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.

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

ATLAS & CMS [1606.02266]
EFTs provide a model-independent answer.

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: $SU(3)_C \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_C \times U(1)_{em}$, $B$, $L$
- At LO: flavor and custodial symmetry

A consistent power counting
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  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 $\phi$
- 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:**
- **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
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Chiral dimensions are a tool to find the loop order of an operator.

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


$[\text{bosons}]_\chi = 0,$

$[\text{fermion bilinears}]_\chi = [\text{derivatives}]_\chi = [\text{weak couplings}]_\chi = 1$
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Example:

\[ [gg'B_{\mu\nu}\langle UT_3 U^\dagger W_{\mu\nu} \rangle F(h)]_\chi = 4 \rightarrow L = 1 \]
I: A graphical way to see the expansion

\[ \xi = \frac{v^2}{f^2} \]

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II: An Example, the SM Singlet Extension

\[ \mathcal{L}_{\text{SM+S}} = \mathcal{L}_{\text{SM}} + \partial^\mu S \partial_\mu S + \frac{\mu_2^2}{2} S^2 - \frac{\lambda_2}{4} S^4 - \frac{\lambda_3}{2} \phi^\dagger \phi S^2 \]

\( S: \) 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 \( \xi = \frac{v^2}{f^2} = \frac{v^2}{v^2 + v_s^2} \)

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

\( d_i = d_i(m^2, M^2, v, \xi, \sin \chi), \quad z_i = z_i(m^2, M^2, v, \xi, \sin \chi) \)
II: We distinguish 2 possible hierarchies.

- **Case a)**
  - $E ightarrow M ightarrow f ightarrow v$
  - $\lambda, \xi^{-1}$
  - $|\lambda_i| \lesssim 32\pi^2$
  - $\xi, \sin\chi = O(1)$
  - $m \sim v \sim f \ll M$

- **Case b)**
  - $E ightarrow M ightarrow f ightarrow v$
  - $\lambda, \xi^{-1}$
  - $\lambda_i = O(1)$
  - $\xi, \sin\chi \ll 1$
  - $m \sim v \ll f \sim M$

Integrate out $H$: solve equation of motion

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

Buchalla/Catà/Celis/CK [1608.03564]
II: Case a), strong coupling, generates the chiral Lagrangian.

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

\[ H_0 = H_0(h) = H_{0,2} \left( \frac{h}{v} \right)^2 + H_{0,3} \left( \frac{h}{v} \right)^3 + H_{0,4} \left( \frac{h}{v} \right)^4 + \ldots \]  
(closed-form solution to all orders in \( h \))

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

→ Expansion in chiral dimensions → ewχL

LO:

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

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.

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

\[ H_0 = 0, \quad H_1 = -\frac{\lambda_3 v_H}{2M} \phi \phi^\dagger \]

→ Allways $\frac{1}{M}$ suppression
→ Expansion in canonical dimensions → SMEFT

LO:
SM with renormalized couplings

NLO (1/$M^2$):

\[ \mathcal{L}_{\text{NLO}} = \frac{1}{4} \frac{\lambda_3^2}{\lambda_2 M^2} \partial^\mu (\phi \phi^\dagger) \partial_\mu (\phi \phi^\dagger) \]
II: How to interpret the result.

Physical picture:

- Large mixing $\rightarrow$ low energy physics is not described well by a doublet.
- We recover the decoupling from the non-decoupling case for $\sin \chi \ll 1$. 

The electroweak chiral Lagrangian:

$$L = \frac{1}{2}c_V (m^2_W W^+ W^- + \mu W^- - \mu^+ + \frac{1}{2}m^2_Z Z^+ Z^- h v) - c_t y_t \bar{t} t h - c_b y_b \bar{b} b h - c_\tau y_\tau \bar{\tau} \tau h + \frac{e^2}{16\pi^2} c_\gamma \gamma F_{\mu\nu} F^{\mu\nu} h v + g^2 s \frac{1}{16\pi^2} c_g \langle G_{\mu\nu} G^{\mu\nu} \rangle h v$$

Buchalla/Catá/Celis/CK [1504.01707]

Claudius Krause (IFIC / LMU)  
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The electroweak chiral Lagrangian:

- is more general than the SM-EFT
- is related to the $\kappa$-framework LHCHXSWG [1209.0040,1307.1347]
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The electroweak chiral Lagrangian:

