HEFT BASIS OVERVIEW

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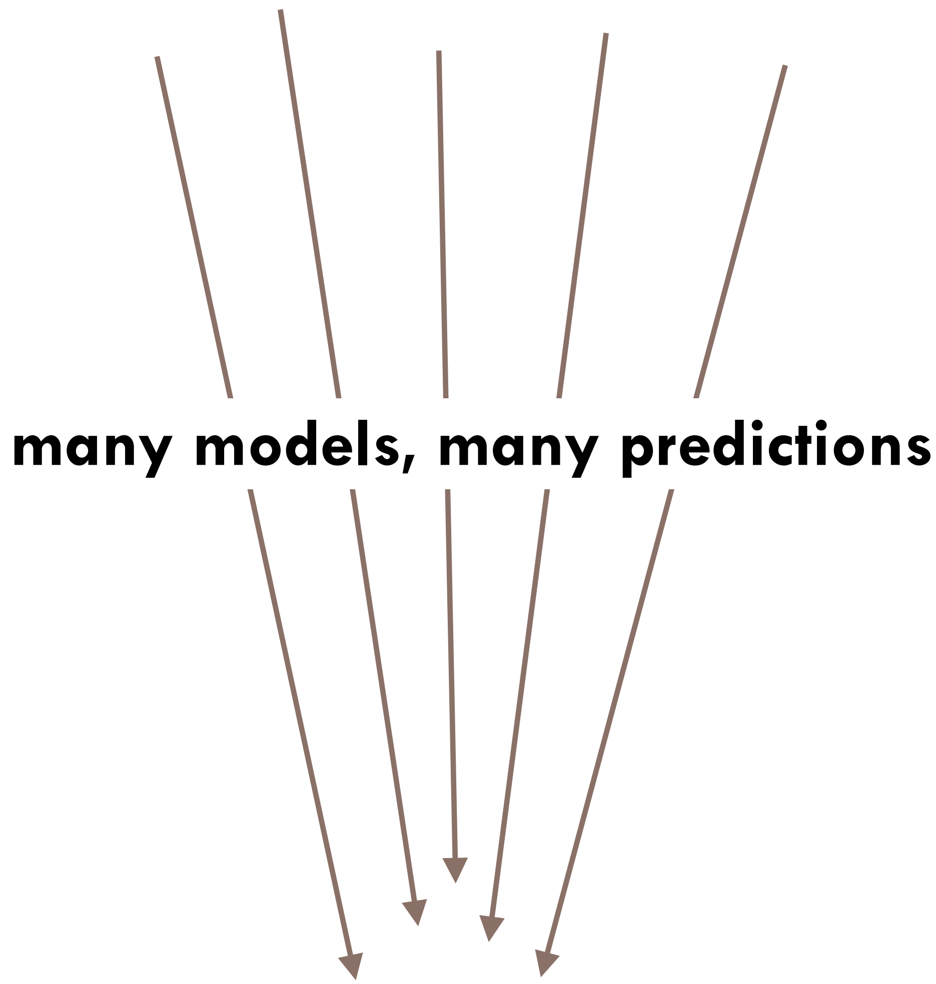
Higgs (N)NLO MC and Tools Workshop for LHC RUN-2, December 17-19, 2014

UV dynamics (BSM models)

Experiments

(performed at "low" energies)

UV dynamics (BSM models)



Experiments

(performed at “low” energies)

UV dynamics (BSM models)

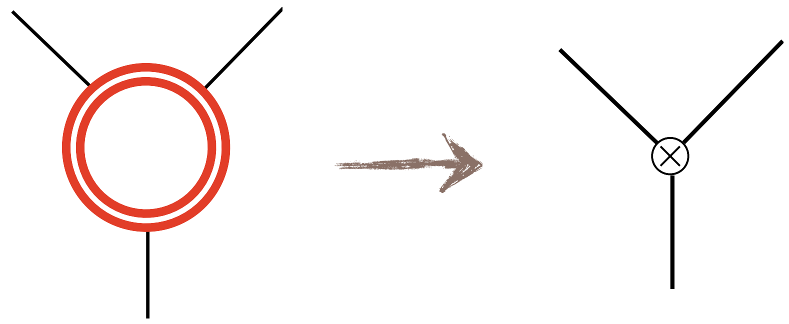
Effective field theory description

Experiments

(performed at “low” energies)

