Effective Field Theory description of SM deviations

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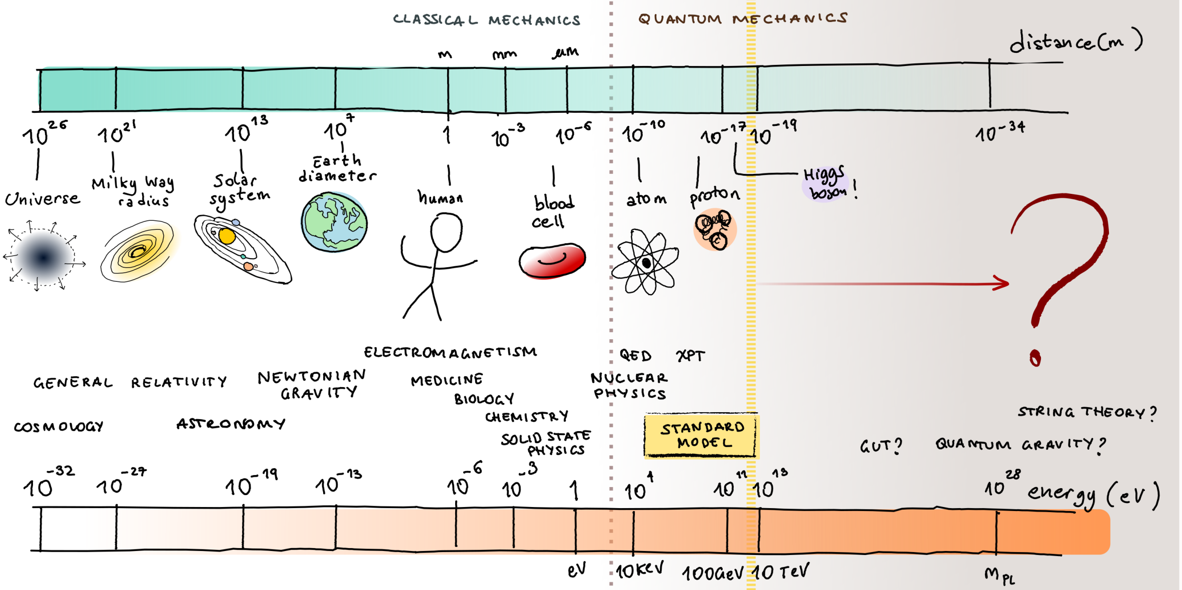
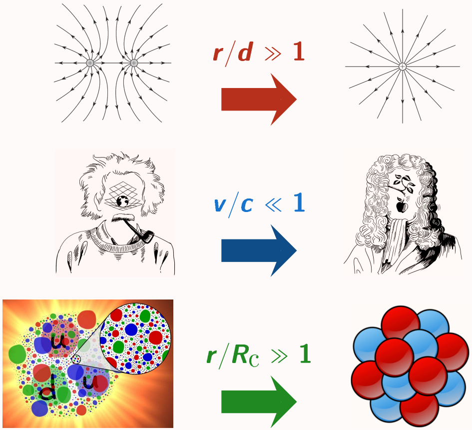
Physics across energy scales



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

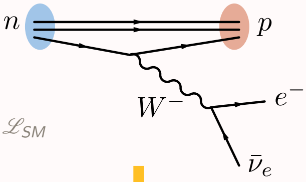
nuclear physics can be formulate w/o QCD

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)

Fermi Theory of β decay

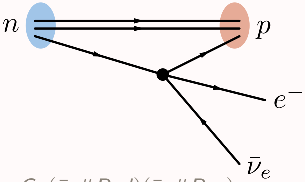
Λ



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

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

μ



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

E

Full theory

$\rightarrow$ renormalizable: $[\mathscr{L}] = 4$

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

Effective Field Theory

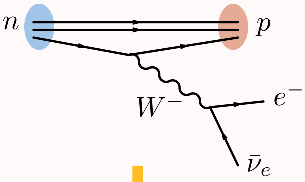
$$\mathscr{L}_{EFT} = \mathscr{L}_4 + \frac{1}{\Lambda}\mathscr{L}_5 + \frac{1}{\Lambda^2}\mathscr{L}_6 + \frac{1}{\Lambda^3}\mathscr{L}_7 \dots$$

Appelquist,Carazzone 1975

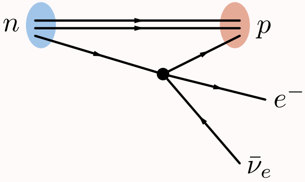
$\rightarrow$ heavy DOFs are removed: cannot be produced at $E \ll M$
$\rightarrow$ local, analytic, higher-dimensional terms added to $\mathscr{L}$

