Nonlinear Higgs EFT at Run-2

Oscar Catà
LMU Munich

LHCHXSWG meeting, CERN, July 15, 2015

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

Motivation

- Higgs couplings currently SM-like to $\mathcal{O}(10\%)$.
- With this precision, nature of Higgs mechanism still unclear.
- Bottomline of this talk:

  (i) Nonlinear Lagrangian as systematic EFT.

  (ii) Natural framework to test for sizable nonstandard Higgs effects.

  (iii) Well-defined limit to the SM.

- Assuming the existence of a mass gap, most conservative and least biased EFT choice.

Nonlinear EFT at LO

Leading order Lagrangian: [Ferruglio'93; Contino et al.'10; Buchalla+OC+Krause'13]

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

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

with

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

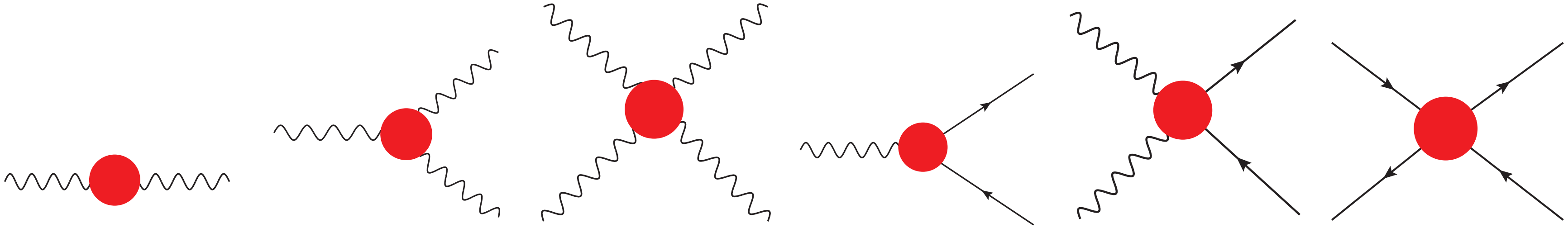
- $\mathcal{L}_{LO} \neq \mathcal{L}_{SM}$ due to red-coded Higgs functions: large deviations (at the percent level) naturally expected.
- Expansion in loops, or equivalently in chiral dimensions

$$[\varphi;\ h;\ A_\mu]_\chi = 0, \qquad [\partial_\mu;\ \bar{\psi}\Gamma\psi;\ g;\ y]_\chi = 1$$

Nonlinear EFT at NLO

Operator building at every order: assemble building blocks $(U, \psi, X$ and derivatives) in accordance with the power-counting formula.

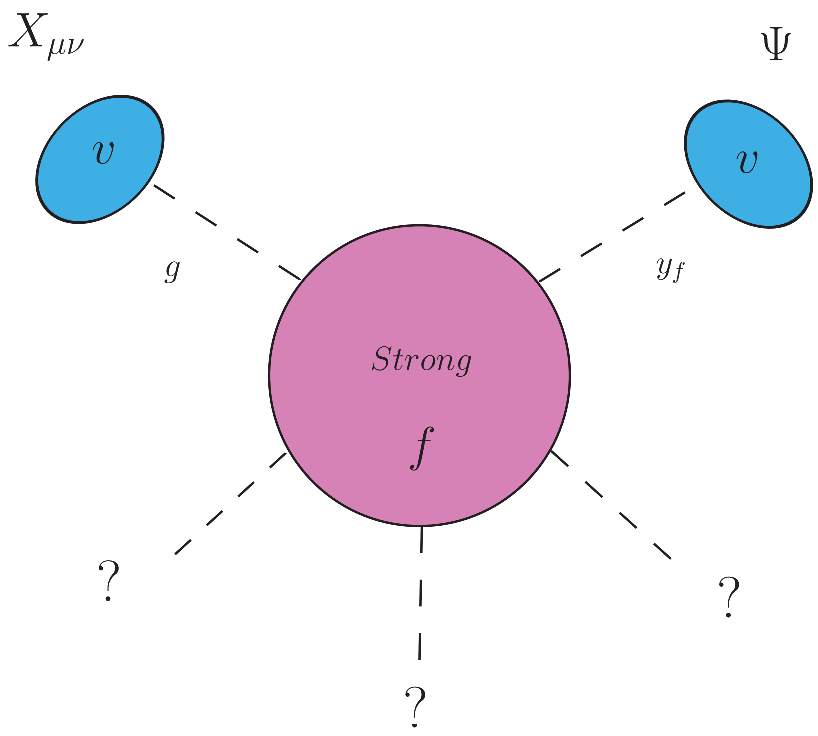
- NLO: 6 classes, which correspond to corrections to the vertices



with an arbitrary number of Higgs insertions.

