Implications of Non-Decoupling UV-Physics

– Higgs Effective Field Theories 2017, Lumley Castle –

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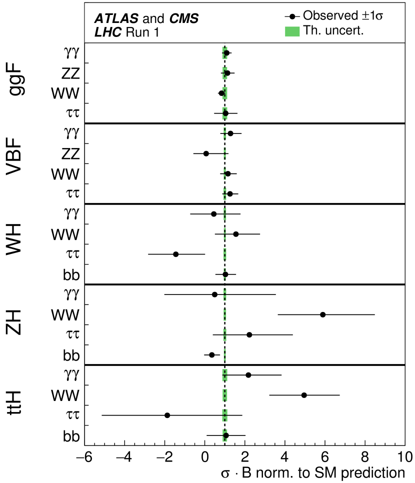
Universitat de València-CSIC

May 23, 2017

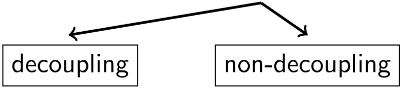
In collaboration with G. Buchalla, O. Catà, A. Celis, A. Pich, I. Rosell, J. Santos, and J. J. Sanz-Cillero

Where is the New Physics?



ATLAS & CMS [1606.02266]

- The LHC gave us the Higgs and nothing else.
- We use bottom-up EFTs.



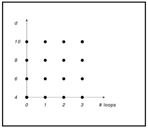
- SMEFT
- chiral Lagrangian

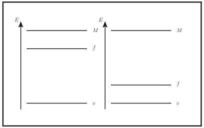
→ Fitting Wilson-coefficients

→ Gain intuition with UV-models

Implications of Non-Decoupling UV-Physics

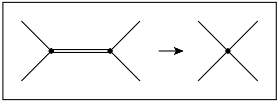
Part I: The Low-Energy Effective Field Theories
[1307.5017,1412.6356]

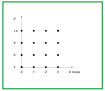




Part II: The SM Singlet Extension
[1608.03564]

Part III: Heavy Resonances
[1609.06659,17xx.xxxxx]

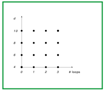




I: We distinguish 2 types of EFTs.

decoupling (linear) EFT:
– SMEFT –

- LO: SM
- Higgs is written as doublet ϕ
- expansion in canonical dimensions
- NLO is of dimension 6
  Buchmüller/Wyler ['86 Nucl. Phys. B], Grzadkowski et al. [1008.4884]



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– $ew\chi\mathcal{L}$ –

- LO: Higgs-less chiral Lagrangian + generic scalar h
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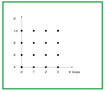
- expansion in loops (L) or chiral dimensions.
- NLO is of chiral order 4
  Buchalla/Catà/CK [1307.5017]



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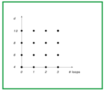
Chiral dimensions are a tool to find the loop order of an operator.

$$2L + 2 = [\text{couplings}]_\chi + [\text{derivatives}]_\chi + [\text{fields}]_\chi$$

Nyffeler/Schenk [hep-ph/9907294], Hirn/Stern [hep-ph/0401032], Buchalla/Catà/CK [1312.5624]

$$[\text{bosons}]_\chi = 0,$$
$$[\text{fermion bilinears}]_\chi = [\text{derivatives}]_\chi = [\text{weak couplings}]_\chi = 1$$



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- expansion in loops (L) or chiral dimensions.
- order 4

Example:
$[gg' B_{\mu\nu} \langle U T_3 U^\dagger W^{\mu\nu} \rangle \mathcal{F}(h)]_\chi = 4$
$\rightarrow L = 1$

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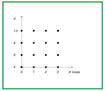

