EFTs, models and matching: the necessity and caveats

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(Re)interpretation of the LHC results for new physics

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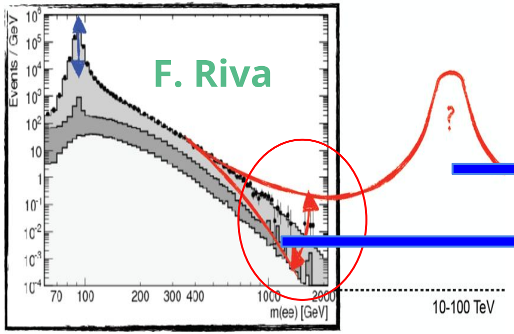
EFT in particle physics: Motivation

LHC has not yet found conclusive evidence of any BSM physics

Two broad methodologies to search for new physics:

Model dependent: Study signatures of a (preferably UV-complete) model carefully
"Model independent": Parametrise our ignorance as a low energy effective theory formalism



SM (or any BSM theory) → **low energy effective theory valid below a cut-off scale Λ**. EFT → **choosing a set of low-energy DOF**, **specifying UV cut-off and symmetries**

Bigger theory assumed to supersede low-energy model above Λ

EFT effects can manifest as deformation in angular distributions, excess events in high-energy tails, etc. → **Extreme precision in theoretical understanding needed!!!**

At perturbative level, heavy (> **Λ**) DOF decoupled from low-energy theory

Standard Model Effective Field Theory (SMEFT)

SMEFT is an **EFT which is constructed about the electroweak preserving vacuum**, out of the Higgs doublet Φ which **linearly realises electroweak symmetry breaking**

SMEFT written as Taylor expansion about $\Phi = 0$ in terms of operators increasing in mass dimensions

$$\boxed{\mathcal{L} = \mathcal{L}_{SM}^{d=4} + \sum_{d\geq 5} \sum_{i} \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_i^d}$$

Operators invariant under SM gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$ and suppressed by powers of new-physics scale, Λ

Expanding SMEFT operators show correlations (in broken phase) between different couplings, Higgs multiplicities

Example: $(H^\dagger \sigma_a H) W^a_{\mu\nu} B^{\mu\nu}$ with $\hat{h} = h + v$ gives the following Higgs deformations;
$hA_{\mu\nu}A^{\mu\nu}, hA_{\mu\nu}Z^{\mu\nu}, hZ_{\mu\nu}Z^{\mu\nu}, hW^+_{\mu\nu}W^{-\mu\nu}$, Triple Gauge Couplings $2igc_{\theta_W} W^-_\mu W^+_\nu (A_{\mu\nu} - t_{\theta_W} Z^{\mu\nu})$, S-parameter $\hat{W}_{\mu\nu}B^{\mu\nu}$

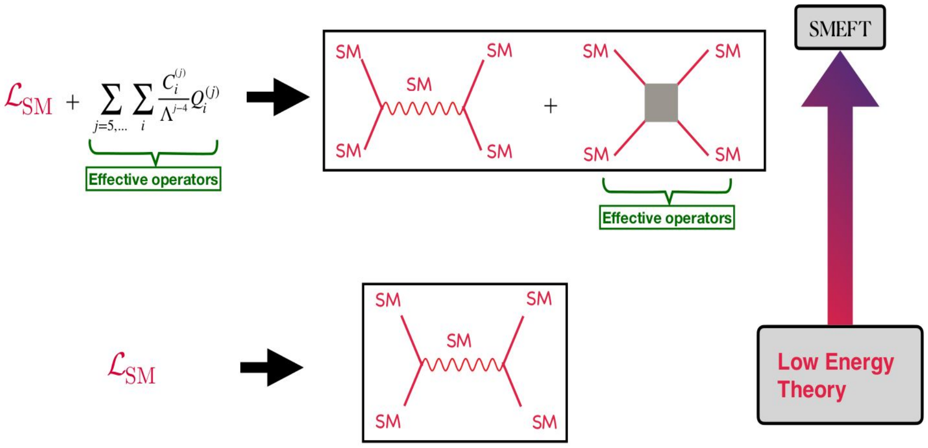
EFT: The two broad philosophies

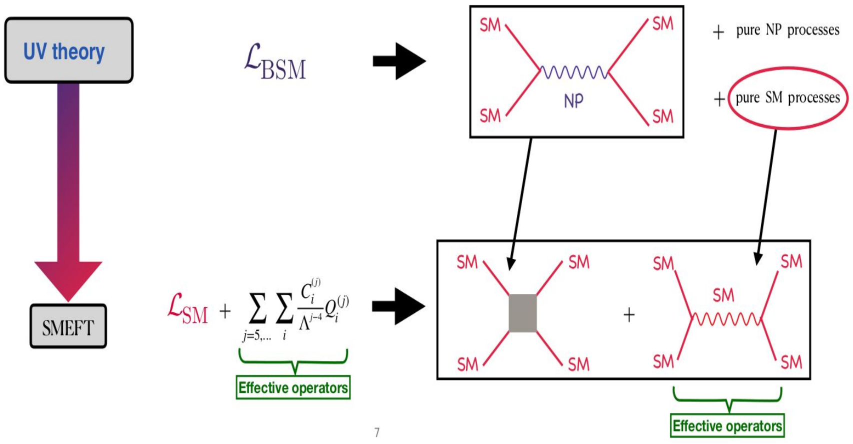
Bottom-Up approach

1. Exact nature of new physics need not be known
2. WCs are free parameters without origin

Top-Down approach

1. WCs determined in terms of BSM parameters
2. UV-complete Lagrangian must be known





Courtesy Supratim Das Bakshi!!!

Higgs Effective Field Theory (HEFT)

HEFT is the most general parametrisation of low-energy physics with only SM DOFs!!!

HEFT ⊃ SMEFT ⊃ SM **Is there any scenario where only HEFT can describe low-energy effects of BSM?**

1. Low-energy interactions only follow $U(1)_{em}$
2. The interactions can't tell us more about the properties of the microscopic theory
3. New non-decoupling strong dynamics → spontaneous EW symmetry breaking → Higgs-like scalar
4. SM not recovered when all BSM masses taken to infinity
5. Non-analyticity in Lagrangians can't be removed by field redefinitions → arises when **new states integrated out acquire mass from EWSB** → **violates decoupling** See Falkowski, Rattazzi

Unlike in the SMEFT, h is considered a gauge singlet and the Goldstone bosons, ω^a as an $SU(2)_L$ triplet. HEFT treats these separately → Goldstones embedded in Unitary matrix, U.

Part of the Lagrangian:

$$\mathcal{L}_{\text{HEFT}} \supset \frac{v^2}{4}\mathcal{F}(h)Tr\{D_\mu U^\dagger D^\mu U\}+\frac{1}{2}(\partial_\mu h)^2 - V(h) - \frac{v}{\sqrt{2}}(\bar{u}_L^i \bar{d}_L^i)\mathcal{F}(h)\begin{pmatrix} y_{ij}^u u_R^j \\ y_{ij}^d d_R^j \end{pmatrix} + \text{h.c.}$$

$$\mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots$$

$$V(h) = \frac{1}{2}m_h^2 v^2(1 + d_3\frac{h}{v} + \frac{d_4}{4}\frac{h^2}{v^2}) + \ldots$$

$$D_\mu U = \partial_\mu U + igW_\mu^a\frac{\sigma^a}{2}U - ig'U\frac{\sigma^3}{2}B_\mu$$

See geometric interpretation of HEFT with Higgs and Goldstone bosons as coordinates of Riemannian manifold

Motivated by Cohen et al.

SMEFT versus HEFT

SMEFT

1. **Most general set of local operators invariant under $SU(3)_C X SU(2)_L X U(1)_Y$**
2. **Operators suppressed by powers of new-physics scale, Λ**
3. **Low energy states modelled using fields transforming linearly under aforementioned symmetries**
4. **Observed Higgs, *h*, is a component of an electroweak doublet scalar, *H***
5. **More restrictive symmetry structure → less number of correlated parameters**

HEFT

1. **Manifest gauge symmetry is $SU(3)_C X U(1)_{em}$**
2. **Operators suppressed by electroweak breaking scale, *v***
3. **The $SU(2)_L X U(1)_Y$ symmetry is non-linearly realised using a multiplet of Goldstone bosons**
4. **No relation between *h* and the Goldstone bosons**
5. **Less restrictive symmetry structure → more number of uncorrelated parameters**

EFT-UV matching: Motivation

Effective field theories are essentially **tools that guide us in understanding any deviations** from SM physics! **EFTs aren't the final answers!!!**

Matching high-scale UV theories to low-energies is essential in capturing the low-energy dynamics correctly → what we usually observe in the LHC experiments

Matching should ideally be performed beyond leading order as several observables like the FCNC, $h \to \gamma\gamma, Z\gamma, gg$ etc. occur at one loop in the SM and other models

Methods to perform matching: **Integrating out heavy particles from UV theory** using path integral formalism, etc

Are RGEs important? [In backup slides.]

Why do we care about matching?

LHC to collect more than 20 times more data!!!

Maximum partonic centre of mass energy would be < 10 TeV

If new physics just outside direct reach of LHC → **resonance searches will not give us hopeful results**

Precise measurements/constraints on EFT WCs would shed a lot of light into the kind and properties of new physics that we might be looking for → Here comes the importance and relevance of EFT-UV matching

Precision is the key as deviations in certain WCs of the level of a few per-mille (after carefully accounting for all uncertainties) can also indicate the presence of new physics

LHC has a lot more to achieve in terms of precision and work is already underway in full force!!!

See Das Bakshi et al. and Cepedello et al. for more insights into mapping EFT → BSM (the inverse problem)

Does EFT-UV matching always work?