Effective Field Theories

Fermi Theory of β decay



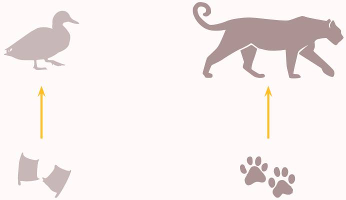
$q^2 < m_N^2 \ll m_W^2$



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 $d = 5$: Majorana neutrino masses

only one operator! Weinberg PRL43(1979)1566

$$\mathcal{L}_5 = C_{5,pr}\left(\overline{\ell^c_{L,p}}\tilde{H}^*\right)\left(\tilde{H}^\dagger \ell_{L,r}\right) + \text{h.c.} = C_{5,pr}\left(\ell^T_{L,p}\tilde{H}^*\right)\mathcal{C}\left(\tilde{H}^\dagger \ell_{L,r}\right) + \text{h.c.}$$

$\downarrow$ EWSB

$$= C_{5,pr}\,\frac{(v+h)^2}{2}\,\overline{\nu^c_{L,p}}\,\nu_{L,r} + \text{h.c.} = C_{5,pr}\,\frac{(v+h)^2}{2}\,\nu^T_{L,p}\,\mathcal{C}\,\nu_{L,r} + \text{h.c.}$$

$\rightarrow$ **Majorana mass term** for neutrinos + Higgs-ν interactions

violates **lepton number** conservation! in SM: L accidental.
in SMEFT: not conserved in general.

↗ impose L conservation. $\Rightarrow$ ν are Dirac particles, $C_5 \equiv 0$, must introduce ν_R to explain m_ν

↘ allow L violation. $\Rightarrow$ ν are Majorana particles, $C_5 \neq 0$. no ν_R needed in EFT

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

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

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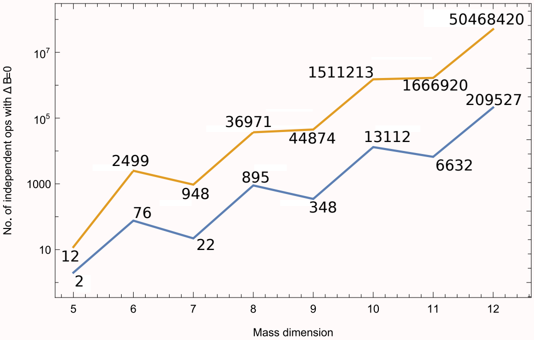
A fast growing series

 # 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

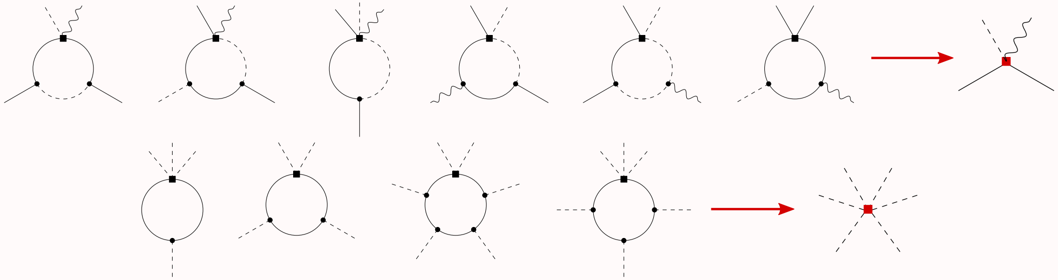
d = 10,11,12 Harlander,Kempksens,Schaaf 2305.06832

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

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

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

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**: $U(1)_{em} \times SU(3)_c$

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

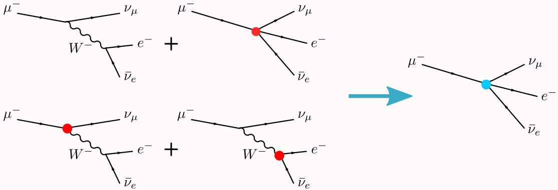
$$\mathscr{L}_{\text{QED+QCD}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} + \sum_\psi \bar\psi i \not{D}\psi - \sum_\psi \left[\bar\psi_R M_\psi \psi_L + \text{h.c.}\right]$$
$$+ \theta_{QED}\frac{e^2}{32\pi^2}F_{\mu\nu}\tilde F^{\mu\nu} + \theta_{QCD}\frac{g_s^2}{32\pi^2}G_{\mu\nu}\tilde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

