The EFT approach to Higgs physics beyond the SM

Mikuláš Gintner

IEAP CTU Prague

CZ-SK ATLAS, Olomouc 2015

Jun 24 – 26, 2015

SM status

- SM Higgs-like 125 GeV particle discovered
- SM validity up to the Planck scale
- no robust deviation from SM predictions observed
  - no BSM particles
  - direct/indirect limits $\Rightarrow$ $M_{BSM} \gg v$

Why EFT?

BSM theory is unknown ...

EFT ... the simplest framework to capture physics essential for a given scale

- fields
- symmetries → most general interactions (ops.)
- appropriate expansion param → decreasing relevance

$$\mathcal{L} = \mathcal{L}^{\mathrm{SM}} + \sum_n \mathcal{L}^{(n)}$$

- unknown "cplngs" from experiment
- desired precision ⇒ max n

The SM building principles

1. relativistic QFT
2. linearly realized local SU(3)xSU(2)xU(1) symmetry
3. vacuum invariant under SU(3)xU(1)
4. SSB due to the non-zero VEV of an elementary scalar
5. “R” interactions

Two classes of effective BSM descriptions

ESB is realized linearly

- elementary Higgs(es), weakly interacting
- expansion in v/Λ
- the leading term $\mathcal{L}^{\rm SM}$ decouples
- SUSY is a typical example

ESB is realized non-linearly

- dynamical Higgs scenarios, strongly interacting
- a derivative expansion
- the leading term does not decouple
- composite Higgs, extra-dim models

EFT for linearly-realized ESB

1. relativistic QFT

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3. vacuum invariant under SU(3)xU(1)

4. SSB due to the non-zero VEV of an elementary scalar

5. ~~"R" interactions~~

the simplest version: SM fields only

The D=6 effective Lagrangian

$$\mathcal{L}_{\text{linear}} = \mathcal{L}^{\text{SM}} + \mathcal{L}^{D=6}, \qquad \mathcal{L}^{D=6} = \frac{1}{v^2} \sum_\alpha c_\alpha O_\alpha$$

where $c_\alpha = \mathcal{O}(v^2/\Lambda^2)$

under "reasonable" assumptions:

76 flavor universal D=6 ops

CP-even Higgs cplngs (hVV, hff)

operator	$D=4$ coupling	$D=6$ coupling	$D=6$ experiment
$m_W/(2c_W^2)hZ_\mu Z^\mu$	g	$(2m_W/v)\delta c_z$	$\delta c_z = -0.12 \pm 0.20$
$\frac{1}{v}hZ_{\mu\nu}Z^{\mu\nu}$	0	$g^2/(2c_W)^2 c_{zz}$	$c_{zz} = 0.5 \pm 1.8$
$\frac{1}{v}hZ^\mu\partial_\nu Z_{\mu\nu}$	0	$g^2 c_{z\Box}$	$c_{z\Box} = -0.21 \pm 0.82$
$\frac{1}{v}hA_{\mu\nu}A^{\mu\nu}$	0	$(e/2)^2 c_{\gamma\gamma}$	$c_{\gamma\gamma} = 0.014 \pm 0.029$
$\frac{1}{v}hA_{\mu\nu}Z^{\mu\nu}$	0	$eg/(2c_W)c_{z\gamma}$	$c_{z\gamma} = 0.01 \pm 0.10$
$\frac{1}{v}hG^a_{\mu\nu}G^{a\mu\nu}$	0	$(g_s/2)^2 c_{gg}$	$c_{gg} = -0.0056 \pm 0.0028$
$h\bar{f}_L f_R + \text{h.c.}$	$-g\frac{m_f}{2m_W}$	$-(m_f/v)e^{i\phi_f}\delta y_f$	$\delta y_u = 0.55 \pm 0.30$
			$\delta y_d = -0.42 \pm 0.45$
			$\delta y_e = -0.17 \pm 0.35$

$$\mu_{X;Y}^{\text{exp}} = \frac{\sigma(pp \to X)_{\text{exp}}}{\sigma(pp \to X)_{\text{SM}}} \frac{\Gamma(h \to Y)_{\text{exp}}/\Gamma(h \to \text{all})_{\text{exp}}}{\Gamma(h \to Y)_{\text{SM}}/\Gamma(h \to \text{all})_{\text{SM}}}.$$