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\[
\mathcal{L} = 2c_V \left( m_W^2 W_\mu^+ W^-\mu + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \right) \left( \frac{h}{v} \right) - c_t y_t \tilde{t} th - c_b y_b \tilde{b} bh - c_\tau y_\tau \tilde{\tau} \tau h \\
+ \frac{e^2}{16\pi^2} c_{\gamma\gamma} F_{\mu\nu} F^{\mu\nu} \frac{h}{v} + \frac{g_s^2}{16\pi^2} c_{gg} \langle G_{\mu\nu} G^{\mu\nu} \rangle \frac{h}{v}
\]

\text{Buchalla/Catà/Celis/CK} [1504.01707]
Summary

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

\[
\begin{align*}
[\text{bosons}]_\chi &= 0 \\
[g]^\chi &= [y]^\chi = 1 \\
[\bar{\psi}\psi]_\chi &= [\partial^\mu]\chi = 1
\end{align*}
\]

[1307.5017, 1312.5624, 1412.6356]

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.
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- I showed how the two EFTs are generated in the Standard Model Singlet Extension.
- I discussed how the EFTs are related in this example.

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Backup
There is a relation between the electroweak chiral Lagrangian and the $\kappa$ framework.

$\mathcal{L}_{\text{ewCh}}$

tree: $c_t, b, \tau$

c_V

$\kappa_i^2 = \Gamma_i / \Gamma_{\text{SM}}$

$LHCHXSWG$ [1209.0040, 1307.1347]

$\kappa_{\gamma, g}^i = \sigma_i / \sigma_{\text{SM}}$
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$$L_{ew\chi h}$$

Tree:

- $c_{t,b,\tau}$
- $c_{V}$

1-loop:

- $c_{t,b,\tau}$
- $c_{V}$
- $c_{\gamma\gamma,gg}$

$$\kappa_{i}^{2} = \Gamma_{i}/\Gamma_{SM}^{i}, \quad \kappa_{i}^{2} = \sigma_{i}/\sigma_{SM}^{i}$$

LHCHXSWG [1209.0040, 1307.1347]

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There is a relation between the electroweak chiral Lagrangian and the $\kappa$ framework.

\[ \mathcal{L}_{ew\chi h} \]

\[ \begin{align*}
\text{tree:} & \quad c_t, b, \tau \\
\text{1-loop:} & \quad c_V
\end{align*} \]

\[ \begin{align*}
\kappa^2_i = \Gamma_i / \Gamma^i_{SM}, \quad \kappa^2_i = \sigma^i / \sigma^i_{SM}
\end{align*} \]

LHCHXSWG [1209.0040, 1307.1347]

Both have the same number of free parameters:

\( \{ c_V, c_t, b, \tau, c_{\gamma\gamma}, c_{gg} \} \) \quad \text{vs.} \quad \{ \kappa_V, \kappa_t, b, \tau, \kappa_{\gamma}, \kappa_g \} 

\Rightarrow \ \kappa$’s are QFT consistent and with small modifications directly interpretable within an EFT!
We performed a Bayesian fit to LHC data.

Results:

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

\[
\rho_{ij} = \frac{\text{cov}(c_i, c_j)}{\sigma_i \sigma_j} =
\begin{pmatrix}
1.0 & 0.01 & 0.67 & 0.37 & 0.41 & 0.1 \\
0.01 & 1.0 & 0.02 & -0.04 & -0.36 & -0.84 \\
0.67 & 0.02 & 1.0 & 0.58 & 0.02 & 0.37 \\
0.37 & -0.04 & 0.58 & 1.0 & -0.05 & 0.26 \\
0.41 & -0.36 & 0.02 & -0.05 & 1.0 & 0.31 \\
0.1 & -0.84 & 0.37 & 0.26 & 0.31 & 1.0
\end{pmatrix}
\]

Buchalla/Catà/Celis/CK [1511.00988]
We performed a Bayesian fit to LHC data.

Flat prior

c_{V} = 0.98^{+0.08}_{-0.09}
c_{V} = -0.25^{+0.38}_{-0.36}
c_{q_{3}} = 1.35^{+0.68}_{-0.69}
c_{q_{3}} = -0.31^{+0.17}_{-0.18}
c_{b} = 0.78^{+0.18}_{-0.17}
c_{b} = 0.92^{+0.13}_{-0.13}
Integrating out at the 1-loop level

non-decoupling case:

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

decoupling case:

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

\[ \delta V(h) \text{ is further suppressed} \]