SMEFT and HEFT for new physics searches at the LHC

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The Standard Model Effective Field Theory – SMEFT

promoting the Standard Model to an EFT → add **higher-dimensional** terms made of SM **fields** and respecting the SM **symmetries**

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots \qquad \mathcal{L}_d = \sum_i C_i \mathcal{O}_i^{(d)}$$

C_i = Wilson coefficients

$\mathcal{O}_i^{(d)}$ = gauge-invariant operators forming a basis: a complete, non-redundant set

Buchmüller,Wyler 1986

- describes **any beyond-SM theory**, provided it lives at $\Lambda \gg v$
- a complete catalogue of all allowed beyond-SM effects, organized by expected size
- not experiment-specific → can be used as **a common framework** for LHC *and* other experiments
- a proper QFT: renormalizable order-by-order, systematically improvable in loops

SMEFT at $d = 6$: the Warsaw basis

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	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star (\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

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

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

free parameters

go down to O(100) imposing flavor symmetries, CP

Faroughy et al 2005.05366
Greljo et al 2203.09561
IB 2012.11343

they are ∼never all relevant at the same time

SMEFT at $d = 6$: the Warsaw basis

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

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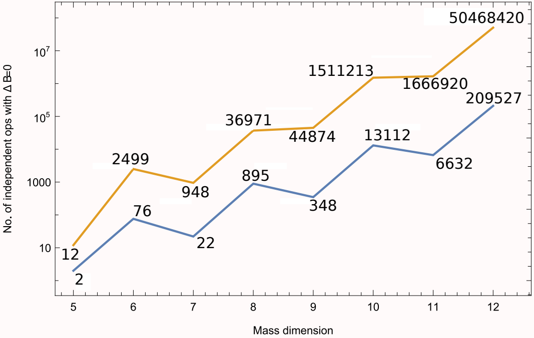
A fast growing series

 # parameters computed with Hilbert series and automated. flavor plays a major role.

Henning,Lu,Melia,Murayama 1512.03433



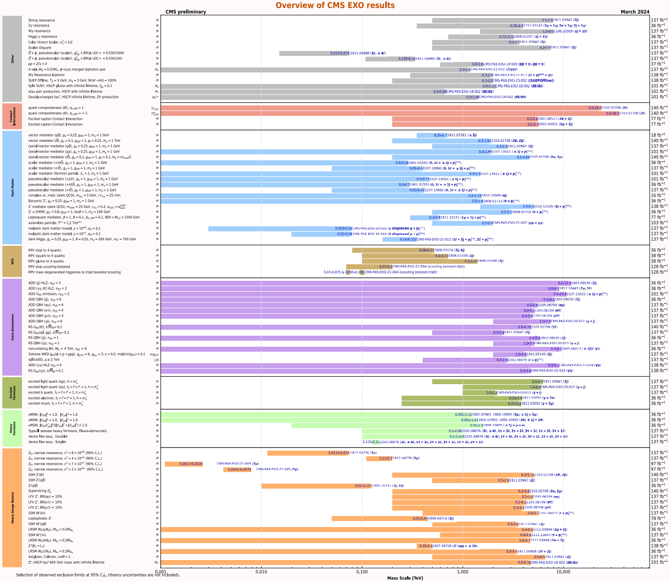
bases available up to dimension 12

- **d = 5** Weinberg PRL43(1979)1566
- **d = 6** Grzadkowski et al 1008.4884 . . .
- **d = 7** Lehman 1410.4193, Henning et al 1512.0343
- **d = 8** Li et al 2005.00008, Murphy 2005.00059
- **d = 9** Li et al 2007.07899, Liao,Ma 2007.08125
- **d = 10,11,12** Harlander,Kempksens,Schaaf 2305.06832

In SMEFT, operators of odd dimension violate the conservation of B and/or L Kobach 1604.05726

