Where are we? State-of-the-art SMEFT fits

- combine observables in EW [EWPO + diboson]
  Higgs [prod + decay]
  top [$\bar{t}t + \bar{t}tV$ + decay]

- constrain **30 – 35** parameters simultaneously. [LHC target ~ 50]

- employ diverse fitting techniques...
  frequentist/bayesian/replica model statistics, various uncertainty modelings, markov chains, nested sampling...

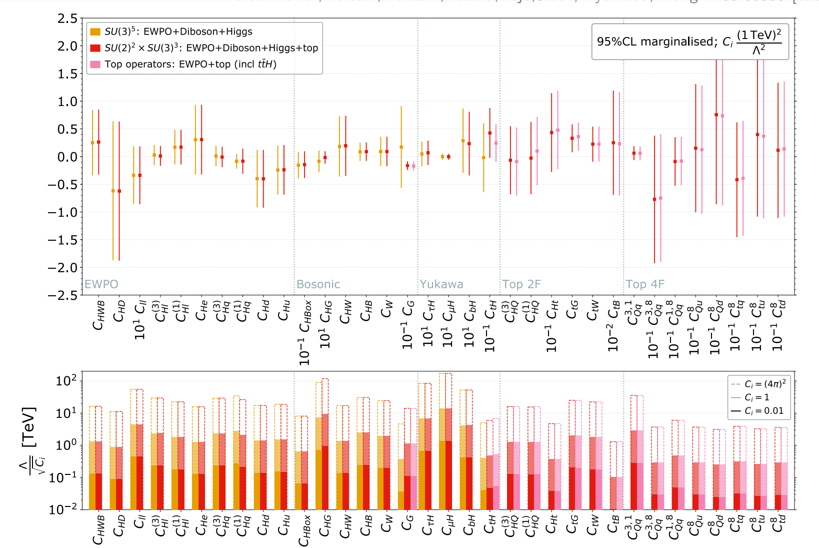
- ...and methods for presenting results
  linear vs linear+quadratics, LO vs NLO, individual vs marginalised/profiled, Fisher information, Principal component analysis...

- including **enough measurements** to constrain all parameters is solved except for some degeneracies in 4-fermion operators → flavor physics

- **sensitivity**: Higgs/EW parameters $\Lambda \gtrsim 1-2$ TeV for $C_i = 1$
  most Top parameters less constrained

Higgs + EW + Top combinations

Ellis, Madigan, Mimasu, Sanz, You 2012.02779
also: Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, Vryonidou, Zhang 2105.00006 [backup]



34 param, linear, LO + ggH

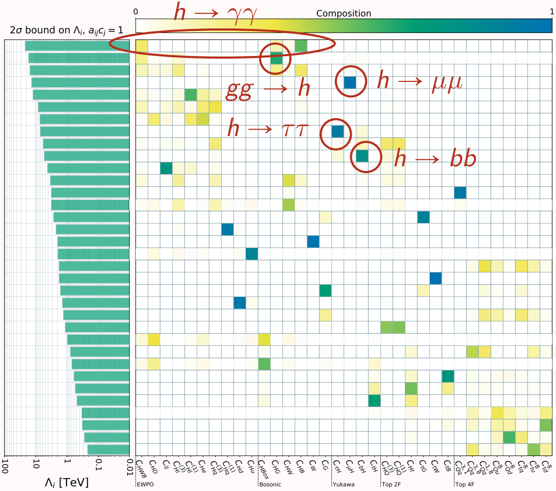
Directions in the fit space

→ with linear SMEFT predictions, fit can be decomposed into uncorrelated constraints
→ **very large hierarchies** between bounds. strongest constraints from H & EWPO

Principal Component Analysis

eigensystem of the Fisher matrix

$$I_{ij} = -\frac{\partial^2 \log \mathcal{L}}{\partial C_i \partial C_j}$$



Relative constraining power (%)