- Of relevance in processes that are subleading (loop-suppressed) in the SM, *e.g.*, $h \to \gamma\gamma$, $h \to gg$, $h \to Z\gamma$.

Scales of the problem



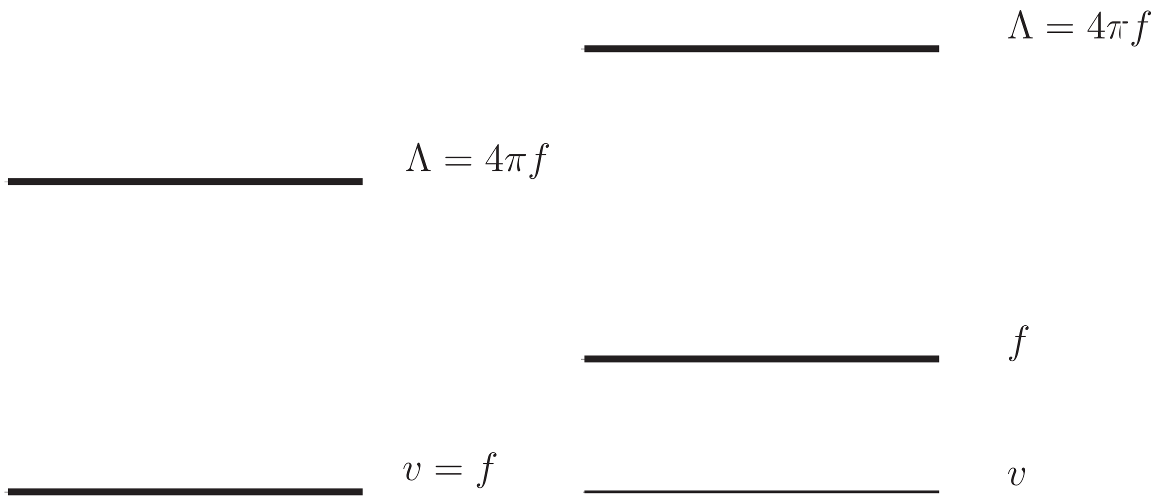
- Multiscale problem: v, f, $\Lambda = 4\pi f$. Dynamics is described with the dimensionless parameters

$$\xi = \frac{v^2}{f^2} \qquad \ell = \frac{f^2}{\Lambda^2} \sim \frac{1}{16\pi^2}$$

- Strong sector can be decoupled, *e.g.* vacuum misalignment mechanism [Georgi et al'84]. SM recovered as a limiting case.

Playing with the ξ knob

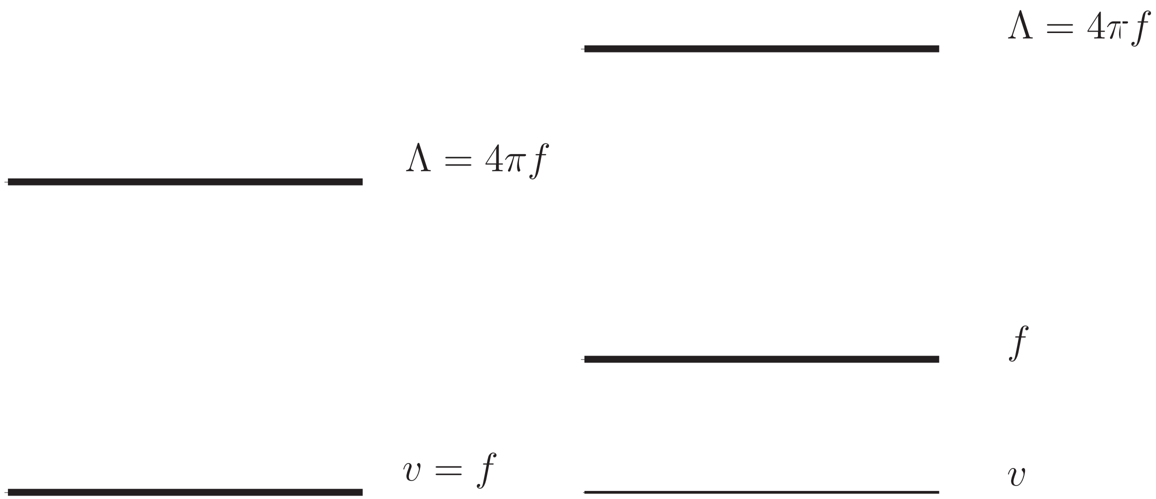
- Transition between nondecoupling (composite) and decoupling (fundamental) interactions.