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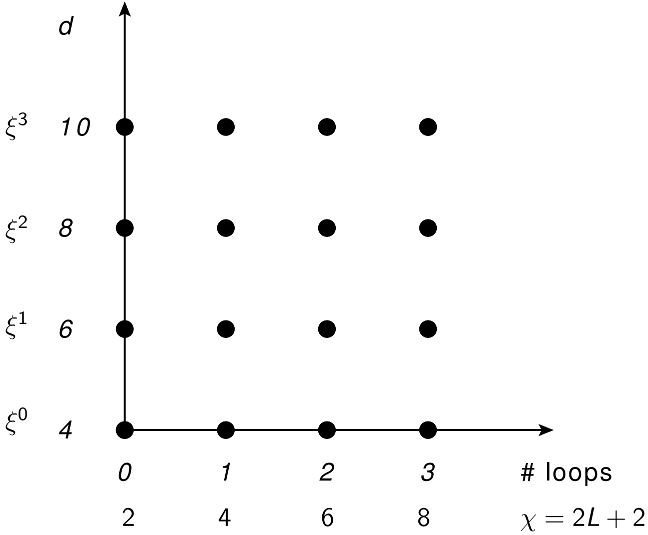

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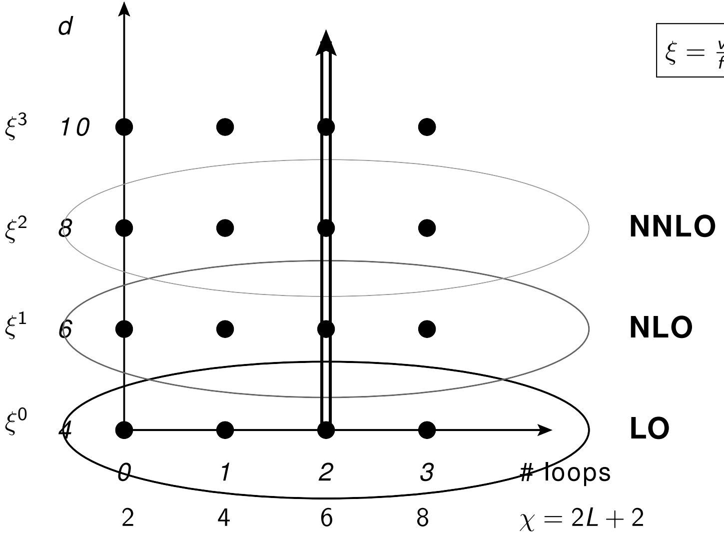

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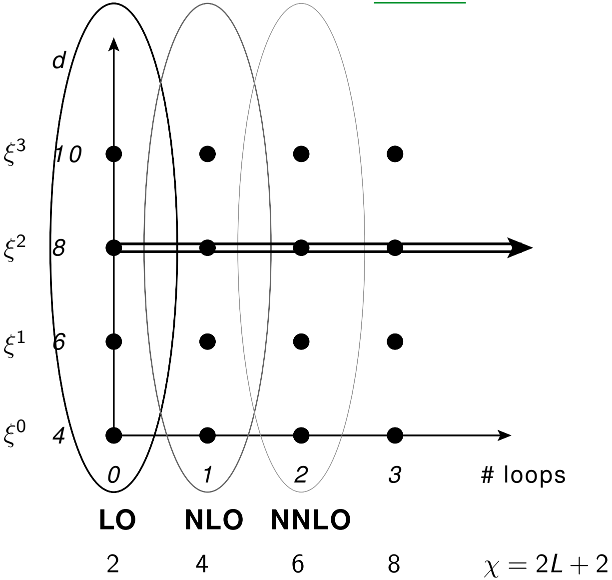

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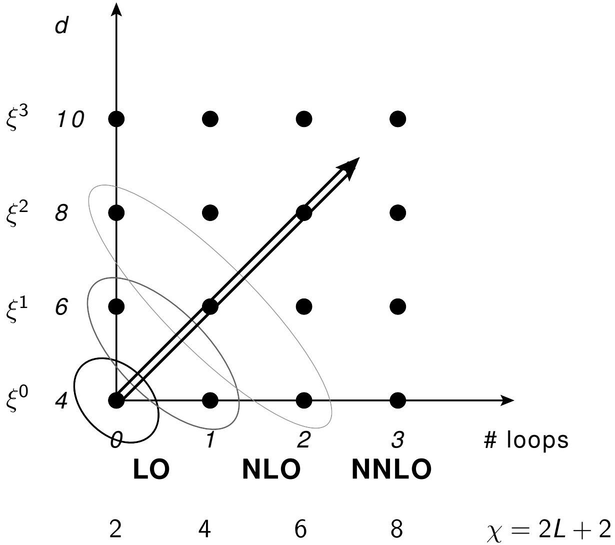

