Choosing the Appropriate EFT for Higgs Analyses

– Higgs Couplings 2016, SLAC –

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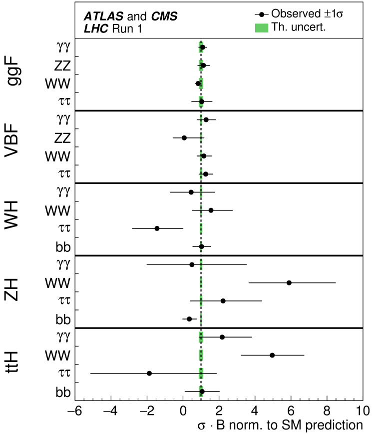
In collaboration with G. Buchalla, O. Catà and A. Celis

Run-1 measured the Higgs-couplings with $\gtrsim 10\%$ precision.

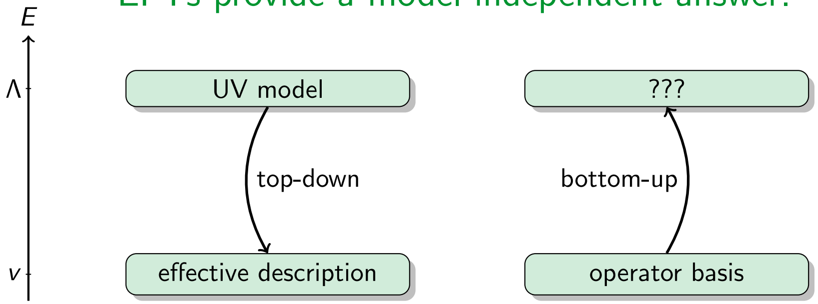


ATLAS & CMS [1606.02266]

- Everything looks like the Standard Model.
- There are no direct signs of new physics.
- Experimental precision of Higgs-couplings is $\sim \mathcal{O}(10\%)$

Is it the SM-Higgs
or something else?

EFTs provide a model-independent answer.



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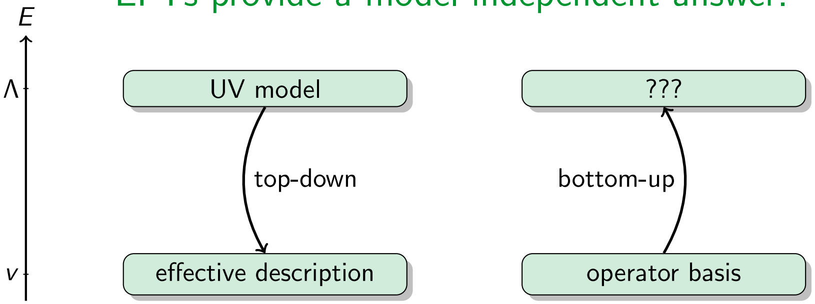


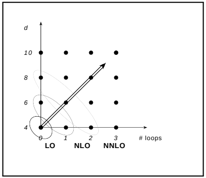
For a model-independent analysis we use the bottom-up approach.

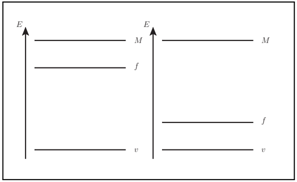
We need:

- Low-energy particles: all SM particles + 3 GBs for the $W^{\pm}/Z$ masses
- Symmetries: $SU(3)_C \times SU(2)_L \times U(1)_Y \to SU(3)_C \times U(1)_{em}$, B, L
  at LO: flavor and custodial symmetry
- A consistent power counting

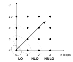
Choosing the Appropriate EFT for Higgs Analyses

Part I: 2 different Higgs EFTs
[1412.6356]





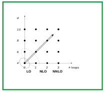
Part II: The SM Singlet Extension
[1608.03564]



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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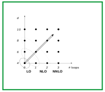
non-decoupling (nonlinear) EFT:
– $ew\chi\mathcal{L}$ –

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



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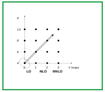
Chiral dimensions are a tool to find the loop order of an operator.