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

LEFT operators

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

example: SMEFT to LEFT match at tree level

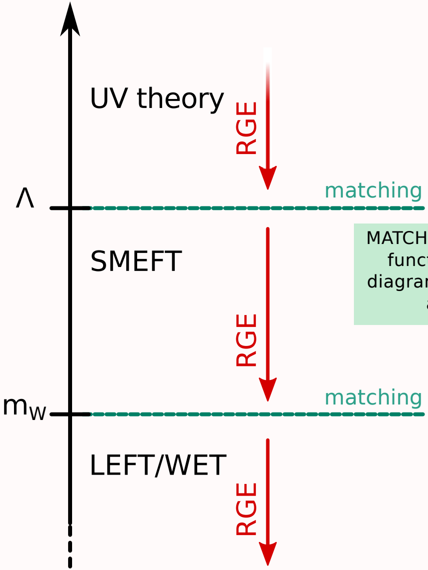


$$c_{V,LL} \sim -\frac{1}{v^2} + \frac{1}{\Lambda^2}\left[C_{ll,1221} - C^{(3)}_{Hl,11} - C^{(3)}_{Hl,22}\right]$$

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 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

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 ...

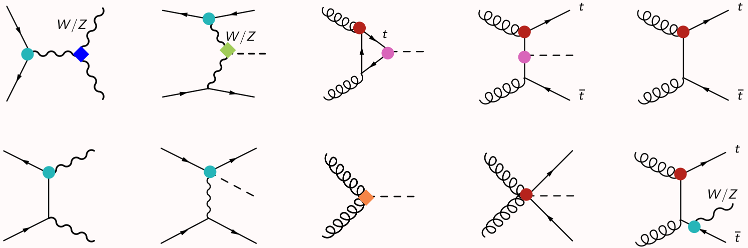
STATISTICAL ANALYSIS
fitting tools, likelihood inference,
infomation geometry, ML-based tools,
interplay with PDFs...

The SMEFT program at the LHC

no BSM particles discovered so far,
no conclusive clue about where to find NP

(HL-)LHC projected to reach **%-ish precision** on many observables

Higgs, EW, top, flavor sectors **intertwined**:
each operator enters many places,
each process corrected by many operators



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↓

adopt SMEFT as a universal tool for **agnostic, bottom-up searches**

perform a broad campaign of measurements,
combined in large **global analyses**

The SMEFT program at the LHC

no BSM partic

no conclusive clue

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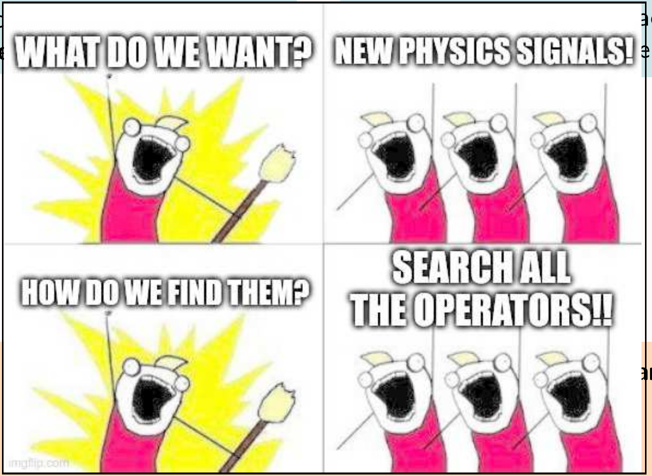
ervables



adopt

arches

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%

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2. making sure that, if we observe a deviation, we interpret it correctly
   - retaining **all relevant contributions**: all operators, NLO corrections...

     ↓

     handling many parameters in predictions and fits, understanding the theory structure
   - correct understanding of uncertainties and correlations
   - systematic mapping to BSM models

SMEFT in Higgs physics

case study: latest ATLAS Higgs combination ATLAS 2402.05742

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observables: Simplified-Template Cross Sections (STXS) Dührssen-Debling et al 2003.01700 (IV.1)

predictions:

$$\mathcal{A}_{SMEFT} = \mathcal{A}_{SM} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{A}_i\,, \qquad \mathcal{A}_i = \text{ amplitude with 1 insertion of operator } \mathcal{O}_i$$

$$\sigma_{SMEFT} = \sigma_{SM,best}\left[1 + \frac{1}{\Lambda^2}\sum_i \frac{2\Re(C_i\,\mathcal{A}_i\mathcal{A}^\dagger_{SM})}{|\mathcal{A}_{SM}|^2} + \frac{1}{\Lambda^4}\sum_i \frac{|C_i\,\mathcal{A}_i|^2}{|\mathcal{A}_{SM}|^2} + \frac{1}{\Lambda^4}\sum_{i>j}\frac{2\Re(C_i C_j^*\,\mathcal{A}_i\mathcal{A}_j^\dagger)}{|\mathcal{A}_{SM}|^2}\right]$$

linear quadratics

$\mathcal{A}_{SM}, \mathcal{A}_i$ computed at the *same* order.
Automated in general-purpose Monte Carlo up to 1 loop in QCD (5 flavor scheme). IB 2012.11343 Degrande et al 2008.11743
1-loop-EW and 2-loop-QCD results available (semi)analytic only for select processes

