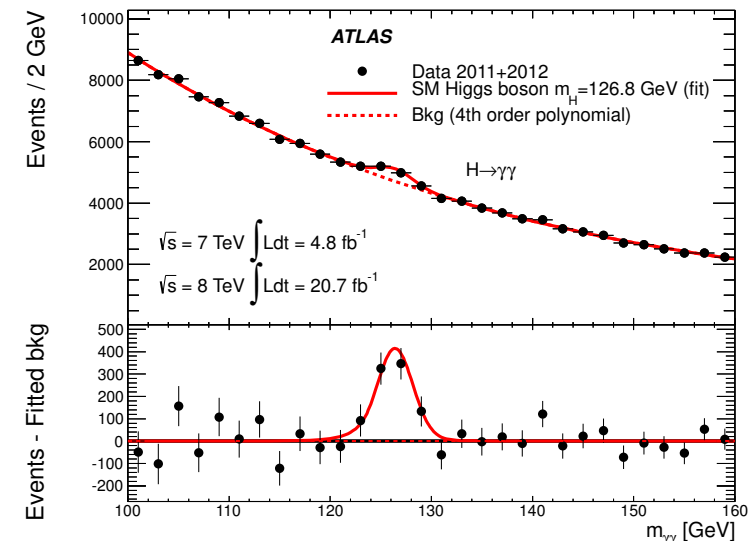


NEW PHYSICS IN THE HIGGS SECTOR – AN EFFECTIVE THEORY APPROACH

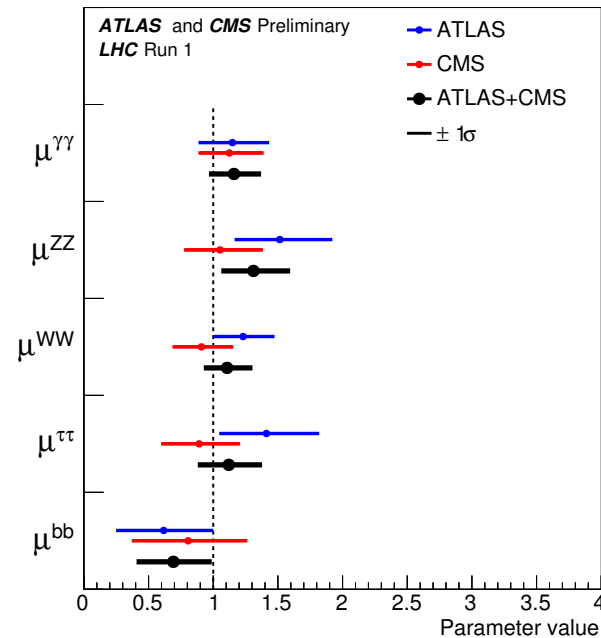
Gerhard Buchalla
LMU München

(Informal) MPP Seminar – 23 February 2017

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



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



↔ electroweak symmetry breaking?

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

→ Effective Field Theory

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

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

Appelquist, Longhitano

- light Higgs h

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

special case:

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

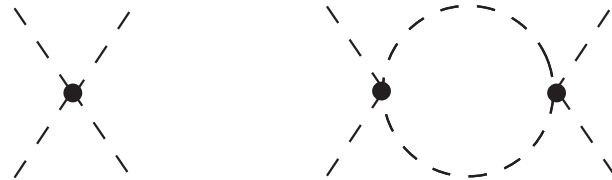
$$\begin{aligned}
 \mathcal{L}_{LO} = & -\frac{1}{2}\langle G_{\mu\nu}G^{\mu\nu}\rangle - \frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \bar{\psi}i\not{D}\psi \\
 & + \frac{v^2}{4}\langle D_\mu U^\dagger D^\mu U\rangle (1 + F_U(h/v)) + \frac{1}{2}\partial_\mu h\partial^\mu h - V(h) \\
 & - v \left[\sum_{n=0}^{\infty} \bar{q}\hat{Y}_u^{(n)}UP_{+r} \left(\frac{h}{v}\right)^n + \text{h.c.} + \dots \right]
 \end{aligned}$$