- The transition can be gauged with the parameter $\xi = \dfrac{v^2}{f^2}$:
  - $\xi \to 1$: Strongly-coupled regime (purely loop expansion).
  - $\ell < \xi < 1$: Strong-dominated dynamics (hybrid expansion in (ℓ, ξ)).
  - $\xi \sim \ell \sim 10^{-2}$: Effectively a dimensional expansion.
  - $\xi \to 0$: decoupling (SM) limit.
- At present, experimental bound at $\xi \sim 10^{-1}$ vs $\ell \sim 10^{-2}$. Strong-dominated dynamics is the setting to explore given the current precision.

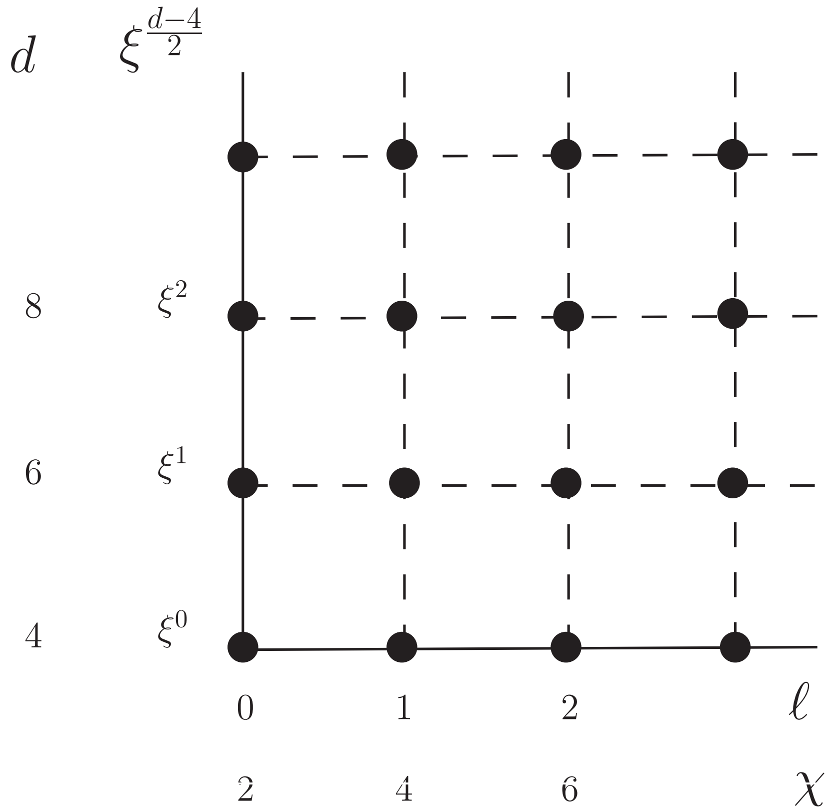
Playing with the ξ knob

- Transition between nondecoupling (composite) and decoupling (fundamental) interactions.