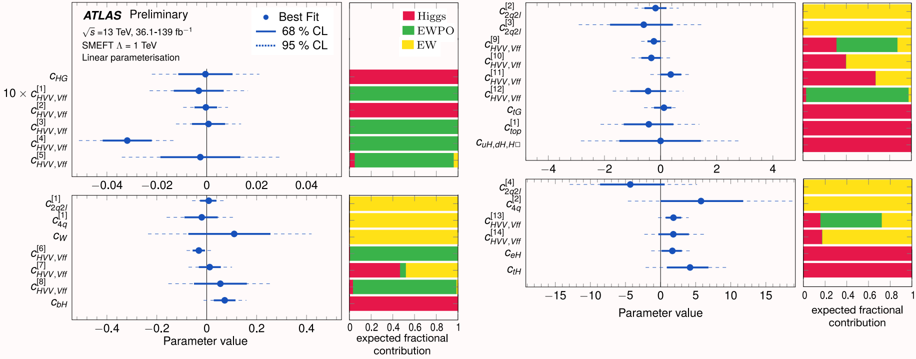
EWPO	LEP WW	Run 1, μH	Run 2, μH	STXS	LHC WW&	LHC Zjj	$t\bar{t}$	single top	$t\bar{t}V$
6	–	15	29	50	–	–	–	–	–
35	–	13	28	23	–	–	–	–	–
59	–	7	16	18	–	–	–	–	–
–	–	5	94	1	–	–	–	–	–
99	–	–	–	–	–	–	–	–	–
95	–	–	–	–	3	–	–	–	–
99	–	–	–	–	–	–	–	–	–
–	–	21	45	33	–	–	–	–	–
74	–	2	4	14	6	–	–	–	–
18	–	8	19	55	–	–	–	–	–
73	22	–	–	–	3	–	–	–	–
7	2	5	53	4	29	–	–	–	–
–	–	–	3	–	–	–	–	96	–
7	–	2	39	2	46	–	–	3	–
–	–	–	10	4	–	–	57	–	28
94	2	–	–	–	2	–	–	–	–
–	2	–	–	–	11	86	–	–	–
65	14	2	4	10	4	1	–	–	–
–	–	–	–	–	–	–	99	–	–
–	–	–	–	–	–	–	84	15	–
–	–	–	13	6	–	–	48	–	32
90	5	–	–	1	2	–	–	–	–
–	–	–	5	2	–	–	79	–	13
–	–	–	–	–	–	–	3	78	18
2	3	27	40	12	6	–	4	–	4
–	–	1	2	–	–	–	15	4	77
4	4	14	33	23	7	1	12	–	2
–	–	1	3	1	–	–	4	–	89
–	–	3	10	4	–	–	28	2	53
1	–	8	27	16	2	–	32	–	12
–	–	–	–	–	–	–	58	–	41
–	–	–	–	–	–	–	90	–	10
–	–	–	–	–	–	–	61	–	38
–	–	–	–	–	–	–	95	–	5

Ellis et al 2012.02779

Global fits within ATLAS & CMS

experiments gearing up for SMEFT **combined studies**. a few already available!

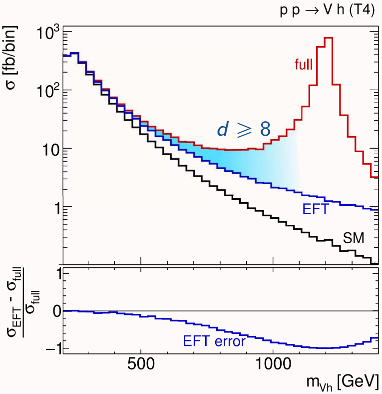
- ATLAS: so far mostly Higgs and EW ATLAS-CONF-2021-053, ATL-PHYS-PUB-2021-010, ATL-PHYS-PUB-2022-037. . .
- CMS: so far mostly Top TOP-19-001, TOP-21-003. . .
- cross-experiment "fitting exercise" ongoing under EFT WG



Open challenges

- reduction of error bars down to $O(1\%)$ (bulk) -$O(10\%)$ (tails)
- refinement/improvement of **predictions** and **uncertainty treatment**
- addressing EFT validity / truncation error question

top-down



adapted from Brehmer, Freitas, López-Val, Plehn 1510.03443

bottom-up

when fit results allow $\dfrac{Cv^2}{\Lambda^2} > 1$

EFT validity is not manifest

→ fit sensitive to $O(\Lambda^{-4})$ terms

→ possible unreliable map to UV

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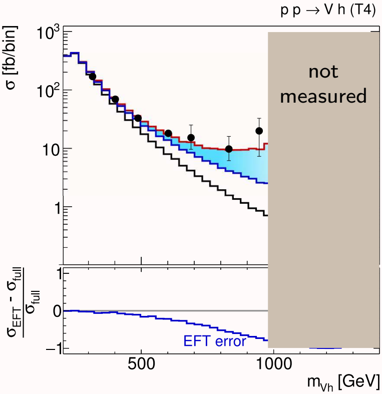

