Effective Higgs Lagrangian

based on arXiv:1303.3876

In collaboration with:
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Introduction

In absence of a direct observation of new particles, our ignorance of the EWSB sector can be parametrized in terms of an effective Lagrangian

Bottom-up approach: the couplings of the operators are free parameters; if new particles are discovered they can be included in the Lagrangian

The detailed form of the Lagrangian depends on which assumptions are made

Assumptions:

- $SU(2)_L \times U(1)_Y$ is linearly realized at high energies
- $h(x)$ is a scalar and it is part of an $SU(2)_L$ doublet $H(x)$
- $h(x)$ is CP-even
- flavour alignment to avoid FCNC

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Effective Higgs Lagrangian

The list of dim-6 operators of Effective Lagrangian has been known since long time:

Buchmüller and Wyler
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A more recent complete and minimal classification:

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$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \bar{c}_i O_i \equiv \mathcal{L}_{SM} + \Delta\mathcal{L}_{SILH} + \Delta\mathcal{L}_{F_1} + \Delta\mathcal{L}_{F_2}$$

$$\begin{aligned}
\Delta\mathcal{L}_{SILH} = {} & \frac{\bar{c}_H}{2v^2}\, \partial^\mu \left(H^\dagger H\right) \partial_\mu \left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2} \left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\, \lambda}{v^2} \left(H^\dagger H\right)^3 \\
& + \left(\frac{\bar{c}_u}{v^2}\, y_u\, H^\dagger H\, \bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\, y_d\, H^\dagger H\, \bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\, y_l\, H^\dagger H\, \bar{L}_L H l_R + h.c. \right) \\
& + \frac{i\bar{c}_W\, g}{2m_W^2} \left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right) (D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B\, g'}{2m_W^2} \left(H^\dagger \overleftrightarrow{D^\mu} H\right) (\partial^\nu B_{\mu\nu}) \\
& + \frac{i\bar{c}_{HW}\, g}{m_W^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\, g'}{m_W^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
& + \frac{\bar{c}_\gamma\, {g'}^2}{m_W^2}\, H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_g\, g_S^2}{m_W^2}\, H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}
\end{aligned}$$

Effective Higgs Lagrangian

$$
\begin{aligned}
\Delta\mathcal{L}_{F_1} = &\frac{i\bar{c}_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu q_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}'_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu\sigma^i q_L\right)\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right) \\
&+ \frac{i\bar{c}_{Hu}}{v^2}\left(\bar{u}_R\gamma^\mu u_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}_{Hd}}{v^2}\left(\bar{d}_R\gamma^\mu d_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \\
&+ \left(\frac{i\bar{c}_{Hud}}{v^2}\left(\bar{u}_R\gamma^\mu d_R\right)\left(H^{c\,\dagger} \overleftrightarrow{D}_\mu H\right) + h.c.\right) \\
&+ \frac{i\bar{c}_{HL}}{v^2}\left(\bar{L}_L\gamma^\mu L_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}'_{HL}}{v^2}\left(\bar{L}_L\gamma^\mu\sigma^i L_L\right)\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right) \\
&+ \frac{i\bar{c}_{Hl}}{v^2}\left(\bar{l}_R\gamma^\mu l_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right),
\end{aligned}
$$

$$
\begin{aligned}
\Delta\mathcal{L}_{F_2} = &\frac{\bar{c}_{uB}\,g'}{m_W^2}\, y_u\, \bar{q}_L H^c \sigma^{\mu\nu} u_R\, B_{\mu\nu} + \frac{\bar{c}_{uW}\,g}{m_W^2}\, y_u\, \bar{q}_L \sigma^i H^c \sigma^{\mu\nu} u_R\, W^i_{\mu\nu} + \frac{\bar{c}_{uG}\,g_S}{m_W^2}\, y_u\, \bar{q}_L H^c \sigma^{\mu\nu}\lambda^a u_R\, G^a_{\mu\nu} \\
&+ \frac{\bar{c}_{dB}\,g'}{m_W^2}\, y_d\, \bar{q}_L H \sigma^{\mu\nu} d_R\, B_{\mu\nu} + \frac{\bar{c}_{dW}\,g}{m_W^2}\, y_d\, \bar{q}_L \sigma^i H \sigma^{\mu\nu} d_R\, W^i_{\mu\nu} + \frac{\bar{c}_{dG}\,g_S}{m_W^2}\, y_d\, \bar{q}_L H \sigma^{\mu\nu}\lambda^a d_R\, G^a_{\mu\nu} \\
&+ \frac{\bar{c}_{lB}\,g'}{m_W^2}\, y_l\, \bar{L}_L H \sigma^{\mu\nu} l_R\, B_{\mu\nu} + \frac{\bar{c}_{lW}\,g}{m_W^2}\, y_l\, \bar{L}_L \sigma^i H \sigma^{\mu\nu} l_R\, W^i_{\mu\nu} + h.c.
\end{aligned}
$$

How many operators?

