Higgs couplings: upgrading the κ formalism with EFTs

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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 κ formalism?

What is the κ formalism?

- Signal-strength based parametrization of Higgs decay channels:

$$\mu_j = \frac{\Gamma_j^{\rm exp}}{\Gamma_j^{SM}}$$

- 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]

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

$\Delta\kappa/\kappa[\%](300\ \text{fb}^{-1})$	$\gamma\gamma$	WW	ZZ	gg	$\tau\tau$	bb	tt	$\mu\mu$	$Z\gamma$
ATLAS	13 (8)	8 (7)	8 (7)	11 (9)	18 (13)	κ_τ	22 (20)	23 (21)	79 (78)
CMS	7 (5)	6 (4)	6 (4)	8 (6)	8 (6)	13 (10)	15 (14)	23 (23)	41 (41)

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 Φ)

$$\Phi = \begin{pmatrix} \varphi_1 + i\varphi_2 \\ \varphi_3 + i\varphi_4 \end{pmatrix}$$

- 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 κ 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: [Buchmueller et al'86;Grzadkowski et al'10]

X^3 (LG)		φ^6 and $\varphi^4 D^2$ (PTG)		$\psi^2\varphi^3$ (PTG)	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$ (LG)		$\psi^2 X\varphi$ (LG)		$\psi^2\varphi^2 D$ (PTG)	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

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

$$\mathcal{L}_{SM} = -\frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + i\sum_j \bar{f}_j \not{D} f_j + \frac{1}{2}\partial_\mu h \partial^\mu h$$
$$+ \frac{v^2}{4}\langle D_\mu U D^\mu U^\dagger\rangle \left(1+\frac{h}{v}\right)^2 - v\left[\bar{\psi} Y_\psi U P_\pm \psi + \text{h.c.}\right]\left(1+\frac{h}{v}\right) - \frac{\lambda}{4}(h^2-v^2)^2$$

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

$$\mathcal{L}_{LO} = -\frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + i\sum_j \bar{f}_j \not{D} f_j + \frac{1}{2}\partial_\mu h \partial^\mu h$$
$$+ \frac{v^2}{4}\langle D_\mu U D^\mu U^\dagger\rangle f_U(h) - v\left[\bar{\psi} f_\psi(h) U P_\pm \psi + \text{h.c.}\right] - V(h)$$

with

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

- 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:

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

- 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.

$$\mathcal{L}_{\chi=2} = -\frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + i\sum_j \bar{f}_j \not{D} f_j + \frac{1}{2}\partial_\mu h \partial^\mu h$$
$$+ \frac{v^2}{4}\langle D_\mu U D^\mu U^\dagger\rangle f_U(h) - v\left[\bar{\psi} f_\psi(h) U P_\pm \psi + \text{h.c.}\right] - V(h)$$