$\sigma_{SM,best}$ can be computed *at higher order* in the SM (eg. NNLO, N^{3}LO QCD)

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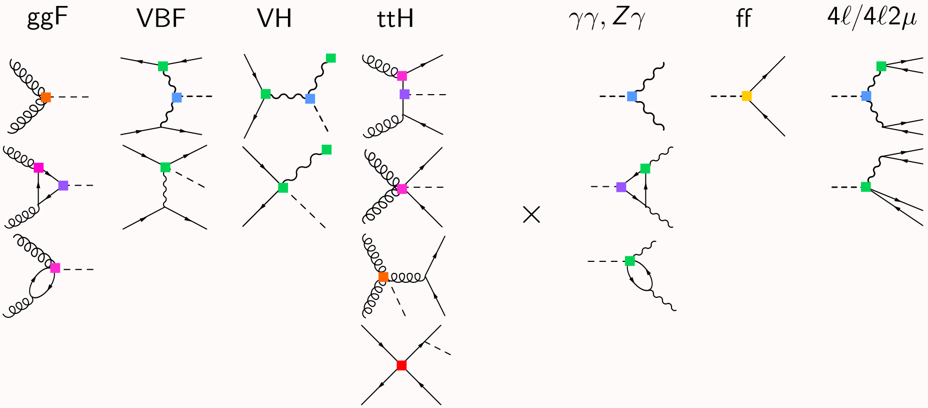

SMEFT in Higgs physics

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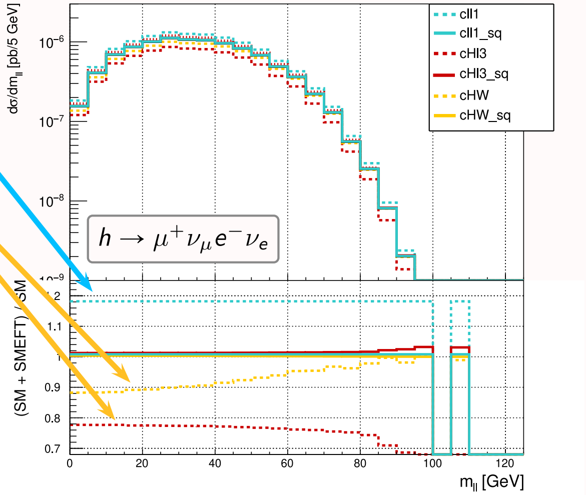
general feature of SMEFT predictions:

certain operators give **normalization** shifts N

certain operators give **kinematic** shapes K



typically:

N operators have linear > quadratic contributions.

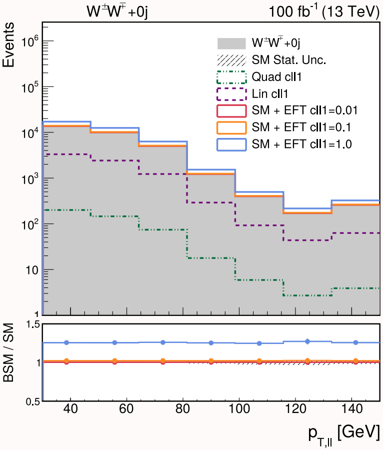
☞ best probed with precision in **bulk**

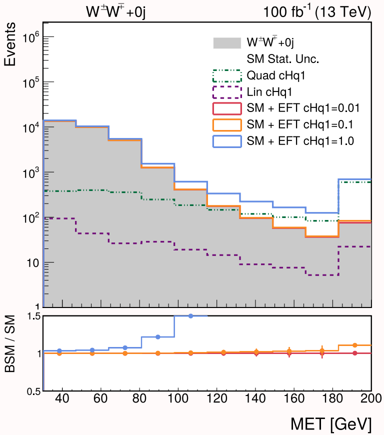
K operators have linear > quadratic in the bulk but linear ≪ quadratic at higher energies

☞ best probed with E growth in **tails**

SMEFT in Higgs physics

case study: latest ATLAS Higgs combination ATLAS 2402.05742





Bellan,Boldrini,Brambilla,IB et al 2108.03199

SMEFT in Higgs physics

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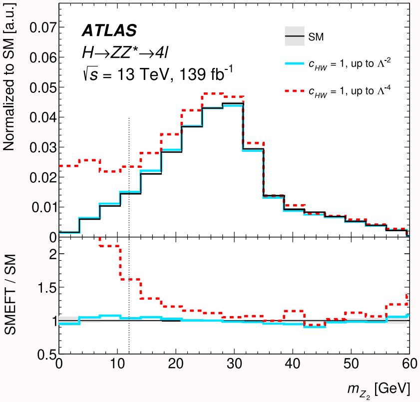
effects in **acceptances**:
operators that alter the kinematics
can change the fraction of selected events

