NEW PHYSICS IN THE HIGGS SECTOR – AN EFFECTIVE THEORY APPROACH

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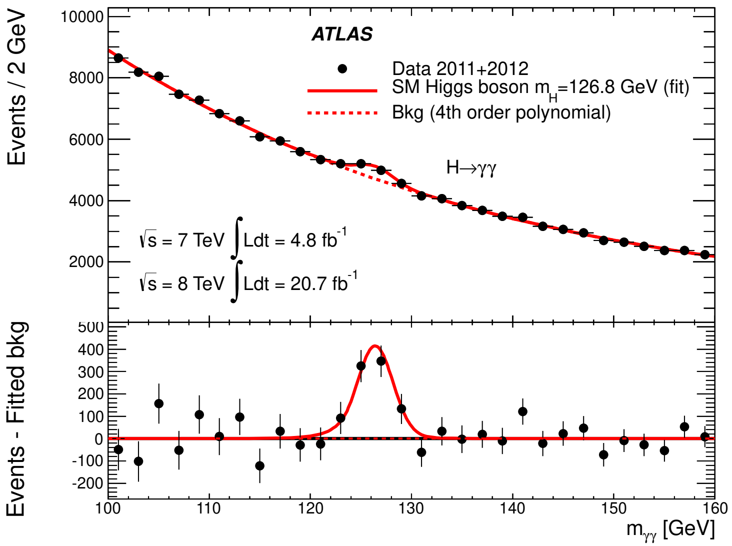
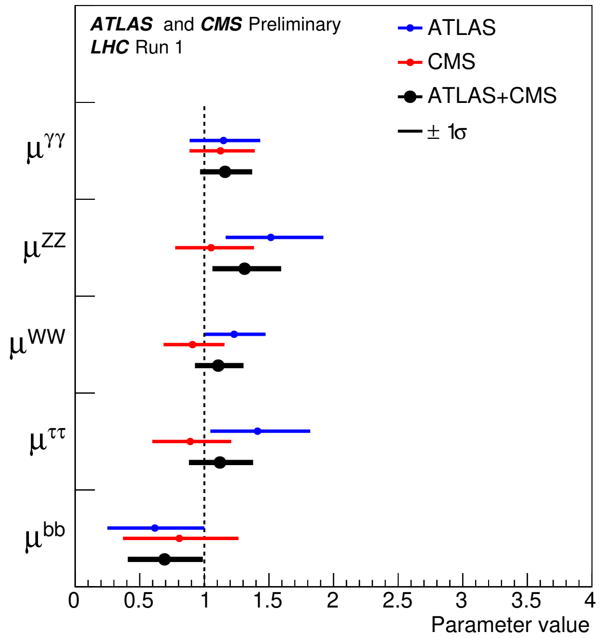
- Anomalous Higgs couplings
- Electroweak chiral Lagrangian
- Systematics and power counting
- Applications



G.B., Oscar Catà, Alejandro Celis, Claudius Krause



$\leftrightarrow$ electroweak symmetry breaking?

SM unnatural, $m_h \ll \Lambda$; no other new particles (so far)

$\rightarrow$ Effective Field Theory

- quarks, leptons, $SU(3)_C$, $SU(2)_L$, $U(1)_Y$

- Goldstones φ^a, $\qquad U = \exp(2i\varphi^a T^a/v)$
  EW chiral Lagrangian *Appelquist, Longhitano*

- light Higgs h

$$U \to g_L U g_R^\dagger, \qquad h \to h, \qquad g_{L,R} \in SU(2)_{L,R}$$

relation to Higgs doublet:

$$(\tilde{\Phi}, \Phi) \equiv (v+h)U$$

$$\mathcal{L}_{LO} = -\frac{1}{2}\langle G_{\mu\nu}G^{\mu\nu}\rangle - \frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \bar{\psi} i \not{D} \psi$$

$$+\frac{v^2}{4}\,\langle D_\mu U^\dagger D^\mu U\rangle\,(1 + F_U(h/v)) + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h)$$

