eHDECAY:
an Implementation of the Higgs Effective Lagrangian into HDECAY

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eHDECAY

http://www.itp.kit.edu/~maggie/eHDECAY/

- It has been obtained from extending HDECAY 5.10
- Fortran program for the calculation of the partial decay widths and branching ratios of the Higgs boson according to the Higgs effective Lagrangian
- QCD and EW higher order contributions are consistently included
- Included parametrizations are:
  - Effective Lagrangian for a light Higgs-like scalar (non-linear σ-model)
  - Effective Lagrangian for a light Higgs weak doublet (Strongly-Interacting Light Higgs Lagrangian)
  - Benchmark Composite Higgs Models: MCHM4 and MCHM5

General Lagrangian for a light Higgs-like scalar

Assumptions:

- CP is conserved
- vector fields couple to conserved currents

$$
\begin{aligned}
\mathcal{L} = & \frac{1}{2}\partial_\mu h\, \partial^\mu h - \frac{1}{2}m_h^2 h^2 - c_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right) h^3 - \sum_{\psi=u,d,l} m_{\psi^{(i)}}\, \bar{\psi}^{(i)}\psi^{(i)} \left(1 + c_\psi \frac{h}{v} + c_{\psi 2}\frac{h^2}{v^2} + \dots\right) \\
& + m_W^2\, W_\mu^+ W^{-\,\mu}\left(1 + 2c_W \frac{h}{v} + c_{W2}\frac{h^2}{v^2} + \dots\right) + \frac{1}{2}m_Z^2\, Z_\mu Z^\mu \left(1 + 2c_Z + c_{Z2}\frac{h^2}{v^2}\frac{h}{v} + \dots\right) + \dots \\
& + \left(c_{WW}\, W_{\mu\nu}^+ W^{-\mu\nu} + \frac{c_{ZZ}}{2} Z_{\mu\nu}Z^{\mu\nu} + c_{Z\gamma}\, Z_{\mu\nu}\gamma^{\mu\nu} + \frac{c_{\gamma\gamma}}{2}\gamma_{\mu\nu}\gamma^{\mu\nu} + \frac{c_{gg}}{2} G_{\mu\nu}^a G^{a\mu\nu}\right)\frac{h}{v} \\
& + \left(\left(c_{W\partial W}\, W_\nu^- D_\mu W^{+\mu\nu} + h.c.\right) + c_{Z\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + c_{Z\partial\gamma}\, Z_\nu\partial_\mu\gamma^{\mu\nu}\right)\frac{h}{v} + \dots
\end{aligned}
$$

(unitary gauge)

Standard Model

- $c_3 = c_\psi = c_W = c_Z = 1 \qquad c_\psi 2 = c_{W2} = c_{Z2} = 0$
- $c_{WW} = c_{ZZ} = c_{Z\gamma} = c_{gg} = c_{W\partial W} = c_{Z\partial Z} = c_{Z\partial\gamma} = 0$

Contino, Grojean, Moretti, Piccinini and Rattazzi, JHEP 05 (2010) 089
Alonso, Gavela, Merlo, Rigolin and Yepes, Phys.Lett. B722 (2013) 330
Contino, MG, Grojean, Mühlleitner and Spira, JHEP 1307 (2013) 035
Buchalla, Catà and Krause, Nucl.Phys. B880 (2014) 552

Minimal Composite Higgs Models

$$SO(5) \xrightarrow{f} SO(4) \xrightarrow{v} SO(3) \quad \text{(custodial symmetry)}$$

1 free parameter: $\xi \equiv \frac{v^2}{f^2} \in [0,1]$ $\qquad f \equiv \frac{M}{g_*}$

- MCHM4: spinorial representation

$$c_V = c_\psi = c_3 = \sqrt{1-\xi}, \qquad c_{V2} = 1 - 2\xi, \qquad c_{\psi 2} = -\frac{\xi}{2}$$

- MCHM5: fundamental representation

$$c_V = \sqrt{1-\xi}, \quad c_{V2} = 1 - 2\xi, \quad c_\psi = c_3 = \frac{1-2\xi}{\sqrt{1-\xi}}, \quad c_{\psi 2} = -2\xi$$

Agashe, Contino and Pomarol, Nucl. Phys. B 719 (2005) 165
Contino, Da Rold and Pomarol, Phys. Rev. D 75 (2007) 055014

Effective Lagrangian for a Higgs doublet

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \bar{c}_i O_i \equiv \mathcal{L}_{SM} + \Delta\mathcal{L}_{SILH} + \Delta\mathcal{L}_{F_1} + \Delta\mathcal{L}_{F_2} + \Delta\mathcal{L}_{V} + \Delta\mathcal{L}_{4F}$$

$$\Delta\mathcal{L}_{SILH} = \frac{\bar{c}_H}{2v^2}\,\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \boxed{\frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)} - \frac{\bar{c}_6\,\lambda}{v^2}\left(H^\dagger H\right)^3$$

$$+ \left(\frac{\bar{c}_u}{v^2}\, y_u\, H^\dagger H\, \bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\, y_d\, H^\dagger H\, \bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\, y_l\, H^\dagger H\, \bar{L}_L H l_R + h.c.\right)$$