important to check these contributions
when fitting *unfolded* observables



Marginalized fit results

all Warsaw basis considered, only 19 combinations meaningfully constrained

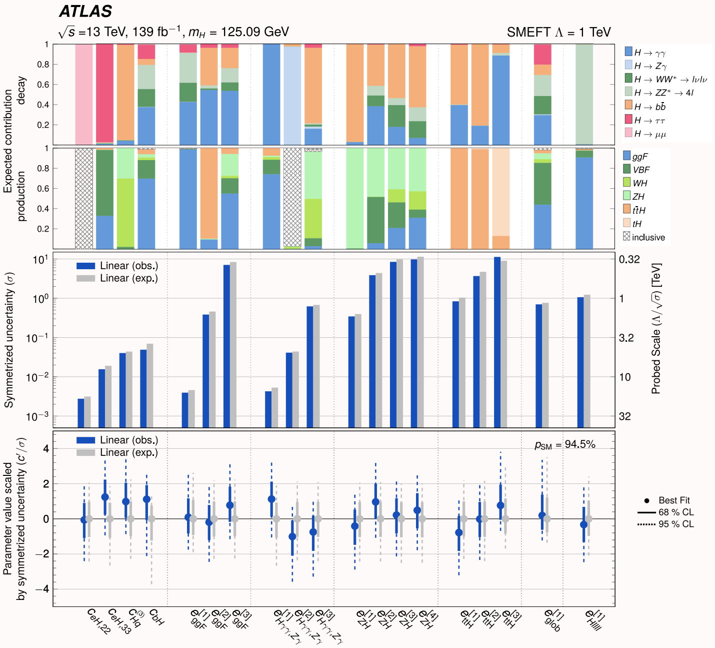
selected with **Principal Component Analysis**:

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

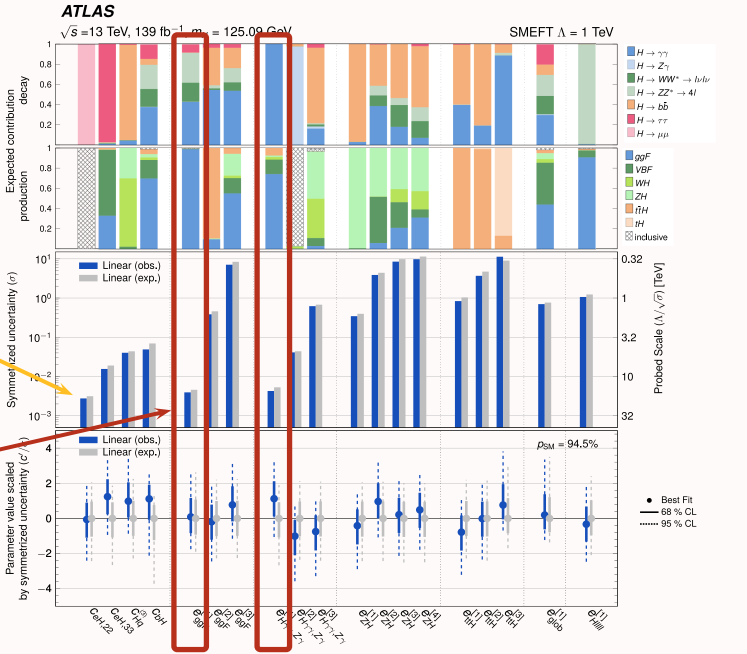
non trivial interplay among production and decay channels, especially involving HVV vertices

