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BSM Benchmarks for Effective Field Theories in Higgs and Electroweak Physics

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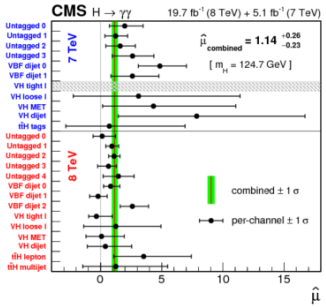
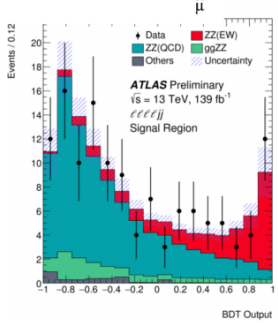
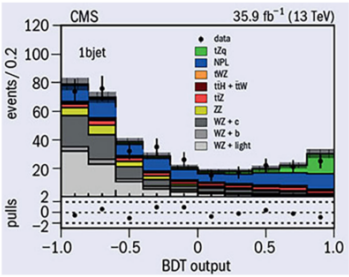
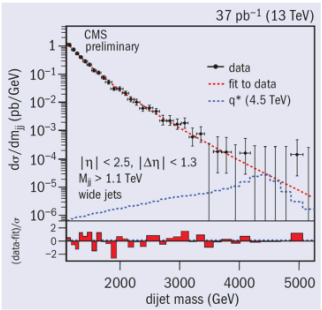
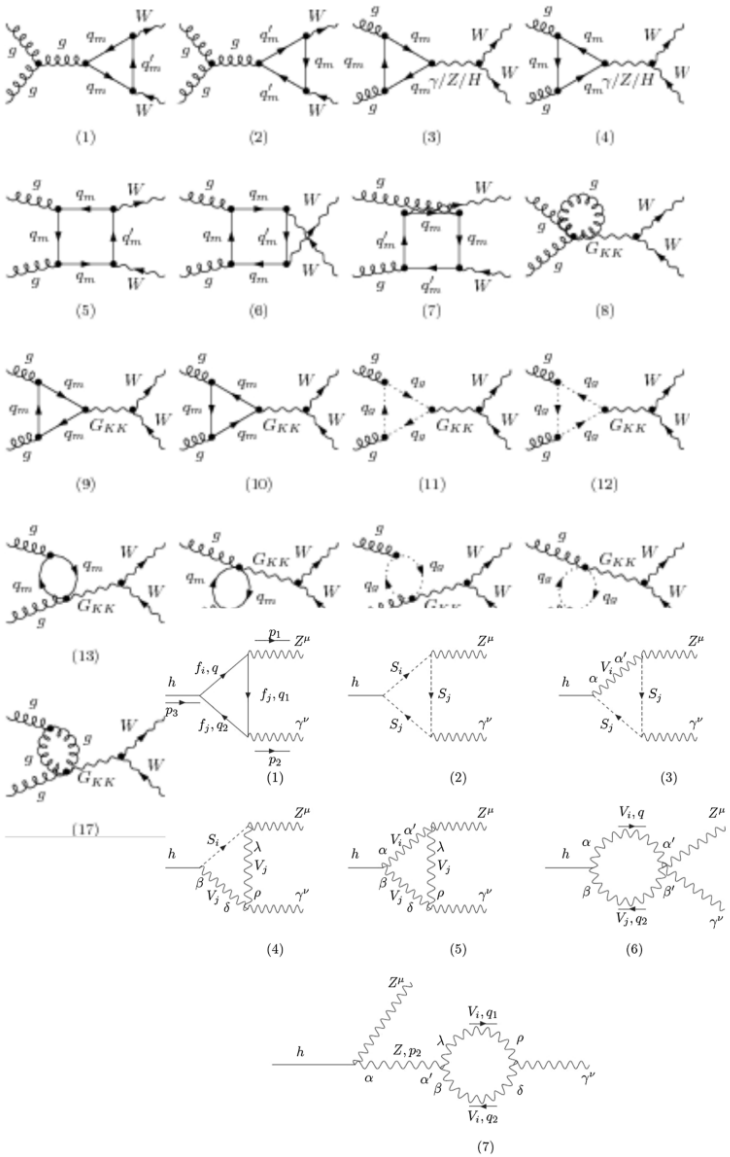
Getting implications of experimental data on new physics models is highly non trivial!