Effective Higgs Lagrangian:

- $12(\Delta\mathcal{L}_{SILH}) + 8\,(\Delta\mathcal{L}_{F_1}) + 8\,(\Delta\mathcal{L}_{F_2}) = 28$
- 2 linear combinations of $\Delta\mathcal{L}_{F_1}$ are equivalent to pure oblique corrections

26 independent operators

Operators that do not affect Higgs physics:

- 5 bosonic operators
- 22 four-fermion baryon-number-conserving operators

27 independent operators

CP-odd operators:

$$\Delta\mathcal{L}_{CP} = \frac{i\tilde{c}_{HW}\, g}{m_W^2}(D^\mu H)^\dagger \sigma^i (D^\nu H)\tilde{W}^i_{\mu\nu} + \frac{i\tilde{c}_{HB}\, g'}{m_W^2}(D^\mu H)^\dagger (D^\nu H)\tilde{B}_{\mu\nu}$$
$$+ \frac{\tilde{c}_\gamma\, g'^2}{m_W^2} H^\dagger H B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{\tilde{c}_g\, g_S^2}{m_W^2} H^\dagger H G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$
$$+ \frac{\tilde{c}_{3W}\, g^3}{m_W^2}\epsilon^{ijk} W^{i\,\nu}_\mu W^{j\,\rho}_\nu \tilde{W}^{k\,\mu}_\rho + \frac{\tilde{c}_{3G}\, g_S^3}{m_W^2} f^{abc} G^{a\,\nu}_\mu G^{b\,\rho}_\nu \tilde{G}^{c\,\mu}_\rho\,,$$

6 independent operators

26 + 27 + 6 = 59 independent, 6-dimensional operators

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- 2 linear combinations of $\Delta\mathcal{L}_{F_1}$ are equivalent to pure oblique corrections:

$$O^Y_{H\Psi} \equiv \sum_\psi Y_\psi \, O_{H\psi} \sim O_T \, , O_B \qquad \text{and} \qquad O'_{Hq} + O'_{HL} \sim O_W$$

By making use of the equations of motion

$$iD^\mu W^i_{\mu\nu} = g\, H^\dagger \frac{\sigma^i}{2} \overleftrightarrow{D}_\nu H - ig\, \bar{\psi} \frac{\sigma^i}{2} \gamma_\nu \psi \qquad i\partial^\mu B_{\mu\nu} = \frac{g'}{2} H^\dagger \overleftrightarrow{D}_\nu H - ig'\, \bar{\psi} Y \gamma_\nu \psi$$

one can rewrite O_W and O_B as

$$O_W = -2\, O_H + \frac{4}{v^2} (H^\dagger H) |D_\mu H|^2 + O'_{Hq} + O'_{HL}$$

$$O_B = 2 \tan^2\theta_W \left(-O_T + O^Y_{H\Psi} \right)$$

and upon the field redefinition $H \to H - 2\bar{c}_W (H^\dagger H) H / v^2$, one gets

$$O_W = -6\, O_H + 2\, (O_u + O_d + O_l) - 8\, O_6 + O'_{Hq} + O'_{HL}$$

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It is always possible to remove O_W and O_B

$\Downarrow$

coefficients of other operators are shifted: $\boxed{\bar{c}_i \to \bar{c}_i + \Delta\bar{c}_i}$

$$\Delta\bar{c}_H = -6\,\bar{c}_W \qquad \Delta\bar{c}_T = -2\tan^2\theta_W\,\bar{c}_B \qquad \Delta\bar{c}_6 = -8\,\bar{c}_W \qquad \Delta\bar{c}_\psi = 2\,\bar{c}_W$$

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- The contribution of O_T to $\Delta\epsilon_1$ is canceled by the vertex correction due to fermionic operators

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Why this basis?