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bottom-up

when fit results allow $\frac{Cv^2}{\Lambda^2} > 1$

EFT validity is not manifest

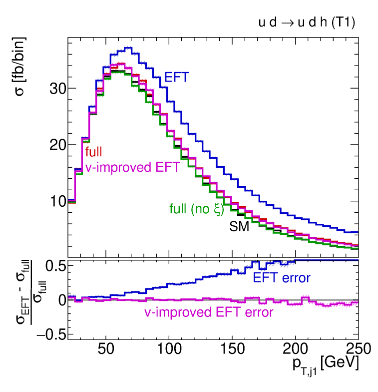
→ fit sensitive to $O(\Lambda^{-4})$ terms

→ possible unreliable map to UV

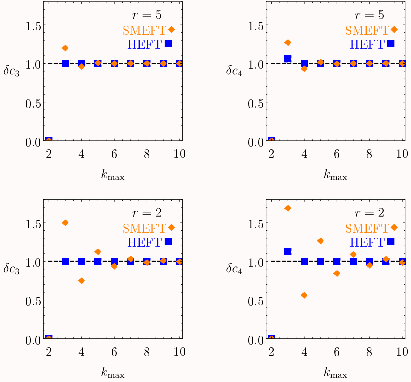
SMEFT or HEFT?

a component of the $d = 6$ vs model discrepancy can be removed by reabsorbing higher powers of v within $d = 6$ coefficients instead of leaving them to $d \geqslant 8$

conceptually same as matching to **HEFT** instead



Brehmer,Freitas,López-Val,Plehn 1510.03443



Cohen,Craig,Lu,Sutherland 2008.08597

which EFT is most convenient?

Higgs EFT

Feruglio 9301281, Grinstein,Trott 0704.1505, Buchalla,Catà 1203.6510, Alonso et al 1212.3305...

$$H \mapsto \frac{v + h}{\sqrt{2}}\mathbf{U}, \qquad \mathbf{U} = \exp\left(\frac{i\vec{\sigma}\cdot\vec{\pi}}{v}\right)$$

HEFT ⊃ SMEFT ⊃ SM

- HEFT expands **around vacuum**, SMEFT around $H = 0$
  $\to$ resums $(H^\dagger H)^n$ series $\rightsquigarrow$ geoSMEFT

- HEFT implements a different **power counting** than SMEFT:
  BSM effects are re-shuffled over the EFT expansion (mostly lowered)

- recent **geometric interpretation** proves that Alonso,Jenkins,Manohar 1511.00724,1605.03602
  there are BSM theories that admit HEFT but not SMEFT
  – with BSM sources of EWSB Cohen et al 2008.0597,Banta et al 2110.02967
  – with BSM particles that take $> 1/2$ of their mass from EWSB

Summary

- SMEFT is a convenient framework for an ambitious program of searches for indirect NP signals

- impressive progress made in past decade!
  state-of-the-art analyses combine EW + H + top, already reach $\Lambda \gtrsim \mathrm{TeV}$

- LHC experiments planning internal and cross-experiment combinations
  → better treatment of uncertainties and correlations

- some challenges still open
  → reduction of measurement & theory **uncertainties**
  → **refined predictions** and error estimates
  → **EFT validity** considerations

- SMEFT or HEFT? question remains open phenomenologically.
  using HEFT increases complexity, but could improve interpretation

Backup slides

SMEFT at $d=6$: the Warsaw basis

Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\square}$	$(\varphi^\dagger\varphi)\square(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\,\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\,\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\,\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