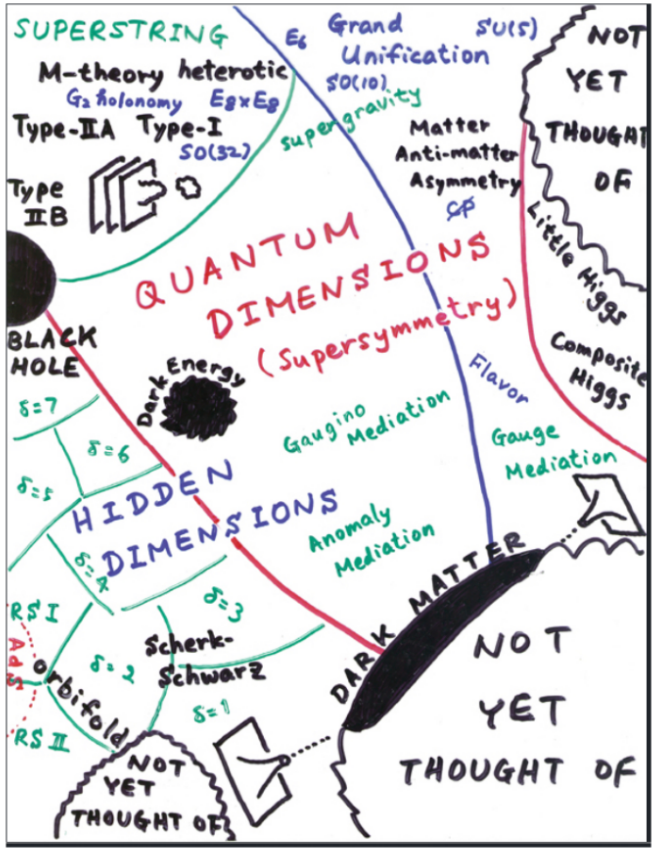












Why EFT?

- EFTs: standard tool to perform this exp-th comparison, providing a very efficient two-step algorithm for it
  - Bottom-up approach (global fits to experimental data):
    - ✔ (Mostly) model-independent parametrization of experimental data, easy to combine different data sets.
    - ✗ Often (too) many parameters in the fits.
  - Top-down approach (matching UV models onto the EFT):
    - ✔ Recovers model discrimination (needed for UV physics)
    - ✗ Needs specific model by model calculations
- EFT benchmarks incorporate some model discrimination and reduce number of parameters.

Why EFT benchmarks?

- EFT benchmarks provide an important roadmap:
  - Model discrimination is back in the game.
  - Number of parameters is reduced.
  - Flat directions in global fits are usually eliminated.
  - Validity of EFT can be unambiguously assessed.
- The choice of benchmarks has to be done very carefully (as always) to capture generic features:
  - Weakly coupled BSM
    - Tree-level new scalars, fermions and vectors
    - One-loop effects
  - Strongly coupled BSM

Why EFT benchmarks?

