The SM as an Effective Field Theory: an overview

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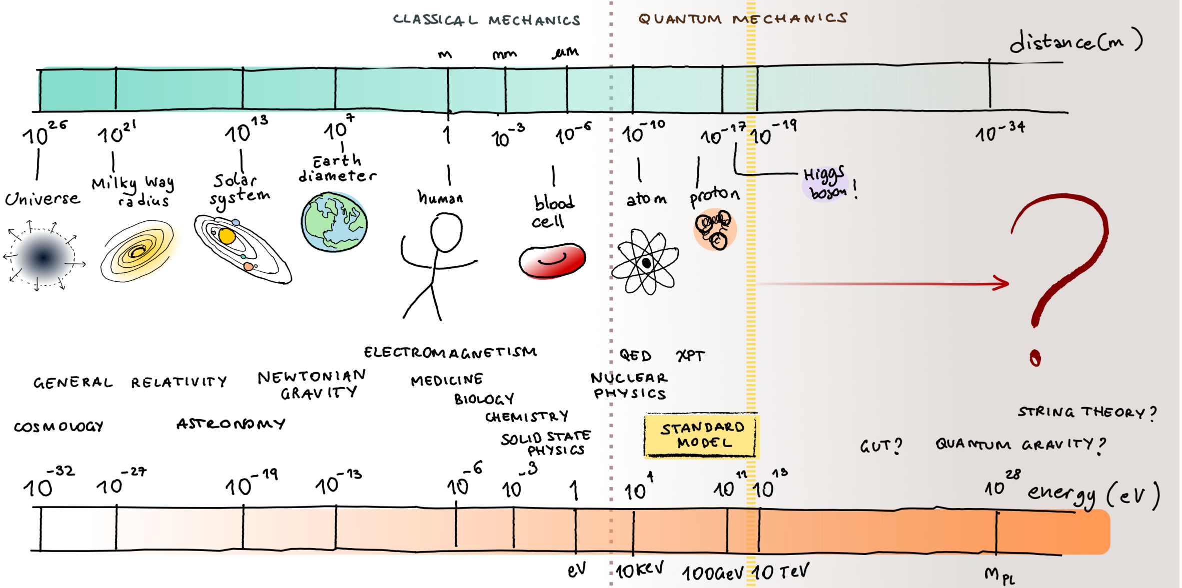
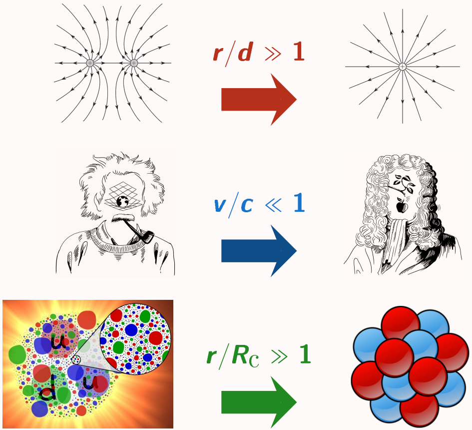
Physics across energy scales



All Theories are Effective

an **Effective Theory** is obtained from a more fundamental one taking a kinematic or parametric limit
→ typically ET = the LO in an **expansion**

- ET typically **simpler** than the full theory in the pertinent regime
- one **doesn't need to know** the full theory to calculate! the ET is enough



separation of scales/decoupling

Newtonian gravity can be formulated w/o general relativity

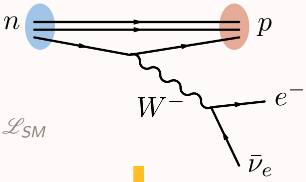
nuclear physics can be formulate w/o QCD

chemistry can be formulated w/o SM. . .

→ we expect any theory to be replaced by another one going to higher energies
(until the ultimate Theory of Everything)

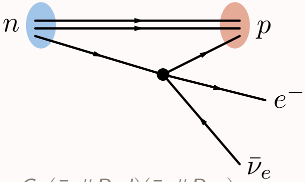
Effective Field Theories

Fermi Theory of β decay



$\mathscr{L} = \mathscr{L}_{SM}$

$q^2 < m_N^2 \ll m_W^2$



$\mathscr{L} = -G_F(\bar{u}\gamma^\mu P_L d)(\bar{\nu}\gamma^\mu P_L e)$

E

Λ **Theory with heavy particles**

TAYLOR SERIES in $(\mu/\Lambda \ll 1)$

μ **Effective Field Theory: only light particles**

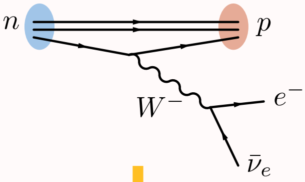
$$\mathscr{L}_{EFT} = \mathscr{L}_4 + \frac{1}{\Lambda}\mathscr{L}_5 + \frac{1}{\Lambda^2}\mathscr{L}_6 + \frac{1}{\Lambda^3}\mathscr{L}_7 \ldots$$