In principle, yes! SMEFT-matching only works in the decoupling regime.

In parts of the parameter space, matching might fail to reproduce exact model results at low-energies with the first or second order expansion of the SMEFT or the HEFT

It will then be **necessary to include even higher-order operators**

Example: Even with the inclusion of D8 operators, matching fails for SMEFT-2HDM for the $hh \to hh$ scattering process **See Dawson et al.**

Example 1: Matching issues: SMEFT/HEFT-2HDM

2HDM Lagrangian: $\mathcal{L}_{2\mathrm{HDM}} \ni \mathcal{L}_{\mathrm{kin}} - V$

$$\mathcal{L}_{\mathrm{kin}} = \left(D_\mu H_1\right)^\dagger \left(D^\mu H_1\right) + \left(D_\mu H_2\right)^\dagger \left(D^\mu H_2\right)$$

Mass parameter

$$V = Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + \left(Y_3 H_1^\dagger H_2 + \mathrm{h.c.}\right)$$
$$+ \frac{Z_1}{2}\left(H_1^\dagger H_1\right)^2 + \frac{Z_2}{2}\left(H_2^\dagger H_2\right)^2 + Z_3\left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) +$$
$$Z_4\left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right) + \left\{\frac{Z_5}{2}\left(H_1^\dagger H_2\right)^2 + Z_6\left(H_1^\dagger H_1\right)\left(H_1^\dagger H_2\right) + Z_7\left(H_2^\dagger H_2\right)\left(H_1^\dagger H_2\right) + \mathrm{h.c.}\right\}$$

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}$$

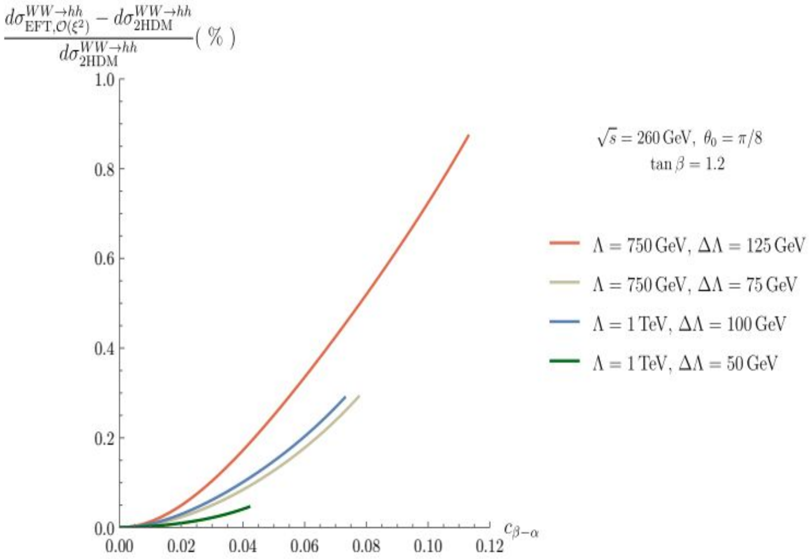
Vevs of $\Phi_1, \Phi_2 = v_1/\sqrt{2}, v_2/\sqrt{2}$

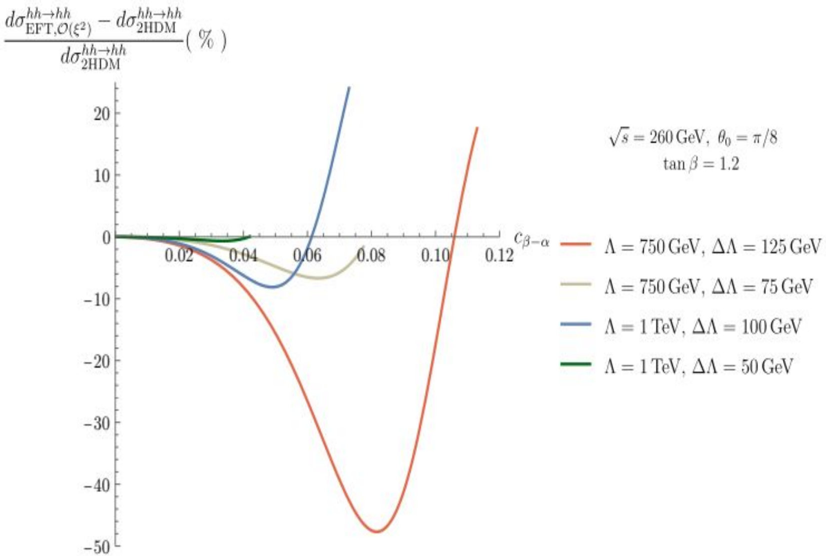
In the decoupling limit of 2HDM, $Y_2 = \Lambda^2, m_H^2 = \Lambda^2 + \Delta m_H^2,$
$m_A^2 = \Lambda^2 + \Delta m_A^2, m_{H^+}^2 = \Lambda^2 + \Delta m_{H^+}^2$

For degenerate mass scenario $m_H = m_A = m_{H^+} = \Lambda + \Delta\Lambda$

See Dawson et al.

Example 1: Matching issues SMEFT/HEFT-2HDM





Relative differential cross-section between 2HDM and EFT matching. **Need higher order operators for latter!!!**

See Dawson et al.

Example 2: LO versus NLO SMEFT matching

D6 operator: $\mathcal{O}_e^{(6)} = -b_{mnpq}(\bar{e}_m\gamma_\mu e_n)(\bar{e}_p\gamma^\mu e_q)$

Scalar: $\mathcal{L} \supset -(\partial_\mu\phi)(\partial^\mu\phi^*) - m_\phi^2|\phi^2| + y_{mn}\phi(\bar{e}_m e_n^c) + y_{mn}^*\phi^*(\bar{e}_m^c e_n)$

Vector: $\mathcal{L} \supset -\frac{1}{4}F^2 - \frac{1}{2}m_A^2 A^2 + c_{mn}A^\mu(\bar{e}_m\gamma_\mu e_n)$

NLO Matching (one of the possibilities):

$$\mathcal{L} \supset \bar{\chi}_a(i\partial\!\!\!/ - M)\chi_a - (\partial_\mu\phi)(\partial^\mu\phi^*) - M^2|\phi^2| + y\phi(\bar{\chi}_m e_m) + y^*\phi^*(\bar{e}_m\chi_m)$$

LO matching results

$$b_{1111} = \frac{|y_{11}|^2}{2m_\phi^2} - \frac{c_{11}^2}{2m_A^2}$$

No heavy fermionic UV completions at LO!!! Possible at NLO!!!

NLO matching results $b_{1111} = -\frac{|y|^4}{384\pi^2 M^2}$

Geometric interpretations of LO versus NLO matching, maximising CPV, etc. $\rightarrow$ SB, Renner, Rodd (in final stages)

See Blas et al. for LO matching dictionary

Also see Remmen and Rodd (1, 2, 3)

Example 3: $\bar{b}s \to \mu^+\mu^-$

Relevant operator at D6: $\mathcal{O}_{ed} = -c^{ed}_{mnpq}(\bar{e}_m\gamma_\mu e_n)(\bar{d}_p\gamma^\mu d_q)$

Relevant coefficient: c_{2232}

Tree-level UV-completions: Vector (1,1,0), Vector (3,1,2/3), Scalar (3,1,-4/3)

c_{22pq} is a positive or negative definite matrix requiring $c^{ed}_{2222}c^{ed}_{2233} \geq |c^{ed}_{2232}|^2$

Size effects of $\bar{b}s \to \mu^+\mu^-$ cannot be larger than product of $\bar{b}b \to \mu^+\mu^-$ and $\bar{s}s \to \mu^+\mu^-$, which control the decay of the Upsilon (1S) and ϕ mesons

See Remenn and Rodd (2022)

Example 3: $\bar{b}s \to \mu^+\mu^-$

SB, Renner, Rodd (in final stages)

Tree-level completion: Vector (1,1,0), Vector (3,1,2/3), Scalar (3,1,-4/3) mediate the process respectively via s, t, and u channels. Let's take the first case

$$\mathcal{L} = -\frac{1}{4}F^2 - \frac{1}{2}m_A^2 A^2 + A^\mu[a(\bar{e}_2\gamma_\mu e_2) + b(\bar{d}_3\gamma_\mu d_2) + b^*(\bar{d}_2\gamma_{mu} d_3)]$$

We need 3 operators to match on to this and get $\mathcal{O}_e, \mathcal{O}_d, \mathcal{O}_{ed}$

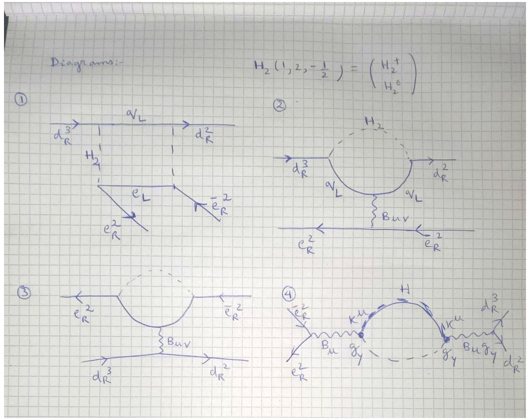
Giving us $c^{ed}_{2222}c^{ed}_{2233} \geq |c^{ed}_{2232}|^2$ and $c^{e}_{2222}c^{d}_{2233} < |c^{ed}_{2232}|^2$