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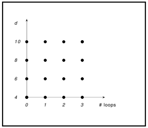

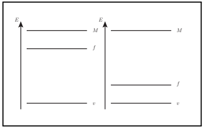

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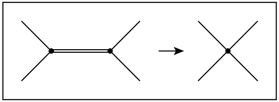


II: An Example, the SM Singlet Extension

$$\mathcal{L}_{\rm SM+S} \;=\; \mathcal{L}_{\rm SM} + \partial^\mu S \partial_\mu S + \frac{\mu_2^2}{2} S^2 - \frac{\lambda_2}{4} S^4 - \frac{\lambda_3}{2} \phi^\dagger \phi S^2$$

S: real scalar singlet with Z_2 symmetry

Schabinger/Wells [hep-ph/0509209], Patt/Wilczek [hep-ph/0605188], Robens/Stefaniak [1601.07880], Englert/Plehn/Zerwas/Zerwas [1106.3097], Buttazzo/Sala/Tesi [1505.05488]

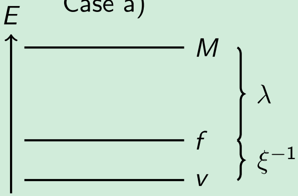
In physical parameters: $m, v, M, \sin\chi$, and $\xi = \frac{v^2}{f^2} = \frac{v^2}{v^2 + v_s^2}$

$$V(h,H) = \frac{1}{2} m^2 h^2 + \frac{1}{2} M^2 H^2 - d_1 h^3 - d_2 h^2 H - d_3 h H^2 - d_4 H^3 - z_1 h^4 - z_2 h^3 H - z_3 h^2 H^2 - z_4 h H^3 - z_5 H^4$$

$$d_i \;=\; d_i(m^2, M^2, v, \xi, \sin\chi), \qquad z_i \;=\; z_i(m^2, M^2, v, \xi, \sin\chi)$$

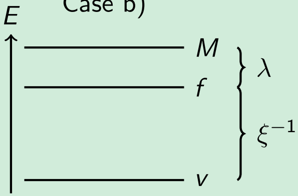
II: We distinguish 2 possible hierarchies.

Case a)



$$|\lambda_i| \lesssim 32\pi^2, \quad \xi, \sin\chi = \mathcal{O}(1), \quad m \sim v \sim f \ll M$$

Case b)

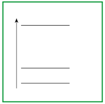


$$\lambda_i = \mathcal{O}(1), \quad \xi, \sin\chi \ll 1, \quad m \sim v \ll f \sim M$$

Buchalla/Catà/Celis/CK [1608.03564]

Integrate out H: solve equation of motion

$$H = H_0 + \frac{H_1}{M} + \frac{H_2}{M^2} + \ldots$$



II: Case a), strong coupling, generates the chiral Lagrangian.

$$H \quad = \quad H_0 \; + \; \frac{H_1}{M} \; + \; \frac{H_2}{M^2} \; + \; \dots$$

$$H_0 = H_0(h) = H_{0,2}\left(\frac{h}{v}\right)^2 + H_{0,3}\left(\frac{h}{v}\right)^3 + H_{0,4}\left(\frac{h}{v}\right)^4 + \dots$$

(closed-form solution to all orders in h)

$\rightarrow$ No $\frac{1}{M}$ suppression, but arbitrarily high canonical dimension

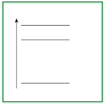
$\rightarrow$ Expansion in chiral dimensions $\rightarrow ew\chi\mathcal{L}$

LO:

$$\mathcal{L}_{\text{LO}} = \mathcal{L}_{\text{kin}} - V(h) + \mathcal{L}_{\text{Yuk}}(h)$$
$$+ \frac{v^2}{4}\langle (D_\mu U)(D^\mu U^\dagger)\rangle \left(1 + F_U(h)\right)$$

NLO ($1/M^2$):

$\mathcal{O}_{D1}, \mathcal{O}_{D7}, \mathcal{O}_{D11}, \dots$ of Buchalla/Catà/CK [1307.5017]



II: Case b), weak coupling, generates the SMEFT.