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

$$+ \frac{i\bar{c}_{HW}\, g}{m_W^2}\left(D^\mu H\right)^\dagger \sigma^i \left(D^\nu H\right) W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\, g'}{m_W^2}\left(D^\mu H\right)^\dagger \left(D^\nu H\right) B_{\mu\nu}$$

$$+ \frac{\bar{c}_\gamma\, g'^2}{m_W^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_g\, g_S^2}{m_W^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$$

flavour alignment

Expansion at the first order in $\frac{v^2}{f^2} \ll 1$

Buchmüller and Wyler, NPB 268 (1986) 621
Giudice, Grojean, Pomarol and Rattazzi, JHEP 0706 (2007) 045
Grzadkowski, Iskrzynski, Misiak and Rosiek, JHEP 1010 (2010) 085
Contino, MG, Grojean, Mühlleitner and Spira, JHEP 1307 (2013) 035

Higgs couplings	$\Delta\mathcal{L}_{SILH}$	MCHM4	MCHM5
c_W	$1-\bar{c}_H/2$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
c_Z	$1-\bar{c}_H/2-\bar{c}_T$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
$c_\psi \;\; (\psi = u, d, l)$	$1-(\bar{c}_H/2+\bar{c}_\psi)$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
c_3	$1+\bar{c}_6-3\bar{c}_H/2$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
c_{gg}	$8\,(\alpha_s/\alpha_2)\,\bar{c}_g$	0	0
$c_{\gamma\gamma}$	$8\sin^2\theta_W\,\bar{c}_\gamma$	0	0

NLO corrections

Beyond the tree level:

- Short-distance corrections:

  RG evolution - not included in eHDECAY for the $\bar{c}_i$

  The input values $\bar{c}_i$ must be given at the low-energy scale $\mu^2 = m_h^2$

- Long-distance corrections:

  multiple perturbative expansion

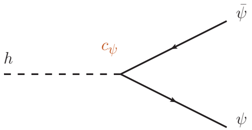
- QCD corrections:

  they generally factorize with respect to the expansion in the number of fields and derivatives

Multiple perturbative expansion: $\frac{\alpha_{SM}}{4\pi}$, $\frac{E}{M}$, $\frac{v^2}{f^2}$

A simple example: $h \to \bar{\psi}\psi$

General case:



Coupling rescaled by

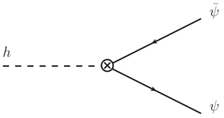
$$c_\psi = 1 + \delta c_\psi$$

- QCD: the same as in the SM ✓
- EW: not factorized X

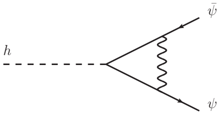
$$\Gamma(\bar{\psi}\psi)\big|_{NL} = c_\psi^2 \, \Gamma_0^{SM}(\bar{\psi}\psi)\left[1 + \delta_\psi\, \kappa^{QCD}\right] \qquad \delta_\psi = \begin{cases} 1 & \psi = \text{quark} \\ 0 & \psi = \text{lepton} \end{cases}$$

SILH case (Higgs doublet close to the SM):

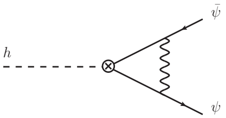
Perturbative expansion in $\frac{v^2}{f^2}$ and $\frac{\alpha_2}{4\pi}$



$\mathcal{O}\left(\frac{v^2}{f^2}\right)$ ✓



$\mathcal{O}\left(\frac{\alpha_2}{4\pi}\right)$ ✓

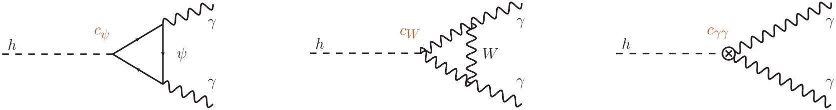


$\mathcal{O}\left(\frac{\alpha_2}{4\pi}\frac{v^2}{f^2}\right)$ X

$$\Gamma(\bar{\psi}\psi)\big|_{SILH} = \Gamma_0^{SM}(\bar{\psi}\psi)\left[1 - \bar{c}_H - 2\bar{c}_\psi + \frac{2}{|A_0^{SM}|^2}\mathrm{Re}\left(A_0^{*SM} A_{1,ew}^{SM}\right)\right]\left[1 + \delta_\psi\,\kappa^{QCD}\right]$$

A loop-process example: $h \to \gamma\gamma$

General case:



$$\Gamma(\gamma\gamma)\big|_{NL} = \frac{G_F \alpha_{em}^2 m_h^3}{128\sqrt{2}\pi^3} \left| \sum_{q=t,b,c} \frac{4}{3} c_q\, 3 Q_q^2\, A_{1/2}^{QCD\,NLO}(\tau_q) + \frac{4}{3} c_\tau\, Q_\tau^2 A_{1/2}(\tau_\tau) + c_W A_1(\tau_W) + \frac{4\pi}{\alpha_{em}} c_{\gamma\gamma} \right|^2$$