Loop-level completion (example) - Two Higgs Doublet Model

$$\begin{aligned}\mathcal{L}_{\mathcal{H}_2} = \mathcal{L}_{\rm SM}^{d\leq 4} &+ |\mathcal{D}_\mu \mathcal{H}_2|^2 - m^2_{\mathcal{H}_2}|\mathcal{H}_2|^2 - \frac{\lambda_{\mathcal{H}_2}}{4}|\mathcal{H}_2|^4 - (\eta_H|\widetilde{H}|^2 + \eta_{\mathcal{H}_2}|\mathcal{H}_2|^2)(\widetilde{H}^\dagger\mathcal{H}_2 + \mathcal{H}_2^\dagger\widetilde{H}) \\ &- \lambda_{\mathcal{H}_2,1}|\widetilde{H}|^2|\mathcal{H}_2|^2 - \lambda_{\mathcal{H}_2,2}|\widetilde{H}^\dagger\mathcal{H}_2|^2 - \lambda_{\mathcal{H}_2,3}\left[(\widetilde{H}^\dagger\mathcal{H}_2)^2 + (\mathcal{H}_2^\dagger\widetilde{H})^2\right] \\ &- \left\{Y^{(e)}_{\mathcal{H}_2,m,n}\bar{l}_{L,m}\,\widetilde{\mathcal{H}}_2\,e_{R,n} + Y^{(u)}_{\mathcal{H}_2,m,n}\bar{q}_{L,m}\,\mathcal{H}_2\,u_{R,n} + Y^{(d)}_{\mathcal{H}_2,m,n}\bar{q}_{L,m}\,\widetilde{\mathcal{H}}_2\,d_{R,n} + \text{h.c.}\right\}.\end{aligned}$$

Example 3: $\bar{b}s \to \mu^+\mu^-$

SB, Renner, Rodd (in final stages)



We have 3 types of loop diagrams: box, penguin, and self-energy correction. Last two diagrams come from E.O.M.

$$D^\mu B_{\mu\nu} = g_Y\left(\tfrac{1}{6}\bar{q}_L\gamma_\nu q_L - \tfrac{1}{2}\bar{l}_L\gamma_\nu l_L + \tfrac{1}{2}H^\dagger i\overleftrightarrow{D}_\nu H + \tfrac{2}{3}\bar{u}_R\gamma_\nu u_R - \tfrac{1}{3}\bar{d}_R\gamma_\nu d_R - \bar{e}_R\gamma_\nu e_R\right)$$

$$c^{ed}_{2232} = -\frac{1}{2m_{\mathcal{H}_2^2}} Y^{(d)}_{\mathcal{H}_2,n,3}(Y^{(d)}_{\mathcal{H}_2,n,2})^*\left(|Y^{(e)}_{\mathcal{H}_2,m,2}|^2 - \frac{g_Y^2}{9m_{\mathcal{H}_2^2}}\left(11 + 6\log\left(\frac{\mu_H^2}{m_{\mathcal{H}_2^2}}\right)\right)\right)$$

$$\begin{aligned} c^{ed}_{2222} &= -\frac{1}{2m_{\mathcal{H}_2^2}}|Y^{(d)}_{\mathcal{H}_2,n,2}|^2\left(|Y^{(e)}_{\mathcal{H}_2,m,2}|^2 - \frac{g_Y^2}{9m_{\mathcal{H}_2^2}}\left(11 + 6\log\left(\frac{\mu_H^2}{m_{\mathcal{H}_2^2}}\right)\right)\right) \\ &\quad - \frac{g_Y^4}{27m_{\mathcal{H}_2^2}} - \frac{g_Y^2}{18m_{\mathcal{H}_2^2}}|Y^{(e)}_{\mathcal{H}_2,m,2}|^2\left(7 + 6\log\left(\frac{\mu_H^2}{m_{\mathcal{H}_2^2}}\right)\right) \end{aligned}$$

$$\begin{aligned} c^{ed}_{2233} &= -\frac{1}{2m_{\mathcal{H}_2^2}}|Y^{(d)}_{\mathcal{H}_2,n,3}|^2\left(|Y^{(e)}_{\mathcal{H}_2,m,2}|^2 - \frac{g_Y^2}{9m_{\mathcal{H}_2^2}}\left(11 + 6\log\left(\frac{\mu_H^2}{m_{\mathcal{H}_2^2}}\right)\right)\right) \\ &\quad - \frac{g_Y^4}{27m_{\mathcal{H}_2^2}} - \frac{g_Y^2}{18m_{\mathcal{H}_2^2}}|Y^{(e)}_{\mathcal{H}_2,m,2}|^2\left(7 + 6\log\left(\frac{\mu_H^2}{m_{\mathcal{H}_2^2}}\right)\right) \end{aligned}$$

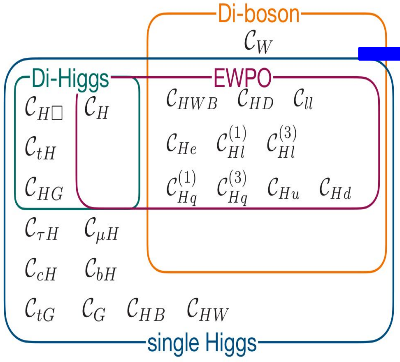
When BSM Yukawas go to 0,

$$c^{ed}_{2222}c^{ed}_{2233} = \frac{g_Y^8}{729m_{\mathcal{H}_2^4}},\ |c^{ed}_{2232}|^2 = 0$$

$$\Rightarrow c^{ed}_{2222}c^{ed}_{2233} > |c^{ed}_{2232}|^2$$

$$g_Y \to 0,\ c^{ed}_{2222}c^{ed}_{2233} = \frac{1}{4m_{\mathcal{H}_2^4}}|Y^{(e)}_{\mathcal{H}_2,l,2}|^4|Y^{(d)}_{\mathcal{H}_2,m,3}|^2|Y^{(d)}_{\mathcal{H}_2,n,2}|^2 = |c^{ed}_{2232}|^2$$