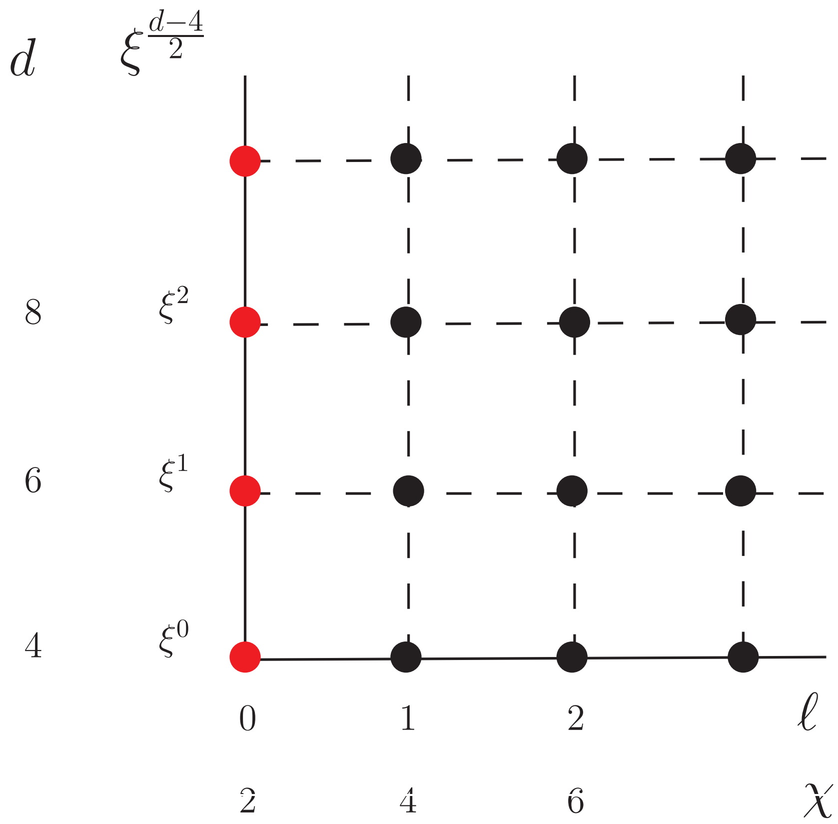


- The transition can be gauged with the parameter $\xi = \dfrac{v^2}{f^2}$:
  - $\xi \to 1$: ~~Strongly coupled regime (purely loop expansion)~~
  - $\ell < \xi < 1$: Strong-dominated dynamics (hybrid expansion in (ℓ, ξ)).
  - $\xi \sim \ell \sim 10^{-2}$: Effectively a dimensional expansion.
  - $\xi \to 0$: decoupling (SM) limit.
- At present, experimental bound at $\xi \sim 10^{-1}$ vs $\ell \sim 10^{-2}$. Strong-dominated dynamics is the setting to explore given the current precision.