- At energies $E \ll m_*$, NP effects are well approximated by local operators

$$\mathcal{L} = \sum_i \bar{c}_i \, O_i(x)$$



Operators "generated" at m_* with coefficients

$$\bar{c}_i(m_*) \sim \left(\frac{1}{m_*}\right)^{d[O]-4}$$

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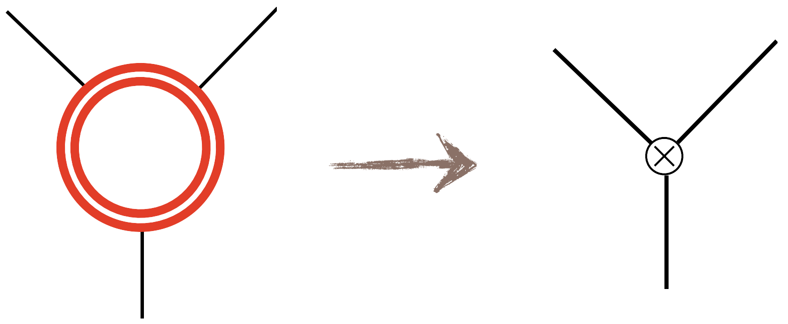

Operators "generated" at m_* with coefficients

$$\bar{c}_i(m_*) \sim \left(\frac{1}{m_*}\right)^{d[O]-4}$$

Assumptions:

1. There is a <u>gap</u> between the NP scale m_* and m_h

2. The new boson is part of an $SU(2)_L$ doublet

$$H = e^{i\pi/v} \begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

Effective Lagrangian for a Higgs doublet

(1 fermion generation)

- Operators can be classified according to their dimension

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \bar{c}_i O_i \equiv \mathcal{L}_{SM} + \Delta\mathcal{L}^{(6)} + \Delta\mathcal{L}^{(8)} + \dots$$

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Leading effects from dim-6 operators

59 independent operators for 1 SM family

Buchmuller and Wyler NPB 268 (1986) 621

⋮

Grzadkowski et al. JHEP 1010 (2010) 085

For a review see:
RC, Ghezzi, Grojean, Muhlleitner, Spira JHEP 1307 (2013) 035

Effective Lagrangian for a Higgs doublet

(1 fermion generation)

$$\Delta\mathcal{L}^{(6)} = \Delta\mathcal{L}_{SILH} + \Delta\mathcal{L}_{cc} + \Delta\mathcal{L}_{dipole} + \Delta\mathcal{L}_{V} + +\Delta\mathcal{L}_{4\psi}$$

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16 operators

(12 CP even, 4 CP odd)

SILH operators

Giudice, Grojean, Pomarol, Rattazzi JHEP 0706 (2007) 045

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

Effective Lagrangian for a Higgs doublet

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$$\Delta\mathcal{L}^{(6)} = \Delta\mathcal{L}_{SILH} + \Delta\mathcal{L}_{cc} + \Delta\mathcal{L}_{dipole} + \Delta\mathcal{L}_{V} + +\Delta\mathcal{L}_{4\psi}$$

6 current-current operators

$$\Delta\mathcal{L}_{cc} = \frac{i\bar{c}_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu q_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}'_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu\sigma^i q_L\right)\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right)$$

$$+ \frac{i\bar{c}_{Hu}}{v^2}\left(\bar{u}_R\gamma^\mu u_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}_{Hd}}{v^2}\left(\bar{d}_R\gamma^\mu d_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)$$

$$+ \left(\frac{i\bar{c}_{Hud}}{v^2}\left(\bar{u}_R\gamma^\mu d_R\right)\left(H^{c\,\dagger} \overleftrightarrow{D}_\mu H\right) + h.c.\right)$$

$$+ \frac{i\bar{c}_{HL}}{v^2}\left(\bar{L}_L\gamma^\mu L_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)$$