SMEFT global fit: An aside



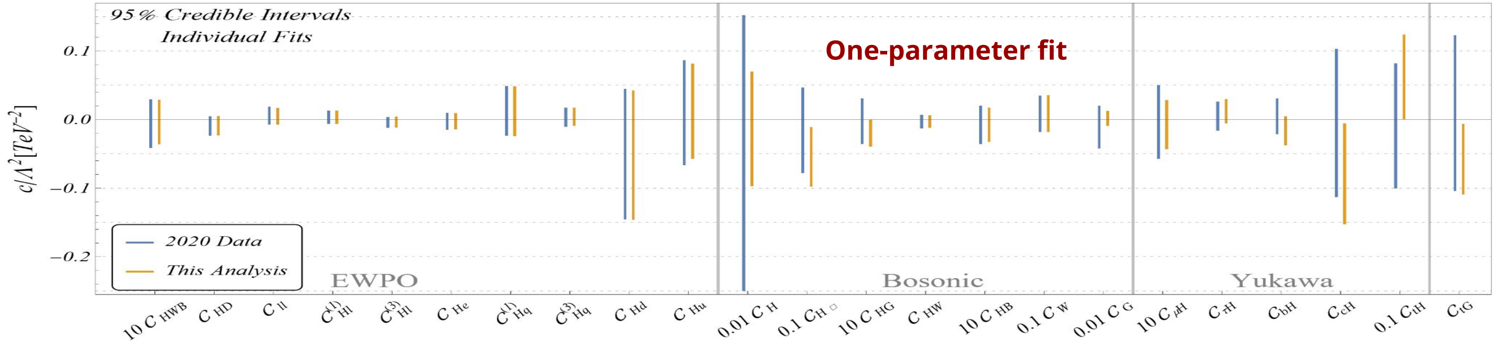
Operators considered in the fit

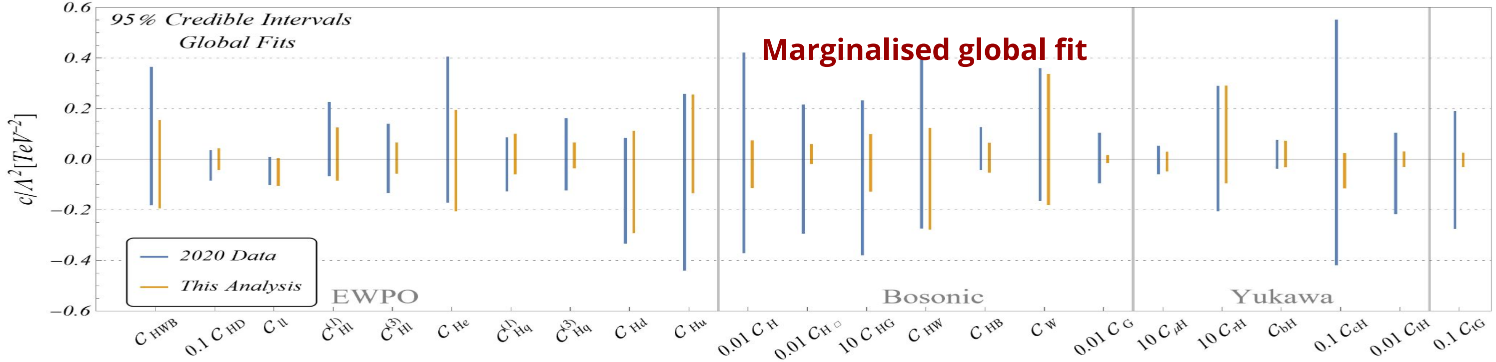
Data considered in the fit

	Observables	no. of measurements	References	2020
	Electroweak Precision Observables (EWPO)			
	Γ_Z, σ^0_{had}, R^0_l, A_l, A_l(SLD), A^l_{FB}, $\sin^2\theta^l_{\text{eff}}$(Tev),	15	tab. 1 of ref. [168]	✓
	R^0_c, A_c, A^c_{FB}, R^0_b, A_b, A^b_{FB}, m_W, Γ_W		correlations in ref. [1]	✓
	LEP-2 WW data	74	tabs. 12-15 of ref. [2]	✓
	Higgs Data			
7 and 8 TeV Run-I data	ATLAS & CMS combination	20	tab. 8 of ref. [3]	✓
	ATLAS & CMS combination $\mu(h \to \mu\mu)$	1	tab. 13 of ref. [3]	✓
	ATLAS $\mu(h \to Z\gamma)$	1	fig. 1 of ref. [4]	✓
13 TeV ATLAS Run-II data	$\mu(h \to Z\gamma)$ at 139 fb^{-1}	1	[5]	✓
	$\mu(h \to \mu\mu)$ at 139 fb^{-1}	1	[6]	✓
	$\mu(h \to \tau\tau)$ at 139 fb^{-1}	4	fig. 14 of ref. [7]	
	$\mu(h \to bb)$ in VBF and ttH at 139 fb^{-1}	1+1	[8, 9]	
	STXS Higgs combination	25	figs. 20/21 of ref. [169]	✓
	STXS $h \to \gamma\gamma/ZZ/b\bar{b}$ at 139 fb^{-1}	42	figs. 1 and 2 of ref. [10]	
	STXS $h \to WW$ in ggF, VBF at 139 fb^{-1}	11	figs. 12 and 14 of ref. [11]	
13 TeV CMS Run-II data	CMS combination at up to 137 fb^{-1}	23	tab. 4 of ref. [12]	✓
	$\mu(h \to b\bar{b})$ in Vh at 35.9/41.5 fb^{-1}	2	entries from tab. 4 of ref. [12]	
	$\mu(h \to WW)$ in ggF at 137 fb^{-1}	1	[13]	
	$\mu(h \to \mu\mu)$ at 137 fb^{-1}	4	fig. 11 of ref. [14]	
	$\mu(h \to \tau\tau/WW)$ in $t\bar{t}h$ at 137 fb^{-1}	3	fig. 14 of ref. [15]	
	STXS $h \to WW$ at 137 fb^{-1} in Vh	4	tab. 9 of ref. [16]	
	STXS $h \to \tau\tau$ at 137 fb^{-1}	11	figs. 11/12 of ref. [17]	
	STXS $h \to \gamma\gamma$ at 137 fb^{-1}	27	tab. 13 and fig. 21 of ref. [18]	
	STXS $h \to ZZ$ at 137 fb^{-1}	18	tab. 6 and fig. 15 of ref. [19]	
	ATLAS WZ 13 TeV m_T^{WZ} at 36.1 fb^{-1}	6 bins	fig. 4(c) of ref. [20]	✓
	ATLAS Zjj 13 TeV $\Delta\phi_{jj}$ at 139 fb^{-1}	12 bins	fig. 7(d) of ref. [21]	✓
	ATLAS WW 13 TeV $p_T^{\ell 1}$ at 36.1 fb^{-1}	7 bins	bins 8-14 of fig. 7(a) of ref. [22]	✓
	Di-Higgs signal strengths ATLAS & CMS 13 TeV data $\mu^{b\bar{b}b\bar{b}}_{HH}$, $\mu^{b\bar{b}\tau\bar{\tau}}_{HH}$, $\mu^{b\bar{b}\gamma\gamma}_{HH}$	6	[23–28]	

See Anisha, Das Bakshi, SB, Biekötter, Chakrabortty, Patra, Spannowsky (2021)

SMEFT global fit: An aside





See Anisha, Das Bakshi, SB, Biekötter, Chakrabortty, Patra, Spannowsky (2021)

Also see Ellis, Madigan, Mimasu, Sanz, You (2020)

Example 4: SMEFT-LQ matching

Do not contribute to present observables

We extend SM by a colour-triplet isospin-doublet scalar Θ_1 with hypercharge Y=1/6

$$\mathcal{L}_{\Theta_1} = \mathcal{L}_{\rm SM}^{d\leq 4} + (D_\mu\Theta_1)^\dagger\,(D^\mu\Theta_1) - m_{\Theta_1}^2\,\Theta_1^\dagger\Theta_1 - \eta_{\Theta_1}^{(1)} H^\dagger H\,\Theta_1^\dagger\Theta_1 - \eta_{\Theta_1}^{(2)}\,(H^\dagger\sigma^i H)\,\left(\Theta_1^\dagger\sigma^i\Theta_1\right) - \lambda_{\Theta_1}^{(1)}\left(\Theta_1^\dagger\Theta_1\right)^2 - \lambda_{\Theta_1}^{(2)}\left(\Theta_1^\dagger\sigma^i\Theta_1\right)^2 + \left\{y_{\Theta_1}\Theta_1^\alpha \overline{d}_R^\alpha i\sigma^2 l_L + \text{h.c.}\right\}$$

Dim-6 Ops.	Wilson coefficients
$Q_{\rm HB}$	$\frac{g_Y^2\eta_{\Theta_1}^{(1)}}{1152\pi^2 m_{\Theta_1}^2}$
$Q_{H\Box}$	$-\frac{g_W^4}{2560\pi^2 m_{\Theta_1}^2} - \frac{\eta_{\Theta_1}^{(1)2}}{32\pi^2 m_{\Theta_1}^2} + \frac{\eta_{\Theta_1}^{(2)2}}{512\pi^2 m_{\Theta_1}^2}$
$Q_{\rm HD}$	$-\frac{g_Y^4}{5760\pi^2 m_{\Theta_1}^2} - \frac{\eta_{\Theta_1}^{(2)2}}{128\pi^2 m_{\Theta_1}^2}$
$Q_{\rm HG}$	$\frac{g_S^2\eta_{\Theta_1}^{(1)}}{192\pi^2 m_{\Theta_1}^2}$
$Q_{\rm HW}$	$\frac{g_W^2\eta_{\Theta_1}^{(1)}}{128\pi^2 m_{\Theta_1}^2}$
$Q_{\rm HWB}$	$\frac{g_W g_Y\eta_{\Theta_1}^{(2)}}{768\pi^2 m_{\Theta_1}^2}$
$Q_{\rm uH}$	$\frac{\eta_{\Theta_1}^{(2)2} Y_u^{\rm SM}}{256\pi^2 m_{\Theta_1}^2}$
$Q_{\rm dH}$	$\frac{\eta_{\Theta_1}^{(2)2} Y_d^{\rm SM}}{256\pi^2 m_{\Theta_1}^2}$
$Q_{\rm eH}$	$\frac{\eta_{\Theta_1}^{(2)2} Y_e^{\rm SM}}{256\pi^2 m_{\Theta_1}^2}$
Q_H	$-\frac{\eta_{\Theta_1}^{(1)3}}{16\pi^2 m_{\Theta_1}^2} - \frac{3\eta_{\Theta_1}^{(1)}\eta_{\Theta_1}^{(2)2}}{256\pi^2 m_{\Theta_1}^2} + \frac{\eta_{\Theta_1}^{(2)2}\lambda_H^{\rm SM}}{128\pi^2 m_{\Theta_1}^2}$
$Q_{\rm ll}$	$-\frac{g_W^4}{2560\pi^2 m_{\Theta_1}^2} - \frac{g_Y^4}{23040\pi^2 m_{\Theta_1}^2}$
$Q_{\rm Hl}{}^{(1)}$	$\frac{g_Y^4}{11520\pi^2 m_{\Theta_1}^2}$
$Q_{\rm Hq}{}^{(1)}$	$-\frac{g_Y^4}{34560\pi^2 m_{\Theta_1}^2}$
$Q_{\rm Hl}{}^{(3)}$	$-\frac{g_W^4}{640\pi^2 m_{\Theta_1}^2}$
$Q_{\rm Hq}{}^{(3)}$	$-\frac{g_W^4}{640\pi^2 m_{\Theta_1}^2}$
Q_G	$\frac{g_S^3}{2880\pi^2 m_{\Theta_1}^2}$
$Q_{\rm Hu}$	$-\frac{g_Y^4}{8640\pi^2 m_{\Theta_1}^2}$
$Q_{\rm Hd}$	$\frac{g_Y^4}{17280\pi^2 m_{\Theta_1}^2}$
$Q_{\rm He}$	$\frac{g_Y^4}{5760\pi^2 m_{\Theta_1}{}^2}$
Q_W	$\frac{g_W^3}{1920\pi^2 m_{\Theta_1}^2}$