Appelquist,Carazzone 1975

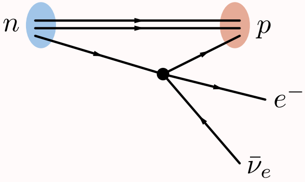
→ heavy DOFs are removed: cannot be produced at $E \ll M$
→ local, analytic, higher-dimensional terms added to $\mathscr{L}$

Effective Field Theories

Fermi Theory of β decay



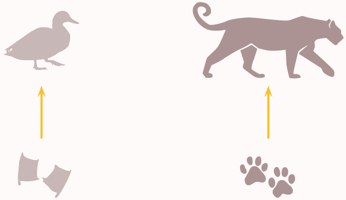
$q^2 < m_N^2 \ll m_W^2$



Bottom-up paradigm

measuring EFT parameters **reveals properties** of full theory

→ *complement* direct searches, reach into higher energies



EFT fully specified by **fields+symmetries at E** $= \mu$

→ no reference to underlying model

→ free couplings that can be measured!

→ higher-d terms ⇒ limited UV validity, due to E growth

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger \varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} T^A u_r) \widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger \varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} u_r) \widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger \varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) \varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r) \tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger \tau^I \varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

free parameters

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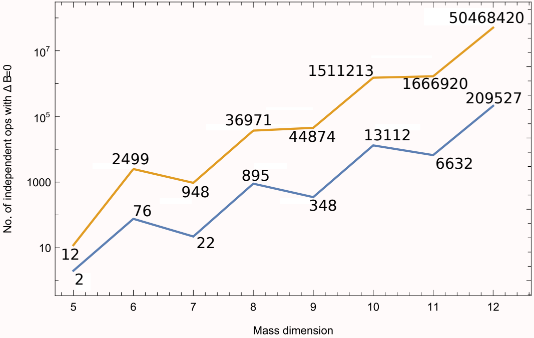
IB 2012.11343

they are ∼never all relevant at the same time

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

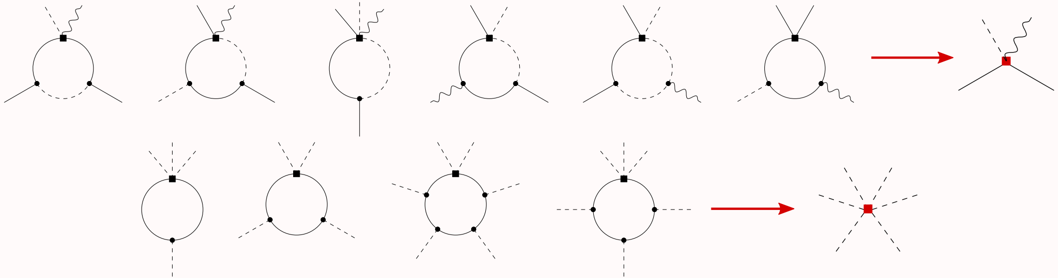
d = 10,11,12 Harlander, Kempksens, Schaaf 2305.06832

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

Renormalization Group evolution

when going to 1-loop divergences appear, reabsorbed by counterterms of the same dimension

→ SMEFT operators **run and mix** with each other, order by order in Λ



fully computed at 1 loop for dim-6, automated in `DsixTools`, `wilson`

Alonso,Jenkins,Manohar,Trott 1308.2627,1310.4838,1312.2014
Celis,Fuentes-Martin,Ruiz-Femenia,Vicente,Virto 1704.04504,2010.16341, Aebischer,Kumar,Straub 1804.05033

partial results for dim6-2loops and dim8-1loop ⇝ Luigi, Stefano

Elias-Miro' et al 2005.06983,2112.12131, Bern,Parra-Martinez 2005.12917, Jin,Ren,Yang 2011.02494, Fuentes-Martin et al 2311.13630,2410.07320
Bresciani,Levati,Mastrolia,Paradisi 2312.05026, Chala et al 2106.05291,2205.03301,2309.16611,2409.15408, Boughezal et al 2408.15378...

Below m_W: the Low Energy EFT (LEFT) or Weak EFT (WET)

at energies $\lesssim m_W$, the heaviest SM particles effectively decouple, and another EFT is more appropriate

fields: SM w/o H, W, Z, t **symmetries**: $U(1)_{em} \times SU(3)_c$

$$\mathscr{L}_{LEFT} = \mathscr{L}_{\text{QED+QCD}} + v\,\mathscr{L}_3 + \frac{1}{v}\mathscr{L}_5 + \frac{1}{v^2}\mathscr{L}_6 + \dots$$