normalization enhancement

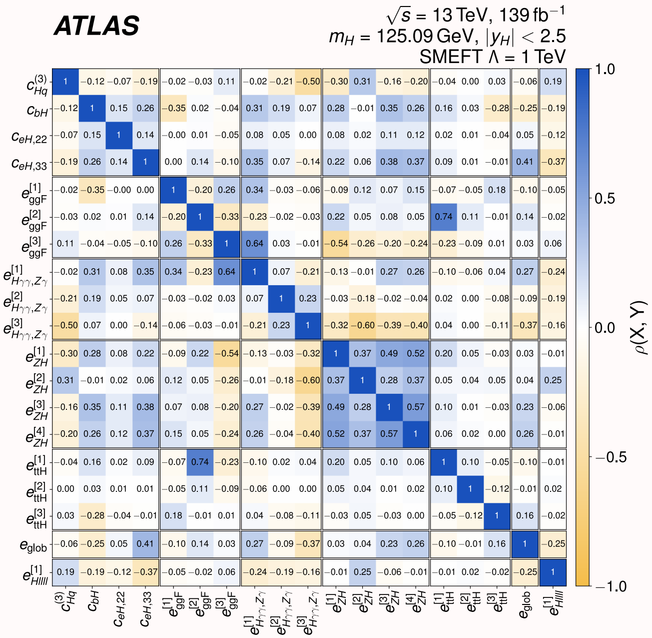
$\mu \sim C_{eH,22}/y_\mu$

strongest constraints from

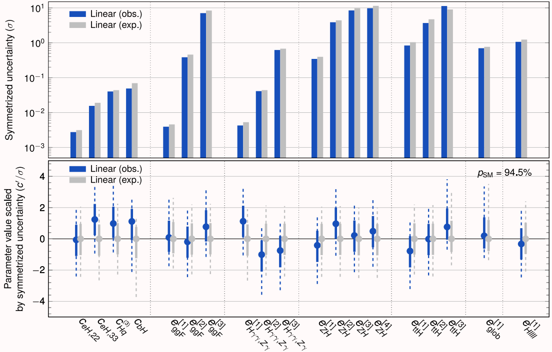
$gg \to h \to \gamma\gamma$

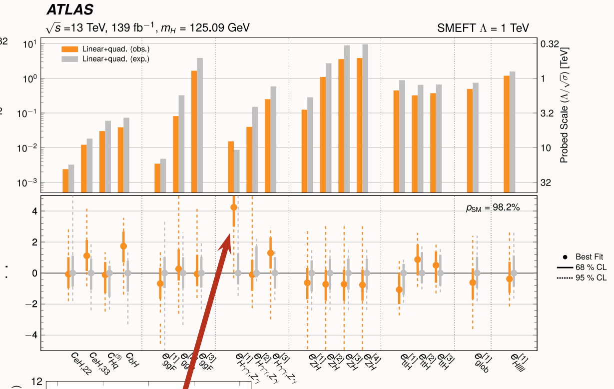


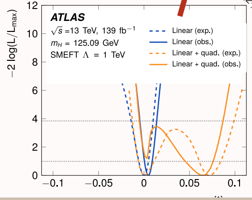
Correlations



Linear vs quadratic EFT parameterization



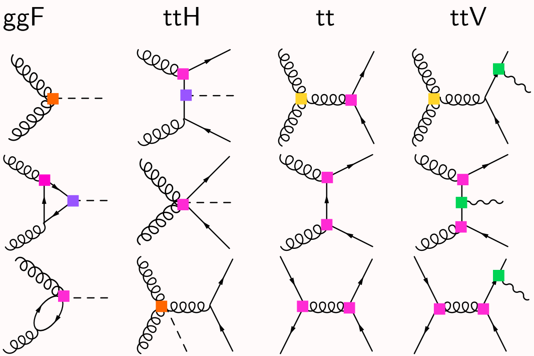




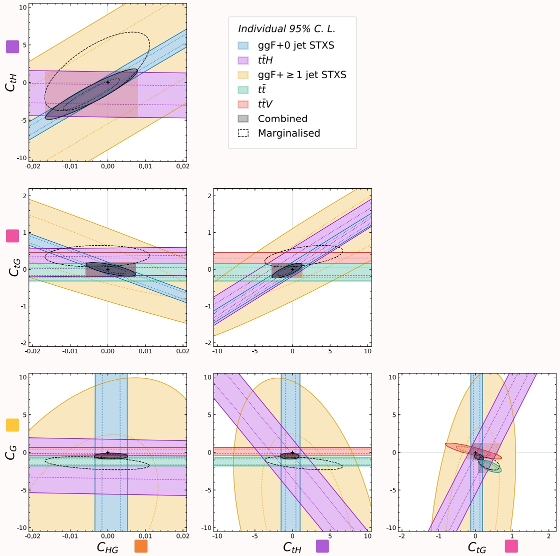
quadratics usually improve constraints
comparison to linear helps checking EFT validity.

secondary minima can also appear in the likelihood

Top and Higgs interplay



Ellis,Madigan,Mimasu,Sanz,You 2012.02779



SMEFT in LEP EWPOs

on the Z pole (LEP1) hep-ex/0509008

Γ_f $\quad f = (e/\mu), \tau, \nu, u, c, (d/s), b$

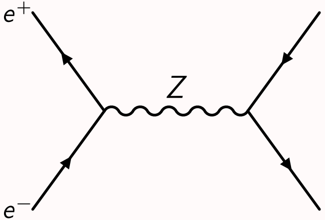
Γ_Z

$R_f = \Gamma_f/\Gamma_{had}$ $\quad f = c, b$

$R_\ell = \Gamma_{had}/\Gamma_\ell$

$\sigma^0_{Had} \sim \Gamma_e \Gamma_{had}/m_Z^2 \Gamma_Z^2$

$A_{FB}^{0,f}$ $\quad f = c, b, \ell$

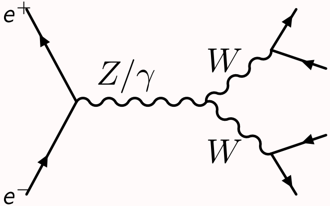


other pre-LHC EW measurements:

m_W CDF,D0 1204.0042

$e^+e^- \to W^+W^-$ diff. ALEPH EPJC(2004)147 LEP2 1302.3415

$e^+e^- \to e^+e^-$ diff. LEP2 1302.3415



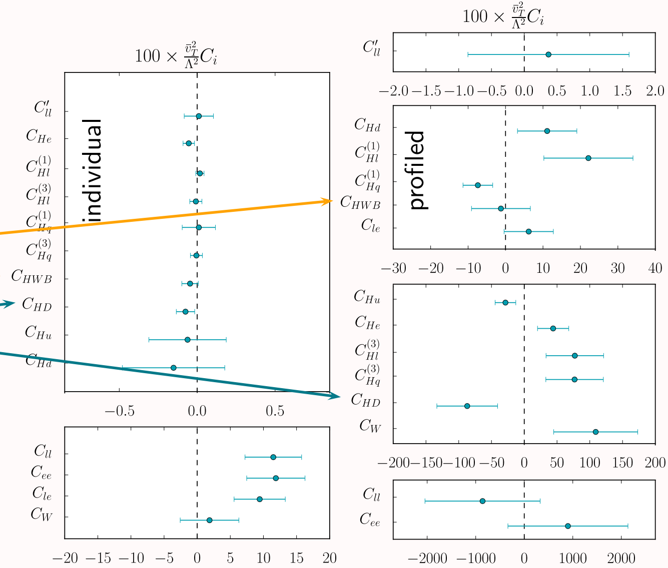
SMEFT in LEP EWPOs

Z-pole data leave 2 directions unconstrained in the Warsaw basis, that are (weakly) closed by WW

IB, Trott 1701.06424

S parameter

T parameter



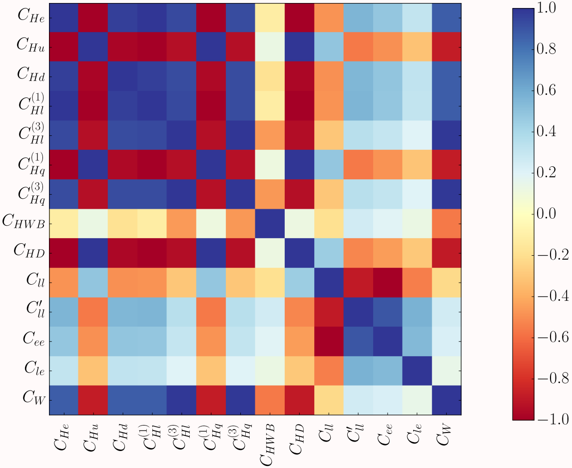
SMEFT in LEP EWPOs

Z-pole data leave 2 directions unconstrained in the Warsaw basis, that are (weakly) closed by WW

IB, Trott 1701.06424

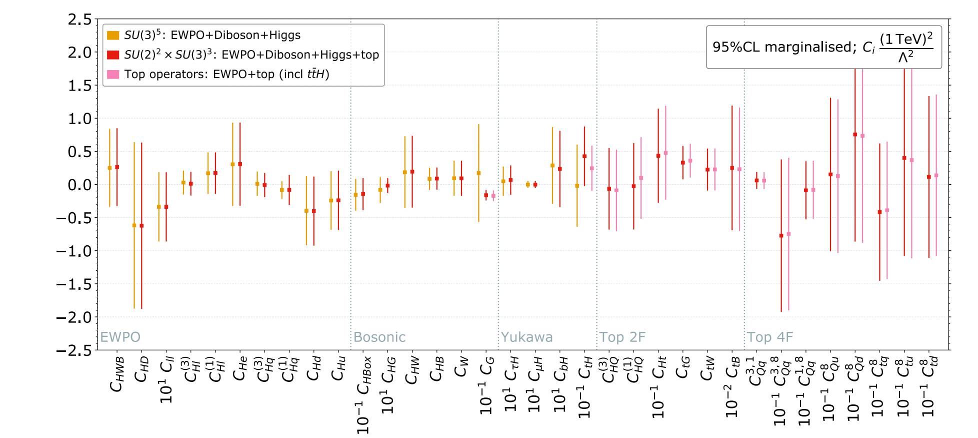
↓

results in strong residual correlations and large differences between individual and profiled bounds