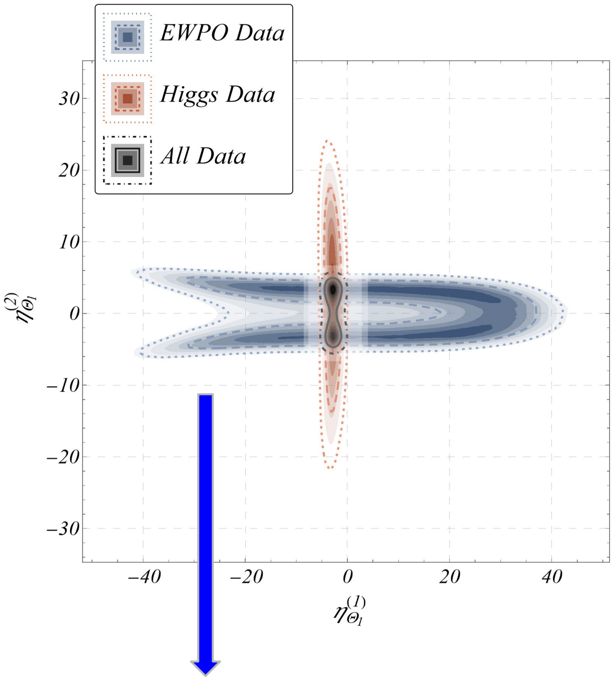
Dim-6 Ops.	Wilson coefficients
$Q_{\rm lq}{}^{(1)}$	$\frac{g_Y^4}{34560\pi^2 m_{\Theta_1}^2}$
$Q_{\rm qd}{}^{(1)}$	$\frac{g_Y^4}{51840\pi^2 m_{\Theta_1}^2}$
$Q_{\rm qq}{}^{(1)}$	$-\frac{g_Y^4}{207360\pi^2 m_{\Theta_1}^2}$
$Q_{\rm qu}{}^{(1)}$	$-\frac{g_Y^4}{25920\pi^2 m_{\Theta_1}^2}$
$Q_{\rm ud}{}^{(1)}$	$\frac{g_Y^4}{12960\pi^2 m_{\Theta_1}^2}$
$Q_{\rm lq}{}^{(3)}$	$-\frac{g_W^4}{1280\pi^2 m_{\Theta_1}^2}$
$Q_{\rm qq}{}^{(3)}$	$-\frac{g_W^4}{2560\pi^2 m_{\Theta_1}^2}$
$Q_{\rm dd}$	$-\frac{g_Y^4}{51840\pi^2 m_{\Theta_1}^2}$
$Q_{\rm ed}$	$-\frac{g_Y^4}{8640\pi^2 m_{\Theta_1}^2}$
$Q_{\rm ee}$	$-\frac{g_Y^4}{5760\pi^2 m_{\Theta_1}^2}$
$Q_{\rm ld}$	$-\frac{g_Y^4}{17280\pi^2 m_{\Theta_1}^2} - \frac{9y_{\Theta_1}^2\left(4\lambda_{\Theta_1}^{(1)}+\lambda_{\Theta_1}^{(2)}\right)}{128\pi^2 m_{\Theta_1}^2} - \frac{y_{\Theta_1}^2}{4m_{\Theta_1}^2}$
$Q_{\rm le}$	$-\frac{g_Y^4}{5760\pi^2 m_{\Theta_1}^2}$
$Q_{\rm lu}$	$\frac{g_Y^4}{8640\pi^2 m_{\Theta_1}^2}$
$Q_{\rm eu}$	$\frac{g_Y^4}{4320\pi^2 m_{\Theta_1}^2}$
$Q_{\rm qu}^{(8)}$	$-\frac{g_S^4}{480\pi^2 m_{\Theta_1}^2}$
$Q_{\rm qe}$	$\frac{g_Y^4}{17280\pi^2 m_{\Theta_1}^2}$
$Q_{\rm uu}$	$-\frac{g_Y^4}{12960\pi^2 m_{\Theta_1}^2}$
$Q_{\rm ud}^{(8)}$	$-\frac{g_S^4}{480\pi^2 m_{\Theta_1}^2}$
$Q_{\rm qd}^{(8)}$	$-\frac{g_S^4}{480\pi^2 m_{\Theta_1}^2}$

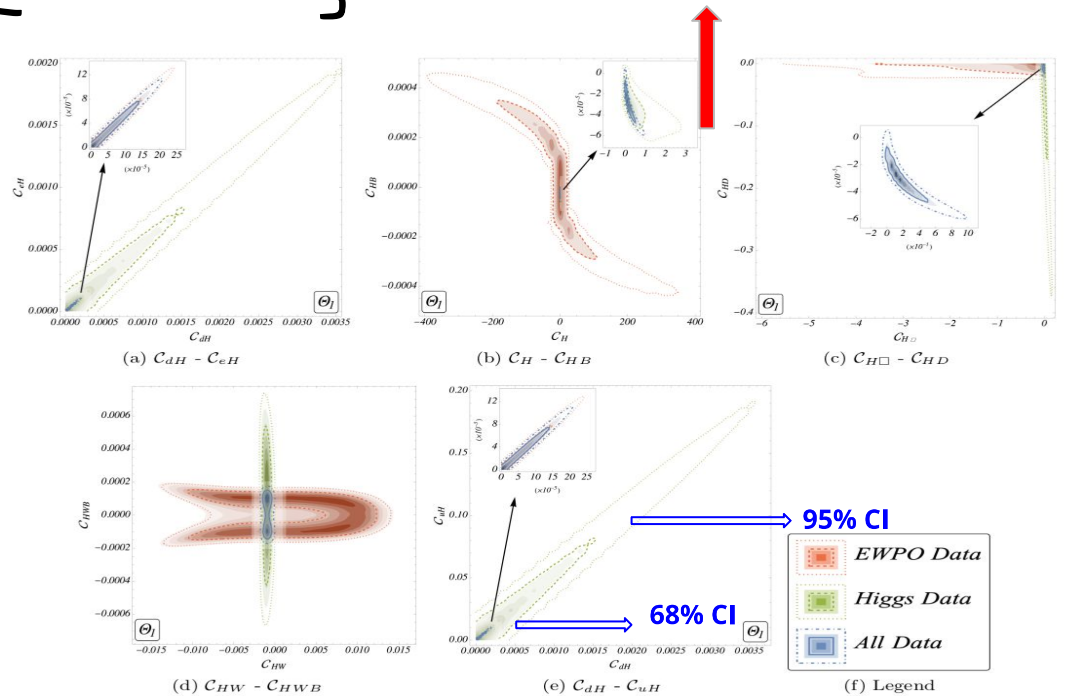
See Anisha, Das Bakshi, SB, Biekötter, Chakrabortty, Patra, Spannowsky (2021)

Functions of SM parameters

Example 4: SMEFT-LQ matching

2D posteriors among relevant WCs





2D marginalised posteriors among BSM parameters.

See Anisha, Das Bakshi, SB, Biekötter, Chakrabortty, Patra, Spannowsky (2021)

Example 5: Contact operator in $pp \to Zh$

How do we estimate the scale of new physics in an EFT for a given size of the couplings, g^h_{Vf}?

$$\Delta\mathcal{L}_6 \supset \sum_f \delta g^Z_f Z_\mu \bar{f}\gamma^\mu f + \delta g^W_{ud}(W^+_\mu \bar{u}_L\gamma^\mu d_L + h.c.)$$

$$+ g^h_{VV}\, h \left[W^{+\mu}W^-_\mu + \frac{1}{2c^2_{\theta_W}} Z^\mu Z_\mu\right] + \delta g^h_{ZZ}\, h \frac{Z^\mu Z_\mu}{2c^2_{\theta_W}}$$

$$+ \sum_f g^h_{Zf} \frac{h}{v} Z_\mu \bar{f}\gamma^\mu f + g^h_{Wud}\frac{h}{v}(W^+_\mu \bar{u}_L\gamma^\mu d_L + h.c.)$$

$$+ \kappa_{Z\gamma}\frac{h}{v}A^{\mu\nu}Z_{\mu\nu} + \kappa_{WW}\frac{h}{v}W^{+\mu\nu}W^-_{\mu\nu} + \kappa_{ZZ}\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu}$$

g^h_{Vf} couplings → current-current operators → integrating out at tree-level a heavy *SU(2)*$_L$ triplet (singlet) vector $W'^a (Z')$ coupled to SM-fermion currents, $\bar{f}\sigma^a\gamma_\mu f\ (\bar{f}\gamma_\mu f)$ with g_f →

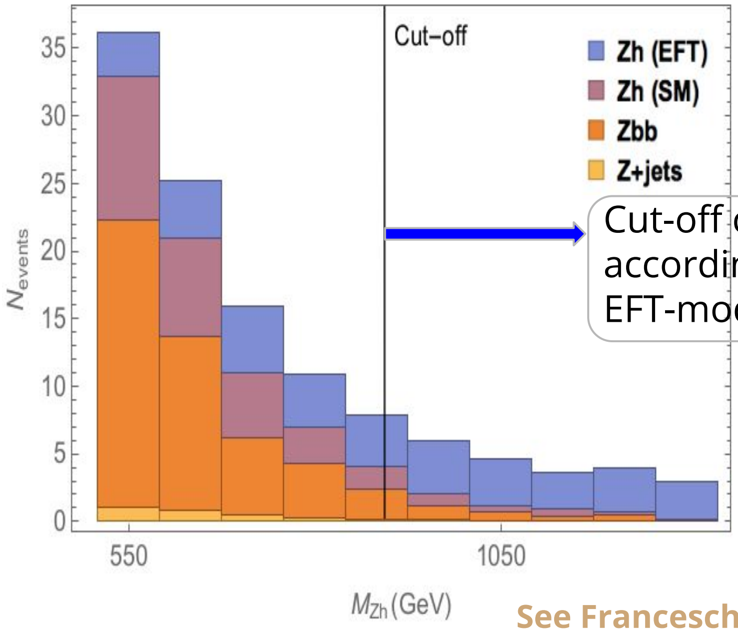
To the Higgs mass current, $iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H\ (iH^\dagger \overleftrightarrow{D}_\mu H)$ with g_H

$$\boxed{g^h_{Zf} \sim \frac{g_H g g_f v^2}{\Lambda^2}}$$

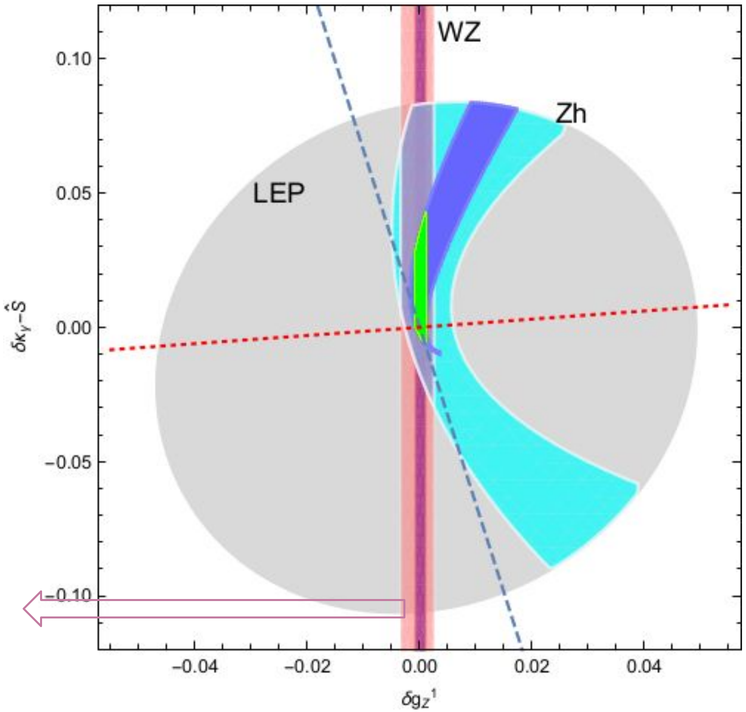
Assuming Universal couplings to SM fermions (g_f combination of $g_W = g/2$ and $g_B = g' Y_f$) and g_H is weakly coupled and equals 1.