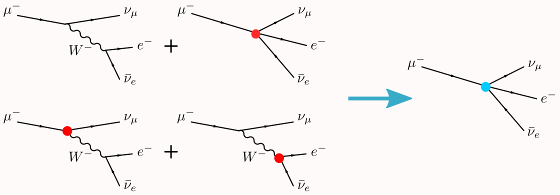
$$\mathscr{L}_{\text{QED+QCD}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} + \sum_\psi \bar\psi i \not{D}\psi - \sum_\psi \left[\bar\psi_R M_\psi \psi_L + \text{h.c.}\right]$$
$$+ \theta_{QED}\frac{e^2}{32\pi^2}F_{\mu\nu}\tilde F^{\mu\nu} + \theta_{QCD}\frac{g_s^2}{32\pi^2}G_{\mu\nu}\tilde G^{A\mu\nu}$$

employed extensively in **flavor physics**. at even lower energies $\lesssim \Lambda_{QCD}$: chiral perturbation theory

LEFT operators

$\mathcal{L}_3$ $(\nu_{Lp}^T C \nu_{Lr})$	$\mathcal{L}_6$
$\mathcal{L}_5$ $(\nu_{Lp}^T C \sigma^{\mu\nu} \nu_{Lr}) F_{\mu\nu}$ $\bar{e}_{Lp}\sigma^{\mu\nu} e_{Rr}\, F_{\mu\nu}$ $\bar{u}_{Lp}\sigma^{\mu\nu} u_{Rr}\, F_{\mu\nu}$ $\bar{d}_{Lp}\sigma^{\mu\nu} d_{Rr}\, F_{\mu\nu}$ $\bar{u}_{Lp}\sigma^{\mu\nu} T^A u_{Rr}\, G^A_{\mu\nu}$ $\bar{d}_{Lp}\sigma^{\mu\nu} T^A d_{Rr}\, G^A_{\mu\nu}$	$f^{ABC} G^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$ $f^{ABC} \widetilde{G}^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$ + 4-fermion interactions

example: SMEFT to LEFT match at tree level

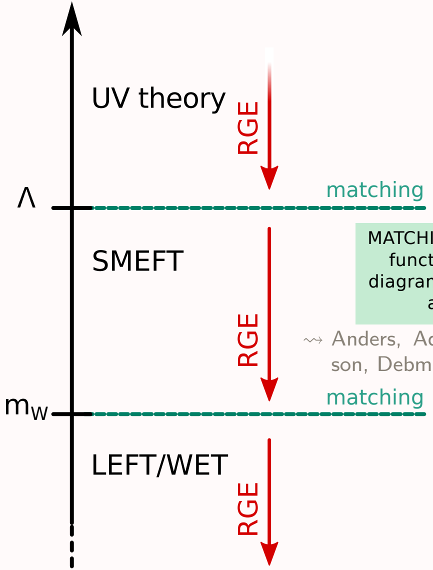


$$c_{V,LL} \sim -\frac{1}{v^2} + \frac{1}{\Lambda^2}\left[C_{ll,1221} - C^{(3)}_{Hl,11} - C^{(3)}_{Hl,22}\right]$$

bases available up to $d = 9$ Jenkins,Manohar,Stoffer 1709.04486, Aebischer,Fael,Greub,Virto 1704.06639 Liao,Ma,Wang 2005.08013, Murphy 2012.13291, Li,Ren,Xiao,Yu,Zheng 2012.09188

matching to SMEFT and RG running ⇝ Ben Aebischer,Crivellin,Fael,Greub 1512.02830, Jenkins,Manohar,Stoffer 1709.04486,1711.05270

The bigger picture – a blooming research field!



MATCHING TECHNIQUES
functional methods, diagrammatic matching, automation

⇝ Anders, Adrián, Fuensanta, Jason, Debmalya, Tisa, Fabian

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 ...

⇝ Victor, Elie, Riccardo, Marion

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

SMEFT @LHC: two main challenges

1. being sensitive to indirect BSM effects → needs uncertainty reduction

in bulk $\sim \dfrac{v^2}{\Lambda^2} = \dfrac{v^2 g_{UV}}{M^2}$. $\qquad g_{UV} \simeq 1, \quad M \simeq 2\,\mathrm{TeV} \quad \rightarrow$ 1.5%

on tails $\sim \dfrac{E^2}{\Lambda^2} \simeq \dfrac{E^2 g_{UV}}{M^2} \qquad E \simeq 1\,\mathrm{TeV}, M \simeq 3\,\mathrm{TeV} \quad \rightarrow$ 10%