Indirect BSM searches at the LHC: motivation

new physics possibly **heavy**



Indirect BSM searches at the LHC: motivation

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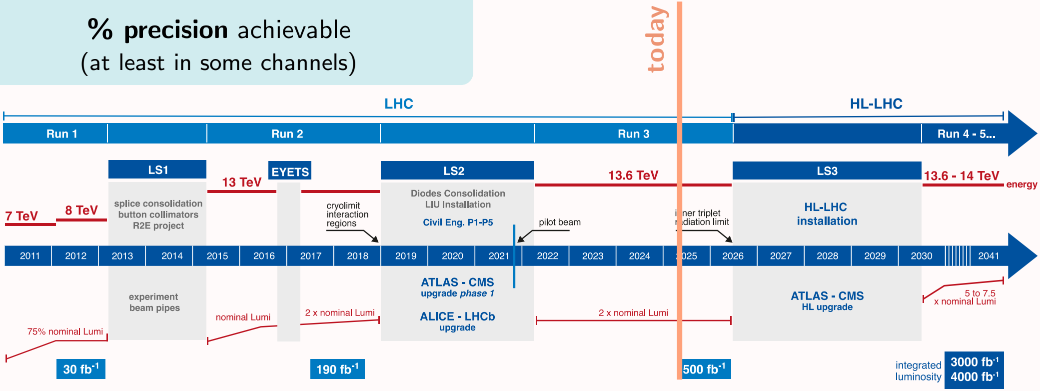
statistics will increase $\times 10$ in next ~ 20 yrs

% precision achievable
(at least in some channels)



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- explored mass range won't move much
- clueless about BSM scale and models
- next colliders very far in the future
- . . .

Indirect BSM searches at the LHC: motivation

new physics possibly **heavy** $\Longrightarrow$ **Effective Field Theory** formalism applies: $E/\Lambda \ll 1$ $\Longrightarrow$ expect **small** BSM signals $v^2/\Lambda^2 \lesssim 6\%, \quad \hat{s}/\Lambda^2 \lesssim 10\%$

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$\longrightarrow$ a concrete shot to probe interesting region!

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- ...

$\longrightarrow$ makes sense to aim for

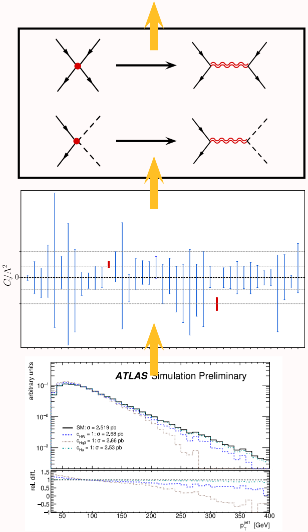
- agnostic setup, covering many BSM scenarios, reinterpretable
- solid QFT framework, general, improvable
- extract as much info as possible

The SMEFT program at the LHC

agnostic bottom-up approach

let data tell us
what NP looks like

$\mathcal{L}_{UV}$



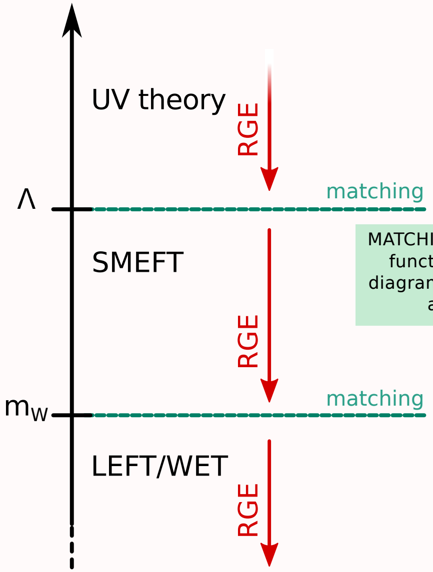
Embed in UV-complete model

Identify compatible simplified models

Global analysis $\rightarrow$ measure $C_i \neq 0$

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

The bigger picture – a blooming research field!



MATCHING TECHNIQUES
functional methods,
diagrammatic matching,
automation

EXPLORING EFT PROPERTIES
parameters, bases, flavor, unitarity, positivity,
on-shell amplitude structure,
geometric formulations...

OBSERVABLES PREDICTIONS
MC tools, analytic calculations,
SMEFT beyond ME, optimal observables ...

STATISTICAL ANALYSIS
fitting tools, likelihood inference,
infomation geometry, ML-based tools,
interplay with PDFs...

SMEFT analyses of LHC data: state of the art

A vast number of LHC processes has been studied in SMEFT at dim-6:

Higgs all main production (STXS) and decay channels

EW diboson, triboson, VBS in several final states

Top $\bar{t}t$, $\bar{t}tV$, tW, tZj, $\bar{t}t\bar{t}t$, $\bar{t}t\bar{b}b$, top decays...

others multi-jet, Drell-Yan, flavor observables, LEP EWPO, LEP-II diboson ...