Loop vs dimensional expansion

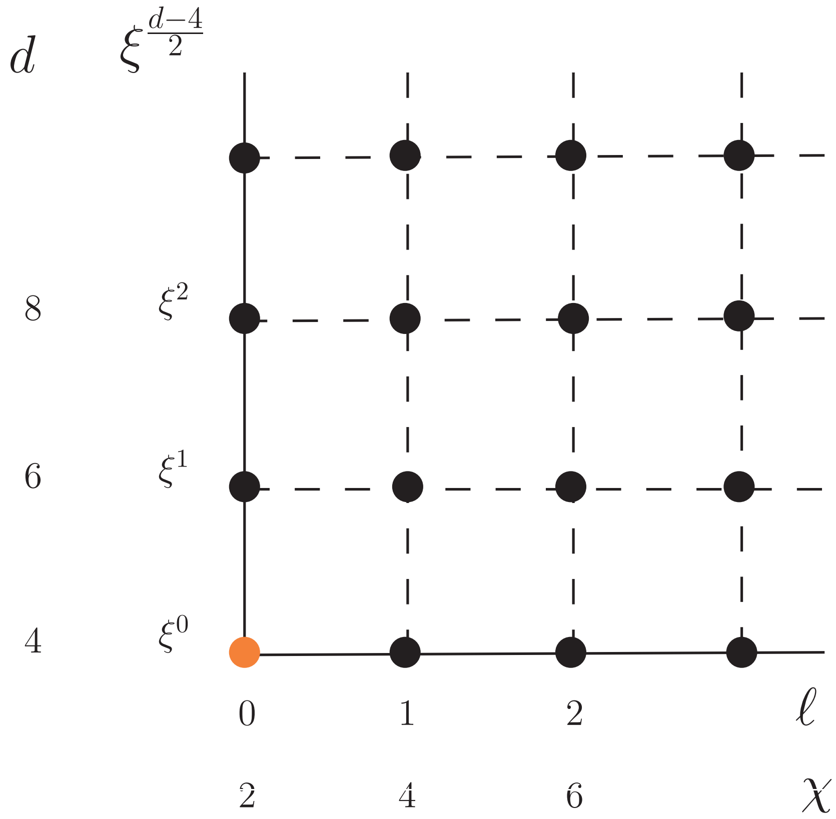


Loop vs dimensional expansion



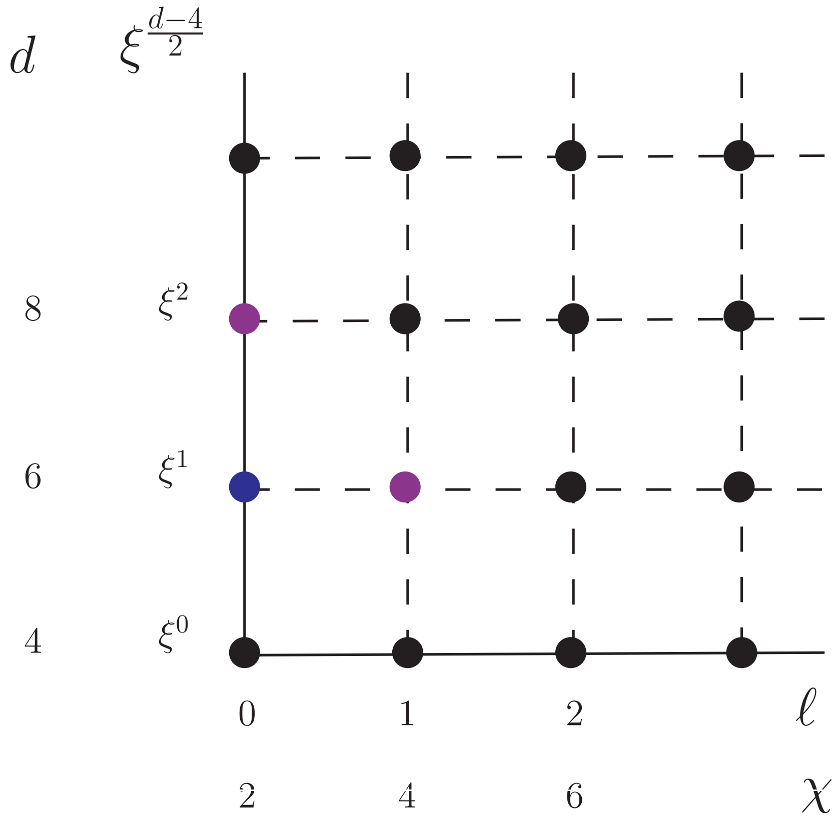
- $\mathcal{L}_{LO}$ amounts to a resummation of the ξ expansion.

Loop vs dimensional expansion



- $\mathcal{L}_{SM}$ is recovered from $\mathcal{L}_{LO}$ when $\xi \to 0$.

Loop vs dimensional expansion



- Beyond LO in the double expansion: $\mathcal{L}_{LO}(\xi^2)$ is in general more important than $\mathcal{L}_{NLO}(\xi)$.

$$\xi = \frac{v^2}{f^2}; \qquad \frac{\xi}{16\pi^2} = \frac{v^2}{f^2}\left(\frac{f^2}{\Lambda^2}\right); \qquad \xi^2 = \frac{v^2}{f^2}\left(\frac{v^2}{f^2}\right)$$

EFT fitting strategy 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 $5-10\%$.

EFT fitting strategy at the LHC

Experiment is allowing right now deviations in the LO SM Higgs couplings around 10%. This is 2 orders of magnitude bigger than the EW precision reached at LEP.

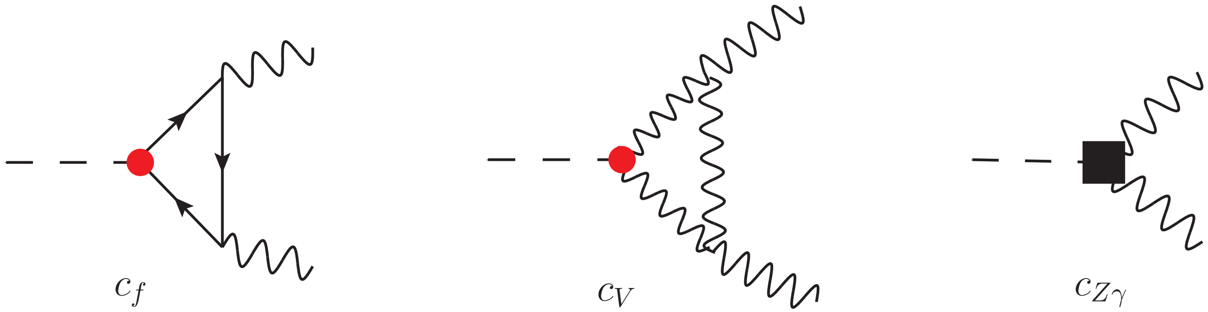
PROPOSAL FOR RUN-2: [Buchalla+OC+Celis+Krause'15]

$$\mathcal{L} = 2c_V \left(m_W^2 W_\mu W^\mu + \frac{1}{2} Z_\mu Z^\mu\right)\frac{h}{v} - \sum_{f=t,b,\tau} c_f y_f \bar{f} f h + c_{gg}\frac{g_s^2}{16\pi^2} G_{\mu\nu}G^{\mu\nu}\frac{h}{v} + c_{\gamma\gamma}\frac{e^2}{16\pi^2}F_{\mu\nu}F^{\mu\nu}\frac{h}{v}$$