SMEFT @LHC: two main challenges

1. being sensitive to indirect BSM effects → needs uncertainty reduction

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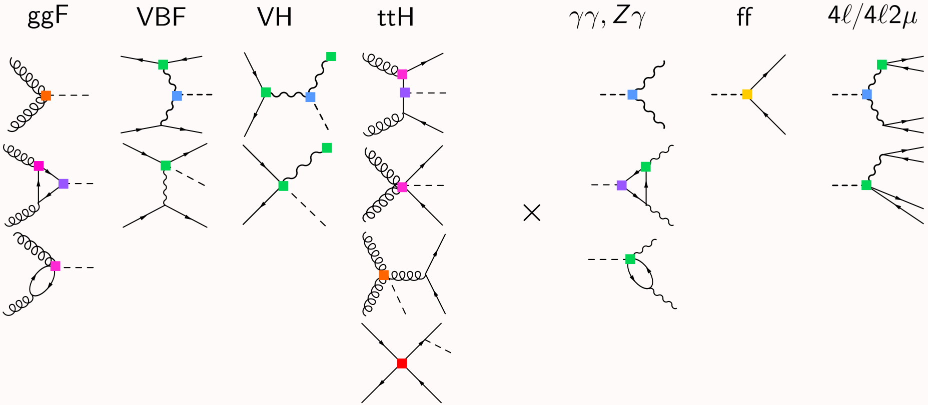
$$\text{on tails} \sim \frac{E^2}{\Lambda^2} \simeq \frac{E^2 g_{UV}}{M^2} \qquad E \simeq 1\,\text{TeV}, M \simeq 3\,\text{TeV} \quad \to \quad 10\%$$

2. making sure that, if we observe a deviation, we interpret it correctly
   - **minimizing bias** by retaining all relevant contributions
   - correct understanding of uncertainties and correlations
   - systematic mapping to BSM models tree-level dictionary: de Blas et al 1711.10391 1-loop dictionary: Guedes et al 2303.16965

→ **global analyses**

Example: SMEFT in Higgs physics



Marginalized fit results

ATLAS 2402.05742

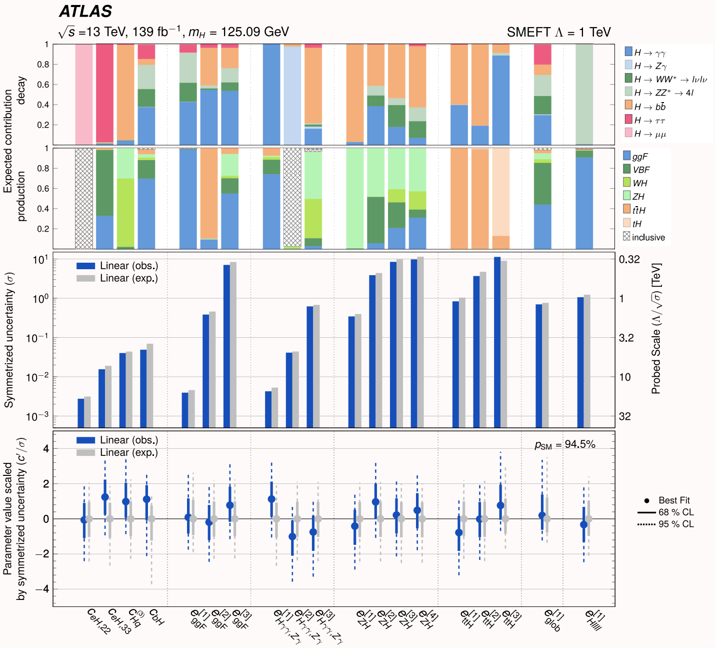
all Warsaw basis considered, only 19 combinations meaningfully constrained

selected with **Principal Component Analysis**: diagonalize Fisher information matrix

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

eigenvalues $\simeq$ (bound)$^{-1}$

☞ keep only eigenvectors with eigenvalues above a chosen sensitivity threshold



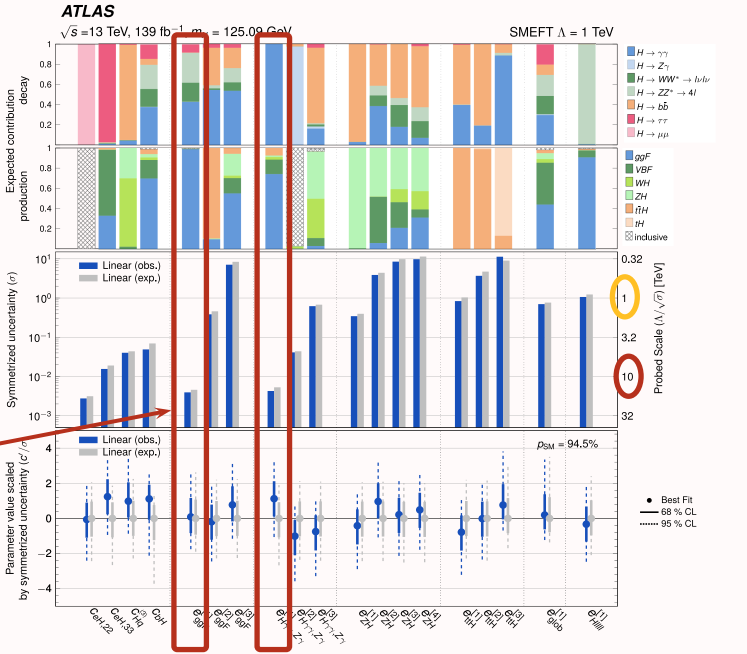
Marginalized fit results

ATLAS 2402.05742

non trivial interplay among production and decay channels, especially involving *HVV* vertices