See SB, Englert, Gupta, Spannowsky (2018)

Example 5: Contact operator in $pp \to Zh$



Cut-off computed according to the EFT-model mapping



See Franceschini et al. for WZ

See SB, Englert, Gupta, Spannowsky (2018)

Matching codes: an incomprehensive review

CoDEx (see Das Bakshi et al.): Uses functional method; Covariant Derivative Expansion! Matches up to D6

Matchete (see Fuentes-Martín et al.): Uses functional method; Covariant Derivative Expansion! Can match some cases up to D8

Matchmakereft (see Carmona et al.): Uses diagrammatic method

There are many other matching codes including SuperTracer, MatchingTools, STrEAM

Advertisement: LHC Effective Field Theory WG

LHC Effective Field Theory WG

To subscribe to the general WG mailing list, used to distribute announcements about WG meetings and available documents, go to http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-eftwg

The working group twiki page is available at https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCEFT

Mandate:

The LHC effective field theory working group (LHC EFT WG) gathers members of the LHC experiments and the theory community to provide a framework for the interpretation of LHC data in the context of effective field theories (EFTs). The LHC EFT WG studies the physics requirements needed to facilitate an interpretation commensurate with the available measurements performed in a wide range of different processes, including Higgs bosons, top quarks, and electroweak bosons. It provides recommendations for the use of EFT by the experiments to interpret their data, and a forum for theoretical discussions of EFT issues. This includes recommendations on the theory setup as well as Monte Carlo simulation and other tools needed for EFT analyses. Further theoretical issues cover, for example, theoretical constraints, higher-order corrections, BSM interpretations. The LHC EFT WG also discusses common uncertainties and combination procedures used by the experiments. It focuses on recommendations, developments, and combinations that require coordination between the existing WGs (Higgs, Top, Electroweak), in order to allow global EFT analyses inside and outside experimental collaborations. EFT-related activities in these working groups will continue if they pertain only to that group, in close contact with the LHC EFT WG.

Please subscribe here and check out the Twiki page for exciting news on EFT activities. There are regular topical meetings that many of you might find interesting!!!

Conclusions and outlook

- **EFTs are fascinating tools to exploit LHC data** and get a first idea of possible new physics
- **SMEFT and HEFT are different ways of approximating the underlying BSM physics**
- Given the prowess and potential of LHC as a precision machine, **matching EFT with the UV-model is imperative** especially if the new physics is lurking outside the LHC reach
- Matching mismatch sometimes require the introduction of higher order operators
- **LO and NLO matching of EFT-UV are potentially different**
- From a practical point of view, **important to assume features of new physics to apply cut-off on event generation**

Thank you!!!

Backup slides

Light-heavy mixing in NLO matching

Only those BSMs generate heavy-light mixed WCs when heavy field couples to SM fields linearly

This can be visualised by considering one-particle-irreducible 1-loop diagrams where loop propagators are both heavy and light (SM) fields, but external legs are only light (SM) fields

Integrating out heavy fields

$$\mathcal{L}(\phi, \Phi) = \Phi_{kin} + \phi_{kin} + \Phi_{si} + \phi_{si} + (\phi * \Phi)_{int}$$

Φ - Heavy field ϕ - Light field

Courtesy Supratim Das Bakshi

$$(\phi * \Phi)_{int} = B(\phi) * \Phi + U(\phi) * \Phi^2 + \mathcal{O}(\Phi^3)$$

$$D_\mu \frac{\partial}{\partial(D_\mu \Phi)} \mathcal{L}(\phi, \Phi) = \frac{\partial}{\partial \Phi} \mathcal{L}(\phi, \Phi)$$

Euler - Lagrange equation

Example - Scalar heavy field

$$(D^2 + m^2 - U(\phi))\Phi = B(\phi) + \mathcal{O}(\Phi^2) \qquad \Rightarrow \Phi_c = \frac{1}{(D^2 + m^2 - U(\phi))} B(\phi) \qquad (leading\ order)$$

$$\approx \frac{1}{m^2} B(\phi) - \frac{1}{m^4}(D^2 - U(\phi))B(\phi)$$

$$B(\phi) * \Phi_c = B(\phi) \frac{1}{m^2} B(\phi) - B(\phi) \frac{(D^2 - U(\phi))}{m^4} B(\phi) \quad \Big\}$$

Dependent only on light fields

Integrating out heavy fields

$$\mathcal{L}(\phi, \Phi) = \Phi_{kin} + \phi_{kin} + \Phi_{si} + \phi_{si} + (\phi * \Phi)_{int}$$

Φ - Heavy field $\qquad$ ϕ - Light field

$$(\phi * \Phi)_{int} = B(\phi) * \Phi + U(\phi) * \Phi^2 + \mathcal{O}(\Phi^3)$$

$$D_\mu \frac{\partial}{\partial(D_\mu \Phi)} \mathcal{L}(\phi, \Phi) = \frac{\partial}{\partial \Phi} \mathcal{L}(\phi, \Phi)$$

Euler - Lagrange equation

Mass dimension of effective operator

$$\mathcal{L}_{BSM,eff} = \mathcal{L}_{SM} + \sum_j \frac{1}{\Lambda} c_j^{(5)} O_j^{(5)} + \sum_j \frac{1}{\Lambda^2} c_j^{(6)} O_j^{(6)} + \ldots$$

Λ : cut-off scale

Wilson coefficients

Effective operators

Courtesy Supratim Das Bakshi

Inclusion of RGEs

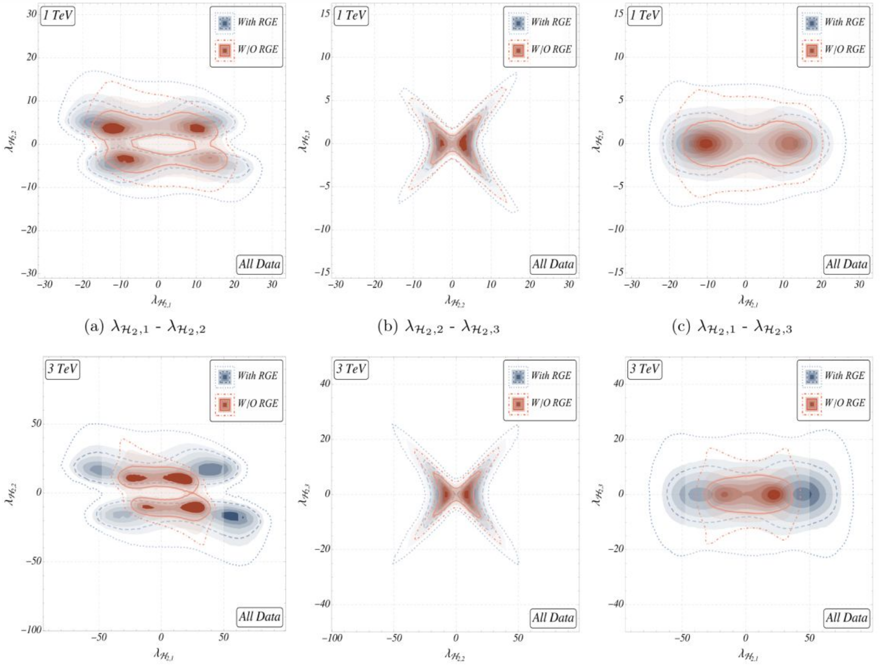
The WCs at $M_Z, \mathcal{C}_i(M_Z)$, are computed using the matching scale WCs, $C_i(\Lambda)$ and SMEFT anomalous dimension matrix, γ_{ij}, in the leading-log approximation,

$$\frac{d\mathcal{C}_i(\mu)}{d\log\mu} = \sum_j \frac{1}{16\pi^2}\gamma_{ij}\mathcal{C}_j$$

and at LO $\mathcal{C}_i(M_Z) = \mathcal{C}_i(\Lambda) + \sum_j \frac{1}{16\pi^2}\gamma_{ij}\mathcal{C}_j(\Lambda)\log\left[\frac{M_Z}{\Lambda}\right]$