- Subset of nonlinear operators capturing leading corrections to single Higgs processes: $h \to \bar{f} f$ and $h \to X_\mu X_\mu$. Corrections at $\mathcal{O}(10\%)$ naturally expected.
- Easy to handle: fit to experimental data with only 6 parameters.
- Precision goal around 5%: feasible target for Run-2.
- New physics at NLO precision not required for Run-2.
- Very similar to κ formalism but EFT-based. In particular, this means that it can be systematically improved with well-known QFT tools if needed (renormalization, etc.)

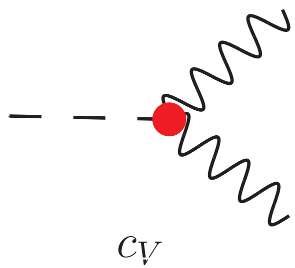
Examples at NLO: $h \to Z\gamma$ *and* $h \to ZZ$

$h \to Z\gamma$ loop-suppressed in the SM.



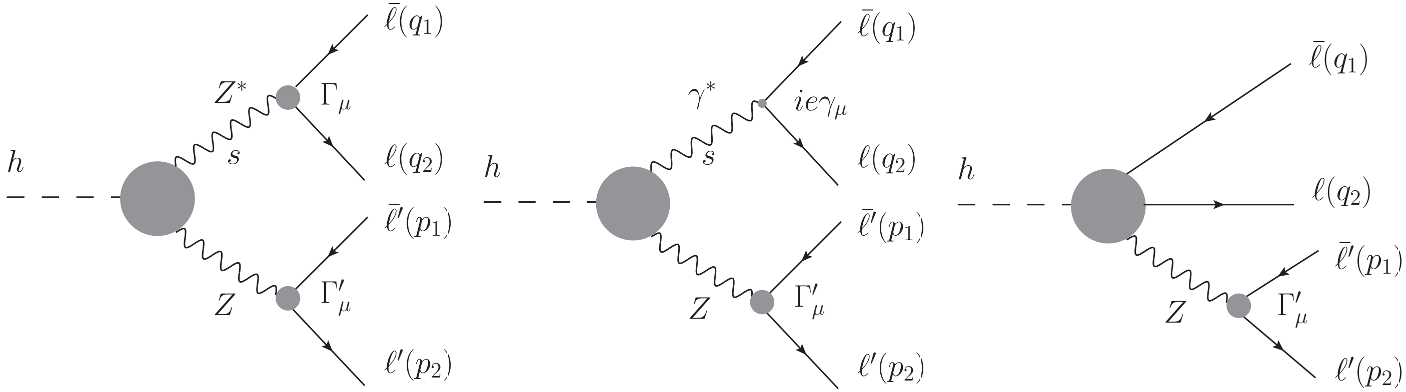
Non-Higgs couplings are suppressed (NNLO). Fewer operators than in the linear case.

$h \to ZZ$ tree-level in the SM ($hZ_\mu Z_\mu$)



Examples at NLO: $h \to Z\gamma$ *and* $h \to ZZ$

$h \to ZZ^*$ at NLO ($hZ_{\mu\nu}Z_{\mu\nu}$): sensitivity in shapes (asymmetries)



- Decorrelations wrt linear case: contact term not constrained by $Z \to \ell^+\ell^-$ at LEP.
- Easy to make contact with Pseudo-Observables.

Conclusions

- EFTs are the right tool to extract unbiased information from experimental data. Important to pick the most generic one allowed by current status of experiments.

- At present, $v^2/f^2 \sim 10^{-1}$ and strong dynamics still experimentally allowed. The most conservative fitting procedure is to consider $\mathcal{L}_{\chi=2} \neq \mathcal{L}_{SM}$. Very few parameters, ideal for the LHC (discovery machine). Justification and systematic extension of the so-called κ-formalism.

- Nonlinear fit is (mostly) LO and requires a precision goal of 5%. Fits Run-2 precision prospects.

- NLO level: renormalization programme not (yet) executed but well-defined. Similar to linear case: more operators and precision goal at the permille level.