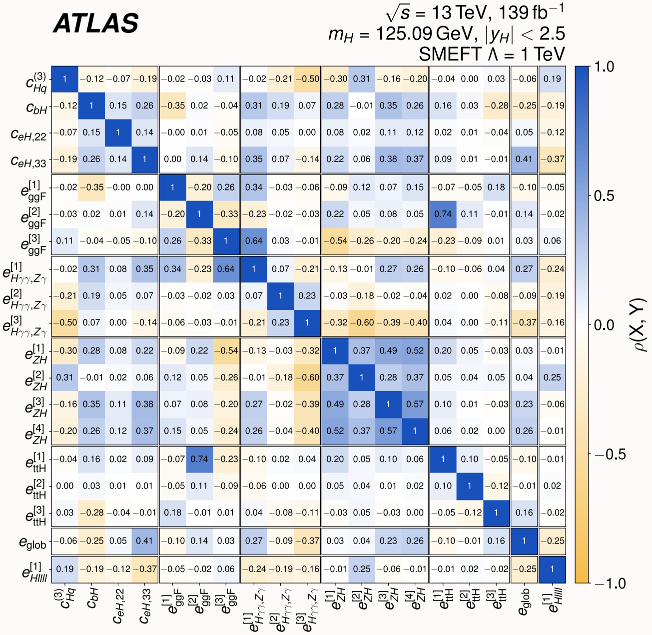
strongest constraints from $gg \to h \to \gamma\gamma$