<u>Notice</u>: two additional operators, O'_{HL} and O_{Hl} , are not independent w.r.t. those in $\Delta\mathcal{L}_{SILH}$

$$O'_{HL} = \left(\bar{L}_L\gamma^\mu\sigma^i L_L\right)\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right)$$

$$O_{Hl} = \left(\bar{l}_R\gamma^\mu l_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)$$

Effective Lagrangian for a Higgs doublet

(1 fermion generation)

$$\Delta\mathcal{L}^{(6)} = \Delta\mathcal{L}_{SILH} + \Delta\mathcal{L}_{cc} + \Delta\mathcal{L}_{dipole} + \Delta\mathcal{L}_{V} + + \Delta\mathcal{L}_{4\psi}$$

8 dipole operators

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

Effective Lagrangian for a Higgs doublet

(1 fermion generation)

$$\Delta\mathcal{L}^{(6)} = \Delta\mathcal{L}_{SILH} + \Delta\mathcal{L}_{cc} + \Delta\mathcal{L}_{dipole} + \Delta\mathcal{L}_{V} + +\Delta\mathcal{L}_{4\psi}$$

7 operators built with gauge fields only

(5 CP even, 2 CP odd)

$$\Delta\mathcal{L}_V = \frac{\bar{c}_{2W}}{m_W^2}\left(D^\mu W_{\mu\nu}\right)^i\left(D_\rho W^{\rho\nu}\right)^i + \frac{\bar{c}_{2B}}{m_W^2}\left(\partial^\mu B_{\mu\nu}\right)\left(\partial_\rho B^{\rho\nu}\right) + \frac{\bar{c}_{2G}}{m_W^2}\left(D^\mu G_{\mu\nu}\right)^a\left(D_\rho G^{\rho\nu}\right)^a$$
$$+ \frac{\bar{c}_{3W}\, g^3}{m_W^2}\,\epsilon^{ijk} W_{\mu}^{i\,\nu} W_{\nu}^{j\,\rho} W_{\rho}^{k\,\mu} + \frac{\bar{c}_{3G}\, g_S^3}{m_W^2}\, f^{abc} G_{\mu}^{a\,\nu} G_{\nu}^{b\,\rho} G_{\rho}^{c\,\mu}$$
$$+ \frac{\tilde{c}_{3W}\, g^3}{m_W^2}\,\epsilon^{ijk} W_{\mu}^{i\,\nu} W_{\nu}^{j\,\rho} \tilde{W}_{\rho}^{k\,\mu} + \frac{\tilde{c}_{3G}\, g_S^3}{m_W^2}\, f^{abc} G_{\mu}^{a\,\nu} G_{\nu}^{b\,\rho} \tilde{G}_{\rho}^{c\,\mu}$$

Effective Lagrangian for a Higgs doublet

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22 four-fermion operators

7 operators built with gauge fields only

(5 CP even, 2 CP odd)

$$\Delta\mathcal{L}_V = \frac{\bar{c}_{2W}}{m_W^2}\left(D^\mu W_{\mu\nu}\right)^i\left(D_\rho W^{\rho\nu}\right)^i + \frac{\bar{c}_{2B}}{m_W^2}\left(\partial^\mu B_{\mu\nu}\right)\left(\partial_\rho B^{\rho\nu}\right) + \frac{\bar{c}_{2G}}{m_W^2}\left(D^\mu G_{\mu\nu}\right)^a\left(D_\rho G^{\rho\nu}\right)^a$$
$$+ \frac{\bar{c}_{3W}\, g^3}{m_W^2}\,\epsilon^{ijk}W_\mu^{i\,\nu}W_\nu^{j\,\rho}W_\rho^{k\,\mu} + \frac{\bar{c}_{3G}\, g_S^3}{m_W^2}\, f^{abc}G_\mu^{a\,\nu}G_\nu^{b\,\rho}G_\rho^{c\,\mu}$$
$$+ \frac{\tilde{c}_{3W}\, g^3}{m_W^2}\,\epsilon^{ijk}W_\mu^{i\,\nu}W_\nu^{j\,\rho}\tilde{W}_\rho^{k\,\mu} + \frac{\tilde{c}_{3G}\, g_S^3}{m_W^2}\, f^{abc}G_\mu^{a\,\nu}G_\nu^{b\,\rho}\tilde{G}_\rho^{c\,\mu}$$