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

Nonlinear realization of EWSB

Weinberg; Callan, Coleman, Wess, Zumino

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



- **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

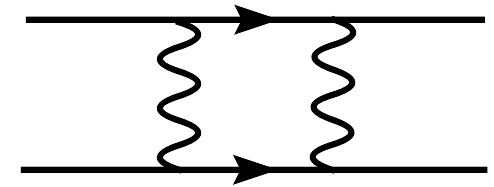
Loop counting \equiv chiral counting

Urech; Nyffeler, Schenk; Hirn, Stern; 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: $4_p - 6_p + 4_g + 2_\psi = 4$



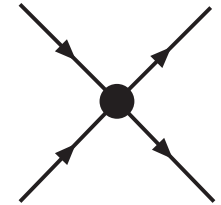
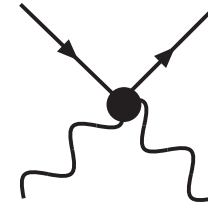
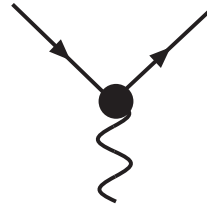
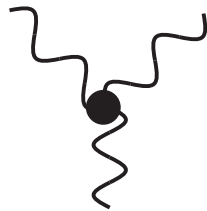
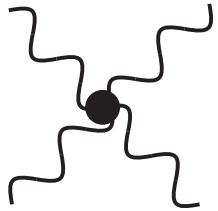
$\Rightarrow [\mathcal{L}_{LO}]_c = 2, \quad [\text{NLO}]_c = 4 \quad (\text{local terms; } D^n, n \geq 0)$

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

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

→ classification of NLO operators

UhD^4 , X^2Uh , $XUhD^2$, ψ^2UhD , ψ^2UhD^2 , ψ^4Uh



related work: [Giudice et al.](#), [Contino et al.](#), [Alonso et al.](#), [Kilian et al.](#)