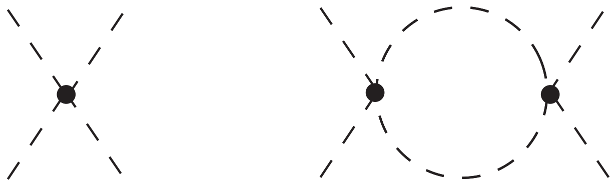
$$-v\left[\sum_{n=0}^{\infty} \bar{q}\hat{Y}_u^{(n)} U P_+ r \left(\frac{h}{v}\right)^n + \text{h.c.} + \ldots\right]$$

- $U = \exp(2i\varphi^a T^a/v)$, $\qquad F_U(h/v) = \sum_{n=1}^{\infty} f_n (h/v)^n$, etc.
- SM: $\qquad f_1 = 2$, $\qquad f_2 = 1$, $\qquad f_{n>2} = 0$, etc.
- deviations $\sim \xi \equiv v^2/f^2$; $\qquad \xi \sim 10\%$ still allowed
- $\mathcal{L}_{LO}$ non-renormalizable, cut-off $\Lambda = 4\pi f$ $\qquad \rightarrow \qquad$ EWχL

Nonlinear realization of EWSB

Weinberg; Callan, Coleman, Wess, Zumino; Gasser, Leutwyler

- $U = \exp(2i\varphi^a T^a/v)$: $SU(2)_L \otimes SU(2)_R \to SU(2)_V$ nonlinear
- $\frac{v^2}{4} \langle D_\mu U^\dagger D^\mu U \rangle$: contains all powers of φ^a
- nonrenormalizable, nonperturbative $\to$ loop expansion
- LO: $\frac{p^2}{v^2}$ $\leftrightarrow$ NLO: $\gtrsim \frac{1}{16\pi^2}\frac{p^4}{v^4}$
- relative correction $p^2/16\pi^2 v^2 \to$ cut-off $\Lambda = 4\pi v$
- NLO coefficient $\gtrsim 1/16\pi^2 = v^2/\Lambda^2$



Basic assumptions

- **particle content** of SM, mass gap

  gauge bosons and fermions weakly coupled to Higgs dynamics

- **symmetries**: SM gauge symmetries

  conservation of lepton and baryon number

  conservation *at lowest order* of custodial symmetry,

  CP invariance in the Higgs sector, (fermion flavour).

- **power counting** by chiral dimensions $\Leftrightarrow$ loop expansion

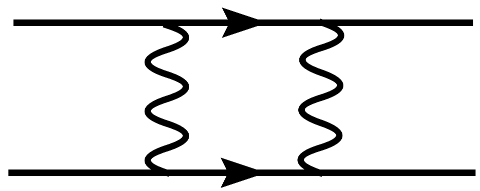
Loop counting $\equiv$ chiral counting

Urech; Knecht, Neufeld, Rupertsberger, Talavera; G.B., Catà, Krause

chiral dimensions: $[A_\mu, \varphi, h]_c = 0, \quad [\partial_\mu, g, y, \psi\bar{\psi}]_c = 1$

loop order: $2L + 2 = \Sigma \; (chiral\ dim.)$

example: $4_p - 6_p + 4_g + 2_\psi = 4$



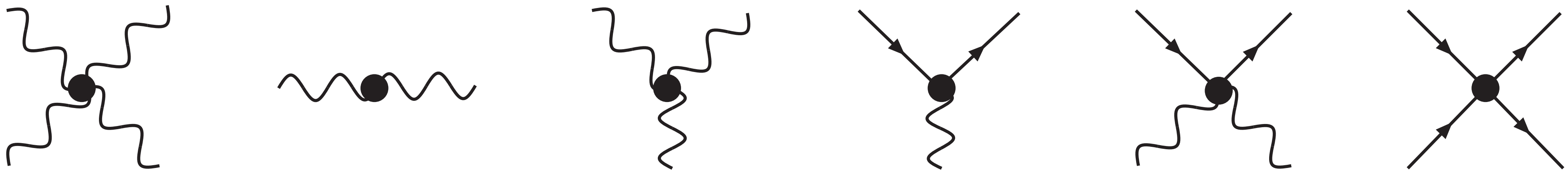
$\Rightarrow [\mathcal{L}_{LO}]_c = 2, \qquad [\mathrm{NLO}]_c = 4 \qquad$ (local terms; D^n, $n \geq 0$)

$$UhD^4, \quad g^2X^2Uh, \quad gXUhD^2, \quad y^2\psi^2UhD, \quad y\psi^2UhD^2, \quad y^2\psi^4Uh$$