sensitivity above 10 TeV



Correlations

ATLAS 2402.05742

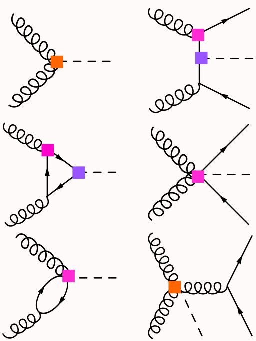


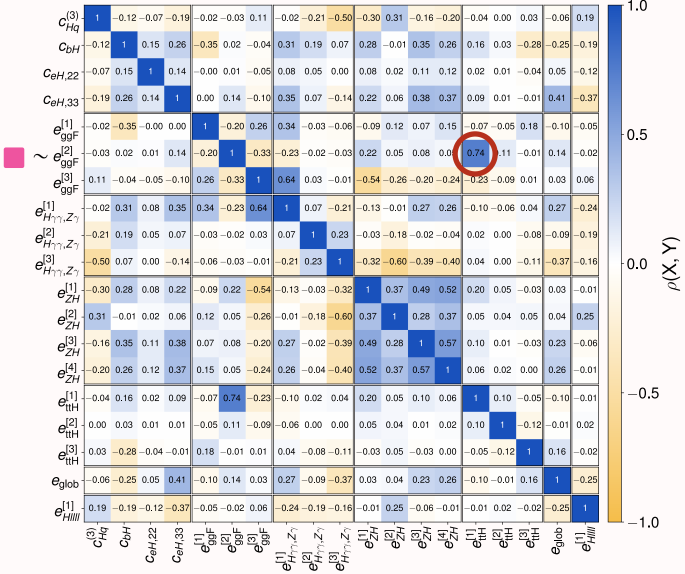
	$c_{Hq}^{(3)}$	c_{bH}	$c_{eH,22}$	$c_{eH,33}$	$e_{ggF}^{[1]}$	$e_{ggF}^{[2]}$	$e_{ggF}^{[3]}$	$e_{H\gamma\gamma,Z\gamma}^{[1]}$	$e_{H\gamma\gamma,Z\gamma}^{[2]}$	$e_{H\gamma\gamma,Z\gamma}^{[3]}$	$e_{ZH}^{[1]}$	$e_{ZH}^{[2]}$	$e_{ZH}^{[3]}$	$e_{ZH}^{[4]}$	$e_{ttH}^{[1]}$	$e_{ttH}^{[2]}$	$e_{ttH}^{[3]}$	e_{glob}	$e_{Hllll}^{[1]}$
$c_{Hq}^{(3)}$	1	−0.12	−0.07	−0.19	−0.02	−0.03	0.11	−0.02	−0.21	−0.50	−0.30	0.31	−0.16	−0.20	−0.04	0.00	0.03	−0.06	0.19
c_{bH}	−0.12	1	0.15	0.26	−0.35	0.02	−0.04	0.31	0.19	0.07	0.28	−0.01	0.35	0.26	0.16	0.03	−0.28	−0.25	−0.19
$c_{eH,22}$	−0.07	0.15	1	0.14	−0.00	0.01	−0.05	0.08	0.05	0.00	0.08	0.02	0.11	0.12	0.02	0.01	−0.04	0.05	−0.12
$c_{eH,33}$	−0.19	0.26	0.14	1	0.00	0.14	−0.10	0.35	0.07	−0.14	0.22	0.06	0.38	0.37	0.09	0.01	−0.01	0.41	−0.37
$e_{ggF}^{[1]}$	−0.02	−0.35	−0.00	0.00	1	−0.20	0.26	0.34	−0.03	−0.06	−0.09	0.12	0.07	0.15	−0.07	−0.05	0.18	−0.10	−0.05
$e_{ggF}^{[2]}$	−0.03	0.02	0.01	0.14	−0.20	1	−0.33	−0.23	−0.02	−0.03	0.22	0.05	0.08	0.05	0.74	0.11	−0.01	0.14	−0.02
$e_{ggF}^{[3]}$	0.11	−0.04	−0.05	−0.10	0.26	−0.33	1	0.64	0.03	−0.01	−0.54	−0.26	−0.20	−0.24	−0.23	−0.09	0.01	0.03	0.06
$e_{H\gamma\gamma,Z\gamma}^{[1]}$	−0.02	0.31	0.08	0.35	0.34	−0.23	0.64	1	0.07	−0.21	−0.13	−0.01	0.27	0.26	−0.10	−0.06	0.04	0.27	−0.24
$e_{H\gamma\gamma,Z\gamma}^{[2]}$	−0.21	0.19	0.05	0.07	−0.03	−0.02	0.03	0.07	1	0.23	−0.03	−0.18	−0.02	−0.04	0.02	0.00	−0.08	−0.09	−0.19
$e_{H\gamma\gamma,Z\gamma}^{[3]}$	−0.50	0.07	0.00	−0.14	−0.06	−0.03	−0.01	−0.21	0.23	1	−0.32	−0.60	−0.39	−0.40	0.04	0.00	−0.11	−0.37	−0.16
$e_{ZH}^{[1]}$	−0.30	0.28	0.08	0.22	−0.09	0.22	−0.54	−0.13	−0.03	−0.32	1	0.37	0.49	0.52	0.20	0.05	−0.03	0.03	−0.01
$e_{ZH}^{[2]}$	0.31	−0.01	0.02	0.06	0.12	0.05	−0.26	−0.01	−0.18	−0.60	0.37	1	0.28	0.37	0.05	0.04	0.05	0.04	0.25
$e_{ZH}^{[3]}$	−0.16	0.35	0.11	0.38	0.07	0.08	−0.20	0.27	−0.02	−0.39	0.49	0.28	1	0.57	0.10	0.01	−0.03	0.23	−0.06
$e_{ZH}^{[4]}$	−0.20	0.26	0.12	0.37	0.15	0.05	−0.24	0.26	−0.04	−0.40	0.52	0.37	0.57	1	0.06	0.02	0.00	0.26	−0.01
$e_{ttH}^{[1]}$	−0.04	0.16	0.02	0.09	−0.07	0.74	−0.23	−0.10	0.02	0.04	0.20	0.05	0.10	0.06	1	0.10	−0.05	−0.10	−0.01
$e_{ttH}^{[2]}$	0.00	0.03	0.01	0.01	−0.05	0.11	−0.09	−0.06	0.00	0.00	0.05	0.04	0.01	0.02	0.10	1	−0.12	−0.01	0.02
$e_{ttH}^{[3]}$	0.03	−0.28	−0.04	−0.01	0.18	−0.01	0.01	0.04	−0.08	−0.11	−0.03	0.05	−0.03	0.00	−0.05	−0.12	1	0.16	−0.02
e_{glob}	−0.06	−0.25	0.05	0.41	−0.10	0.14	0.03	0.27	−0.09	−0.37	0.03	0.04	0.23	0.26	−0.10	−0.01	0.16	1	−0.25
$e_{Hllll}^{[1]}$	0.19	−0.19	−0.12	−0.37	−0.05	−0.02	0.06	−0.24	−0.19	−0.16	−0.01	0.25	−0.06	−0.01	−0.01	0.02	−0.02	−0.25	1

Correlations

ATLAS 2402.05742

ggF ttH





Open challenges and active lines of development

- improve **predictions** to higher perturbative orders
- improve **matching and running** to higher perturbative and EFT orders
- combine Higgs/top/EW measurements with **flavor** measurements
- improve **statistical** analyses with likelihoods, optimal observables...
- explore interplay of SMEFT constraints with **direct searches**
- truncation uncertainties and impact of dim-8
- move (partially) to HEFT ?

Origin of SMEFT truncation uncertainties / EFT validity concern

- Λ is **unknown**
- LHC measurements often reach into **high energies** $(m, p_T, m_T \ldots)$
- often **measurement** precision is not sufficient to guarantee that deviations from SM are small

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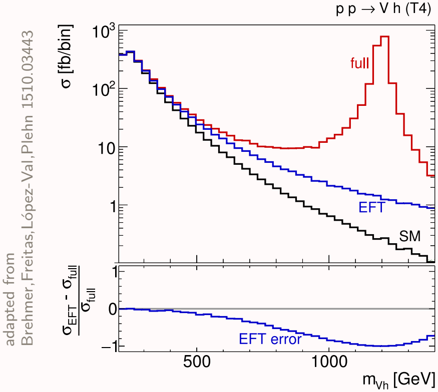
is $(E, v) \ll \Lambda$ a valid assumption?