SILH basis vs Warsaw basis

SILH basis
JHEP 0706 (2007) 045

$$\left\{O_W, O_B, O_{HW}, O_{HB}\right\}$$

basis of Grzadkowski et al.
JHEP 1010 (2010) 085

$$\left\{O_{WW}, O_{WB}, O'_{HL}, O_{Hl}\right\}$$

$$O_W + O_B = 2\tan^2\theta_W\left(-O_T + O^Y_{H\Psi}\right) + O'_{Hq} + O'_{HL} + [\ldots]$$

$$O_W - O_B = 2\tan^2\theta_W\left(-O_T + O^Y_{H\Psi}\right) - O'_{Hq} - O'_{HL} - [\ldots]$$

$$O_{HW} = O'_{HL} + O'_{Hq} - O_{WB} - O_{WW} + [\ldots]$$

$$O_{HB} = 2\tan^2\theta_W\left(-O_T + O^Y_{H\Psi}\right) - O_{WB} - \frac{1}{4}O_\gamma$$

$$O_{WW} = \frac{g^2}{4m_W^2}\, H^\dagger H\, W^i_{\mu\nu} W^{i\,\mu\nu}$$

$$O_{WB} = \frac{gg'}{4m_W^2}\, H^\dagger \sigma^i H\, W^i_{\mu\nu} B^{\mu\nu}$$

$$O^Y_{H\Psi} \equiv \frac{1}{6}O_{Hq} + \frac{2}{3}O_{Hu} - \frac{1}{3}O_{Hd} + \frac{1}{2}O_{HL} - O_{Hl}$$

$$[\ldots] = 2\,(O_u + O_d + O_l + h.c.) - 6\,O_H - 8\,O_6$$

does not contribute to 0-Higgs processes

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$$\left\{O_{WW}, O_{WB}, O'_{HL}, O_{Hl}\right\}$$

constrained by LEP at 10^{-3} level (parameter ϵ_3) →

$$O_W + O_B = 2\tan^2\theta_W\left(-O_T + O^Y_{H\Psi}\right) + O'_{Hq} + O'_{HL} + [\dots]$$

two combinations constrained by TGC at 10^{-2} level, third one bounded only by $h \to Z\gamma$ →

$$O_W - O_B = 2\tan^2\theta_W\left(-O_T + O^Y_{H\Psi}\right) - O'_{Hq} - O'_{HL} - [\dots]$$

$$O_{HW} = O'_{HL} + O'_{Hq} - O_{WB} - O_{WW} + [\dots]$$

$$O_{HB} = 2\tan^2\theta_W\left(-O_T + O^Y_{H\Psi}\right) - O_{WB} - \frac{1}{4}O_\gamma$$

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- the most convenient basis is the one which more easily encodes the largest UV effects and matches with the experimental observables

Estimating the coefficients at m_* : the SILH power counting

Giudice et al. JHEP 0706 (2007) 045

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Assumption:

the UV physics is broadly characterized by 1 scale (m_*) and 1 coupling strength (g_*)

Estimating the coefficients at m_* : the SIHL power counting

Giudice et al. JHEP 0706 (2007) 045

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- each extra (covariant) derivative costs a factor $\dfrac{1}{m_*}$
- each extra power of H(x) costs a factor $\dfrac{g_*}{m_*} \equiv \dfrac{1}{f}$

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For a strongly-interacting light Higgs (SILH):

$$g_* \gg 1 \quad \Rightarrow \quad \frac{1}{f} \gg \frac{1}{m_*}$$

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For a strongly-interacting light Higgs (SILH):