- We are going to focus on operators relevant for Higgs (and EW) physics

$\mathcal{O}$	Operator definition	Main On-shell (Higgs)	Dominant Off-shell
$\mathcal{O}_H$	$\frac{1}{2}\,\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H)$	$h \to \psi\bar{\psi}, VV^*$	$V_L V_L \to V_L V_L, hh$
$\mathcal{O}_T$	$\frac{1}{2}\,(H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger \overleftrightarrow{D}^\mu H)$	$h \to ZZ^*$	$V_L V_L \to V_L V_L, hh$
$\mathcal{O}_6$	$\lambda_h (H^\dagger H)^3$	None	$h \to hh, V_L V_L \to V_L V_L h(4V_L)$
$\mathcal{O}_\psi$	$y_\psi\ \overline{\psi}_L H \psi_R (H^\dagger H)$	$h \to \psi\bar{\psi}$	$V_L V_L \to t\bar{t}, V_L b \to t V_L V_L$
$\mathcal{O}_W$	$\frac{i}{2}\ g(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H)(D_\nu W^{\mu\nu})^i$	$h \to VV^*, V^* \to hV$	$q\bar{q} \to V_L V_L\,(hV_L)$
$\mathcal{O}_B$	$\frac{i}{2}\ g'(H^\dagger \overleftrightarrow{D}_\mu H)(\partial_\nu B^{\mu\nu})$	$h \to VV^*$	$q\bar{q} \to V_L V_L\,(hV_L)$
$\mathcal{O}_{HW}$	$ig(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu}$	$h \to \gamma Z$	$q\bar{q} \to VV$
$\mathcal{O}_{HB}$	$ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$h \to \gamma Z$	$q\bar{q} \to VV$
$\mathcal{O}_g$	$g_s^2 H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$	$h \to gg$	$pp \to V_L V_L, hh$
$\mathcal{O}_\gamma$	$g'^2 H^\dagger H B_{\mu\nu} B^{\mu\nu}$	$h \to \gamma\gamma, \gamma Z, ZZ$	$V_L V_L \to \gamma\gamma, \gamma Z, ZZ$
$\mathcal{O}_{2G}$	$-\frac{1}{2}(D^\mu G_{\mu\nu})^a (D_\rho G^{\rho\nu})^a$	None	$pp \to jj$
$\mathcal{O}_{2W}$	$-\frac{1}{2}(D^\mu W_{\mu\nu})^i (D_\rho W^{\rho\nu})^i$	None	$q\bar{q} \to \psi\bar{\psi}, VV$
$\mathcal{O}_{2B}$	$-\frac{1}{2}(\partial^\mu B_{\mu\nu})(\partial_\rho B^{\rho\nu})$	None	$q\bar{q} \to \psi\bar{\psi}, VV$
$\mathcal{O}_{3G}$	$g_s f_{abc} G^{a\nu}_\mu G^{b\rho}_\nu G^{c\mu}_\rho$	None	$pp \to jj$
$\mathcal{O}_{3W}$	$g\epsilon_{ijk} W^{i\nu}_\mu W^{j\rho}_\nu W^{k\mu}_\rho$	None	$q\bar{q} \to VV$

Weakly coupled BSM: tree level

- New scalars, fermions or vectors that contribute at tree level and dimension 6 to the SMEFT have been classified

Contribution to operators with the Higgs

Scalars	$\mathcal{S}$	φ	Ξ	Ξ_1	Θ_1	Θ_3
	$(1,1)_0$	$(1,2)_{1/2}$	$(1,3)_0$	$(1,3)_1$	$(1,4)_{1/2}$	$(1,4)_{3/2}$

Fermions							
	N	E	Δ_1	Δ_3	Σ	Σ_1	
	$(1,1)_0$	$(1,1)_{-1}$	$(1,2)_{-1/2}$	$(1,2)_{-3/2}$	$(1,3)_0$	$(1,3)_{-1}$	
	U	D	Q_1	Q_5	Q_7	T_1	T_2
	$(3,1)_{2/3}$	$(3,1)_{-1/3}$	$(3,2)_{1/6}$	$(3,2)_{-5/6}$	$(3,2)_{7/6}$	$(3,3)_{-1/3}$	$(3,3)_{2/3}$

Vectors	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$
	$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$

Weakly coupled BSM: tree level

- New scalars, fermions or vectors that contribute at tree level and dimension 6 to the SMEFT have been classified