$$H = H_0 + \frac{H_1}{M} + \frac{H_2}{M^2} + \dots$$

$H_0 = 0, \qquad H_1 = -\frac{\lambda_3 v_H}{2M}\phi^\dagger\phi$

→ Allways $\frac{1}{M}$ suppression

→ Expansion in canonical dimensions → SMEFT

LO:

SM with renormalized couplings

NLO $(1/M^2)$:

$$\mathcal{L}_{\rm NLO} = \frac{1}{4}\frac{\lambda_3^2}{\lambda_2 M^2}\partial^\mu(\phi^\dagger\phi)\partial_\mu(\phi^\dagger\phi)$$

II: The physical picture helps to relate the two EFTs.

a)	b)
strongly coupled, large mixing	weakly coupled, small mixing
$\rightarrow$ EFT in terms of U, h	$\rightarrow$ EFT in terms of ϕ

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$\rightarrow$ EFT in terms of U, h

$\rightarrow$ EFT in terms of ϕ

In the limit $\sin\chi \ll 1$, we should recover the decoupling scenario.

$\rightarrow$ Indeed, $\sin\chi \ll 1$ corresponds to $\xi \ll 1$ and we do recover the decoupling case.

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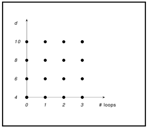

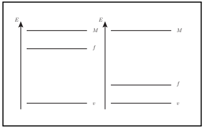

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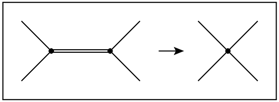

III: Now, we add (Technicolor) Resonances.

$E \uparrow$

QCD $(q_a, G_{\mu\nu})$	Fundamental EW Theory (???)
$\updownarrow$	$\updownarrow$
Resonance Chiral Theory $(\sigma, \rho, \dots)$	Resonance EW Theory $(S, V, \dots)$
$\updownarrow$	$\updownarrow$
Chiral Perturbation Theory (f_π, π_i)	Electroweak Chiral Lagrangian (v, φ_i)

Diagram by J. Santos [CPAN Meeting 2016, Zaragoza]

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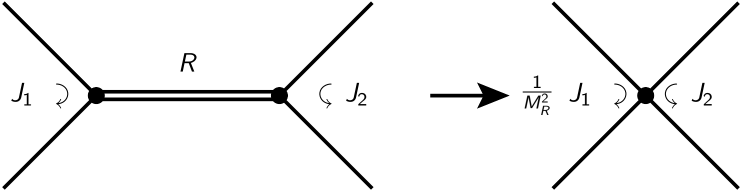
- Electroweak resonances are still allowed by current phenomenology.

  Pich/Rosell/Sanz-Cillero [1310.3121]
- We assume scalar (0^{++}), pseudo-scalar (0^{-+}), vector (1^{--}), and axial-vector (1^{++}) resonances.
  They can be singlets or triplets of $SU(2)$, and singlets or octets of $SU(3)_C$.

III: The expansion is still organized by Chiral Dimensions.



We consider effects up to $\mathcal{O}(v^2/M_R^2) = \mathcal{O}(1/16\pi^2)$:

Resonances couple linearly to currents of light fields J_i.
This is justified for $c_i \sim \mathcal{O}(1) \Leftrightarrow$ only scalar singlet is different ($\Rightarrow$ Part II)

$$[J_i]_\chi \leq 2 \implies [\Delta\mathcal{L}]_\chi \leq 4$$

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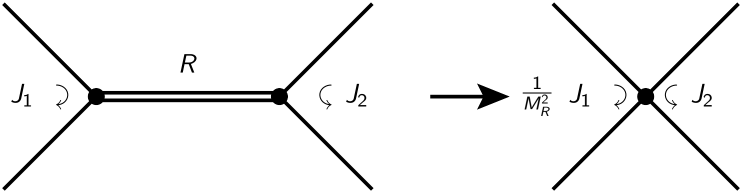

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$$[J_i]_\chi \quad \leq \quad 2 \quad \Longrightarrow \quad [\Delta\mathcal{L}]_\chi \quad \leq \quad 4$$

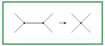
$\rightarrow$ We obtain the pattern of low-energy constants (LECs).