☞ Typically predicted at tree-level or to 1-loop QCD in SMEFT, only a few at 1-loop EW
most used MC: MG5 with `SMEFTsim` (tree-level IB+ '17,'20) or `SMEFT@NLO` (1-loop QCD Degrande+ '20)

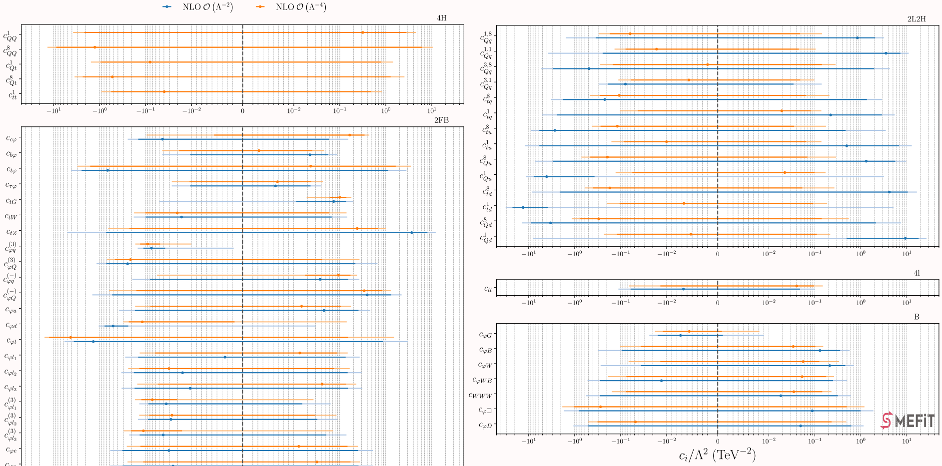
☞ state-of-the-art global fits can handle $\mathcal{O}(50)$ parameters simultaneously

☞ main upcoming challenges:
incorporate flavor observables, improve predictions, uncertainties, correlations etc,
streamline likelihood exchanges, integrate matching-running-fitting ecosystems...

Global analyses by theory groups

example: EWPO + Higgs + EW + top combination by SMEFiT Celada et al 2404.12809

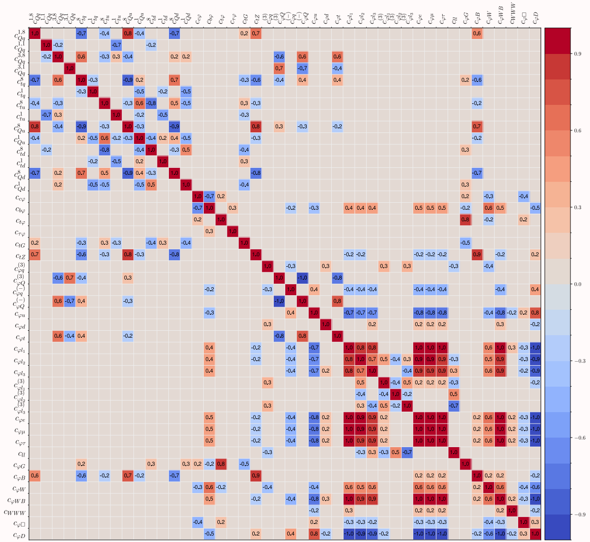
see also: fitmaker 1803.03252, 2012.02779 Sfitter 1812.07587, 1910.03606, 2312.12502... Éboli+ 1812.01009 ,2108.04828...



