Higgs couplings: upgrading the $\kappa$ formalism with EFTs

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(based on collaborations with G. Buchalla, A. Celis, and C. Krause)
**Motivation**

- Higgs discovery at the LHC confirms the Standard Model as an excellent low-energy approximation to the electroweak interactions.

- Current uncertainty in Higgs couplings, $\mathcal{O}(10\%)$, still far from gauge-fermion sector, $\mathcal{O}(0.1\%)$.

- Description of Higgs anomalous couplings: scrutiny of scalar sector and New Physics.

- Consistent QFT-based tool for indirect searches: Effective Field Theories (EFTs). Compatible with $\kappa$ formalism?
What is the $\kappa$ formalism?

- Signal-strength based parametrization of Higgs decay channels:

$$\mu_j = \frac{\Gamma_{\text{exp}}^j}{\Gamma_{\text{SM}}^j}$$

- Limited scope: conceived for potential deviations in rates (scope of Run I).

- Upgrading needed to go beyond, e.g., study kinematical distributions (scope of Run $\geq$ II).

- QFT interpretation: modification of SM vertices. Typically parametrized as

$$\mathcal{L}_\kappa = 2\kappa_V \left( m_W^2 W_\mu W^\mu + \frac{m_Z^2}{2} Z_\mu Z^\mu \right) \frac{h}{v} - \sum_{f=t,b,\tau} \kappa_f y_f \bar{f} f h + \kappa_{gg} \frac{g_s^2}{16\pi^2} G_{\mu\nu} G^{\mu\nu} \frac{h}{v} + \kappa_{\gamma\gamma} \frac{e^2}{16\pi^2} F_{\mu\nu} F^{\mu\nu} \frac{h}{v}$$

- A priori not clear how to upgrade it (renormalizability and unitarity are lost...). It has even been claimed it is inconsistent...

- SM can be a model, $\mathcal{L}_\kappa$ can only be an EFT. Which one?
Higgs couplings at the LHC

Run-2 prospects: [Numbers borrowed from H. Kroha at Aspen 2014]

<table>
<thead>
<tr>
<th>$\Delta \mu/\mu[%],(300,fb^{-1})$</th>
<th>$\gamma\gamma$</th>
<th>$WW$</th>
<th>$ZZ$</th>
<th>$\tau\tau$</th>
<th>$bb$</th>
<th>$\mu\mu$</th>
<th>$Z\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>14 (9)</td>
<td>13 (8)</td>
<td>12 (6)</td>
<td>22 (16)</td>
<td>—</td>
<td>39 (38)</td>
<td>147 (145)</td>
</tr>
<tr>
<td>CMS</td>
<td>12 (6)</td>
<td>11 (6)</td>
<td>11 (7)</td>
<td>14 (8)</td>
<td>14 (11)</td>
<td>42 (40)</td>
<td>62 (62)</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>$\Delta \kappa/\kappa[%],(300,fb^{-1})$</th>
<th>$\gamma\gamma$</th>
<th>$WW$</th>
<th>$ZZ$</th>
<th>$gg$</th>
<th>$\tau\tau$</th>
<th>$bb$</th>
<th>$tt$</th>
<th>$\mu\mu$</th>
<th>$Z\gamma$</th>
</tr>
</thead>
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<tr>
<td>ATLAS</td>
<td>13 (8)</td>
<td>8 (7)</td>
<td>8 (7)</td>
<td>11 (9)</td>
<td>18 (13)</td>
<td>$\kappa_\tau$</td>
<td>22 (20)</td>
<td>23 (21)</td>
<td>79 (78)</td>
</tr>
<tr>
<td>CMS</td>
<td>7 (5)</td>
<td>6 (4)</td>
<td>6 (4)</td>
<td>8 (6)</td>
<td>8 (6)</td>
<td>13 (10)</td>
<td>15 (14)</td>
<td>23 (23)</td>
<td>41 (41)</td>
</tr>
</tbody>
</table>

Precision goal between 5 – 10%. At full luminosity, expected few % at best.
EFTs at the EW scale: weakly-coupled new dynamics

- The Higgs is in a weak doublet (SM Higgs $\Phi$)

$$\Phi = \left( \begin{array} {c} \varphi_1 + i\varphi_2 \\ \varphi_3 + i\varphi_4 \end{array} \right)$$

- EFT is defined as an expansion in canonical dimensions, whose first term is the SM itself:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \mathcal{L}_{d=6} + \frac{1}{\Lambda^4} \mathcal{L}_{d=8} + \cdots$$

Remarks:

- The theory is renormalizable: Higgs nature and New Physics are decoupled.