We find contributions to $\mathcal{L}_{\text{LO}}$ and $\mathcal{L}_{\text{NLO}}$ arising at $\mathcal{O}(v^2/M_R^2)$.

III: The representation of the Spin-1 resonances is not unique.

Proca, R_μ	*vs.*	Anti-symmetric, $R_{\mu\nu}$
$\mathcal{L}_{int}^{(P)} = \text{Tr}\, R_\mu J^\mu + 2\,\text{Tr}\, \partial_\mu R_\nu J^{\mu\nu}$		$\mathcal{L}_{int}^{(A)} = \text{Tr}\, R_{\mu\nu} J^{\mu\nu} + 2\,\text{Tr}\, R_{\mu\nu} \partial^\mu J^\nu$

$\rightarrow$ We obtain different LECs.



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They are related through a change of variables in the path integral,

$$\mathcal{L}_{Res}^{(P)} + \mathcal{L}_{non-Res}^{(P)} \Longleftrightarrow \mathcal{L}_{Res}^{(A)} + \mathcal{L}_{non-Res}^{(A)},$$

but non-resonant, local terms are also modified.

Pich/Rosell/Santos/Sanz-Cillero [1609.06659]

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Pich/Rosell/Santos/Sanz-Cillero [1609.06659]

The total contributions to the LECs are the same.
$\rightarrow$ Proca *vs.* Anti-symmetric becomes a choice of convenience.

Summary

- I presented the two Higgs EFTs.
- I discussed the power counting of the $ew\chi\mathcal{L}$.

$$[\text{bosons}]_\chi = 0$$
$$[g]_\chi = [y]_\chi = 1$$
$$[\bar{\Psi}\Psi]_\chi = [\partial_\mu]_\chi = 1$$

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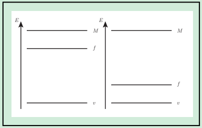
- I discussed how the EFTs are related in this example.



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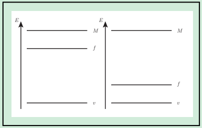
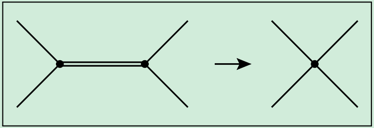


[1608.03564]

- Like in QCD / ChPT, we add resonances.
- After integrating them out, we study the pattern of LECs.



[1609.06659]

Backup

Effective Lagrangian at leading order

Assumptions

Feruglio [hep-ph/9301281], Bagger *et al.* [hep-ph/9306256], Chivukula *et al.* [hep-ph/9312317], Wang/Wang [hep-ph/0605104], Grinstein/Trott[0704.1505], Contino[1005.4269], Alonso *et al.* [1212.3305], ...

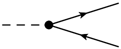
- A new strong sector generates the 3 GBs of EWSB and the h at the scale f.
- The transverse gauge bosons and the fermions of the SM are weakly coupled.
- The pattern of symmetry breaking is $SU(2)_L \times SU(2)_R \to SU(2)_{V=L+R}$

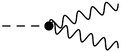
$\rightarrow$ The GBs become the longitudinal components of the gauge bosons.
In unitary gauge:
$\frac{v^2}{4}\langle(D_\mu U)(D^\mu U^\dagger)\rangle = \frac{g^2 v^2}{4} W_\mu^+ W^{\mu -} + \frac{(g^2+g'^2)v^2}{8} Z_\mu Z^\mu$

$$\begin{aligned}\mathcal{L}_{\text{LO}} =& \frac{v^2}{4}\langle(D_\mu U)(D^\mu U^\dagger)\rangle\ (1+F_U(h)) + \frac{1}{2}(\partial_\mu h)(\partial^\mu h) - \mathcal{V}(h)\\ &+ i\bar{\Psi}_f \not{D} \Psi_f - v\left(\bar{\Psi}_f Y_{j,f} U \Psi_f + \text{h.c.}\right)\ \left(\frac{h}{v}\right)^j\\ &- \frac{1}{2}\langle G_{\mu\nu}G^{\mu\nu}\rangle - \frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}\end{aligned}$$

There is a relation between the electroweak chiral Lagrangian and the κ framework.