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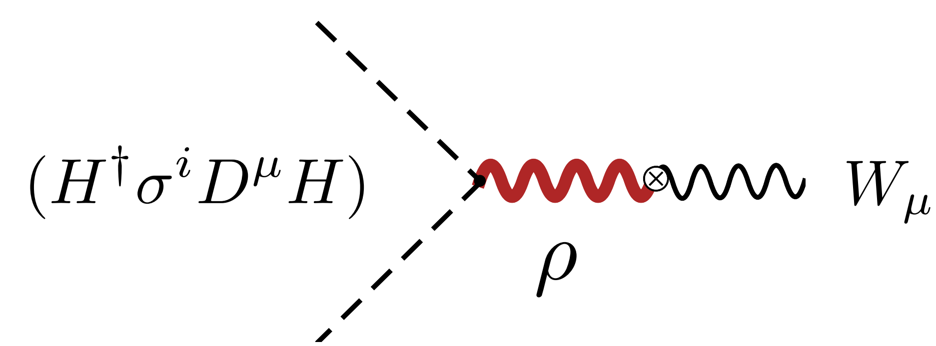
Example:

$$O_W = \frac{ig}{2m_W^2} \left(H^\dagger \sigma^i D^\mu H\right) \left(D^\nu W_{\mu\nu}\right)^i$$

$$\bar{c}_W \sim \left(\frac{m_W^2}{m_*^2}\right)$$



Secondary Assumptions:

1. The UV physics is minimally coupled

True for some of the popular models (e.g. weakly-coupled SUSY, holographic Higgs), but not necessarily so in more general contexts

see for example: Jenkins, Manohar, Trott JHEP 1309 (2013) 063

☞ operators generated at loop level suppressed by $(g_*^2/16\pi^2)$

ex: dipole operators

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ex: dipole operators

2. (light) SM fermions are weakly coupled to the UV dynamics

Equivalent to assuming "universality" of NP effects, easier to comply with LEP

☞ current-current operators subdominant

$$\sim \frac{1}{f^2}$$

$$\partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H)$$

$$\bar{\psi} H \psi \, (H^\dagger H)$$

$$(H^\dagger H)^3$$

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$$\sim \frac{1}{m_*^2}$$

$$\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right) (D^\nu W_{\mu\nu})^i \,, \qquad \left(H^\dagger \overleftrightarrow{D^\mu} H\right) (\partial^\nu B_{\mu\nu})$$

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$$B_{\mu\nu} B^{\mu\nu} \, H^\dagger H \,, \qquad G_{\mu\nu} G^{\mu\nu} \, H^\dagger H$$

$$(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} \,, \qquad (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$F_{\mu\nu} \, \bar{\psi} \sigma^{\mu\nu} H \psi$$

$$\sim \frac{1}{f^2}$$

$$\partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H)$$

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$$\sim \frac{1}{m_*^2} \times \left(\frac{\lambda^2}{g_*^2} \right)$$

$$(H^\dagger D_\mu H)(\bar{\psi} \gamma^\mu \psi)$$

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$$\partial_\mu (H^\dagger H)\partial^\mu (H^\dagger H)$$

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Leading effects

$$\sim \frac{1}{m_*^2}$$

$$\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i\,, \qquad \left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})$$

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Strongly constrained by LEP

$$\sim \frac{1}{m_*^2} \times \left(\frac{g_*^2}{16\pi^2} \right)$$

$$B_{\mu\nu} B^{\mu\nu} \, H^\dagger H \,, \qquad G_{\mu\nu} G^{\mu\nu} \, H^\dagger H$$

$$(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} \,, \qquad (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$F_{\mu\nu} \, \bar{\psi} \sigma^{\mu\nu} H \psi$$

$$\sim \frac{1}{m_*^2} \times \left(\frac{\lambda^2}{g_*^2} \right)$$

$$(H^\dagger D_\mu H)(\bar{\psi} \gamma^\mu \psi)$$

$\sim \frac{1}{f^2}$

$\partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H)$

$\bar{\psi} H \psi \, (H^\dagger H)$

$(H^\dagger H)^3$

Leading effects

$\sim \frac{1}{m_*^2}$

$\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right) (D^\nu W_{\mu\nu})^i \,, \qquad \left(H^\dagger \overleftrightarrow{D^\mu} H\right) (\partial^\nu B_{\mu\nu})$