Global analyses by theory groups

Celada et al 2404.12809

Linear fit

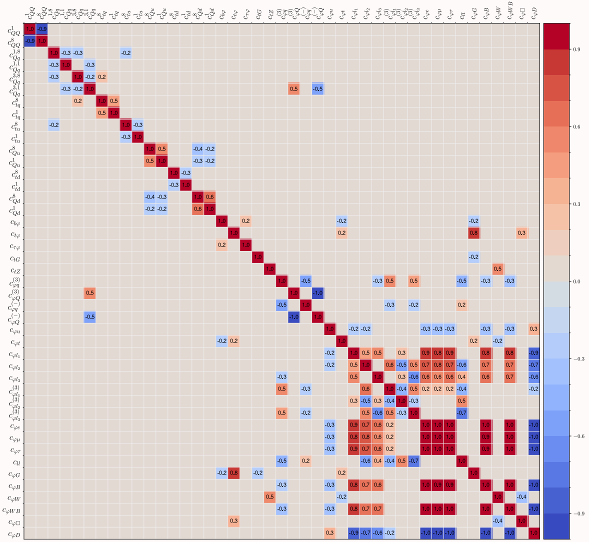


Correlation: NLO $\mathcal{O}\left(\Lambda^{-2}\right)$

Global analyses by theory groups

Celada et al 2404.12809

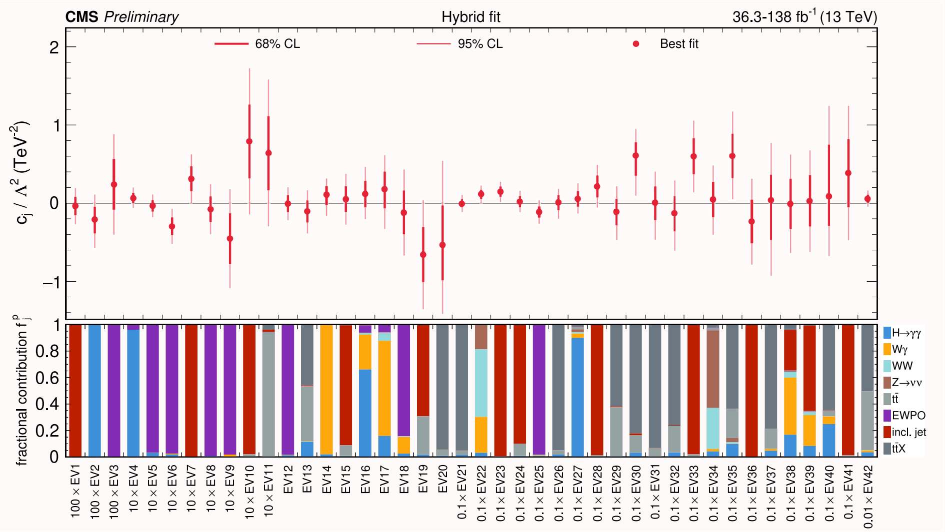
Quadratic fit



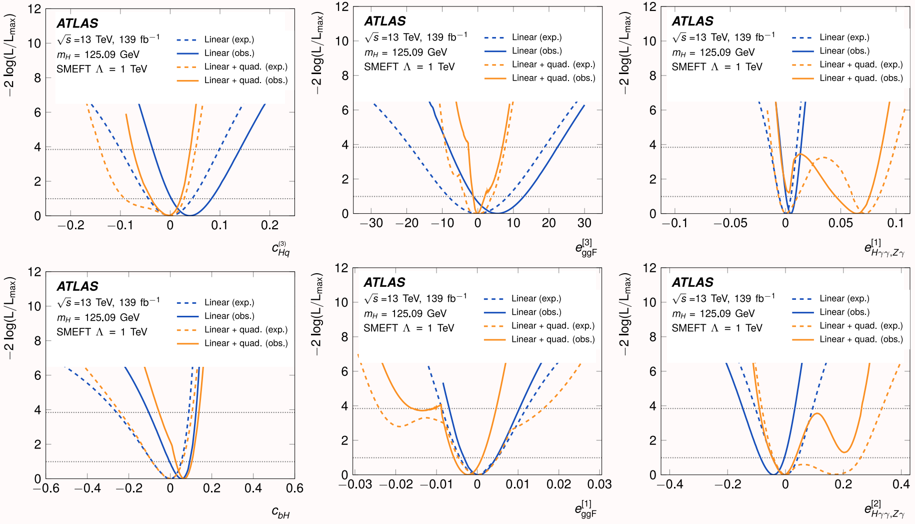
Correlation: NLO $\mathcal{O}\left(\Lambda^{-4}\right)$

Global analyses by LHC experiments

CMS EWPO + Higgs + EW + top + multi-jet combination CMS SMP-24-003



ATLAS Higgs combination ATLAS 2402.05742



The Higgs Effective Field Theory – HEFT

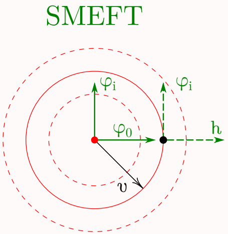
rather than H doublet:
singlet h + Goldstones $\mathbf{U}$