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& + \frac{i\bar{c}_W\, g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B\, g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu}) \\
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\end{aligned}
$$

- one can describe the oblique corrections in terms of $\Delta\mathcal{L}_{SILH}$ operators instead of operators with fermionic currents
- it isolates the contribution to the decays $h \to \gamma\gamma$ (from O_γ) and $h \to \gamma Z$ (from O_γ and $O_{HW} - O_{HB}$) that occur only at the radiative level in minimally coupled theories
- it is more appropriate to establish the nature of the Higgs boson and determine the strength of its interactions

Naive Dimensional Analysis

- a factor $1/M$ for each extra derivative
- a factor $g_*/M \equiv 1/f$ for each extra power of $H(x)$

estimates valid at the UV scale M

$$\bar{c}_H\,, \bar{c}_T\,, \bar{c}_6\,, \bar{c}_\psi \sim O\left(\frac{v^2}{f^2}\right) \quad \bar{c}_W\,, \bar{c}_B \sim O\left(\frac{m_W^2}{M^2}\right) \quad \bar{c}_{HW}\,, \bar{c}_{HB}\,, \bar{c}_\gamma\,, \bar{c}_g \sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right)$$

$$\bar{c}_{H\psi}\,, \bar{c}'_{H\psi} \sim O\left(\frac{\lambda_\psi^2}{g_*^2}\,\frac{v^2}{f^2}\right) \quad \bar{c}_{Hud} \sim O\left(\frac{\lambda_u \lambda_d}{g_*^2}\,\frac{v^2}{f^2}\right) \quad \bar{c}_{\psi W}\,, \bar{c}_{\psi B}\,, \bar{c}_{\psi G} \sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right)$$

- $\bar{c}_{W,B}$, $\bar{c}_{H\psi}$, $\bar{c}'_{H\psi}$, $\bar{c}_T$: valid when generated at tree-level
- $\bar{c}_{HW,HB,g,\gamma}$: suppressed by an additional loop factor $(g_*^2/16\pi^2)$

- strong dynamics: $g_* \gg 1 \quad \Rightarrow \quad f \ll M$
- weak dynamics: $g_* \sim g$
- leading New Physics effects: $O_{H,T,6,\psi}$ (and fermionic operators if $\lambda_\psi \sim g_*$)

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- a factor $g_*/M \equiv 1/f$ for each extra power of $H(x)$

estimates valid at the UV scale M

$$\bar{c}_H, \bar{c}_T, \bar{c}_6, \bar{c}_\psi \sim O\left(\frac{v^2}{f^2}\right) \quad \bar{c}_W, \bar{c}_B \sim O\left(\frac{m_W^2}{M^2}\right) \quad \bar{c}_{HW}, \bar{c}_{HB}, \bar{c}_\gamma, \bar{c}_g \sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right)$$

$$\bar{c}_{H\psi}, \bar{c}'_{H\psi} \sim O\left(\frac{\lambda_\psi^2}{g_*^2}\frac{v^2}{f^2}\right) \quad \bar{c}_{Hud} \sim O\left(\frac{\lambda_u \lambda_d}{g_*^2}\frac{v^2}{f^2}\right) \quad \bar{c}_{\psi W}, \bar{c}_{\psi B}, \bar{c}_{\psi G} \sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right)$$

- $\bar{c}_{W,B}$, $\bar{c}_{H\psi}$, $\bar{c}'_{H\psi}$, $\bar{c}_T$: valid when generated at tree-level
- $\bar{c}_{HW,HB,g,\gamma}$: suppressed by an additional loop factor $(g_*^2/16\pi^2)$

- strong dynamics: $g_* \gg 1 \quad \Rightarrow \quad f \ll M$
- weak dynamics: $g_* \sim g$
- leading New Physics effects: $O_{H,T,6,\psi}$ (and fermionic operators if $\lambda_\psi \sim g_*$)

Naive Dimensional Analysis

If the Higgs doublet is a composite Nambu–Goldstone boson
of a spontaneously-broken symmetry $\mathcal{G} \to \mathcal{H}$:

$$\frac{\bar{c}_6\, \lambda}{v^2}\left(H^\dagger H\right)^3$$

$$\frac{\bar{c}_\psi}{v^2}\, y_\psi\, H^\dagger H\, \bar{\psi}_L H \psi_R$$

$$\frac{\bar{c}_\gamma\, g'^2}{m_W^2}\, H^\dagger H B_{\mu\nu} B^{\mu\nu}$$

$$\frac{\bar{c}_g\, g_S^2}{m_W^2}\, H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$$

$$\frac{\bar{c}_{\psi B}\, g'}{m_W^2}\, y_\psi\, \bar{\psi}_L H \sigma^{\mu\nu} \psi_R\, B_{\mu\nu}$$

$$\frac{\bar{c}_{\psi W}\, g}{m_W^2}\, y_\psi\, \bar{\psi}_L \sigma^i H \sigma^{\mu\nu} \psi_R\, W^i_{\mu\nu}$$

$$\frac{\bar{c}_{\psi G}\, g_S}{m_W^2}\, y_\psi\, \bar{\psi}_L H \sigma^{\mu\nu} \lambda^a \psi_R\, G^a_{\mu\nu}$$