Strongly constrained by LEP

$\sim \frac{1}{m_*^2} \times \left(\frac{g_*^2}{16\pi^2}\right)$

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(compete with SM at 1-loop)

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- Add flavor indices to all operators

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Ex: flavor alignment in O_ψ $\qquad \dfrac{(\bar{c}_\psi)_i}{v^2} (y_\psi)_{ij} \; H^\dagger H \, \bar{\psi}^i_L H \psi^j_R$

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- Some constraints much weaker on third generation operators

  Ex: dipole operators

Operators that affect Higgs physics only

Elias-Miro, Espinosa, Masso, Pomarol JHEP 1311 (2013) 066

Pomarol, Riva JHEP 01 (2014) 151

$$O_H = (\partial_\mu |H|^2)^2$$

$$O_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$

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$$O_6 = \lambda |H|^6$$

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notice: $$\frac{g^2}{4m_W^2} H^\dagger H \, W^i_{\mu\nu} W^{i\,\mu\nu} \equiv O_{WW} = O_W - O_B + O_{HB} - O_{HW} + \frac{1}{4} O_\gamma$$

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modify inclusive rates and differential distributions (constrained by fit to Higgs couplings)

$$O_{y_d} = y_d |H|^2 \bar{q}_L H d_R$$

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shift $h\psi\psi$

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$gg \to hh$ yet un-probed

$+$ other 3 CP odd

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Modified SILH basis

Elias-Miro, Espinosa, Masso, Pomarol JHEP 1311 (2013) 066

Higgs Physics Only	
$\mathcal{O}_H = [\partial_\mu(H^\dagger H)]^2$	1
$\mathcal{O}_{BB} = \frac{g'^2}{4}\lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$	2
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$\mathcal{O}_{y_u} = y_u\lvert H\rvert^2\bar{Q}_L\widetilde{H}u_R$	1
$\mathcal{O}_{y_d} = y_d\lvert H\rvert^2\bar{Q}_L H d_R$	1
$\mathcal{O}_{y_e} = y_e\lvert H\rvert^2\bar{L}_L H e_R$	1
$\mathcal{O}_6 = \lambda\lvert H\rvert^6$	1

EW and Higgs Physics	
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$	2
$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$	2
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$	2
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	1
$\mathcal{O}_{Hu} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$	1
$\mathcal{O}_{Hd} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$	1
$\mathcal{O}_{He} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$	1
$\mathcal{O}_{HQ} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L)$	1
$\mathcal{O}'_{HQ} = (iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L\sigma^a\gamma^\mu Q_L)$	1

Compared to SILH basis: $\mathcal{O}_{HW} \longrightarrow O_{WW}$

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$\mathcal{O}_W + \mathcal{O}_B$

Constrained by LEP

Compared to SILH basis: $\mathcal{O}_{HW} \longrightarrow O_{WW}$

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EW and Higgs Physics		
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$	2	$\mathcal{O}_W + \mathcal{O}_B$
$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$	2	$\mathcal{O}_W - \mathcal{O}_B$ TGC
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$	2	TGC, $h \to Z\gamma$
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	1	Constrained by LEP
$\mathcal{O}_{Hu} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$	1	Constrained by LEP
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Higgs Lagrangian in the unitary basis

- In the unitary gauge operators are written in terms of physical fields and physical vertices

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

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&+ m_W^2\, W_\mu^+ W^{-\,\mu} \left(1 + 2c_W \frac{h}{v} + \dots\right) + \frac{1}{2} m_Z^2\, Z_\mu Z^\mu \left(1 + 2c_Z \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(c_{W\partial W}\left(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
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- In fact, the same Lagrangian holds for a generic scalar h non necessarily part of an $SU(2)_L$ doublet (non-linear Lagrangian)