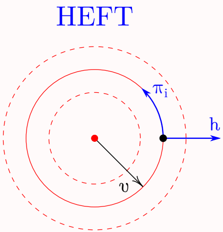
Feruglio 9301281, Grinstein,Trott 0704.1505, Buchalla,Catà 1203.6510, Alonso et al 1212.3305, IB et al 1311.1823,1604.06801, Buchalla et al 1307.5017,1511.00988. . .

$$H \mapsto \frac{v + h}{\sqrt{2}} \mathbf{U} \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \qquad \mathbf{U} = \exp\left(\frac{i\vec{\sigma}\cdot\vec{\pi}}{v}\right)$$

SMEFT expands around **EW-symmetric point**, HEFT expands around **EW vacuum**

Alonso,Jenkins,Manohar 1511.00724,1605.03602





Main HEFT features

- **more general** than SMEFT, because implements weaker symmetry requirement
  $\rightarrow$ $\exists$ UV scenarios that can be matched to HEFT but <u>not</u> SMEFT   Cohen et al 2008.0597, Banta et al 2110.02967

HEFT $\supset$ SMEFT $\supset$ SM

- in general **more convergent** than SMEFT: takes fewer orders to reproduce well UV model
  $\rightarrow$ $\mathcal{F}(h)$ resums series in $(H^\dagger H)^n$ $\sim$ geoSMEFT: Helset, Martin, Trott 2001.01453
  $\rightarrow$ classic example: composite Higgs for largish ξ

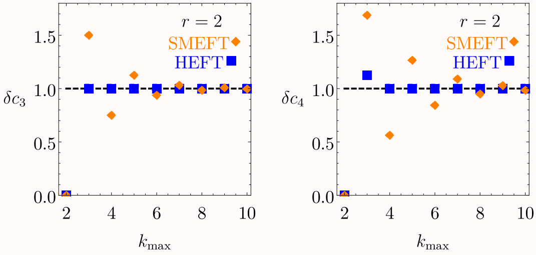
e.g. SO(5)/SO(4)

$$\mathcal{F}(h) = \frac{4}{\xi}\sin^2\frac{\varphi}{2f}$$

$$= 1 + \sqrt{4-\xi}\,\frac{h}{v} + \left(1-\frac{\xi}{2}\right)\frac{h^2}{v^2} - \frac{\xi\sqrt{4-\xi}}{6}\frac{h^3}{v^3} + \dots$$

$$\xi = \frac{v^2}{f^2}$$

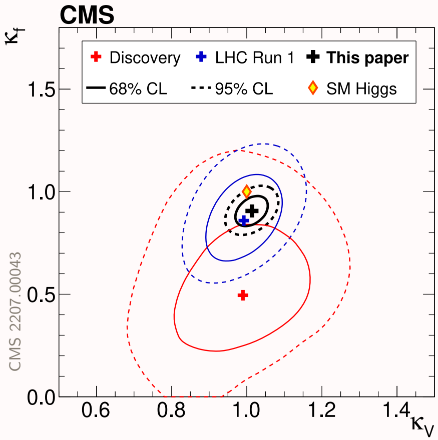
see eg. Alonso et al 1409.1589

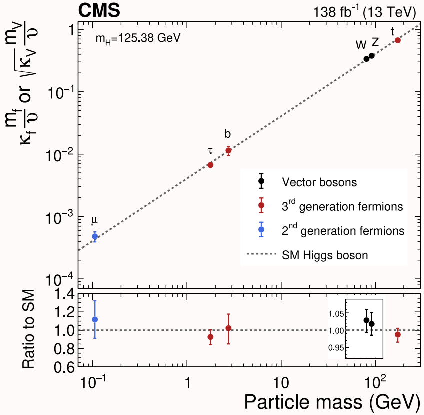


Cohen, Craig, Lu, Sutherland 2008.08597

Is HEFT phenomenologically relevant?