Loop vs. dimensional counting

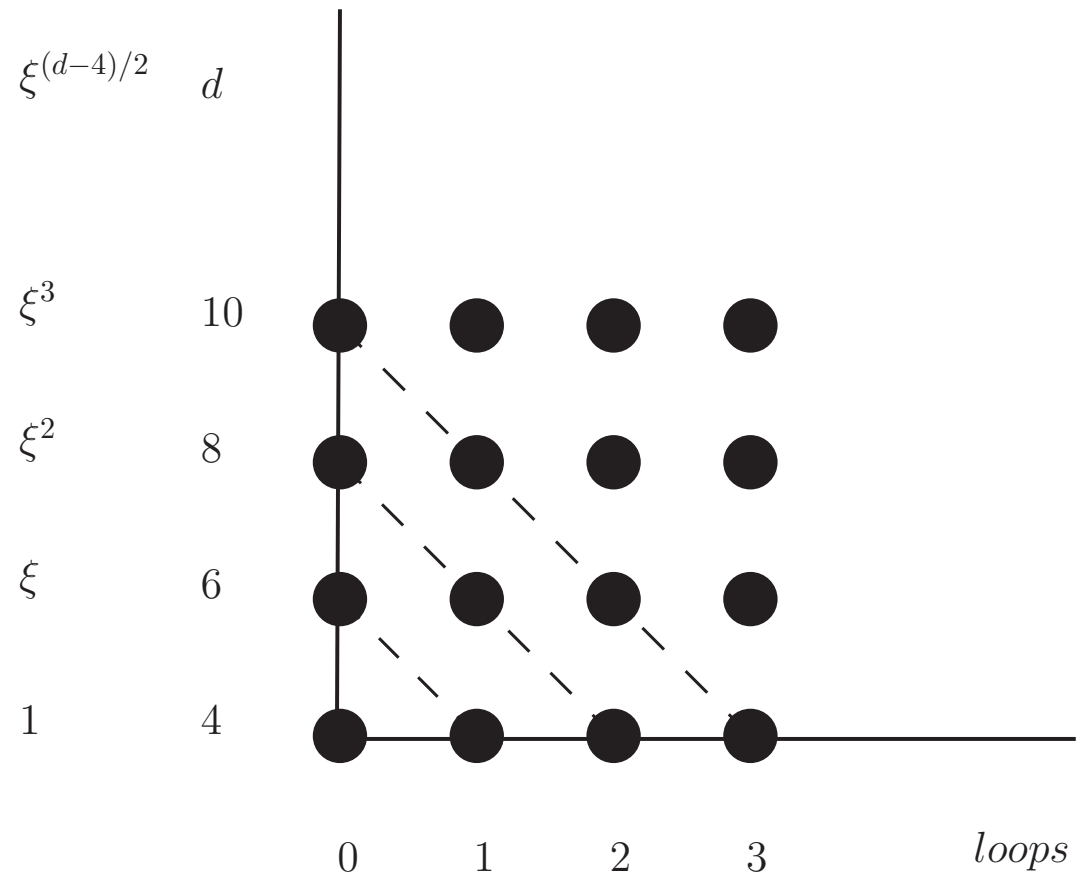
$$\Lambda = 4\pi f$$

f

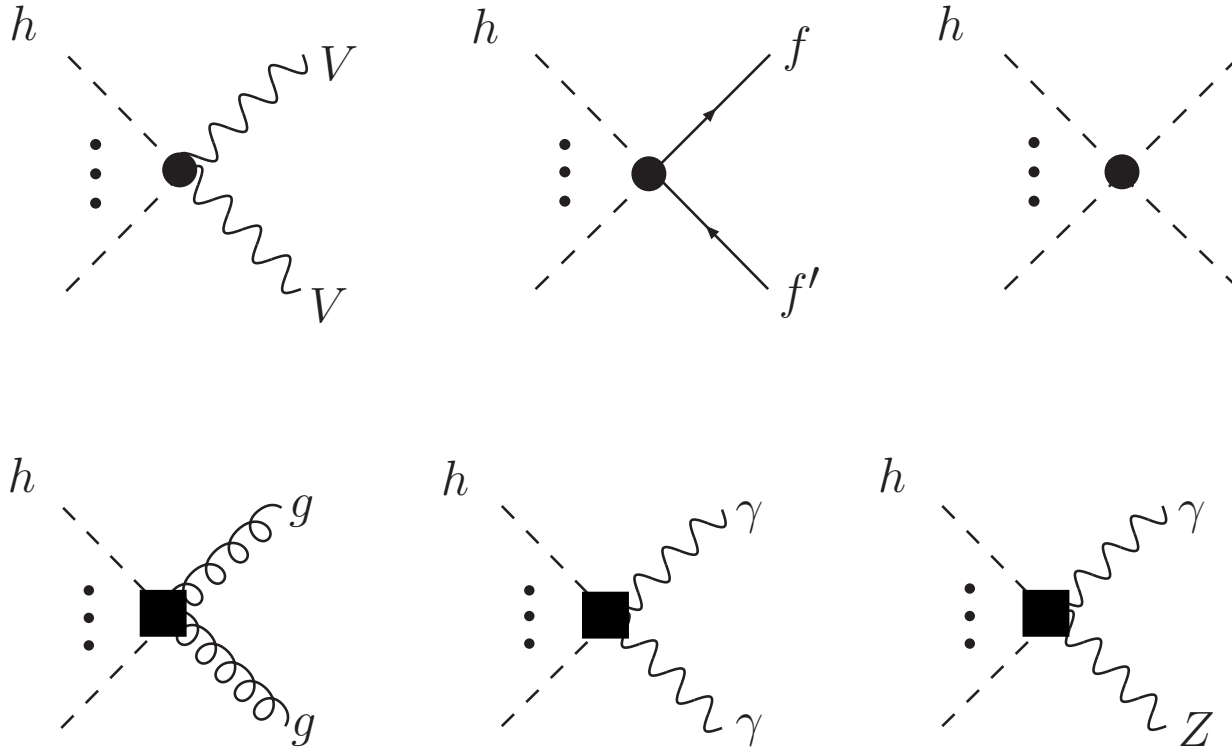
v

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

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



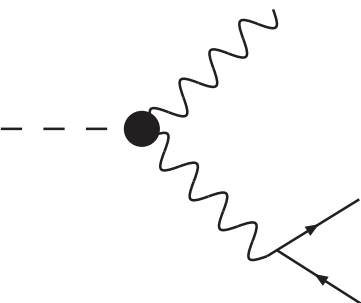
LO couplings



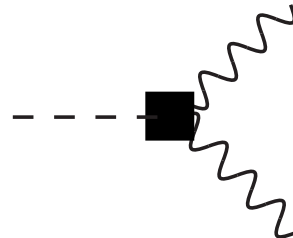
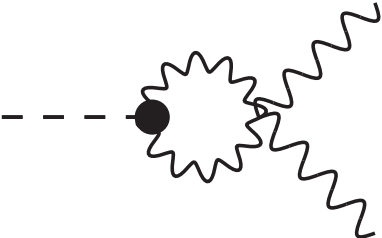
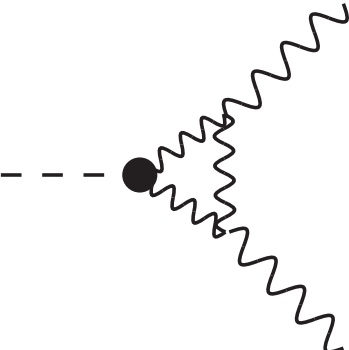
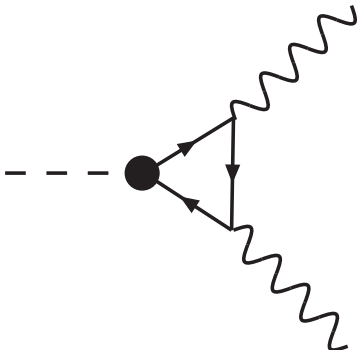
$$\begin{aligned}
 \mathcal{L} = & 2c_V \left(m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \right) \frac{h}{v} - c_t y_t \bar{t} t h - c_b y_b \bar{b} b h - c_\tau y_\tau \bar{\tau} \tau h \\
 & + \frac{e^2}{16\pi^2} c_{\gamma\gamma} F_{\mu\nu} F^{\mu\nu} \frac{h}{v} + \frac{g_s^2}{16\pi^2}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