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

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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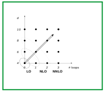
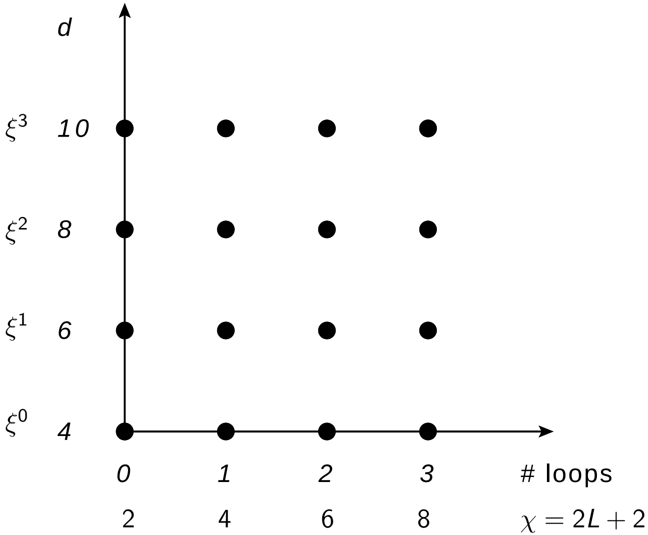


I: A graphical way to see the expansion

$$\xi = \frac{v^2}{f^2}$$



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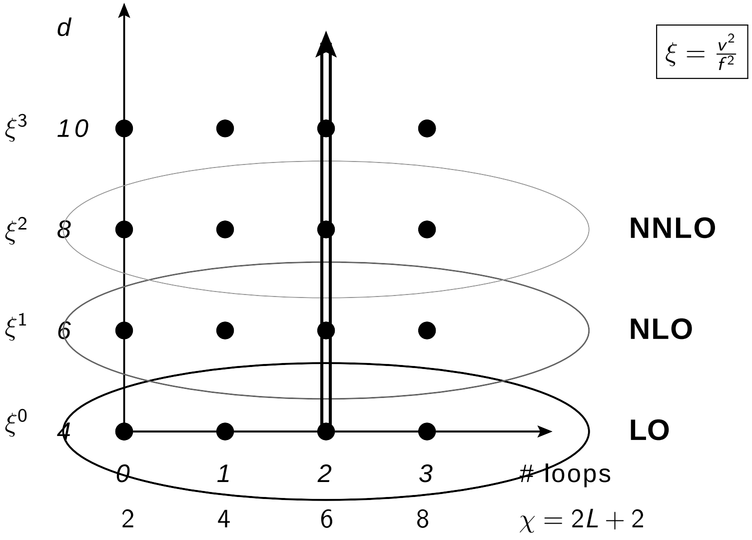

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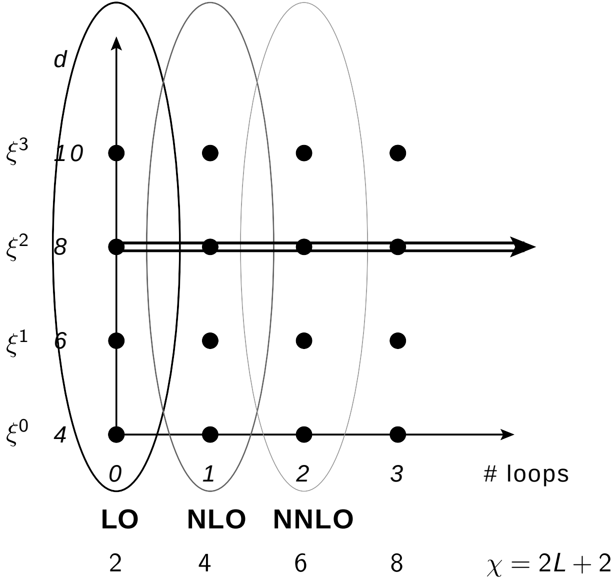