- $\bar{\psi}\psi\bar{\psi}\psi$, X^2Uh not LO

$\longrightarrow$ classification of NLO operators

$$UhD^4, \quad X^2Uh, \quad XUhD^2, \quad \psi^2UhD, \quad \psi^2UhD^2, \quad \psi^4Uh$$



NLO counterterms: *G.B., Catà, Celis, Knecht, Krause; Alonso et al.*

super-heat-kernel expansion: *Neufeld, Gasser, Ecker*

Loop vs. dimensional counting

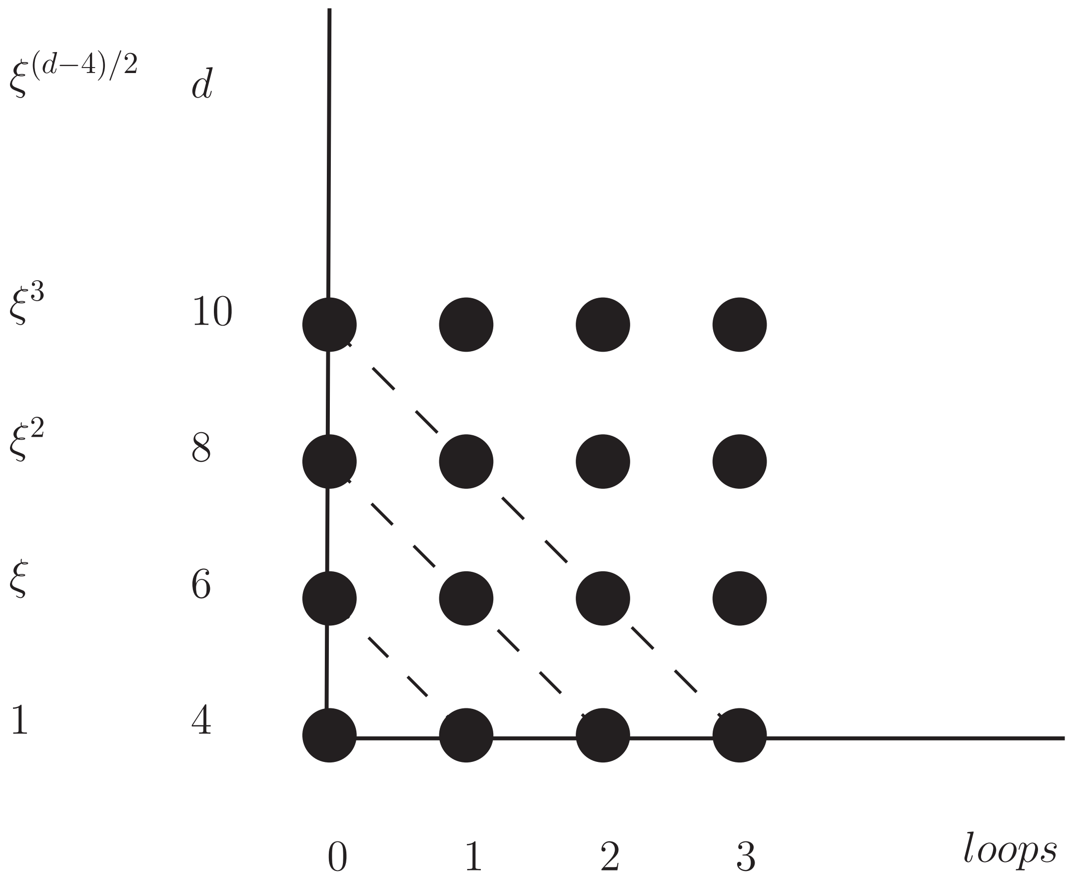
$$\Lambda = 4\pi f$$

$$f$$

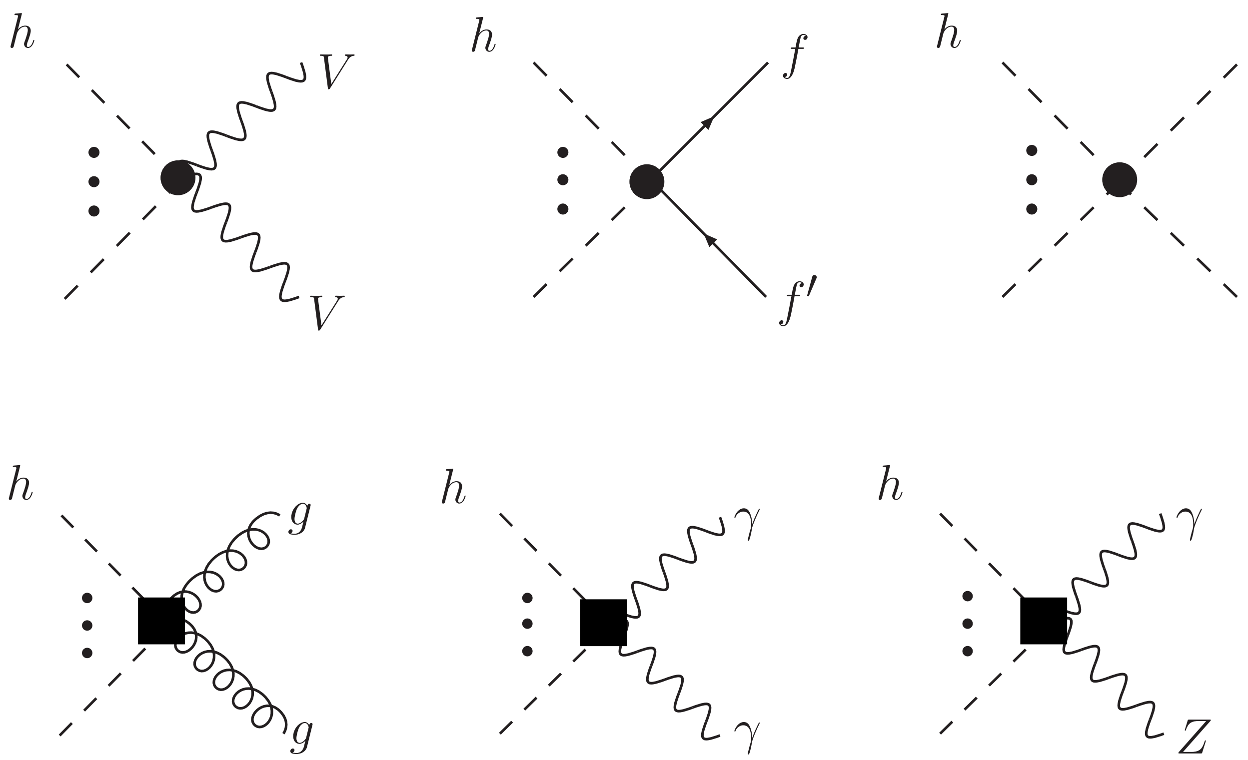
$$v$$

$$\xi = \frac{v^2}{f^2} \to \text{dim. exp.}$$