EFT for nonlinearly-realized ESB

1. relativistic QFT
2. ~~linearly realized~~ local SU(3)xSU(2)xU(1) symmetry
3. ~~vacuum invariant under SU(3)xU(1)~~
4. ~~SSB due to the non-zero VEV of an elementary scalar~~
5. ~~"R" interactions~~

the simplest version: SM fields only

NL Lagrangian for a light Higgs

Higgs h(x) … a singlet of the EW symm.

$$U(x) = \exp[i\sigma^a \pi^a(x)/v],$$

$$T = U\sigma^3 U^\dagger, \qquad V_\mu(x) = (D_\mu U)U^\dagger,$$

$$D_\mu U = \partial_\mu U + igW_\mu U - ig' U B_\mu,$$

$$\mathcal{L}_{\rm NL} = \mathcal{L}^{\rm SM} + \Delta\mathcal{L}$$

all CP-even bosonic operators with up to four derivatives:

$$\begin{aligned}\Delta\mathcal{L} \quad = \quad & \tilde{c}_H \mathcal{P}_H(h) + \tilde{c}_G \mathcal{P}_G(h) + \tilde{c}_W \mathcal{P}_W(h) + \tilde{c}_B \mathcal{P}_B(h) + \tilde{c}_C \mathcal{P}_C(h) \\ & + \tilde{c}_{\Box H} \mathcal{P}_{\Box H}(h) + \tilde{c}_T \mathcal{P}_T(h) + \sum_{i=1}^{26} \tilde{c}_i \mathcal{P}_i(h),\end{aligned}$$

The NL CP-even bosonic ops up to 4 derivatives

operator	composition	dim
$\mathcal{P}_H$	$(1/2)\,(\partial_\mu h)(\partial^\mu h)\,\mathcal{F}_H(h)$	4
$\mathcal{P}_G$	$-g_s^2\,(1/4)\,G^a_{\mu\nu}G^{a\mu\nu}\,\mathcal{F}_G(h)$	4
$\mathcal{P}_W$	$-g^2\,(1/4)\,W^a_{\mu\nu}W^{a\mu\nu}\,\mathcal{F}_W(h)$	4
$\mathcal{P}_B$	$-g'^2\,(1/4)\,B_{\mu\nu}B^{\mu\nu}\,\mathcal{F}_B(h)$	4
$\mathcal{P}_C$	$-(v^2/4)\,\mathrm{Tr}(\boldsymbol{V}_\mu\boldsymbol{V}^\mu)\,\mathcal{F}_C(h)$	2
$\mathcal{P}_{\Box H}$	$(1/v^2)\,(\partial_\mu\partial^\mu h)^2\,\mathcal{F}_{\Box H}(h)$	6
$\mathcal{P}_T$	$(v^2/4)\,\left[\mathrm{Tr}(\boldsymbol{T}\boldsymbol{V}_\mu)\right]^2\,\mathcal{F}_T(h)$	2
$\mathcal{P}_2$	$ig'\,B_{\mu\nu}\mathrm{Tr}(\boldsymbol{T}[\boldsymbol{V}^\mu,\boldsymbol{V}^\nu])\,\mathcal{F}_2(h)$	4
$\mathcal{P}_3$	$ig\,\mathrm{Tr}(W_{\mu\nu}[\boldsymbol{V}^\mu,\boldsymbol{V}^\nu])\,\mathcal{F}_3(h)$	4
$\mathcal{P}_4$	$ig'\,B_{\mu\nu}\mathrm{Tr}(\boldsymbol{T}\boldsymbol{V}^\mu)\,\partial^\nu\mathcal{F}_4(h)$	4
$\mathcal{P}_5$	$ig\,\mathrm{Tr}(W_{\mu\nu}\boldsymbol{V}^\mu)\,\partial^\nu\mathcal{F}_5(h)$	4
$\mathcal{P}_{14}$	$g\varepsilon^{\mu\nu\rho\lambda}\,\mathrm{Tr}(\boldsymbol{T}\boldsymbol{V}_\mu)\mathrm{Tr}(\boldsymbol{V}_\nu W_{\rho\lambda})\,\mathcal{F}_{14}(h)$	4
$\mathcal{P}_{25}$	$\left[\mathrm{Tr}(\boldsymbol{T}\boldsymbol{V}_\mu)\right]^2\,\partial_\nu\partial^\nu\mathcal{F}_{25}(h)$	4