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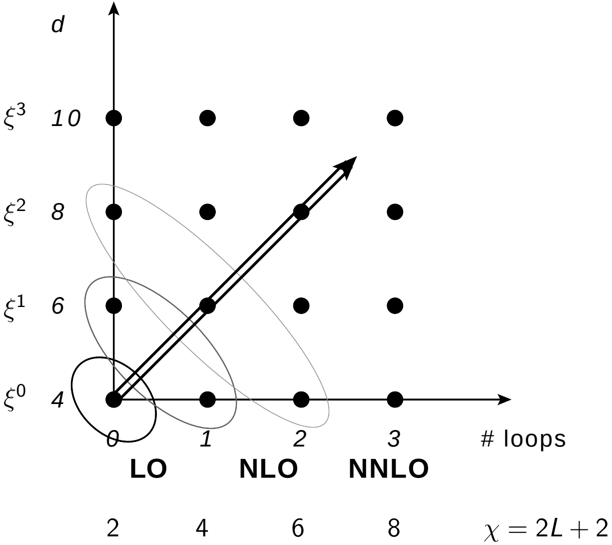

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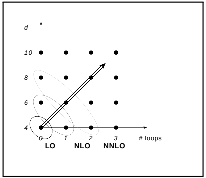
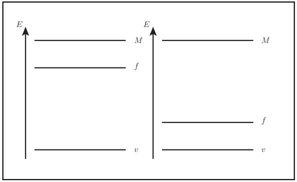




Part II: The SM Singlet Extension
[1608.03564]

II: An Example, the SM Singlet Extension

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

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]

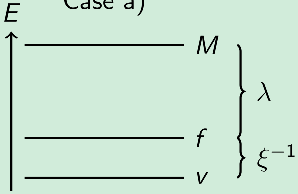
In physical parameters: $m, v, M, \sin\chi$, and $\xi = \frac{v^2}{f^2} = \frac{v^2}{v^2 + v_s^2}$

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

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

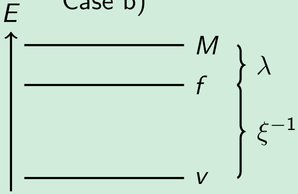
II: We distinguish 2 possible hierarchies.

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)

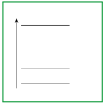


$$\lambda_i = \mathcal{O}(1), \quad \xi, \sin\chi \ll 1, \quad m \sim v \ll f \sim M$$

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.

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

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

(closed-form solution to all orders in h)

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

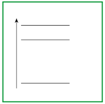
→ Expansion in chiral dimensions → $ew\chi\mathcal{L}$

LO:

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

NLO ($1/M^2$):

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



II: Case b), weak coupling, generates the SM-EFT.

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

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

→ Allways $\frac{1}{M}$ suppression

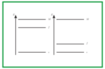
→ Expansion in canonical dimensions → SMEFT

LO:

SM with renormalized couplings

NLO ($1/M^2$):

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

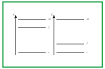


II: How to interpret the result.

Physical picture:

large mixing $\rightarrow$ low energy physics is not described well by a doublet

$\rightarrow$ We recover the decoupling from the non-decoupling case for $\sin\chi \ll 1$.



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The electroweak chiral Lagrangian:

- is more general than the SM-EFT
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$$\mathcal{L} = 2c_V \left(m_W^2 W_\mu^+ W^{-\mu} + \tfrac{1}{2} m_Z^2 Z_\mu Z^\mu\right)\left(\tfrac{h}{v}\right) - c_t y_t \bar{t}th - c_b y_b \bar{b}bh - c_\tau y_\tau \bar{\tau}\tau h$$
$$+ \tfrac{e^2}{16\pi^2} c_{\gamma\gamma} F_{\mu\nu} F^{\mu\nu} \tfrac{h}{v} + \tfrac{g_s^2}{16\pi^2} c_{gg} \langle G_{\mu\nu} G^{\mu\nu}\rangle \tfrac{h}{v}$$

Buchalla/Catà/Celis/CK [1504.01707]

Summary

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

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

[1307.5017,1312.5624,1412.6356]

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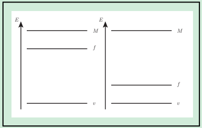
- I discussed how the EFTs are related in this example.



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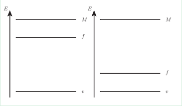


[1608.03564]

The question to ask is therefore NOT:

'Linear *vs.* Non-Linear?' or 'Doublet *vs.* Singlet?'

but rather

'Decoupling *vs.* Non-Decoupling New Physics?'

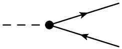
However, the electroweak chiral Lagrangian is more general.