☹ spectacularly large deviations in Higgs couplings to V, f mostly excluded. bounds at $\sim 10\%$





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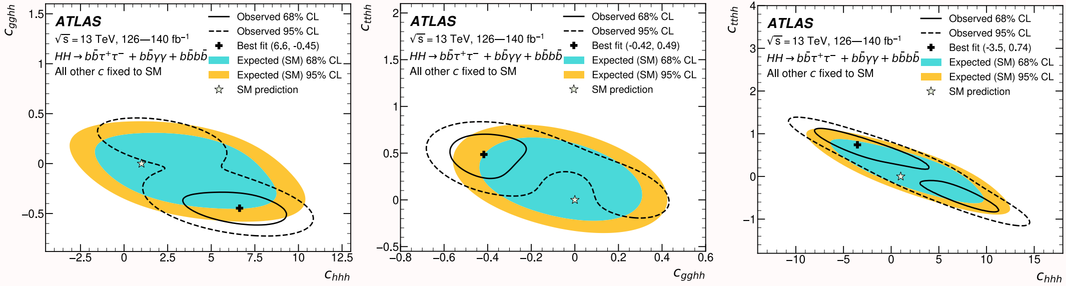
- 😐 Higgs **self-couplings** leave more freedom

ATLAS 2406.09971



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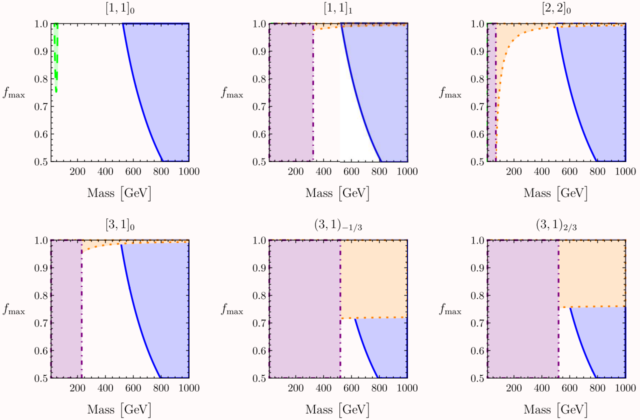

Banta, Cohen, Craig, Lu, Sutherland 2110.02967

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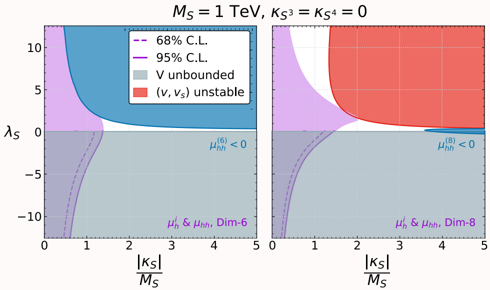
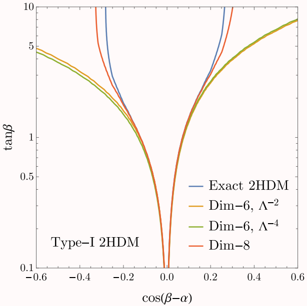
- 😐 Higgs **self-couplings** leave more freedom
- ☺ some models that *cannot* match onto SMEFT (**loryons**) are **still allowed**, despite requiring $\Lambda \lesssim 3\,\mathrm{TeV}$ for unitarity arguments
- ☺ in models that *can* match onto SMEFT, but for which SMEFT is **poorly convergent**, HEFT should be at least as relevant as dim-8 corrections



Ellis,Mimasu,Zampedri 2304.06663



Dawson,Fontes,Homiller,Sullivan 2205.01561

HEFT power counting

IB,Gröber,Schmid WIP

one of the main complications in working with HEFT: organization of the EFT expansion

Gavela,Jenkins,Manohar,Merlo 1601.07551
Buchalla,Catà,(Celis),Krause 1312.5624,1603.03062

from analysis of mass and $\hbar$ dimensions:

$$\sigma \sim \frac{(4\pi)^3}{p^2}\left(\frac{p}{\Lambda}\right)^{\alpha^p_\Lambda}\left(\frac{4\pi v}{\Lambda}\right)^{\alpha^g_\Lambda}\left(\frac{g}{4\pi}\right)^{\alpha^g_\chi} = \frac{(4\pi)^3}{p^2}\left(\frac{p}{\Lambda}\right)^{2(N-2)+\alpha^p_\chi}\left(\frac{4\pi v}{\Lambda}\right)^{\alpha^g_\Lambda}\left(\frac{g}{4\pi}\right)^{\alpha^g_\chi}$$

$N = \#$ ext legs, $\alpha_\chi^{(p,g)}$ counts **chiral dimensions**: $d_\chi = -(d_{4\pi} + d_\Lambda)$

SMEFT expands in $\alpha^p_\Lambda + \alpha^g_\Lambda \sim d_\Lambda$ “orthogonal” to loop expansion

HEFT? non-linear fields $\Rightarrow$ no expansion in v

$\alpha^g_\chi, \alpha^p_\chi$ non homogeneous by operator, p/Λ powers depend on N...