SMEFT at $d = 6$: the Warsaw basis

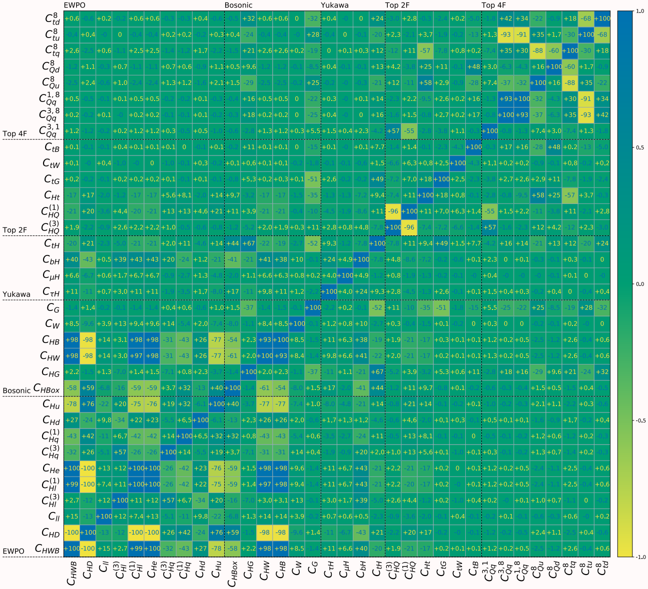
Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

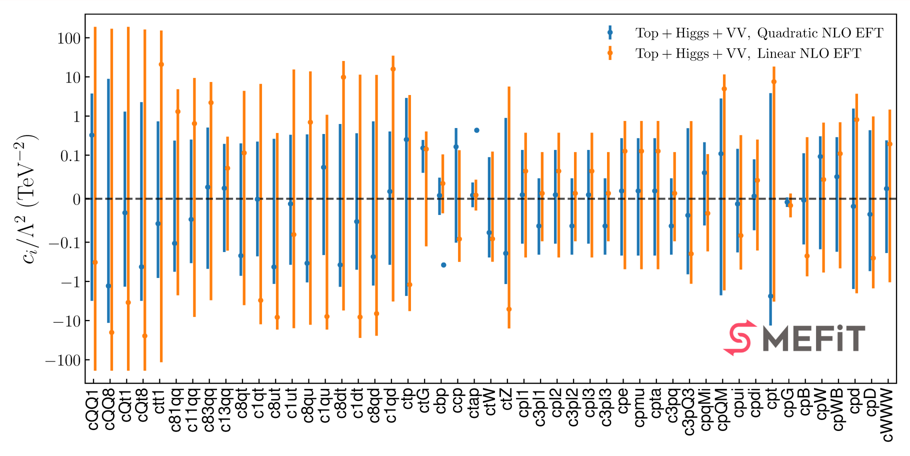
EW + H + top fit: correlations

Ellis, Madigan, Mimasu, Sanz, You 2012.02779



Higgs + EW + Top combinations

Ethier,Maltoni,Mantani,Nocera,Rojo,Slade,Vryonidou,Zhang 2105.00006



50 param (36 indep.), $U(2)^2 \times U(3) \times U(1)^3$ flavor sym, linear+quadratic, NLO QCD

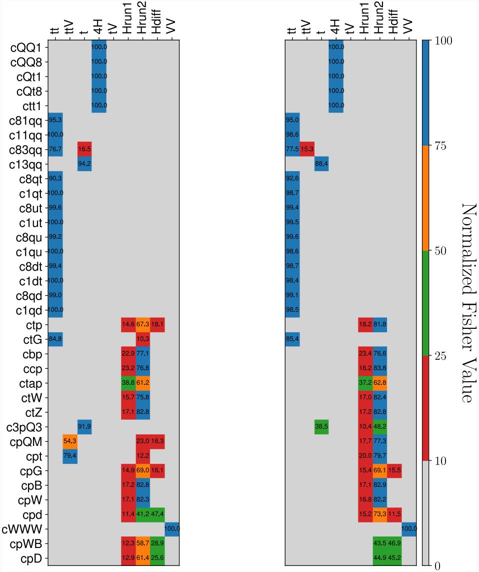
Fisher information matrix

$$I_{ij} = -E\left[\frac{\partial^2 \log \mathcal{L}_{\text{observed}}(\vec{C})}{\partial C_i \partial C_j}\right]$$

compute for sub-datasets and
normalize to 1 for each coefficient

↓

strongest constraint on each C_i



Linear Quadratic

Ethier et al 2105.00006

see also: Brehmer et al 1612.05261,1712.02350,1908.06980