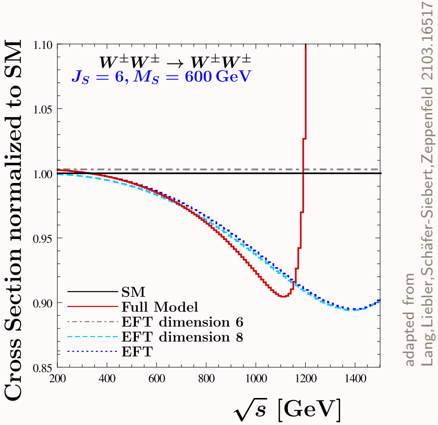
are $d \geqslant 8$ terms always negligible?

can there be UV scenarios for which SMEFT does not describe the low-E limit?

Poor SMEFT convergence

EFT obtained from matching to full model

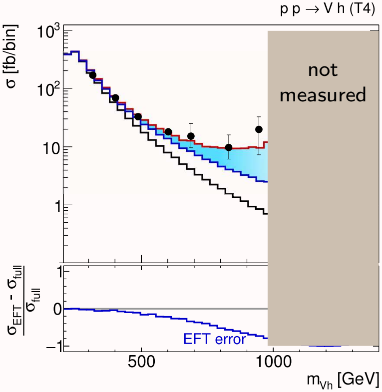




$d = 6$ contribution dominant at low m_{VH}

$d = 6$ contribution negligible

Poor SMEFT convergence



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

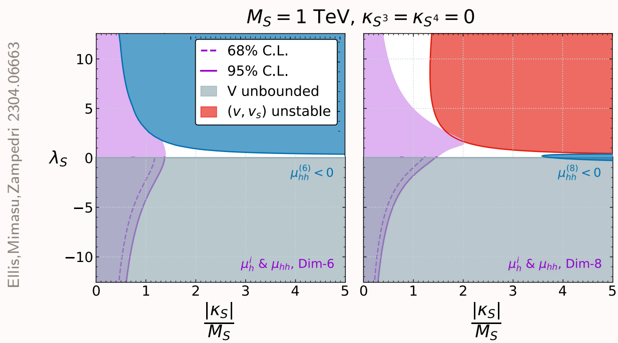
👎 **top-down**: truncated EFT does not reproduce full model at high-E

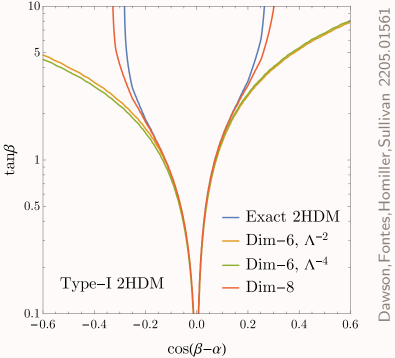
👎 **bottom-up**: fit to data finds wrong values of C_i

→ several studies of $d = 8$ impact

Exploring the impact of dim-8 terms

- hard to establish true relevance when left free (eg in a fit)
- checking impact when matched to specific models helps accounting for natural size





The Higgs Effective Field Theory – HEFT

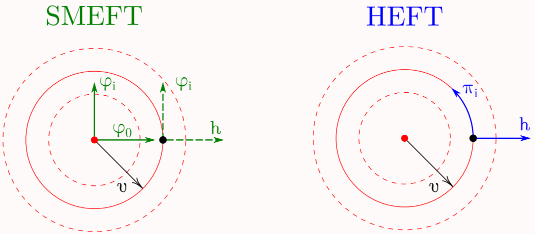
rather than H doublet:
singlet h + Goldstones $\mathbf{U}$

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



HEFT expansion

- **more complicated power counting**, mix of χPT and canonical dimensions
  Gavela,Jenkins,Manohar,Merlo 1601.07551
  Buchalla,Catà,(Celis),Krause 1312.5624,1603.03062

  orders are defined as $\mathscr{L}_{HEFT} = \mathscr{L}_0 + \mathscr{L}_1 + \mathscr{L}_2 + \dots$

  $\mathscr{L}_1$ = leading deviations from SM = "4 derivatives" = NLO

- order-by-order, **more operators** than SMEFT: for 3 flavors, L, B conserving: $\mathscr{L}_1$: 6573, $\mathscr{L}_2$: 10^6+

  Hilbert series counting is available Gráf,Henning,Lu,Melia,Murayama 2211.06725

  complete bases available up to $\mathscr{L}_2$ Buchalla,Catà,Krause 1307.5017, IB et al 1604.06801
  Sun,Xiao,Yu 2210.14939, Sun,Wang,Yu 2211.11598

- looking at the bosonic sector, $\mathscr{L}_1$ contains 39 operators → better than dim-8!