QCD corrections: $A_{1/2}^{QCD\,NLO}(\tau_q) = A_{1/2}(\tau_q)(1+\kappa_{QCD})$

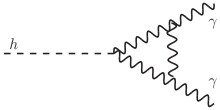
EW corrections: not factorized and not available

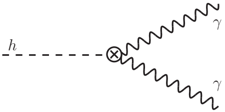
A loop-process example: $h \to \gamma\gamma$

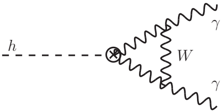
SILH case:

$$\Gamma(\gamma\gamma)\big|_{SILH} = \frac{G_F \alpha_{em}^2 m_h^3}{128\sqrt{2}\pi^3} \Bigg\{ |A^{SM}_{QCD\ NLO}(\gamma\gamma)|^2 + 2\,\mathrm{Re}\Big(A^{SM*}_{QCD\ LO}(\gamma\gamma)\, A^{SM}_{ew}(\gamma\gamma)\Big) + 2\,\mathrm{Re}\left[A^{SM*}_{QCD\ NLO}(\gamma\gamma)\left(\Delta A(\gamma\gamma) + \frac{32\pi \sin^2\theta_W\, \bar{c}_\gamma}{\alpha_{em}}\right)\right] \Bigg\}$$

- $A^{SM}_{QCD\ NLO} \sim A^{SM}_{LO}\left[1 + \mathcal{O}\left(\frac{\alpha_S}{4\pi}\right)\right]$
- $A^{SM}_{ew} \sim \mathcal{O}\left(\frac{\alpha_2}{4\pi}\right)$
- $\left(\Delta A(\gamma\gamma) + \frac{32\pi \sin^2\theta_W\, \bar{c}_\gamma}{\alpha_{em}}\right) \sim \mathcal{O}\left(\frac{v^2}{f^2}\right)$







Approximated formulas

Higgs decays into vector bosons

$$\frac{\Gamma(h\to W^{(*)}W^{*})}{\Gamma(h\to W^{(*)}W^{*})_{SM}} \simeq 1-\bar{c}_H+2.2\,\bar{c}_W+3.7\,\bar{c}_{HW}\,,$$

$$\frac{\Gamma(h\to Z^{(*)}Z^{*})}{\Gamma(h\to Z^{(*)}Z^{*})_{SM}} \simeq 1-\bar{c}_H+2.0\,\left(\bar{c}_W+\tan^2\theta_W\,\bar{c}_B\right)+3.0\,\left(\bar{c}_{HW}+\tan^2\theta_W\,\bar{c}_{HB}\right)-0.26\,\bar{c}_\gamma\,,$$

$$\frac{\Gamma(h\to Z\gamma)}{\Gamma(h\to Z\gamma)_{SM}} \simeq 1-\bar{c}_H+0.12\,\bar{c}_t-5\cdot 10^{-4}\,\bar{c}_c-0.003\,\bar{c}_b-9\cdot 10^{-5}\,\bar{c}_\tau$$
$$+4.2\,\bar{c}_W+0.19\,\left(\bar{c}_{HW}-\bar{c}_{HB}+8\,\bar{c}_\gamma\,\sin^2\theta_W\right)\frac{4\pi}{\sqrt{\alpha_2\alpha_{em}}}\,,$$

$$\frac{\Gamma(h\to\gamma\gamma)}{\Gamma(h\to\gamma\gamma)_{SM}} \simeq 1-\bar{c}_H+0.54\,\bar{c}_t-0.003\,\bar{c}_c-0.007\,\bar{c}_b-0.007\,\bar{c}_\tau+5.04\,\bar{c}_W-0.54\,\bar{c}_\gamma\,\frac{4\pi}{\alpha_{em}}\,,$$

$$\frac{\Gamma(h\to gg)}{\Gamma(h\to gg)_{SM}} \simeq 1-\bar{c}_H-2.12\,\bar{c}_t+0.024\,\bar{c}_c+0.1\,\bar{c}_b+22.2\,\bar{c}_g\,\frac{4\pi}{\alpha_2}\,.$$

$$\alpha_2\equiv\frac{\sqrt{2}G_F m_W^2}{\pi}\qquad\qquad \alpha_{em}\equiv\alpha_{em}(q^2=0)$$

Conclusions

- We have presented eHDECAY, a numerical program for the calculation of the Higgs branching ratios according to the Higgs effective Lagrangian.
- Parametrizations included:
  - General non-linear effective Lagrangian
  - Efffective Lagrangian for a weak Higgs doublet
  - Minimal Composite Higgs Models MCHM4 and MCHM5
- QCD corrections are included
- EW corrections are included in the SILH case, according to the multiple perturbative expansion
- Enjoy eHDECAY!

Thanks for your attention!