$$\mathcal{F}_i(h) = 1 + 2a_i\frac{h}{v} + b_i\left(\frac{h}{v}\right)^2 + \cdots$$

$$\mathcal{L}_{\rm NL} = \mathcal{L}^{\rm SM} + \sum_{i=1}^{33}\tilde{c}_i\mathcal{P}_i$$

Linear vs. Non-linear

the bridge:

$$\Phi(h,\vec{\pi}) = \frac{v+h(x)}{\sqrt{2}}\,\boldsymbol{U}(\vec{\pi})\begin{pmatrix}0\\1\end{pmatrix}$$

two effects:

(a) independent NL ops tied to a single linear op

(b) leading NL corrections correspond to higher orders in linear expansion

✗ no one-to-one correspondence of the leading corrections

Linear vs. NL: example of (a)

$$\mathcal{O}_B = \frac{ig'}{2} B_{\mu\nu} D^\mu \Phi^\dagger D^\nu \Phi \quad \longrightarrow \quad \frac{v^2}{16} [\mathcal{P}_2(h) + 2\mathcal{P}_4(h)].$$

$$\mathcal{O}_W = \frac{ig}{2} W^a_{\mu\nu} D^\mu \Phi^\dagger \sigma^\mu D^\nu \Phi \quad \longrightarrow \quad \frac{v^2}{8} [\mathcal{P}_3(h) + 2\mathcal{P}_5(h)].$$

$\mathcal{P}_2, \mathcal{P}_3$ ... anomalous TGC's κ_Z, κ_γ

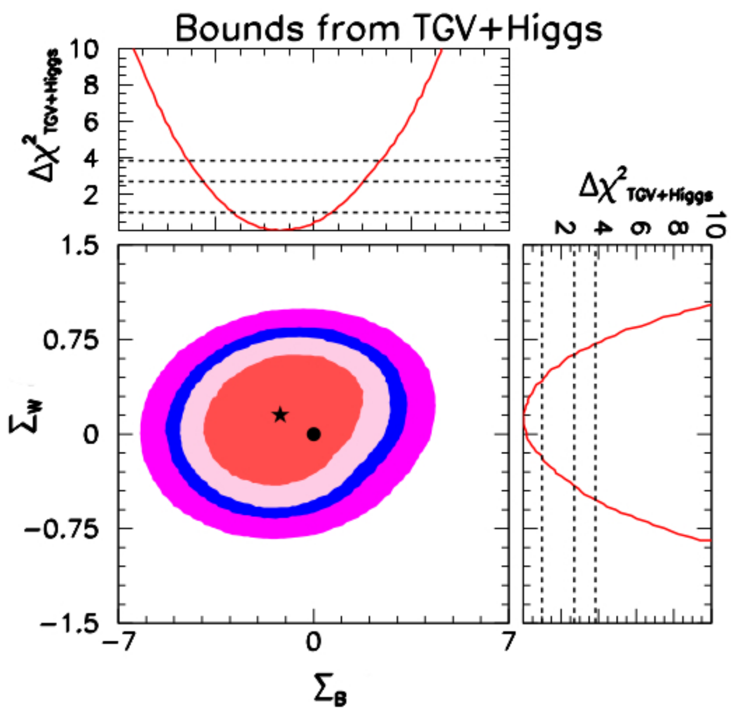
$\mathcal{P}_4, \mathcal{P}_5$ ... anomalous HZZ and HZγ vertices