Contribution to operators with the Higgs

Name	Operator	Fields that generate it
$\star\,\mathcal{O}_{\phi}$	$\lvert H\rvert^6$	$\mathcal{S}$, φ, Ξ, Ξ_1, Θ_1, Θ_3, $\mathcal{B}_1$, $\mathcal{W}$
$\star\,\mathcal{O}_{\phi\Box}$	$\lvert H\rvert^2\Box\lvert H\rvert^2$	$\mathcal{S}$, Ξ, Ξ_1, $\mathcal{B}$, $\mathcal{B}_1$, $\mathcal{W}$, $\mathcal{W}_1$
$\mathcal{O}_{\phi D}$	$\lvert H^\dagger D_\mu H\rvert^2$	Ξ, Ξ_1, $\mathcal{B}$, $\mathcal{B}_1$, $\mathcal{W}$, $\mathcal{W}_1$
$\bullet\,\mathcal{O}_{e\phi}$	$\lvert H\rvert^2\bar{l}_L H e_R$	$\mathcal{S}$, φ, Ξ, Ξ_1, E, Δ_1, Δ_3, Σ, Σ_1, $\mathcal{B}$, $\mathcal{B}_1$, $\mathcal{W}$, $\mathcal{W}_1$
$\bullet\,\mathcal{O}_{d\phi}$	$\lvert H\rvert^2\bar{q}_L H d_R$	$\mathcal{S}$, φ, Ξ, Ξ_1, D, Q_1, Q_5, T_1, T_2, $\mathcal{B}$, $\mathcal{B}_1$, $\mathcal{W}$, $\mathcal{W}_1$
$\star\,\mathcal{O}_{u\phi}$	$\lvert H\rvert^2\bar{q}_L \tilde{H} u_R$	$\mathcal{S}$, φ, Ξ, Ξ_1, U, Q_1, Q_7, T_1, T_2 $\mathcal{B}$, $\mathcal{B}_1$, $\mathcal{W}$, $\mathcal{W}_1$
$\mathcal{O}_{\phi l}^{(1)}$	$(\bar{l}_L\gamma^\mu l_L)(H^\dagger i\overleftrightarrow{D}_\mu H)$	N, E, Σ, Σ_1, $\mathcal{B}$
$\mathcal{O}_{\phi l}^{(3)}$	$(\bar{l}_L\gamma^\mu\sigma^a l_L)(H^\dagger i\overleftrightarrow{D}^a_\mu H)$	N, E, Σ, Σ_1, $\mathcal{W}$

Weakly coupled BSM: tree level

- In general it is not easy to have large effects in Higgs physics compatible with other constraints (mostly EW)
  - Example: Vector-like quark U~$(3,1)_{2/3}$

$$\mathcal{L}_{\rm BSM} = \mathcal{L}_{\rm SM} + i\bar{U}\not{D}U + M\bar{U}U - \left(\lambda_i \bar{U}_R \tilde{H}^\dagger q_{Li} + \text{h.c.}\right)$$

$(C^{(1)}_{\phi q})_{ij}$	$(C^{(3)}_{\phi q})_{ij}$	$(C_{u\phi})_{ij}$
$\frac{\lambda_i^*\lambda_j}{4M^2}$	$-\frac{\lambda_i^*\lambda_j}{4M^2}$	$2y^{u*}_{jk}\frac{\lambda_i^*\lambda_k}{4M^2}$

Effects too small for all fermions but the top

$$\delta\lambda_t \approx g^L_{Ztt} \approx 2\delta V^L_{tb}$$

Coupling to Z, W

Couplings to the Higgs

Weakly coupled BSM: tree level

- In general it is not easy to have large effects in Higgs physics compatible with other constraints unless cancellations are enforced (maybe by symmetries)
  - **Quark bidoublet:** $Q_1 \sim (3,2)_{1/6}$ **and** $Q_7 \sim (3,2)_{7/6}$
    We introduce two quark doublets,

$$Q_7 = \begin{pmatrix} X \\ T \end{pmatrix}, \qquad Q_1 = \begin{pmatrix} T' \\ B \end{pmatrix},$$

with the same mass and coupling to the top quark:

$$\begin{aligned} \mathcal{L}_{\rm BSM} = \mathcal{L}_{\rm SM} &+ i\bar{Q}_7 \not{D} Q_7 + i\bar{Q}_1 \not{D} Q_1 \\ &+ M\left(\bar{Q}_7 Q_7 + \bar{Q}_1 Q_1\right) \\ &- \left[\lambda\left(\bar{Q}_{7L} H t_R + \bar{Q}_{1L} \tilde{H} t_R\right) + \text{h.c.}\right]. \end{aligned}$$