$$\frac{1}{16\pi^2} \approx \frac{f^2}{\Lambda^2} \to \text{loop exp.}$$



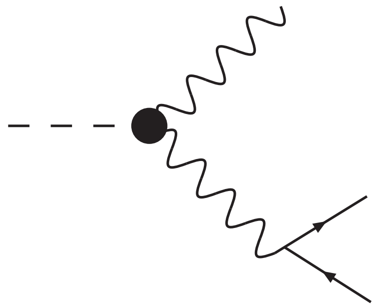
LO couplings



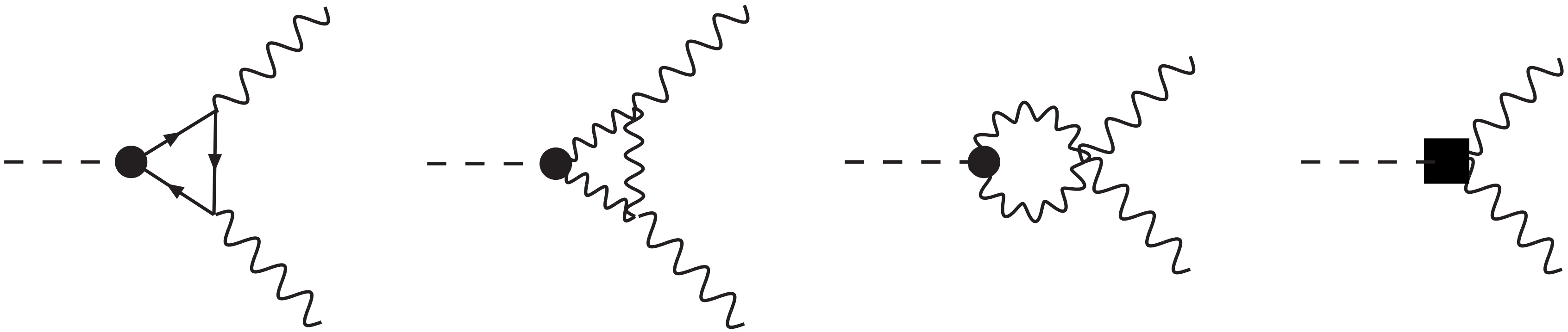
$$\mathcal{L} = 2c_V \left(m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu\right) \frac{h}{v} - c_t y_t \bar{t} t h - c_b y_b \bar{b} b h - c_\tau y_\tau \bar{\tau} \tau h$$
$$+ \frac{e^2}{16\pi^2} c_{\gamma\gamma} F_{\mu\nu} F^{\mu\nu} \frac{h}{v} + \frac{g_s^2}{16\pi^2} c_{gg} \langle G_{\mu\nu}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