Backup

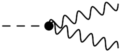
There is a relation between the electroweak chiral Lagrangian and the κ framework.

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

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]

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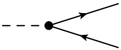
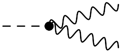


$\kappa_{t,b,\tau}$



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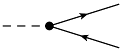
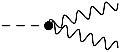
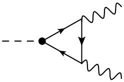


$c_{t,b,\tau}$



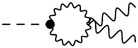
c_V

1-loop:



$c_{t,b,\tau}$

+



c_V

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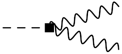

$c_{\gamma\gamma,gg}$

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

LHCHXSWG [1209.0040,1307.1347]

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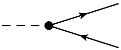
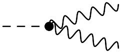
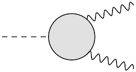


$\kappa_{t,b,\tau}$



κ_V

1-loop:



$\kappa_{\gamma,g}$

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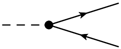
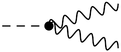


$c_{t,b,\tau}$



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LHCHXSWG [1209.0040,1307.1347]

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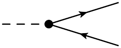
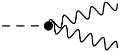


$\kappa_{t,b,\tau}$

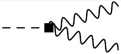


κ_V

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!



$c_{\gamma\gamma,gg}$

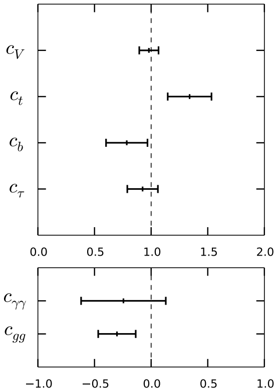
We performed a Bayesian fit to LHC data.

Results:

$$\begin{pmatrix} c_V \\ c_t \\ c_b \\ c_\tau \\ c_{\gamma\gamma} \\ c_{gg} \end{pmatrix} = \begin{pmatrix} 0.98 & \pm & 0.09 \\ 1.34 & \pm & 0.19 \\ 0.79 & \pm & 0.18 \\ 0.92 & \pm & 0.14 \\ -0.24 & \pm & 0.37 \\ -0.30 & \pm & 0.16 \end{pmatrix}$$

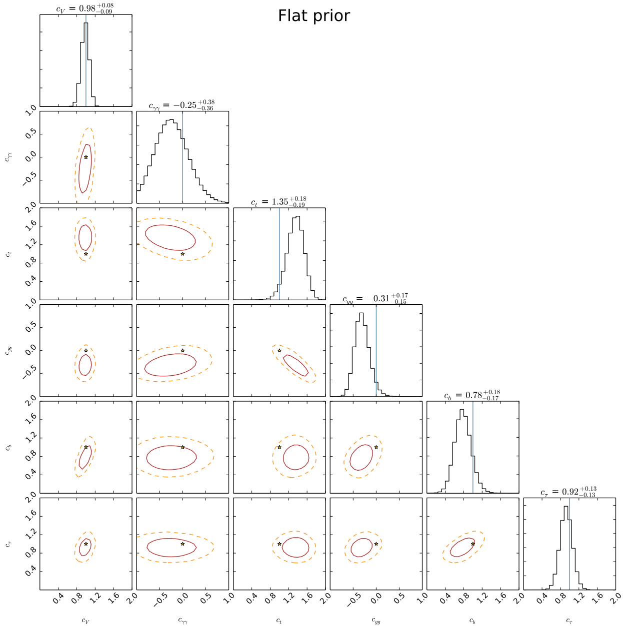
$$\rho_{ij} = \frac{\mathrm{cov}(c_i, c_j)}{\sigma_i \sigma_j} =$$

$$\begin{pmatrix} 1.0 & 0.01 & 0.67 & 0.37 & 0.41 & 0.1 \\ . & 1.0 & 0.02 & -0.04 & -0.36 & -0.84 \\ . & . & 1.0 & 0.58 & 0.02 & 0.37 \\ . & . & . & 1.0 & -0.05 & 0.26 \\ . & . & . & . & 1.0 & 0.31 \\ . & . & . & . & . & 1.0 \end{pmatrix}$$



Buchalla/Catà/Celis/CK [1511.00988]

We performed a Bayesian fit to LHC data.



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:

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

$\delta V(h)$ is further suppressed