- Useful tool for indirect searches of New Physics only: Higgs assumed SM. Orthogonal to the spirit of the $\kappa$ formalism...

- Typical size of the deviations (constrained by direct searches) at NLO:

$$\frac{v^2}{\Lambda^2} \lesssim 1\%$$

- Naturally, small corrections in both gauge-fermion and Higgs sectors. Effects anticipated at the end of LHC running.
**EFTs at the EW scale: weakly-coupled new dynamics**

A sample of the full basis:

<table>
<thead>
<tr>
<th>$X^3$ (LG)</th>
<th>$\varphi^6$ and $\varphi^4D^2$ (PTG)</th>
<th>$\psi^2\varphi^3$ (PTG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_G$</td>
<td>$f^{ABC}G^{A\mu}<em>\nu G^{B\rho}</em>\mu G^{C\rho}_\nu$</td>
<td>$Q_\varphi$</td>
</tr>
<tr>
<td>$Q_{\tilde{G}}$</td>
<td>$f^{ABC}\tilde{G}^{A\mu}<em>\nu G^{B\rho}</em>\mu G^{C\rho}_\nu$</td>
<td>$Q_\varphi^\Box$</td>
</tr>
<tr>
<td>$Q_W$</td>
<td>$e^{IJK}W^I_\mu W^J_\nu W^K_\rho$</td>
<td>$Q_\varphi D$</td>
</tr>
<tr>
<td>$Q_{\tilde{W}}$</td>
<td>$e^{IJK}\tilde{W}^I_\mu W^J_\nu W^K_\rho$</td>
<td></td>
</tr>
</tbody>
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<tr>
<th>$X^2\varphi^2$ (LG)</th>
<th>$\psi^2X\varphi$ (LG)</th>
<th>$\psi^2\varphi^2D$ (PTG)</th>
</tr>
</thead>
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<tr>
<td>$Q_{\varphi G}$</td>
<td>$\varphi^\dagger G^{A\mu\nu} G^{A\mu\nu}$</td>
<td>$Q_{eW}$</td>
</tr>
<tr>
<td>$Q_{\varphi \tilde{G}}$</td>
<td>$\varphi^\dagger \tilde{G}^{A\mu\nu} G^{A\mu\nu}$</td>
<td>$Q_{eB}$</td>
</tr>
<tr>
<td>$Q_{\varphi W}$</td>
<td>$\varphi^\dagger \varphi W^I_\mu W^I_\mu$</td>
<td>$Q_{uG}$</td>
</tr>
<tr>
<td>$Q_{\varphi \tilde{W}}$</td>
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</tr>
<tr>
<td>$Q_{\varphi \tilde{B}}$</td>
<td>$\varphi^\dagger \tilde{B}^\mu\nu B^\mu\nu$</td>
<td>$Q_{dG}$</td>
</tr>
<tr>
<td>$Q_{\varphi W B}$</td>
<td>$\varphi^\dagger \tau^I\varphi W^I_\mu B^\mu\nu$</td>
<td>$Q_{dW}$</td>
</tr>
<tr>
<td>$Q_{\varphi \tilde{W} B}$</td>
<td>$\varphi^\dagger \tau^I\varphi \tilde{W}^I_\mu B^\mu\nu$</td>
<td>$Q_{dB}$</td>
</tr>
</tbody>
</table>

Taken from [Wudka & Einhorn’13]
EFTs at the EW scale: the generic case

- Higgs not necessarily a doublet: $h$ as singlet, EW Goldstones inside $U$. Technically, express the SM as

$$
\mathcal{L}_{SM} = -\frac{1}{2} \langle W_\mu W^{\mu} \rangle - \frac{1}{4} B_\mu B^{\mu} + i \sum_j \bar{f}_j \not{D} f_j + \frac{1}{2} \partial_\mu h \partial^\mu h
$$

$$
+ \frac{v^2}{4} \langle D_\mu U D^\mu U^\dagger \rangle \left( 1 + \frac{h}{v} \right)^2 - v \left[ \bar{\psi} Y_\psi U P_\pm \psi + \text{h.c.} \right] \left( 1 + \frac{h}{v} \right) - \frac{\lambda}{4} (h^2 - v^2)^2
$$

and generalize the Higgs couplings (both in magnitude and number of legs) to

$$
\mathcal{L}_{LO} = -\frac{1}{2} \langle W_\mu W^{\mu} \rangle - \frac{1}{4} B_\mu B^{\mu} + i \sum_j \bar{f}_j \not{D} f_j + \frac{1}{2} \partial_\mu h \partial^\mu h
$$

$$
+ \frac{v^2}{4} \langle D_\mu U D^\mu U^\dagger \rangle f_U(h) - v \left[ \bar{\psi} f_\psi(h) U P_\pm \psi + \text{h.c.} \right] - V(h)
$$

with

$$
f_U(h) = 1 + \sum_j a_U^j \left( \frac{h}{v} \right)^j; \quad f_\psi(h) = Y_\psi + \sum_j Y_\psi^{(j)} \left( \frac{h}{v} \right)^j; \quad V(h) = \sum_{j \geq 2} a_V^j \left( \frac{h}{v} \right)^j
$$