$\rightarrow$ correpondence between $\mathscr{L}$ and σ expansions? interplay with perturbative expansion?

in the end we expect $n_{SMEFT-6} \leqslant n_{HEFT-NLO} \leqslant n_{SMEFT-8}$ $\rightarrow$ alternative to dim-8 to stress-test dim-6?

SMEFT/HEFT geometrical interpretation

the comparison between SMEFT and HEFT can be obscured by the **field redefinition** relating them, which must be unphysical! geometry was introduced in this context to obviate this problem

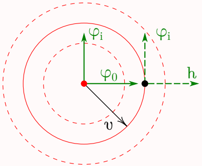
let us consider only the 4 scalar fields : they can be seen as coordinates on 4D manifold

Alonso, Jenkins, Manohar 1511.00724, 1605.03602

SMEFT $\sim$ **cartesian** coord.

$$(\mathbb{R}^4) \qquad \vec{\phi} = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \end{pmatrix}$$

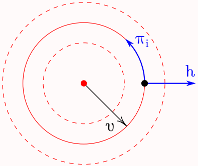
$$(SU(2)) \qquad H = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_2 + i\phi_1 \\ \phi_4 - i\phi_3 \end{pmatrix}$$



HEFT $\sim$ **polar** coord.

$$\vec{\phi} = (v+h) \exp\left[\frac{2\pi^i t_i}{v}\right] \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

$$\mathbf{U} = \exp\left[\frac{\pi^i \sigma_i}{v}\right]$$



SMEFT/HEFT geometrical interpretation

the comparison between SMEFT and HEFT can be obscured by the **field redefinition** relating them, which must be unphysical! geometry was introduced in this context to obviate this problem

let us consider only the 4 scalar fields : they can be seen as coordinates on 4D manifold

Alonso, Jenkins, Manohar 1511.00724, 1605.03602

SMEFT $\sim$ **cartesian** coord.

$$(\mathbb{R}^4) \qquad \vec{\phi} = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \end{pmatrix}$$

$$(SU(2)) \qquad H = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_2 + i\phi_1 \\ \phi_4 - i\phi_3 \end{pmatrix}$$

HEFT $\sim$ **polar** coord.

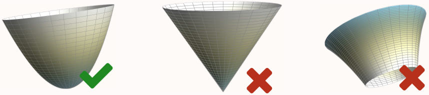
$$\vec{\phi} = (v + h) \exp\left[\frac{2\pi^i t_i}{v}\right] \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

$$\mathbf{U} = \exp\left[\frac{\pi^i \sigma_i}{v}\right]$$

- field redefinition $\leftrightarrow$ change of coordinates
- physics can be associated to geometry of the field space, independent of coordinates

Geometrical interpretation: achievements and limitations

- **model-independent amplitudes**: can be evaluated for different theories w/o recomputing diagrams
- applications to RGEs and matching Jenkins,Manohar,Naterop,Pagés 2308.06315, 2310.19883, Li,Lu,Zhang 2411.04173
- applications with gauge fields and fermions Helset+ 2212.03253, 2210.08000, 2307.03187, Pilaftsis+ 2006.05831, 2307.01126
- allow a characterization of theories that *cannot* be matched onto SMEFT Cohen,Craig,Lu,Sutherland 2008.08597



main limitations [scalars-only]

- invariance fails for **field redefinitions involving derivatives**, eg $\phi \to \phi(1 + \Box\phi)$
  $\to$ only works for "fixed basis"
- only describes operators with exactly **2 derivatives**: geometry from metric $\mathscr{L} \supset \frac{1}{2} g_{ij}(\phi)\, \partial_\mu \phi^i \partial^\mu \phi^j$

addressed in Cohen+ 2202.06965,2307.15742,2410.21378 Craig+ 2312.06748,2305.09722

Towards a geometrical description for arbitrary scalar EFTs

Alminawi,IB,Davighi 2308.00017

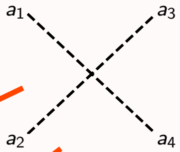
developing a formalism that keeps into account the fact that fields depend on spacetime
$\rightarrow$ account for $\phi(x),\ \partial_\mu\phi_i(x),\ \partial_\mu\partial_\nu\phi_i(x)\ldots$