These operators violate the shift symmetry

$$H^i \to H^i + \zeta^i$$

(part of the $\mathcal{G}/\mathcal{H}$ transformation)

$$\Downarrow$$

they cannot be generated
in absence of an explicit breaking

$$\Downarrow$$

additional suppression factor $\frac{g_{\not{\mathcal{G}}}^2}{g_*^2}$:

$$\bar{c}_\gamma, \bar{c}_g \sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right) \times \frac{g_{\not{\mathcal{G}}}^2}{g_*^2}$$

Bounds on flavour-preserving operators

95% of probability

$$-1.5 \times 10^{-3} < \bar{c}_T(m_Z) < 2.2 \times 10^{-3}$$

$$-1.4 \times 10^{-3} < \bar{c}_W(m_Z) + \bar{c}_B(m_Z) < 1.9 \times 10^{-3}$$

$$-0.02 < \bar{c}_{Hq1} < 0.03 \quad -0.002 < \bar{c}'_{Hq1} < 0.003$$

$$-0.003 < \bar{c}_{Hq2} < 0.005 \quad -0.003 < \bar{c}'_{Hq2} < 0.005$$

$$-0.008 < \bar{c}_{Hu} < 0.02 \quad -0.03 < \bar{c}_{Hd} < 0.02 \quad -0.03 < \bar{c}_{Hs} < 0.02$$

$$-0.0002 < \bar{c}_{HL} + \bar{c}'_{HL} < 0.003 \quad -0.002 < \bar{c}_{HL} - \bar{c}'_{HL} < 0.004$$

$$-0.005 < \bar{c}_{Hq_2} - \bar{c}'_{Hq_2} < 0.02 \quad -0.009 < \bar{c}_{Hq_3} + \bar{c}'_{Hq_3} < 0.003$$

$$-0.02 < \bar{c}_{Hc} < 0.03 \quad -0.07 < \bar{c}_{Hb} < -0.005 \quad -0.0007 < \bar{c}_{Hl} < 0.003$$

$$-0.4 \times 10^{-3} < \bar{c}_{Htb}(m_W) < 1.3 \times 10^{-3}$$

Bounds on flavour-preserving operators

95% of probability

$$-7.01\times10^{-6} < \mathrm{Im}(\bar{c}_{uB}+\bar{c}_{uW}) < 7.86\times10^{-6}$$

$$-1.62\times10^{-6} < \mathrm{Im}(\bar{c}_{uG}) < 2.01\times10^{-6}$$

$$-9.42\times10^{-7} < \mathrm{Im}(\bar{c}_{dB}-\bar{c}_{dW}) < 8.40\times10^{-7}$$

$$-7.71\times10^{-7} < \mathrm{Im}(\bar{c}_{dG}) < 5.70\times10^{-7}$$

$$-1.39\times10^{-4} < \mathrm{Im}(\bar{c}_{tG}) < 1.21\times10^{-4}$$

$$-0.057 < \mathrm{Re}(\bar{c}_{tW}+\bar{c}_{tB}) - 2.65\,\mathrm{Im}(\bar{c}_{tW}+\bar{c}_{tB}) < 0.20$$

$$-6.12\times10^{-3} < \mathrm{Re}(\bar{c}_{tG}) < 1.94\times10^{-3}$$

$$-1.2 < \mathrm{Re}(\bar{c}_{bW}) < 1.1\,, \qquad -0.01 < \mathrm{Re}(\bar{c}_{tW}) < 0.02$$

eHDECAY

http://www-itp.particle.uni-karlsruhe.de/~maggie/eHDECAY/

- It has been obtained from extending HDECAY 5.10
- It allows for the calculation of the partial decay widths and branching ratios of the Higgs boson according to the effective Higgs Lagrangian
- QCD and EW higher order contributions are consistently included
- The non-linear extension of the effective Lagrangian is included, as well as the specific models MCHM4 and MCHM5.

Conclusions

- We have reviewed the construction of the effective Lagrangian for a light Higgs doublet.
- By means of a naive power counting we have estimated the coefficients of the various operators.
- This analysis allows one to identify which operators can probe the Higgs coupling strength to the new states and which instead are sensitive only to the mass scale M.
- It also gives the possibility to distinguish between weakly- coupled UV completions of the Standard Model (like SUSY) and theories where the EW symmetry is broken by a strongly-interacting dynamics which forms the Higgs boson as a bound state.
- We have shown the most important bounds set on them by present experimental results on electroweak (EW) and flavor observables.
- We have presented the program eHDECAY, an extension of HDECAY which allows for the calculation of the Higgs branching ratios according to the effective Higgs Lagrangian.