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$$+ m_W^2\, W_\mu^+ W^{-\,\mu} \left(1 + 2c_W\, \frac{h}{v} + \dots\right) + \frac{1}{2} m_Z^2\, Z_\mu Z^\mu \left(1 + 2c_Z\, \frac{h}{v} + \dots\right) + \dots$$

$$+ \left(c_{WW}\, W_{\mu\nu}^+ W^{-\mu\nu} + \frac{c_{ZZ}}{2}\, Z_{\mu\nu}Z^{\mu\nu} + c_{Z\gamma}\, Z_{\mu\nu}\gamma^{\mu\nu} + \frac{c_{\gamma\gamma}}{2}\, \gamma_{\mu\nu}\gamma^{\mu\nu} + \frac{c_{gg}}{2}\, G_{\mu\nu}^a G^{a\mu\nu}\right) \frac{h}{v}$$

$$+ \left(c_{W\partial W}\, \left(W_\nu^- D_\mu W^{+\mu\nu} + h.c.\right) + c_{Z\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + c_{Z\partial\gamma}\, Z_\nu \partial_\mu \gamma^{\mu\nu}\right) \frac{h}{v} + \dots$$

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- Equivalent to BSM Primaries of arXiv:1405.0181 (Gupta, Pomarol, Riva)

Higgs couplings	$\Delta\mathcal{L}_{SILH}$
c_W	$1 - \bar{c}_H/2$
c_Z	$1 - \bar{c}_H/2 - \bar{c}_T$
$c_\psi \;\; (\psi = u, d, l)$	$1 - (\bar{c}_H/2 + \bar{c}_\psi)$
c_3	$1 + \bar{c}_6 - 3\bar{c}_H/2$
c_{gg}	$8\,(\alpha_s/\alpha_2)\,\bar{c}_g$
$c_{\gamma\gamma}$	$8\sin^2\theta_W\,\bar{c}_\gamma$
$c_{Z\gamma}$	$\left(\bar{c}_{HB} - \bar{c}_{HW} - 8\,\bar{c}_\gamma \sin^2\theta_W\right)\tan\theta_W$
c_{WW}	$-2\,\bar{c}_{HW}$
c_{ZZ}	$-2\left(\bar{c}_{HW} + \bar{c}_{HB}\tan^2\theta_W - 4\bar{c}_\gamma \tan^2\theta_W \sin^2\theta_W\right)$
$c_{W\partial W}$	$-2(\bar{c}_W + \bar{c}_{HW})$
$c_{Z\partial Z}$	$-2(\bar{c}_W + \bar{c}_{HW}) - 2\,(\bar{c}_B + \bar{c}_{HB})\tan^2\theta_W$
$c_{Z\partial\gamma}$	$2\,(\bar{c}_B + \bar{c}_{HB} - \bar{c}_W - \bar{c}_{HW})\tan\theta_W$

from: RC, Ghezzi, Grojean, Muhlleitner, Spira JHEP 1307 (2013) 035

Implementing the Effective Lagrangian into software tools

- MC event generators

At least two FeynRules models implementing the Higgs Effective Lagrangian:

"Higgs Effective Lagrangian"

Alloul, Fuks, Sanz JHEP 1404 (2014) 110

http://feynrules.irmp.ucl.ac.be/wiki/HEL

"Higgs Characterization Model"

P. Artoisenet et al. JHEP 1311 (2013) 043

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- Higgs decay rates and BRs

eHDECAY [based on HDECAY v5.10]

RC, Ghezzi, Grojean, Muhlleitner, Spira arXiv:1403.3381

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

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eHDECAY [based on HDECAY v5.10] → implements the non-linear Lagrangian, the SILH basis and two Composite Higgs models

RC, Ghezzi, Grojean, Muhlleitner, Spira arXiv:1403.3381

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- Advantages of the SILH basis:

  - straightforward matching to popular UV models

  - easily matches to LEP observables

- Perhaps Lagrangian in the unitary basis (non-linear Lagrangian/BSM primaries) is the most convenient and general one. Easier connection to observables, does not assume Higgs in a doublet; not suitable for loop calculations though; correlations among processes must be input