$(C_{u\phi})_{33}$
$\frac{\lvert\lambda\rvert^2}{M^2}$

Arbitrary top Yukawa couplings with no other effects

Weakly coupled BSM: tree level

- In general it is not easy to have large effects in Higgs physics compatible with other constraints
  - New scalar multiplets. Can mix with the Higgs and have a non-custodial vev (strongly constrained by T parameter)

Model	ρ	3σ **upper limit on** β
Singlet	1	none
2HDM	1	none
Real Triplet	$\sec^2\beta$	0.030
Complex Triplet	$2\left(3-\cos 2\beta\right)^{-1}$	0.014
Quartet: $Y=\frac{1}{2}$	$7\left(4+3\cos 2\beta\right)^{-1}$	0.033
Quartet: $Y=\frac{3}{2}$	$\left(2-\cos 2\beta\right)^{-1}$	0.010

Weakly coupled BSM: tree level

- In general it is not easy to have large effects in Higgs physics compatible with other constraints
  - New scalar multiplets. Can mix with the Higgs and have a non-custodial vev (strongly constrained by T parameter)

Model	$\hat{\mathbf{c}}_{\mathbf{H}}$	$\hat{\mathbf{c}}_{\mathbf{6}}\lambda_{\mathbf{SM}}$	$\hat{\mathbf{c}}_{\mathbf{T}}$	$\hat{\mathbf{c}}_{\mathbf{t}}$	$\hat{\mathbf{c}}_{\mathbf{b}} = \hat{\mathbf{c}}_{\tau}$
Real Singlet: exp. $\not{\mathbb{Z}}_2$	$\tan^2\alpha$	$\tan^2\alpha\left(\lambda_\alpha - \frac{m_2}{v}\tan\alpha\right)$	0	0	0
Real Singlet: spont. $\not{\mathbb{Z}}_2$	$\tan^2\alpha$	0	0	0	0
2HDM: Type I	0	$-c^2_{\beta-\alpha}\frac{\Lambda^2}{v^2}$	0	$-c_{\beta-\alpha}\cot(\beta)$	$-c_{\beta-\alpha}\cot(\beta)$
2HDM: Type II	0	$-c^2_{\beta-\alpha}\frac{\Lambda^2}{v^2}$	0	$-c_{\beta-\alpha}\cot(\beta)$	$c_{\beta-\alpha}\tan(\beta)$
Real Triplet	$-2\hat{c}_T$	$\hat{c}_T\lambda_\alpha$	✓	$\hat{c}_T$	$\hat{c}_T$
Complex Triplet	$\hat{c}_T$	$-\hat{c}_T\left(\lambda_{\alpha 1} - \frac{\lambda_{\alpha 2}}{2}\right)$	✓	$-\hat{c}_T$	$-\hat{c}_T$
Quartet: $Y = \frac{1}{2}$	0	$-2\hat{c}_T\frac{\Lambda^2}{v^2}$	✓	0	0
Quartet: $Y = \frac{3}{2}$	0	$\frac{2}{3}\hat{c}_T\frac{\Lambda^2}{v^2}$	✓	0	0

Weakly coupled BSM: one-loop

- Some effects can only be generated at loop level
- Great progress has been made recently towards automating one-loop matching calculations (both functional and diagrammatic)
- Some general patterns can be found.