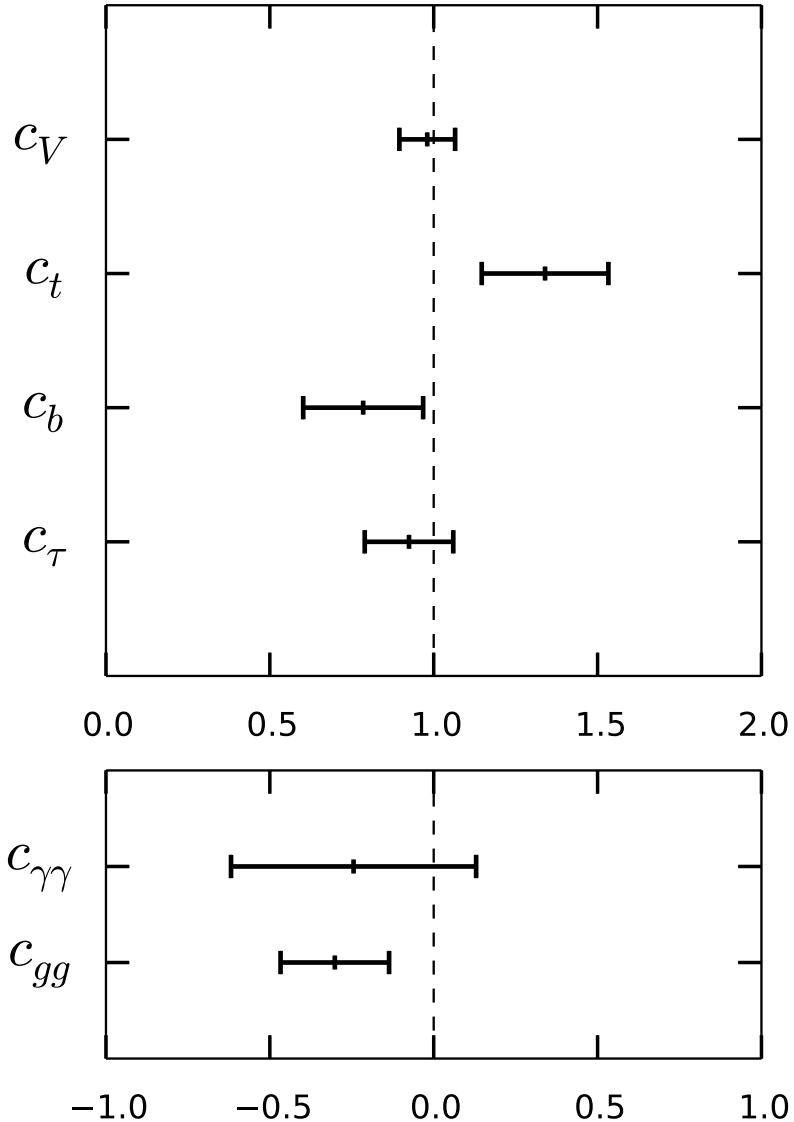
Sample applications

$$h \rightarrow Zl^+l^-$$



$$h \rightarrow \gamma\gamma$$





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

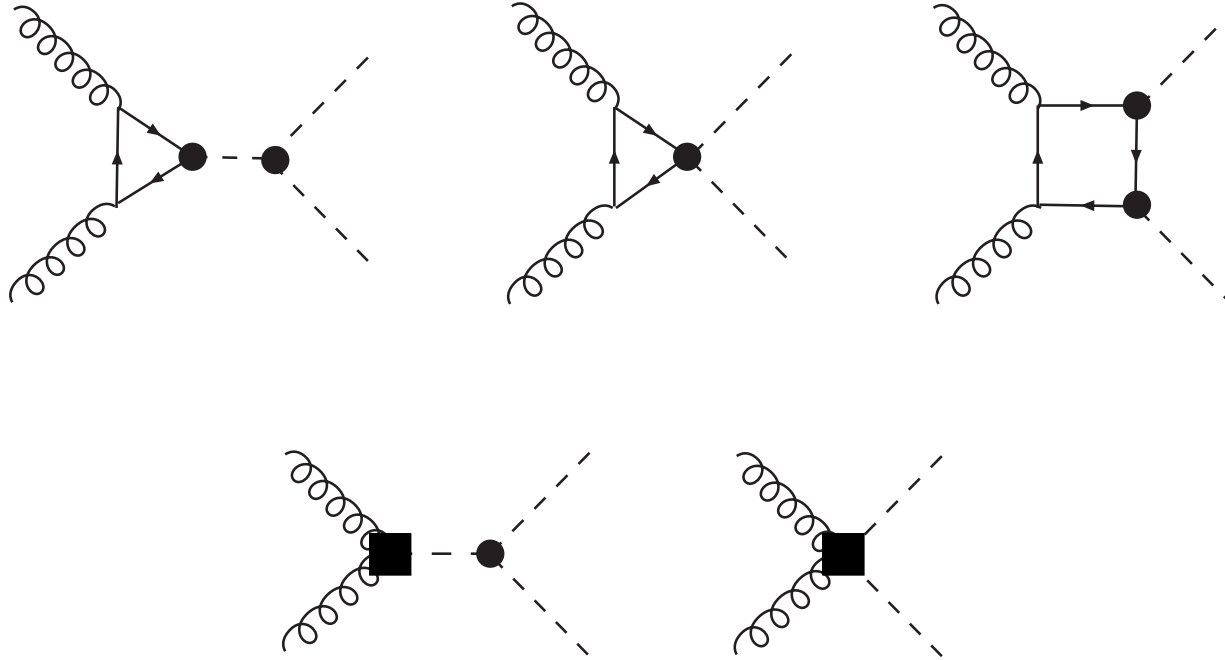
decay: $h \rightarrow \gamma\gamma$, WW , ZZ , $b\bar{b}$, $\tau\bar{\tau}$

G.B., Catà, Celis, Krause

Lilith Bernon, Dumont

- 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*

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