- Declare it a leading-order Lagrangian

[Contino et al.'10; Buchalla, O.C., Krause'13]
EFTs at the EW scale: the generic case

- The previous Lagrangian arises naturally in scenarios where the Higgs is a pseudo-Goldstone (of internal or spacetime symmetries).

- EFT is defined as an expansion in chiral dimensions (loops), whose first term is not the SM:

\[
\mathcal{L}_{\text{eff}} = \mathcal{L}_{\chi=2} + \frac{\xi}{16\pi^2} \mathcal{L}_{\chi=4} + \frac{\xi}{(16\pi^2)^2} \mathcal{L}_{\chi=6} + \cdots
\]

- Chiral dimensions are defined as

\[
[\partial_\mu]_\chi = 1, \quad [\varphi]_\chi = [h]_\chi = 0, \quad [X_{\mu\nu}]_\chi = 1, \quad [\psi_{L,R}]_\chi = \frac{1}{2}, \quad [g]_\chi = [y]_\chi = 1
\]

and make the expansion homogeneous.

\[
\mathcal{L}_{\chi=2} = -\frac{1}{2} \langle W_{\mu\nu}W^{\mu\nu} \rangle - \frac{1}{4} B_{\mu\nu}B^{\mu\nu} + i \sum_j \bar{f}_j \not{D} f_j + \frac{1}{2} \partial_\mu h \partial^\mu h
\]

\[
+ \frac{v^2}{4} \langle D_\mu U D^{\mu} U^\dagger \rangle f_U(h) - v \left[ \bar{\psi} \psi(h) U P_{\pm} \psi + \text{h.c.} \right] - V(h)
\]
EFTs at the EW scale: the generic case

Remarks:

• The theory is nonrenormalizable: Higgs nature and New Physics are related. Natural cutoff at $\Lambda = 4\pi f$.

• Useful tool for indirect searches of Higgs couplings and New Physics: a priori Higgs is not assumed SM. In the spirit of the $\kappa$ formalism...

• Typical size of the deviations (not constrained by direct searches) at LO:

$$\xi \lesssim 10\%$$

• Naturally, hierarchy between gauge-fermion (constrained by LEP) and Higgs sectors. Effects possible at $O(10\%)$ level.

• Natural framework for the $\kappa$ formalism, with deviations in shapes at NLO ($\sim 10^{-2}\xi$).

• Going to the unitary gauge, the LO Lagrangian relevant for Higgs couplings reads:

$$\mathcal{L}_{LO} = 2c_V \left( m_W^2 W_\mu W^\mu + \frac{m_Z^2}{2} Z_\mu Z^\mu \right) \frac{h}{v} - \sum_{f=t,b,\tau} c_f y_f \bar{f} f h + c_{gg} \frac{g_s^2}{16\pi^2} G_{\mu\nu} G^{\mu\nu} \frac{h}{v} + c_{\gamma\gamma} \frac{e^2}{16\pi^2} F_{\mu\nu} F^{\mu\nu} \frac{h}{v}$$
Example: Double Higgs production

- **Nonlinear EFT.** Modifications at LO:

- **Linear EFT.** LO is the SM diagrams. Modifications: similar topologies but at NLO...
Conclusions

- The $\kappa$ formalism can be embedded in a consistent QFT framework if interpreted as the leading Lagrangian of a (nonlinear) EFT. Well-defined way to improve it to include kinematical distributions (though very suppressed...)

- Nonlinear EFT has a modified Higgs sector: anomalous couplings at LO $\mathcal{L}_{\chi=2} \neq \mathcal{L}_{SM}$; anomalous shapes at NLO. Natural hierarchy between the Higgs and gauge-fermion sector. Transition to the SM (Standard Higgs without New Physics) smooth ($\xi$) and well-defined.

- Linear EFT not the right tool: canonical Higgs boson with anomalous Higgs couplings generated from New Physics at NLO (\% effects).

- For more info, check YR4 (soon to be released).