Weakly coupled BSM: one-loop

- Example: Vector triplet $Q^a_\mu \sim (1,3)_0$

$$\begin{aligned}\mathcal{L}_{\rm UV} =& \mathcal{L}_{\rm SM} + \tilde{g} Q^a_\mu J^{\mu a}_W \\ &+ \frac{1}{2}\left(D_\mu Q^a_\nu D^\nu Q^{\mu a} - D_\mu Q^a_\nu D^\mu Q^{\nu a} - g\epsilon^{abc} Q^a_\mu Q^b_\nu W^{\mu\nu c}\right) \\ &+ \frac{1}{2}\left(M^2 + \frac{1}{2}\tilde{g}^2 |H|^2\right) Q^a_\mu Q^{\mu a}.\end{aligned}$$

$$\Delta\mathcal{L}_{\rm tree} = \frac{\tilde{g}^2}{M^2}\mathcal{O}_{2W},$$

$$\Delta\mathcal{L}_{\text{1-loop}} = \frac{1}{(4\pi)^2}\frac{1}{M^2}\left[\frac{g^2}{20}\left(3\mathcal{O}_{3W} - 37\mathcal{O}_{2W}\right) + \frac{\tilde{g}^4}{4}\left(\mathcal{O}_H - \frac{\tilde{g}^2}{6}\mathcal{O}_6\right)\right]$$

$\mathcal{O}_H$	$\frac{1}{2}\,\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H)$
$\mathcal{O}_T$	$\frac{1}{2}\,(H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger \overleftrightarrow{D^\mu} H)$
$\mathcal{O}_6$	$\lambda_h (H^\dagger H)^3$

$\mathcal{O}_{2G}$	$-\frac{1}{2}(D^\mu G_{\mu\nu})^a(D_\rho G^{\rho\nu})^a$
$\mathcal{O}_{2W}$	$-\frac{1}{2}(D^\mu W_{\mu\nu})^i(D_\rho W^{\rho\nu})^i$
$\mathcal{O}_{2B}$	$-\frac{1}{2}(\partial^\mu B_{\mu\nu})(\partial_\rho B^{\rho\nu})$
$\mathcal{O}_{3G}$	$g_s f_{abc} G^{a\nu}_\mu G^{b\rho}_\nu G^{c\mu}_\rho$
$\mathcal{O}_{3W}$	$g\epsilon_{ijk} W^{i\nu}_\mu W^{j\rho}_\nu W^{k\mu}_\rho$

Weakly coupled BSM: one-loop

- 2W/3W ratio depends only on new particle spin

$$\frac{c_{2W}}{c_{3W}} = -\frac{W}{\lambda_\gamma}$$

Oblique W

aTGC

1 1 for a real scalar

$$\mathcal{L}_{\text{eff,1-loop}} \supset \frac{1}{(4\pi)^2}\frac{1}{M^2}\frac{g^2}{60}\mu(R)\Big(a_{2\,s}\mathcal{O}_{2W}+a_{3\,s}\mathcal{O}_{3W}\Big)$$

$a_{2\,s}$	$a_{3\,s}$	
2	2	scalar
16	-4	Dirac fermion
-37	3	vector

	c_{2W}/c_{3W}
scalar	1
Dirac fermion	-4
vector	$-37/3$

Only for a vector triplet O2W is generated at tree level so $|c_{2W}/c_{3W}| \sim 16\pi^2 \gg 1$

Strongly coupled BSM

- With strong coupling perturbative arguments have to be replaced with symmetries and power counting.
  - Composite Higgs models: Strongly coupled NP characterized by a single scale Λ, a single coupling g*, the Higgs is part of the strongly coupled sector and fermions are partially composite

$$\delta\mathcal{L}_{\rm NDA} = \frac{\Lambda^4}{g_*^2}\hat{\mathcal{L}}\left(\frac{g_* H}{\Lambda}, \epsilon_\psi \frac{g_*\psi}{\Lambda^{3/2}}, \frac{D_\mu}{\Lambda}\right)$$

  - Different assumptions about UV model imply different scaling of Wilson coefficients

Strongly coupled BSM

- With strong coupling perturbative arguments have to be replaced with symmetries and power counting.
  - Different assumptions about UV model imply different scaling of Wilson coefficients