$\mathcal{L}_{ew\chi h}$

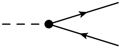


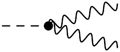


tree: $c_{t,b,\tau}$ c_V

$\kappa_i^2 = \Gamma^i/\Gamma^i_{\text{SM}}, \quad \kappa_i^2 = \sigma^i/\sigma^i_{\text{SM}}$

LHCHXSWG [1209.0040,1307.1347]



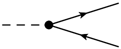


tree: $\kappa_{t,b,\tau}$ κ_V

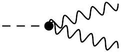
There is a relation between the electroweak chiral Lagrangian and the κ framework.

$\mathcal{L}_{ew\chi h}$

tree:

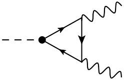


$c_{t,b,\tau}$



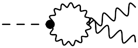
c_V

1-loop:



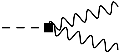
$c_{t,b,\tau}$

+



c_V

+

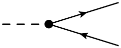


$c_{\gamma\gamma,gg}$

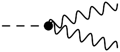
$\kappa_i^2 = \Gamma^i/\Gamma^i_{\mathrm{SM}}, \quad \kappa_i^2 = \sigma^i/\sigma^i_{\mathrm{SM}}$

LHCHXSWG [1209.0040,1307.1347]

tree:

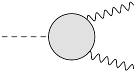


$\kappa_{t,b,\tau}$



κ_V

1-loop:

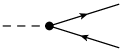


$\kappa_{\gamma,g}$

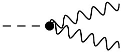
There is a relation between the electroweak chiral Lagrangian and the κ framework.

$\mathcal{L}_{ew\chi h}$

tree:



$c_{t,b,\tau}$

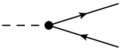


c_V

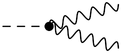
$\kappa_i^2 = \Gamma^i/\Gamma^i_{\text{SM}}, \quad \kappa_i^2 = \sigma^i/\sigma^i_{\text{SM}}$

LHCHXSWG [1209.0040,1307.1347]

tree:



$\kappa_{t,b,\tau}$

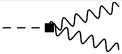


κ_V

Both have the same number of free parameters:

$$\{c_V, c_{t,b,\tau}, c_{\gamma\gamma}, c_{gg}\} \quad vs. \quad \{\kappa_V, \kappa_{t,b,\tau}, \kappa_\gamma, \kappa_g\}$$

$\Rightarrow$ κ's are QFT consistent and with small modifications directly interpretable within an EFT!



$c_{\gamma\gamma,gg}$

Integrating out at the 1-loop level

non-decoupling case:

$$\delta m^2, \delta V(h) \quad \sim \quad \frac{M^4}{16\pi^2} \quad \xrightarrow[M<4\pi f]{\text{approx. } SO(5),} \quad \lesssim \quad v^2 f^2$$

decoupling case:

$$\delta m^2 \quad \sim \quad \frac{M^2}{16\pi^2} \quad \rightarrow \text{renormalization of } m$$

$\delta V(h)$ is further suppressed

Closed-form solution of $H_0(h)$

$$
\begin{aligned}
H &= H_0 + \frac{H_1}{M} + \frac{H_2}{M^2} + \ldots, \\
H_0(h) &= H_{0,2}\left(\frac{h}{v}\right)^2 + H_{0,3}\left(\frac{h}{v}\right)^3 + H_{0,4}\left(\frac{h}{v}\right)^4 + \ldots
\end{aligned}
$$

$$
\begin{aligned}
H_0 &= -\frac{v+(s^2c-c^2sW)h}{s^3+Wc^3} + \sqrt{\frac{(v+(s^2c-c^2sW)h)^2}{(s^3+Wc^3)^2} - \frac{(sc^2+cs^2W)h^2}{s^3+Wc^3}} \\
&= -\frac{v}{2}(cs(c+sW))\frac{h^2}{v^2} - \frac{v}{2}\left(c^2s^2(cW-s)(c+sW)\right)\frac{h^3}{v^3} \\
&\quad - \frac{v}{8}\left(c^2s^2(c+sW)\left(5c^3sW^2+W\left(c^4-8c^2s^2+s^4\right)+5cs^3\right)\right)\frac{h^4}{v^4} + \ldots,
\end{aligned}
$$

$$
\text{with } W = \sqrt{\xi/(1-\xi)}.
$$