EFTs at the EW scale: the generic case

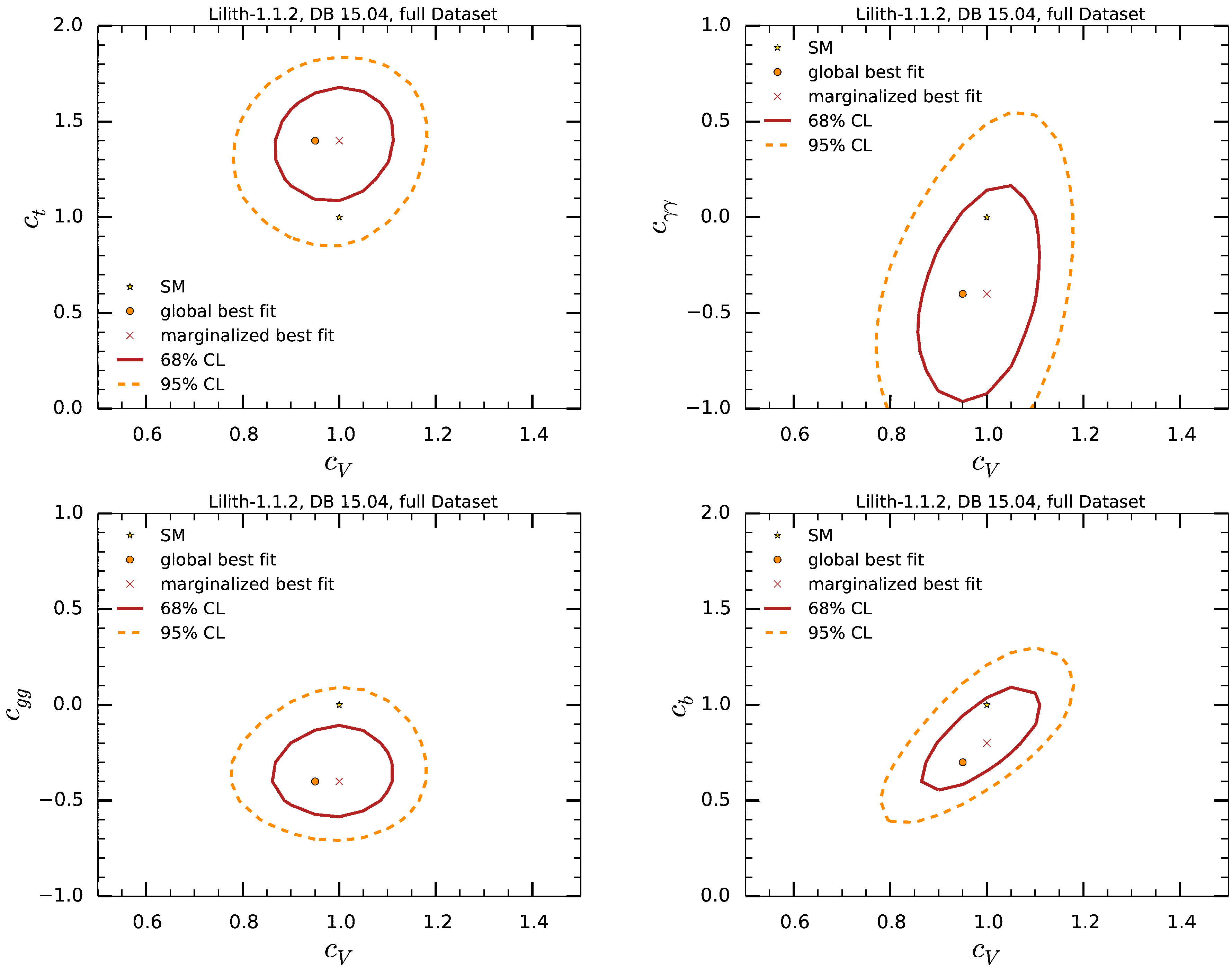
REMARKS:

- 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 κ 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 $\mathcal{O}(10\%)$ level.
- Natural framework for the κ formalism, with deviations in shapes at NLO ($\sim 10^{-2}\xi$).
- Going to the unitary gauge, the LO Lagrangian relevant for Higgs couplings reads:

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


Lilith-1.1.2, DB 15.04, full Dataset
SM
global best fit
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Lilith-1.1.2, DB 15.04, full Dataset
SM
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marginalized best fit
68% CL
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c_b
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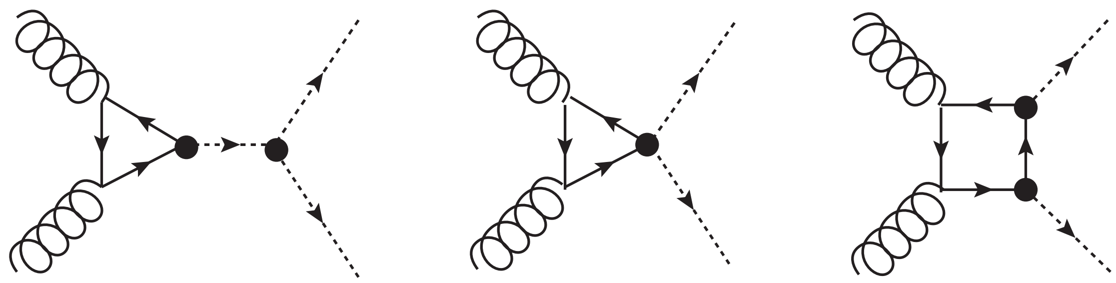
Example: Double Higgs production

- Nonlinear EFT. Modifications at LO:



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

Conclusions

- The κ 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 (ξ) 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).