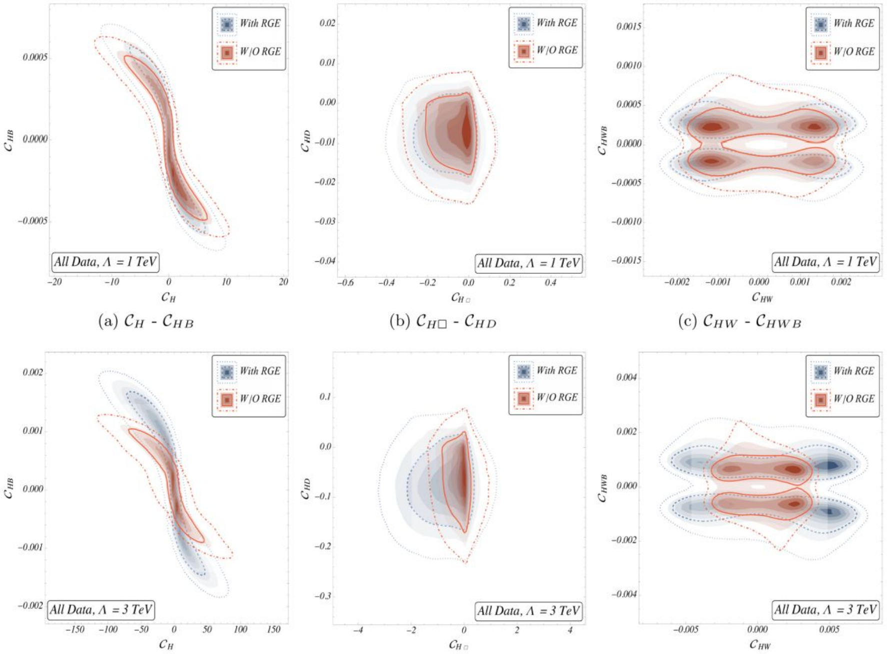
For the 2HDM, 51 operators are generated with the RGEs, 14 of which are exclusively generated owing to RG running

Inclusion of RGEs: Example 2HDM



(a) $\lambda_{\mathcal{H}_2,1}$ - $\lambda_{\mathcal{H}_2,2}$ (b) $\lambda_{\mathcal{H}_2,2}$ - $\lambda_{\mathcal{H}_2,3}$ (c) $\lambda_{\mathcal{H}_2,1}$ - $\lambda_{\mathcal{H}_2,3}$

(d) $\lambda_{\mathcal{H}_2,1}$ - $\lambda_{\mathcal{H}_2,2}$ (e) $\lambda_{\mathcal{H}_2,2}$ - $\lambda_{\mathcal{H}_2,3}$ (f) $\lambda_{\mathcal{H}_2,1}$ - $\lambda_{\mathcal{H}_2,3}$

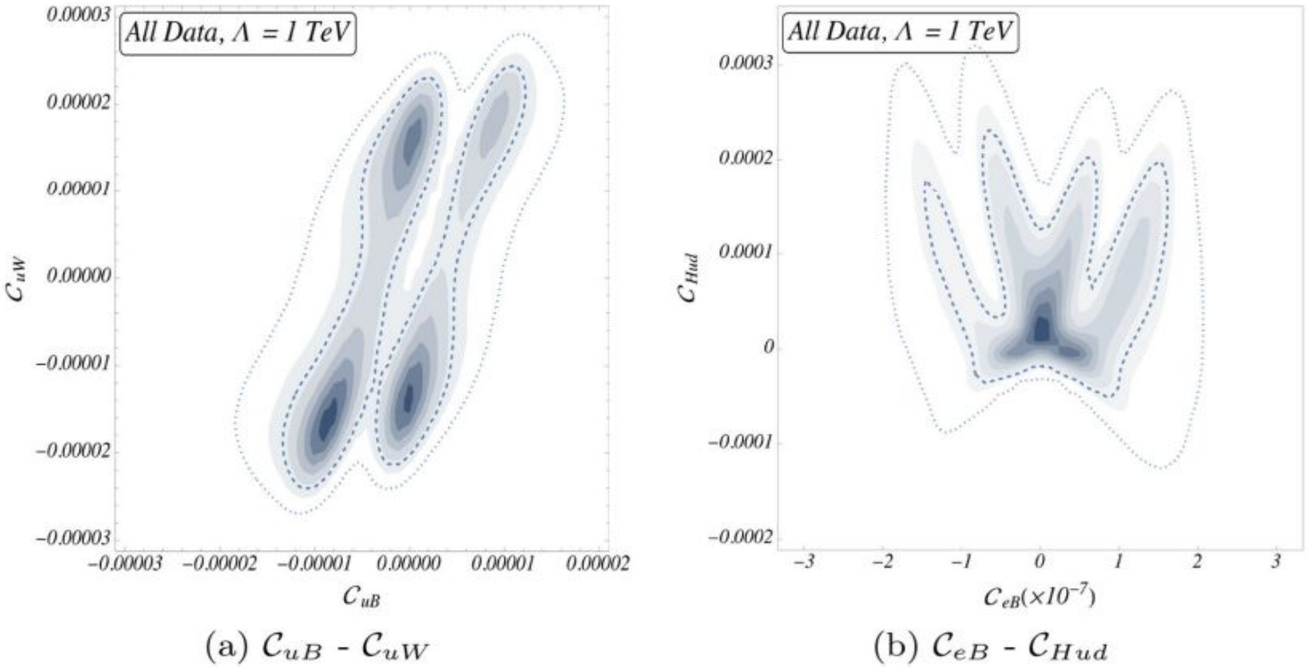


(a) $\mathcal{C}_H$ - $\mathcal{C}_{HB}$ (b) $\mathcal{C}_{H\Box}$ - $\mathcal{C}_{HD}$ (c) $\mathcal{C}_{HW}$ - $\mathcal{C}_{HWB}$

(d) $\mathcal{C}_H$ - $\mathcal{C}_{HB}$ (e) $\mathcal{C}_{H\Box}$ - $\mathcal{C}_{HD}$ (f) $\mathcal{C}_{HW}$ - $\mathcal{C}_{HWB}$

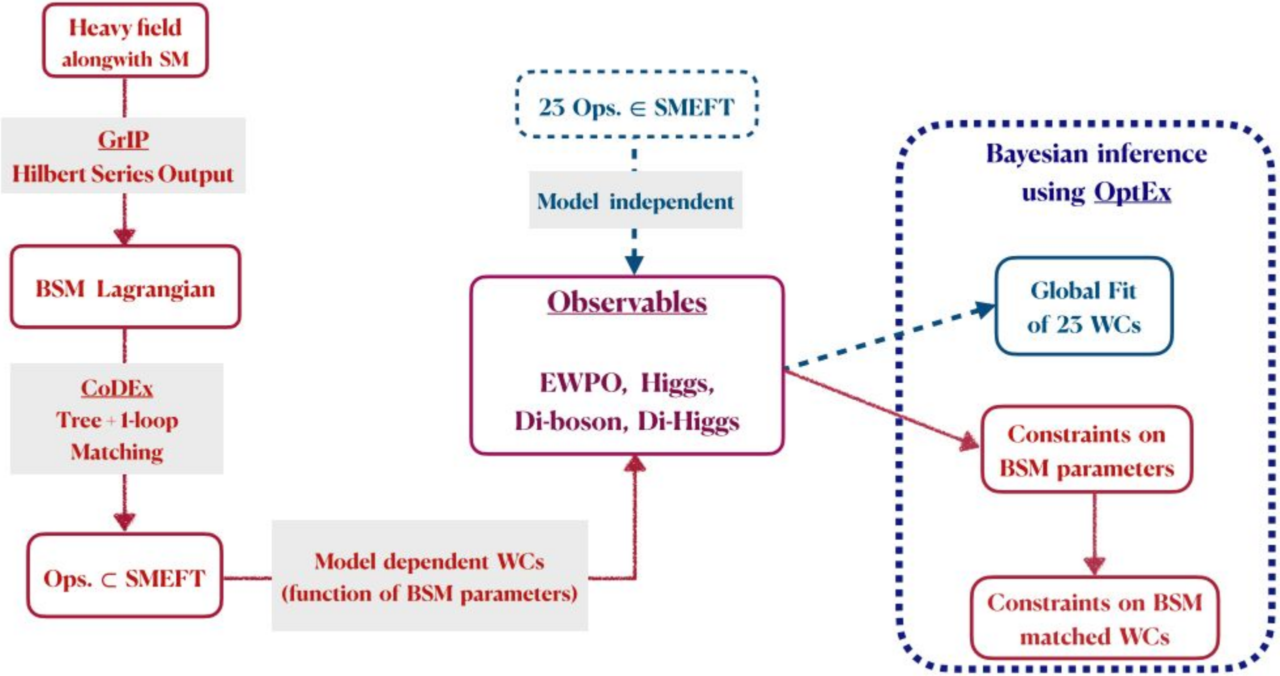
See Anisha, Das Bakshi, SB, Biekötter, Chakrabortty, Patra, Spannowsky (2021)

Inclusion of RGEs: Example 2HDM (operators generated from RG running only)



See Anisha, Das Bakshi, SB, Biekötter, Chakrabortty, Patra, Spannowsky (2021)

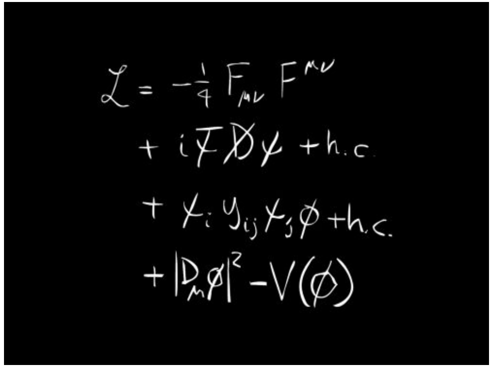
The analysis flowchart



What more should be done (an incomplete review)?