Sample applications

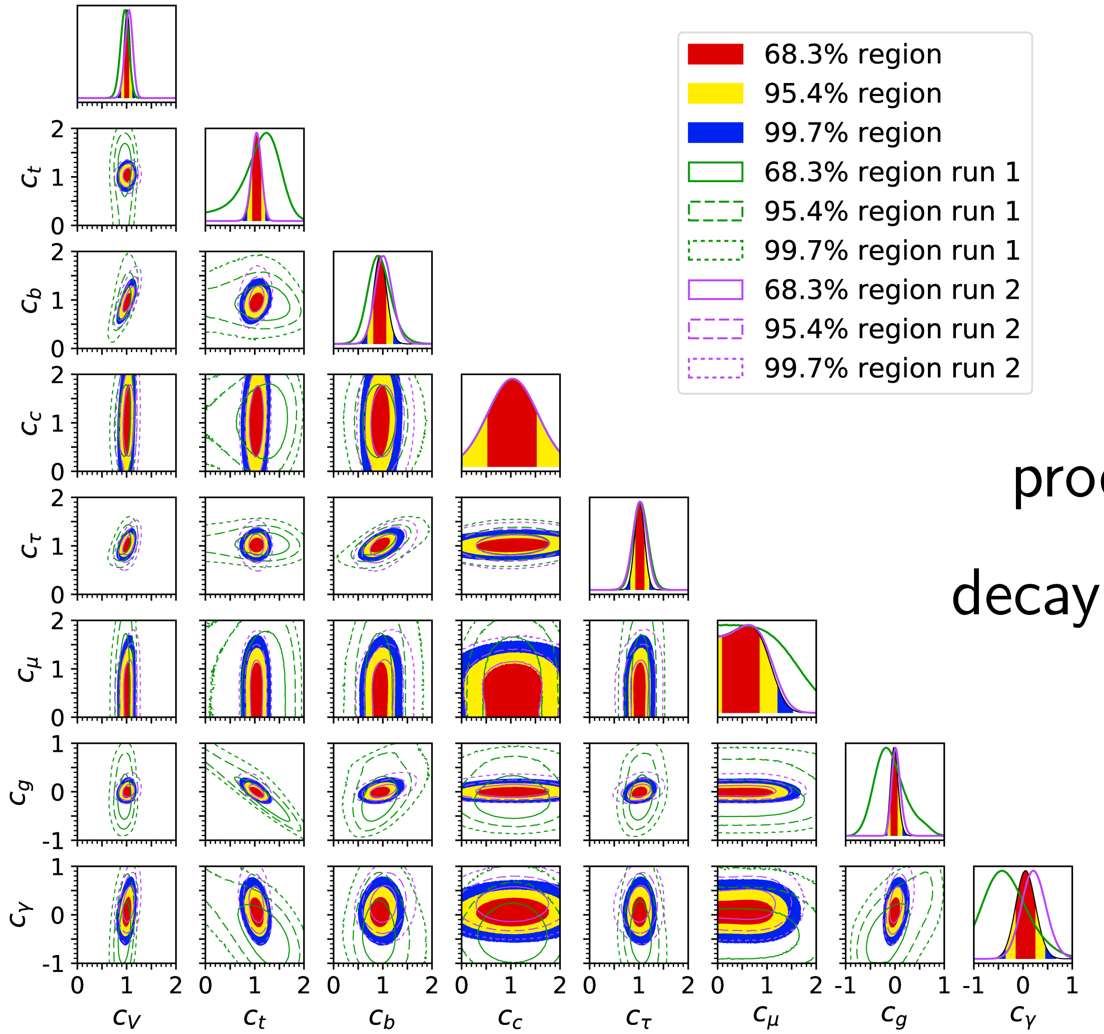
$h \to Z\ell^+\ell^-$



$h \to \gamma\gamma$



Higgs coupling fit ATLAS/CMS/Tevatron



production: ggh, Wh/Zh, VBF, $t\bar{t}h$

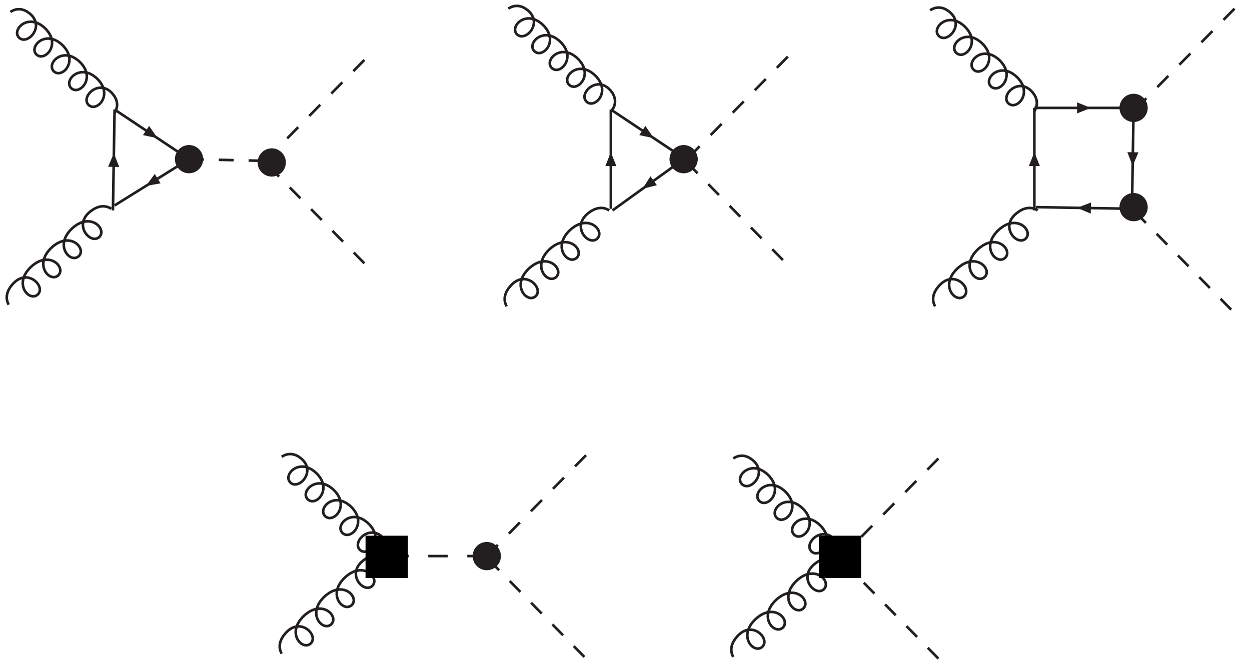
decay: $h \to \gamma\gamma$, WW, ZZ, $b\bar{b}$, $\tau\bar{\tau}$, $\ldots$

de Blas, Eberhardt, Krause, '18

Main benefits

- focus on anomalous Higgs couplings
- limited number of parameters
- well adapted to LHC precision with 300 fb^{-1} (Run 2 and 3)
- QFT justification of (one particular) κ-formalism

Higgs-pair production in gluon fusion



Gröber, Mühlleitner, Spira, Streicher

Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Zirke

G.B., Capozi, Celis, Heinrich, Scyboz

Summary

- natural framework for sizable NP in Higgs couplings
- power counting by chiral dimensions
- consistent EFT, systematic improvement possible
- LO description $\leftrightarrow$ κ-formalism