Higgs, top and EW combinations

so far performed only by theorists: Fitmaker: Ellis, Madigan, Mimasu, Sanz, You 2012.02779
SMEFiT: Ethier, Maltoni, Mantani, Nocera, Rojo 2105.00006
SMEFiT: Celada, Giani, ter Hoeve, Mantani, Rojo, Rossia, Thomas, Vryonidou 2404.12809
SFitter: Elmeri, Madigan, Plehn, Schmal 2312.12502



latest SMEFiT: **45 (50)** parameters constrained simultaneously for the linear (quadratic) case

From SMEFT to concrete BSM models

Automated matching tools

matchete

Fuentes-Martin, König, Pagès, Thomsen, Wilsch
2012.08506, 2212.04510

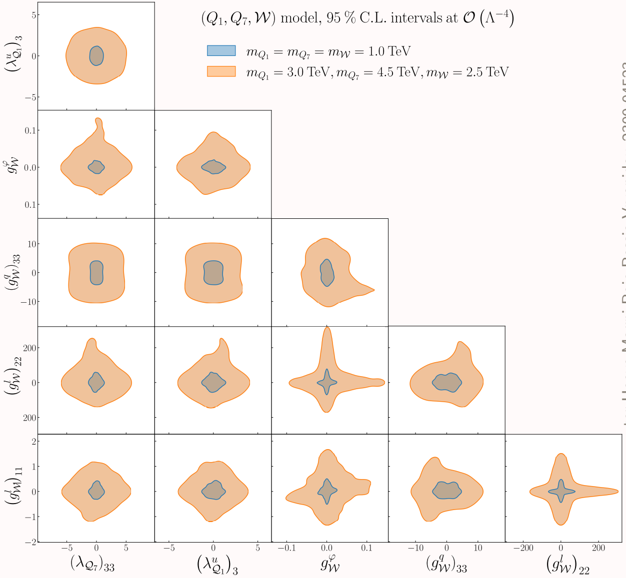
matchmakereft
Carmona, Lazopoulos, Olgoso, Santiago 2112.10787

dictionaries

tree-level: complete deBlas, Criado, Perez-Victoria, Santiago 1711.10391

1-loop: partial Guedes, Olgoso, Santiago 2303.16965

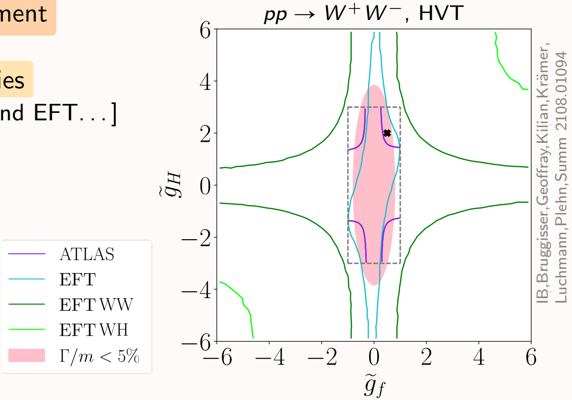
☞ fit model parameters through SMEFT fitting infrastructure



ter Hoeve, Magni, Rojo, Rossia, Vryonidou 2309.04523

Open challenges for the future

- refine theory predictions, properly accounting for RG running in fits
- extend matching and running to **higher orders**
- properly account for experimental **uncertainties and correlations**
- understand SMEFT effects beyond matrix element
- understand and treat SMEFT-born uncertainties
  [scale dependence, missing higher orders in loops and EFT. . .]
- relax Gaussianity assumptions in fit,
  incorporate full likelihoods from experiments
- relax **flavor indices and CP** assumptions
- explore interplay with resonance searches
- . . .



An alternative to SMEFT? the Higgs EFT

changing the symmetry properties of the Higgs field changes the classification of BSM effects

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. . .

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

HEFT $\supset$ SMEFT $\supset$ SM

- HEFT expands **around vacuum**, SMEFT around $H = 0$
- recent **geometric interpretation** proves that there are BSM theories that admit HEFT but not SMEFT
  Alonso,Jenkins,Manohar 1511.00724,1605.03602
  – with BSM sources of EWSB
  – with BSM particles that take $> 1/2$ of their mass from EWSB
  Cohen et al 2008.0597,Banta et al 2110.02967
- HEFT more **convergent** than SMEFT
- unclear whether unique HEFT phenomenological signatures exist

Wrapping up

- Effective Field Theories are a powerful theoretical concept, long used to investigate nature
- in particular, SMEFT has become a very popular tool for BSM searches
  → enable **model-independent** "agnostic" searches
  → allow exploitation of high projected **precision** of HL-LHC measurements
  → allow joining information from LHC searches and measurements at other experiments
- the SMEFT program for LHC is blooming.
  → massive developments in several directions, theoretical and technical
  → sensitivity already in the interesting region for many operator classes!

(hopefully)
a powerful way to obtain **guidance**
for the future of particle physics!

xkcd.com/1437/