  15 in dim-6 Warsaw basis $<$ **39** $<$ 89 in dim-8 Murphy basis

Main HEFT features

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

HEFT ⊃ SMEFT ⊃ SM

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

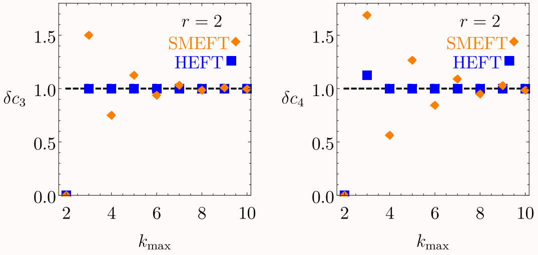
e.g. SO(5)/SO(4)

$$\mathcal{F}(h) = \frac{4}{\xi}\sin^2\frac{\varphi}{2f} = \frac{4}{\xi}\sin^2\left[\frac{\langle\varphi\rangle + h}{2f}\right]$$

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

$$\xi = \frac{v^2}{f^2} = 4\sin^2\frac{\langle\varphi\rangle}{2f}$$

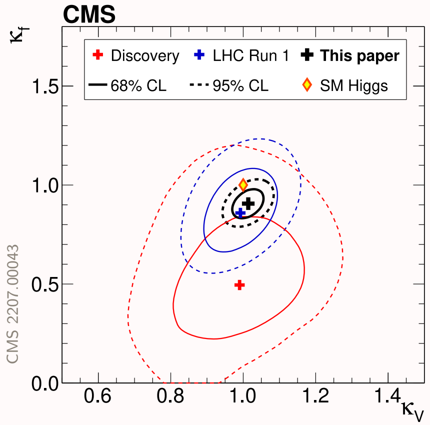
see eg. Alonso et al 1409.1589

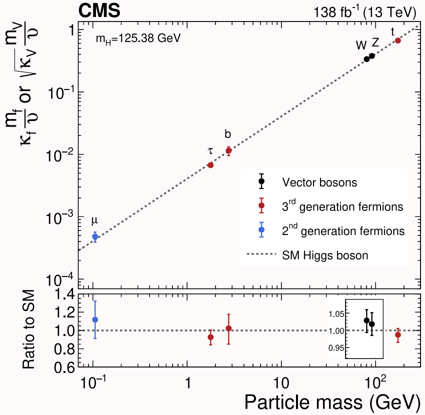


Cohen, Craig, Lu, Sutherland 2008.08597

Is HEFT phenomenologically relevant?

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





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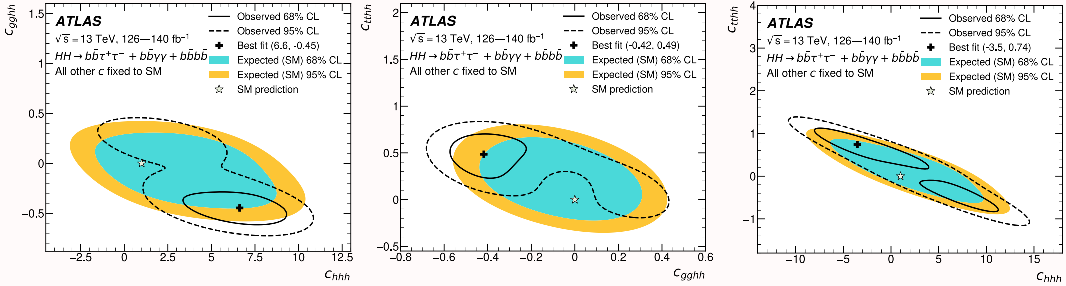
- 😐 Higgs **self-couplings** leave more freedom ⇝ Anisha

ATLAS 2406.09971



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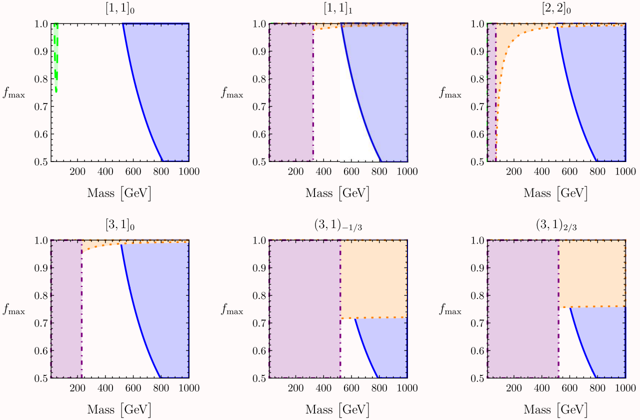

Banta, Cohen, Craig, Lu, Sutherland 2110.02967

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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

  → HEFT as an alternative to dim-8?

Wrapping up

- Effective Field Theories are a powerful theoretical concept, long used to investigate nature
- SMEFT has become a very popular tool for BSM searches
  → enable **model-independent** "agnostic" searches
  → allow joining information from LHC searches and measurements at other experiments
- the SMEFT program for LHC is blooming.
  → massive developments in **several directions**, theoretical, experimental, technical...
  → sensitivity already in the interesting region for many operator classes
- HEFT is an alternative formulation that has been recently resurfacing
  → particularly intersesting for multi-Higgs measurements
  → could help describe cases where SMEFT convergence is not so good