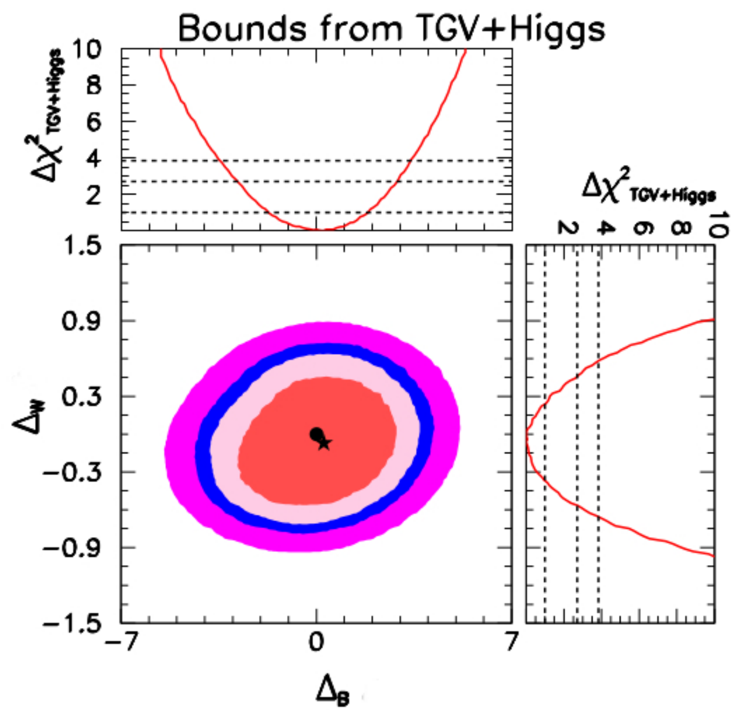
linear → deviations correlated
NL → independent

Linear vs. NL: example of (a) … cont'd

$$\Sigma_B = 4(2\tilde{c}_2 + \quad \tilde{c}_4), \qquad \Delta_B = 4(2\tilde{c}_2 - \quad \tilde{c}_4).$$

$$\Sigma_W = 4(2\tilde{c}_3 + \quad \tilde{c}_5), \qquad \Delta_W = 4(2\tilde{c}_3 - \quad \tilde{c}_5).$$





$\Sigma \neq 0 \quad \Rightarrow \quad$ BSM physics

$\Delta \neq 0 \quad \Rightarrow \quad$ NL BSM physics

Linear vs. NL: example of (b)

$$\underbrace{g\varepsilon^{\mu\nu\rho\lambda}W^a_{\mu\nu}(\Phi^\dagger \overleftrightarrow{D}_\rho\Phi)(\Phi^\dagger\sigma^a \overleftrightarrow{D}_\lambda\Phi)}_{\text{dim = 8}} \longrightarrow \underbrace{v^2\mathcal{P}_{14}(h)}_{\text{leading correction}}.$$

$\mathcal{P}_{14}$ ... TGC's g_5^Z

experiment	g_5^Z the best fit	g_5^Z 68%CL	g_5^Z 95%CL	$\tilde{c}_{14}$ 95%CL
OPAL	-0.04	$(-0.12; 0.13)$	$(-0.28; 0.21)$	$(-0.16; 0.12)$
L3	0.00	$(-0.13; 0.13)$	$(-0.21; 0.20)$	$(-0.12; 0.11)$
ALEPH	-0.064	$(-0.13; 0.13)$	$(-0.317; 0.19)$	$(-0.18; 0.11)$

EWPD: $-0.08 \leq g_5^Z \leq 0.04$ @ 90%CL

Conclusions

EFT provides:

- model-independent incorporation of assumed principles;
- model-independent parameterization of deviations from SM;
- simplifying tool focusing at the scale of interest;
- bridge between theory and experiment;
- strongly-interacting BSM's treatable by EFT's only

➢ EFT can investigate the nature of the ESB mechanism via its low-energy manifestation;

➢ symmetry realization related to weak vs. strong physics;

References

[1] A. Falkowski, arXiv:1505.00046 [hep-ph].

[2] I. Brivio *et al*, JHEP03 (2014) 024; I. Brivio, arXiv:1505.00637 [hep-ph].

[3] T. Appelquist, C. Bernard, Phys. Rev. D22 (1980) 200.