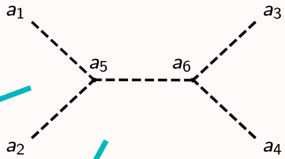
- change the geometric space from the field configurations one to r-jet bundles over spacetime
  which have coordinates: $(x^\mu, u_i, u_i^\mu, u_i^{\mu\nu}\ldots) \leftrightarrow (x^\mu, \phi_i, \partial^\mu\phi_i, \partial^\mu\partial^\nu\phi_i\ldots)$

- proved that a *complete* basis of scalar operators with **up to** $2n$ derivatives can be obtained from the metric of a $(n-1)$-jet bundle
  $\rightarrow$ gives geometric interpretation of higher-∂ operators but also to scalar potential !

$$\mathscr{L} \supseteq -\frac{1}{2}\eta^{\alpha\beta}\begin{pmatrix}\partial_\alpha x^\mu & \partial_\alpha\phi^i & \partial_\alpha\partial_\rho\phi^i & \ldots\end{pmatrix}\begin{pmatrix} g_{\mu\nu} & g_{\mu j} & g_{\mu j}^{\sigma} & \cdots \\ g_{\nu i} & g_{ij} & g_{ij}^{\sigma} & \cdots \\ g_{\nu i}^{\rho} & g_{ij}^{\rho} & g_{ij}^{\rho\sigma} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}\begin{pmatrix}\partial_\beta x^\nu \\ \partial_\beta\phi^j \\ \partial_\beta\partial_\sigma\phi^j \\ \vdots\end{pmatrix}$$

Example: $2 \to 2$ on-shell, tree-level amplitude (0 and 2 ∂)





$$\frac{i}{48}\left[\overline{\nabla_{a_1}\nabla_{a_2}R^{\mu}_{a_3\,\mu\,a_4}} + \mathrm{perm}_{1234}\right]$$

$$+\,i\left[-\frac{2}{3}\overline{R^{\mu}_{a_1\,\nu\,a_2}R^{\nu}_{a_3\,\mu\,a_4}} + \frac{1}{3}s_{12}\left(\overline{R_{a_1a_4a_3a_2}} + \overline{R_{a_2a_4a_3a_1}}\right) + \frac{1}{4}\Delta^{b_1b_2}(s_{12})(\overline{\nabla_{b_1}R^{\mu}_{a_1\,\mu\,a_2}})(\overline{\nabla_{b_2}R^{\mu}_{a_3\,\mu\,a_4}}) + \mathrm{perm}_{23} + \mathrm{perm}_{24}\right]$$

$$\overline{R^{\mu}_{i\,\mu\,j}} = \eta^{\mu\nu}\partial_i\partial_j g_{\mu\nu}\Big|_{\phi=0} = -2\partial_i\partial_j V(\phi)|_{\phi=0} = -2M^2_{ij}$$

$$\Delta^{ij}(p^2) = i\left[\overline{g_{ij}}p^2 - \overline{R^{\mu}_{i\,\mu\,j}}/2\right]^{-1}$$

Outlook

- the EFT program at LHC has already reached many milestones!
- strong interplay with precision calculations: requires few-10 % sensitivity
- main open challenges related to
  - improve EFT **predictions and statistical treatment**
  - incorporate **flavor** constraints into Higgs/EW/Top analyses
  - address potential **EFT validity / convergence** concerns
- turning to HEFT and geometrical methods as ways to
  - investigate the structure of the **EWSB sector** at a more fundamental level
  - identify and test BSM scenarios that do *not* match onto SMEFT
  - understand the structure of **scattering amplitudes**, obviating ambiguities from FR

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a COST Action focusing on Multiboson processes @LHC

currently 258 members in 35 countries covering TH + ATLAS/CMS + ML

what we do

- support conference attendance and scientific exchanges
- topical meetings and training schools
- online activities

2025 events

Polarized Perspectives: Tagging and Learning in the SM – Vienna (Austria), February 20 - 21

COMETA Workshop on EFT in HH and VBS – Paris Saclay (France), March 17 - 19

Positivity, Amplitudes and Phenomenology – CERN, April 7 - 11

2nd General Meeting – Krakow (Poland), April 28 - 30

COMETA Summer school on Machine Learning – Ljubljana (Slovenia), June 26 - July 3

Uncertainty quantification in AI: Physics and Mathematics Perspectives – Saclay (France), September