1. In order to make precise predictions with EFTs, it is **imperative to have a robust understanding of the theoretical calculations, the multifarious sources of uncertainties**, and more
2. It is **extremely important to study higher-order corrections** to the EFT calculations, including **EW corrections**, which often become very important, especially in high-energy tails
3. **Exploit as many processes as possible to break blind WC directions → A true global analysis**
4. Understand and apply the relevant symmetries and identities

A brief history of particle physics



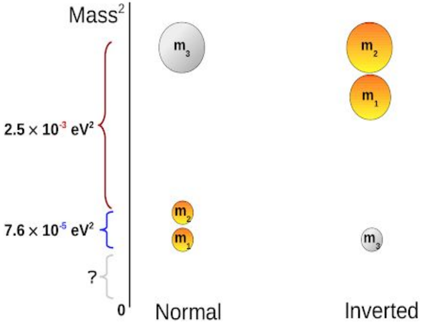
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c. + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

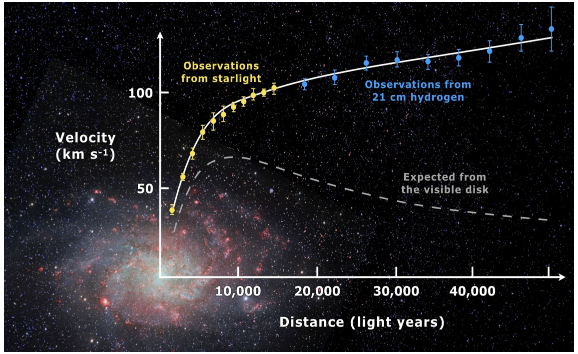
Standard Model of particle physics - **a grand success**!!! All particles observed and all parameters measured.

Still to be measured: $\lambda_{hhh}, \lambda_{hhhh}, h \to Z\gamma, h \to f_{1(2)}\bar{f}_{1(2)}$ **More data!!!**

Still to be confirmed: possible (tiny) deviations from SM expectations (CP, magnitude, correlations and structure of couplings, exotic decays, new resonances, etc.) **Multiple experimental talks on such searches!!!**

Still not measured/well understood: **Neutrino masses**, **Nature/properties of dark matter**, **Matter-antimatter asymmetry**

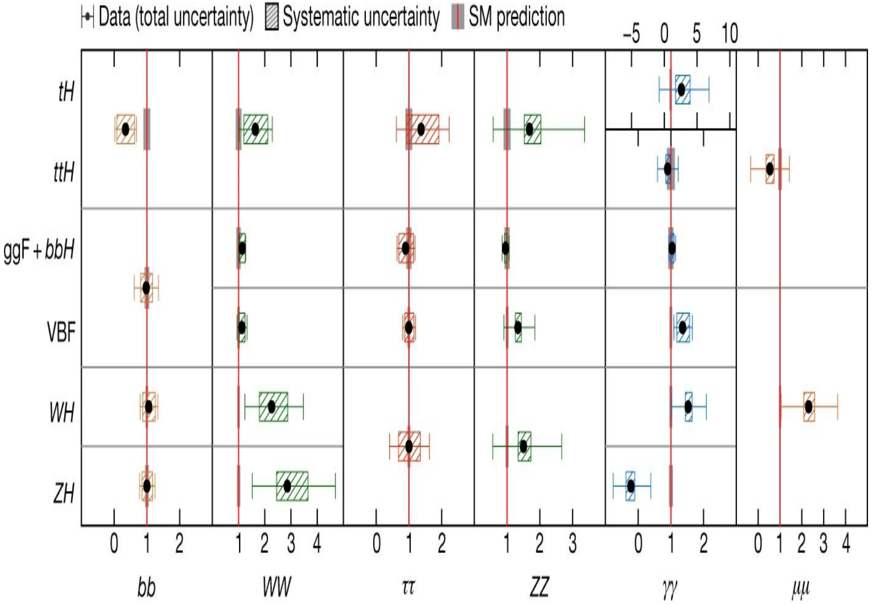


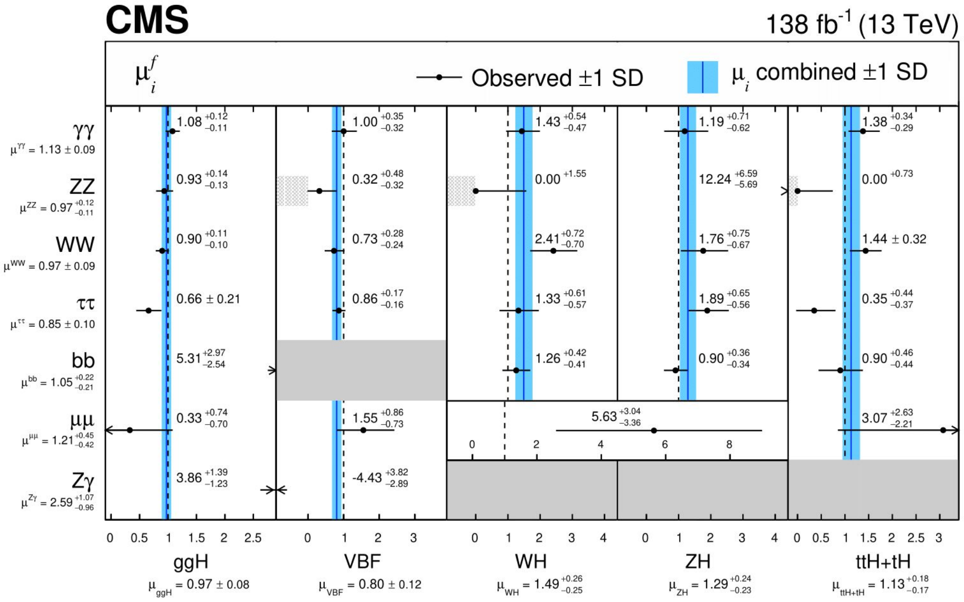


Structural issues: **Strong CP problem**, **Naturalness**, **generational (flavour) hierarchies**

Current signal strengths: An aside

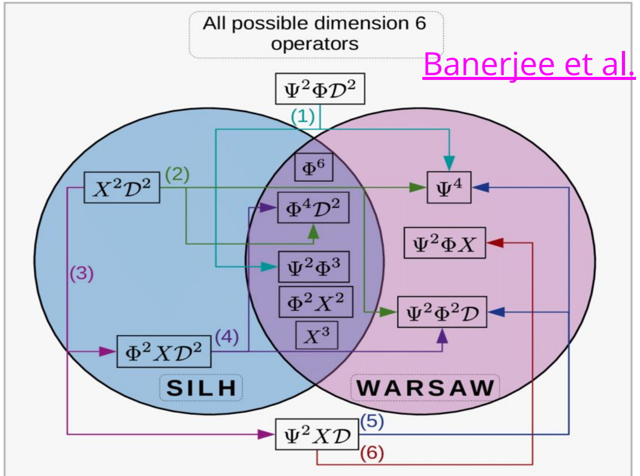
Can new physics hide within such deviations? Too early to say.





SMEFT: Operators at dimension-6

Assuming Baryon number conservation, we have 59 (**15 bosonic**, **19 single-fermionic current** and **25 *B*-conserving four-fermion**) dimension-6 operators Grzadkowski et al. (Warsaw basis). Similarly, we have the SILH basis (Giudice et al.)



Banerjee et al.

(1) $(\bar\Psi_L\,\Psi_R)\,\mathcal{D}^2\,\Phi = c_0\,(\bar\Psi_L\,\Psi_R\,\Phi)\,(\Phi^\dagger\,\Phi) + c_1\,(\bar\Psi_L\,\Psi_R)\,(\bar\Psi_R\,\Psi_L)$

(2) $(\mathcal{D}_\mu\,X^{\mu\nu})^2 = c_2\,(\bar\Psi\,\gamma_\nu\,\Psi)(\bar\Psi\,\gamma^\nu\,\Psi) + c_3\,(\Phi^\dagger\,i\overleftrightarrow{\mathcal{D}}_\nu\,\Phi)(\Phi^\dagger\,i\overleftrightarrow{\mathcal{D}}^\nu\,\Phi) + c_4\,(\bar\Psi\,\gamma_\nu\,\Psi)(\Phi^\dagger\,i\overleftrightarrow{\mathcal{D}}^\nu\,\Phi)$

(3) $(\mathcal{D}_\mu\,X^{\mu\nu})^2 = c_5\,(\bar\Psi\,\gamma_\mu\,\Psi)(\mathcal{D}_\nu\,X^{\mu\nu}) + c_6\,(\Phi^\dagger\,i\overleftrightarrow{\mathcal{D}}_\mu\,\Phi)(\mathcal{D}_\nu\,X^{\mu\nu})$

(4) $(\Phi^\dagger i\overleftrightarrow{\mathcal{D}}_\nu\,\Phi)\,\mathcal{D}_\mu\,X^{\mu\nu} = c_7\,(\bar\Psi\,\gamma_\nu\,\Psi)(\Phi^\dagger\,i\overleftrightarrow{\mathcal{D}}^\nu\,\Phi) + c_8\,(\Phi^\dagger\,i\overleftrightarrow{\mathcal{D}}_\nu\,\Phi)(\Phi^\dagger\,i\overleftrightarrow{\mathcal{D}}^\nu\,\Phi)$

(5) $(\mathcal{D}_\mu\,X^{\mu\nu})(\bar\Psi_{L,R}\,\gamma_\nu\,\Psi_{L,R}) = c_9\,\Psi^4_{L,R}\,/\,\Psi^2_L\,\Psi^2_R + c_{10}\,\Psi_L\,\Psi_R\,\Phi^2\,\mathcal{D}$

(6) $X^{\mu\nu}\,(\bar\Psi_{L,R}\,\gamma_\mu\,\mathcal{D}_\nu\,\Psi_{L,R}) = c_{11}\,X^{\mu\nu}\,(\bar\Psi_{L,R}\,\sigma_{\mu\nu}\,\Psi_{R,L})\,\Phi$

Warsaw basis is renormalised at one-loop (self consistent) Grojean et al., Jenkins et al., Jenkins et al., Alonso et al.

New physics effects also expressed via the **BSM primary basis** (more suited for bottom-up approach), formulated in terms of mass eigenstates; Gupta et al.