Extra slides

	SILH basis	Modified SILH basis
TGC:	$O_{HW} + O_{HB}$	$O_{HB} - \frac{1}{2} O_{WW}$
	$(O_W - O_B) + (O_{HW} - O_{HB})$	$(O_W - O_B) - \frac{1}{2} O_{WW}$
	O_{3W}	O_{3W}
$h \to Z\gamma$	$O_{HW} - O_{HB}$	O_{WW}
	O_γ	O_γ

Radiative corrections

- QCD radiative corrections usually important, can be often derived (and re-summed) from SM calculations

Example: h→gg rate

[RC, Ghezzi, Grojean, Muhlleitner, Spira arXiv:1403.3381]

$$\Gamma(gg)\big|_{SILH} = \frac{G_F \alpha_s^2 m_h^3}{4\sqrt{2}\pi^3}\Bigg[\frac{1}{9}\sum_{q,q'=t,b,c}(1-\bar{c}_H-\bar{c}_q-\bar{c}_{q'})\,A^*_{1/2}(\tau_{q'})\,A_{1/2}(\tau_q)\;c^2_{eff}\,\kappa_{soft}$$
$$+2\,\mathrm{Re}\left(\sum_{q=t,b,c}\frac{1}{3}A^*_{1/2}(\tau_q)\,\frac{16\pi\,\bar{c}_g}{\alpha_2}\right)c_{eff}\,\kappa_{soft}$$
$$+\left|\sum_{q=t,b,c}\frac{1}{3}A_{1/2}(\tau_q)\right|^2 c^2_{eff}\,\kappa_{ew}\,\kappa_{soft}$$
$$+\frac{1}{9}\sum_{q,q'=t,b}(1-\bar{c}_H-\bar{c}_q-\bar{c}_{q'})A^*_{1/2}(\tau_q)\,A_{1/2}(\tau_{q'})\,\kappa^{NLO}(\tau_q,\tau_{q'})\Bigg].$$

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

- Inclusion of EW radiative corrections requires ad-hoc calculations. They are usually very small because α_W is small and $\log(\Lambda_{EW}/\Lambda_{UV})$ is also small (interesting case is one with big gap of scales, since NP effects scale like $1/\Lambda^2_{UV}$)

A closer look to eHDECAY

RC, Ghezzi, Grojean, Muhlleitner, Spira arXiv:1403.3381

$$\frac{\Gamma(\bar{\psi}\psi)}{\Gamma(\bar{\psi}\psi)_{SM}} \simeq 1 - \bar{c}_H - 2\,\bar{c}_\psi\,,$$

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

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

$$\frac{\Gamma(h\to Z\gamma)}{\Gamma(h\to Z\gamma)_{SM}} \simeq 1 - \bar{c}_H + 0.12\,\bar{c}_t - 5\cdot10^{-4}\,\bar{c}_c - 0.003\,\bar{c}_b - 9\cdot10^{-5}\,\bar{c}_\tau + 4.2\,\bar{c}_W + 0.19\left(\bar{c}_{HW} - \bar{c}_{HB} + 8\,\bar{c}_\gamma\sin^2\theta_W\right)\frac{4\pi}{\sqrt{\alpha_2\alpha_{em}}}\,,$$

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

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

$$\alpha_2 \equiv \frac{\sqrt{2}\,G_F m_W^2}{\pi}$$

$$\alpha_{em} \equiv \alpha_{em}(q^2=0)$$

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RC, Ghezzi, Grojean, Muhlleitner, Spira arXiv:1403.3381

- Decay rates computed by making a multiple perturbative expansion in (E/Λ), (v/f), $(\alpha_{SM}/4\pi)$

- QCD (long-distance) corrections factorize and can be easily included

- EW corrections do not factorize and can be included at $O(\alpha_2/4\pi)$, i.e. neglecting $O[(\alpha_2/4\pi)(v^2/f^2)]$

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

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QCD corrections

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EW corrections $O(\alpha_2/4\pi)$

QCD corrections