Coefficient	Generic CH	Light $j=0$	Light $j=1$	Only Higgs	$SU(2)$ custodial	NGB-Higgs
$c_{H,\psi}$	g_*^2	g_*^2	g_*^2	g_*^2	g_*^2	g_*^2
c_T	g_*^2	g_*^2	g_*^2	g_*^2	$g_*^2 \times \frac{g'^2}{16\pi^2}$	g_*^2
c_6	$\frac{g_*^4}{\lambda_h}$	$\frac{g_*^4}{\lambda_h}$	$\frac{g_*^4}{\lambda_h}$	$\frac{g_*^4}{\lambda_h}$	$\frac{g_*^4}{\lambda_h}$	$\frac{g_*^4}{\lambda_h} \times \left(\frac{g_{\not{g}}^2}{g_*^2} \text{ or } \frac{g_{\not{g}}^2}{16\pi^2} \right)$
$c_{W,B}$	1	$\frac{g_*^2}{16\pi^2}$	1	$\frac{g_*^2}{16\pi^2}$	1	1
$c_{HW,HB}$	1	$\frac{g_*^2}{16\pi^2}$	$\frac{g_*^2}{16\pi^2}$	$\frac{g_*^2}{16\pi^2}$	1	1
$c_{g,\gamma}$	1	$\frac{g_*^2}{16\pi^2}$	$\frac{g_*^2}{16\pi^2}$	$\frac{g_*^2}{16\pi^2}$	1	$\frac{g_{\not{g}}^2}{16\pi^2}$
$c_{2G,2W,2B}$	$\frac{g_{SM}^2}{g_*^2}$	$\frac{g_{SM}^2}{g_*^2} \times \frac{g_*^2}{16\pi^2}$	$\frac{g_{SM}^2}{g_*^2}$	$\frac{g_{SM}^2}{g_*^2} \times \frac{g_*^2}{16\pi^2}$	$\frac{g_{SM}^2}{g_*^2}$	$\frac{g_{SM}^2}{g_*^2}$
$c_{3G,3W}$	$\frac{g_{SM}^2}{g_*^2}$	$\frac{g_{SM}^2}{g_*^2} \times \frac{g_*^2}{16\pi^2}$	$\frac{g_{SM}^2}{g_*^2} \times \frac{g_*^2}{16\pi^2}$	$\frac{g_{SM}^2}{g_*^2} \times \frac{g_*^2}{16\pi^2}$	$\frac{g_{SM}^2}{g_*^2}$	$\frac{g_{SM}^2}{g_*^2}$

Strongly coupled BSM

- With strong coupling perturbative arguments have to be replaced with symmetries and power counting.
  - Different assumptions about UV model imply different scaling of Wilson coefficients
  - Transverse vector polarizations can be also composite

Model	$\mathcal{O}_H$	$\mathcal{O}_{2W}$	$\mathcal{O}_{2B}$	$\mathcal{O}_{3W}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_{W,B}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{\psi}$
SILH (see sec. 3.1)	g_*^2	$\frac{g^2}{g_*^2}$	$\frac{g'^2}{g_*^2}$	$\frac{g^2}{16\pi^2}$	$\frac{g_*^2}{16\pi^2}$	$\frac{g_*^2}{16\pi^2}$	1	$\frac{g^2}{16\pi^2}$	$\frac{g_*^2}{g^2}$
Remedios		1	1	$\frac{g_*}{g}$					
Remedios+MCHM	g_*^2	1	1	$\frac{g_*}{g}$	1	1	1	1	g_*^2
Remedios+$ISO(4)$	λ_h	1	1	$\frac{g_*}{g}$	$\frac{g_*}{g}$	1	1	1	λ_h

Summary

- EFTs allow to bridge experiment and theory in an efficient way.
- BSM benchmarks can provide useful roadmaps for bottom-up EFT analyses.
- At tree level, models with few fields are very constrained except for cancellations (via symmetries)
- At loop level new (sometimes universal) effects appear
- Symmetries and power counting provide estimates for NP effects in strongly coupled theories
- Global likelihoods and UV/IR dictionaries still necessary