NEW PHYSICS IN THE HIGGS SECTOR – AN EFFECTIVE THEORY APPROACH

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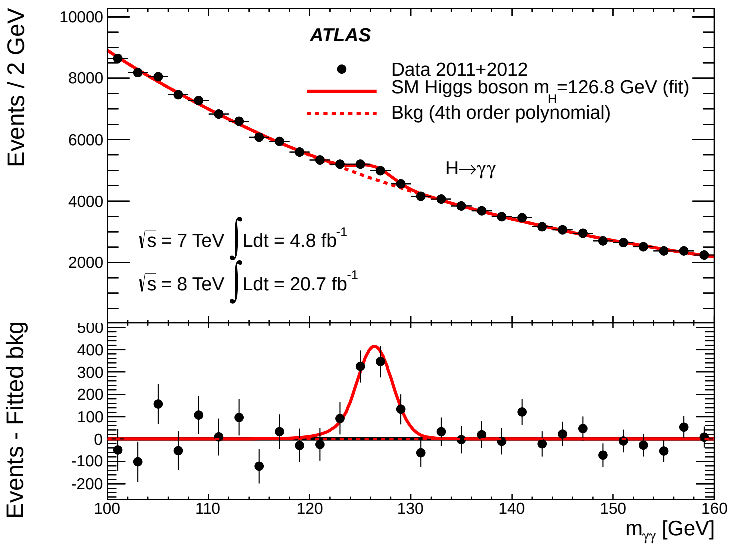
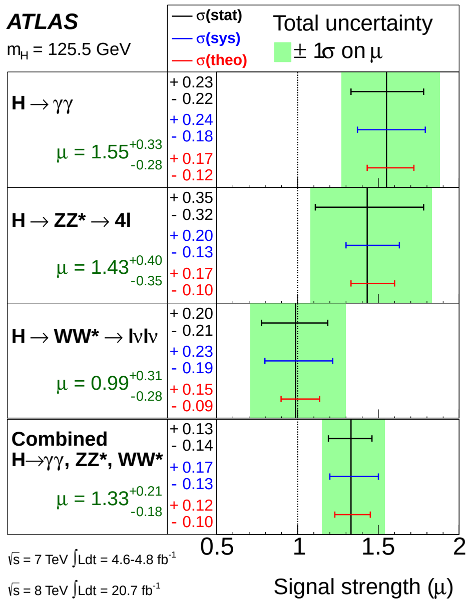
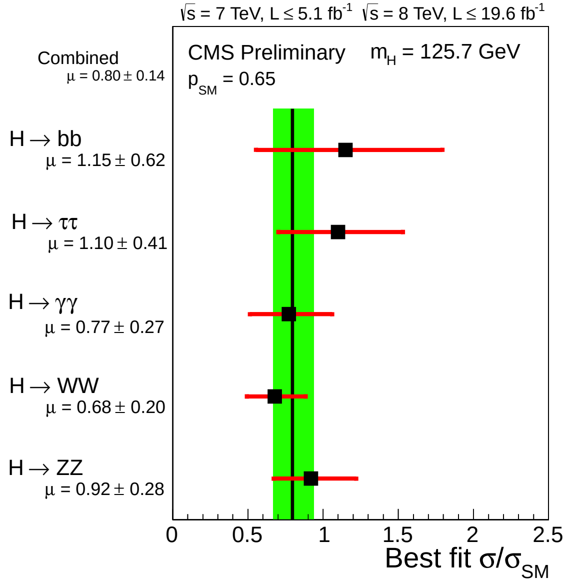
- Effective theory of EWSB
- Lagrangian and power counting
- Applications

G.B., Oscar Catà, Claudius Krause







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

$\rightarrow$ Effective Field Theory

- symmetries, particle content, power counting
- model independent

- 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*

- include light Higgs h

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

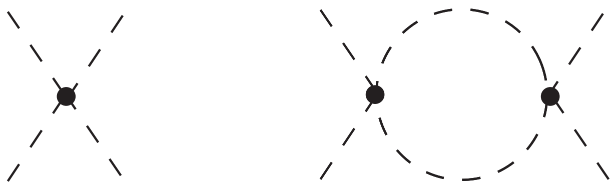
special case:

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

Nonlinear realization of EWSB

Weinberg; Callan, Coleman, Wess, Zumino

- $U = \exp(2i\varphi^a T^a/v)$: $SU(2)_L \otimes SU(2)_R \to SU(2)_V$ 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 $\gtrsim 1/16\pi^2 = v^2/\Lambda^2$



Leading-order Lagrangian

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

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

$$-v\left[\sum_{n=0}^{\infty}\bar{q}\hat{Y}_u^{(n)}UP_+r\left(\frac{h}{v}\right)^n + \text{h.c.} + \ldots\right] \qquad \sim v^4$$

Contino et al.

- h pseudo-Goldstone: $m_h^2h^2 \sim 1/(16\pi^2)\,\Lambda^2h^2 \sim v^2h^2$
- $\mathcal{L}_{LO}$: dimension 2, 3, 4 $\quad\rightarrow$ loop expansion, $v^2/\Lambda^2 \sim 1/16\pi^2$

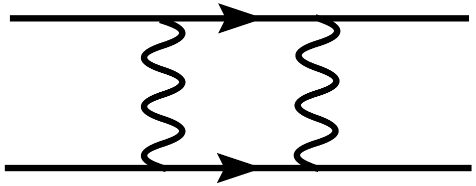
Loop counting $\equiv$ chiral counting

Urech; Nyffeler, Schenk; Hirn, Stern; G.B., Catà, Krause

chiral dimensions: $[A_\mu, \varphi, h]_c = 0$, $[\psi]_c = 1/2$, $[g, y, \partial_\mu]_c = 1$

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

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



$\Rightarrow [\mathcal{L}_{LO}]_c = 2, \qquad [\mathrm{NLO}]_c = 4:$

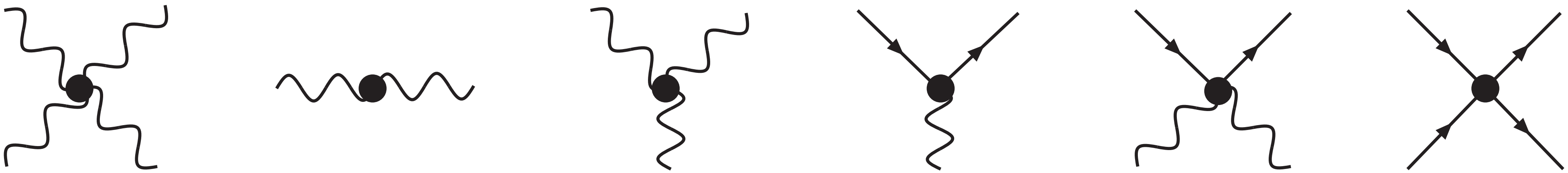
$$UhD^4, \quad g^2X^2Uh, \quad gXUhD^2, \quad y^2\psi^2UhD, \quad y\psi^2UhD^2, \quad y^2\psi^4Uh$$

- $\bar\psi\psi\bar\psi\psi$, X^2Uh not LO
- corrects NDA *Georgi, Manohar*

Power counting — operator classes

$\rightarrow$ classification of NLO operators

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



Loop vs. dimensional counting

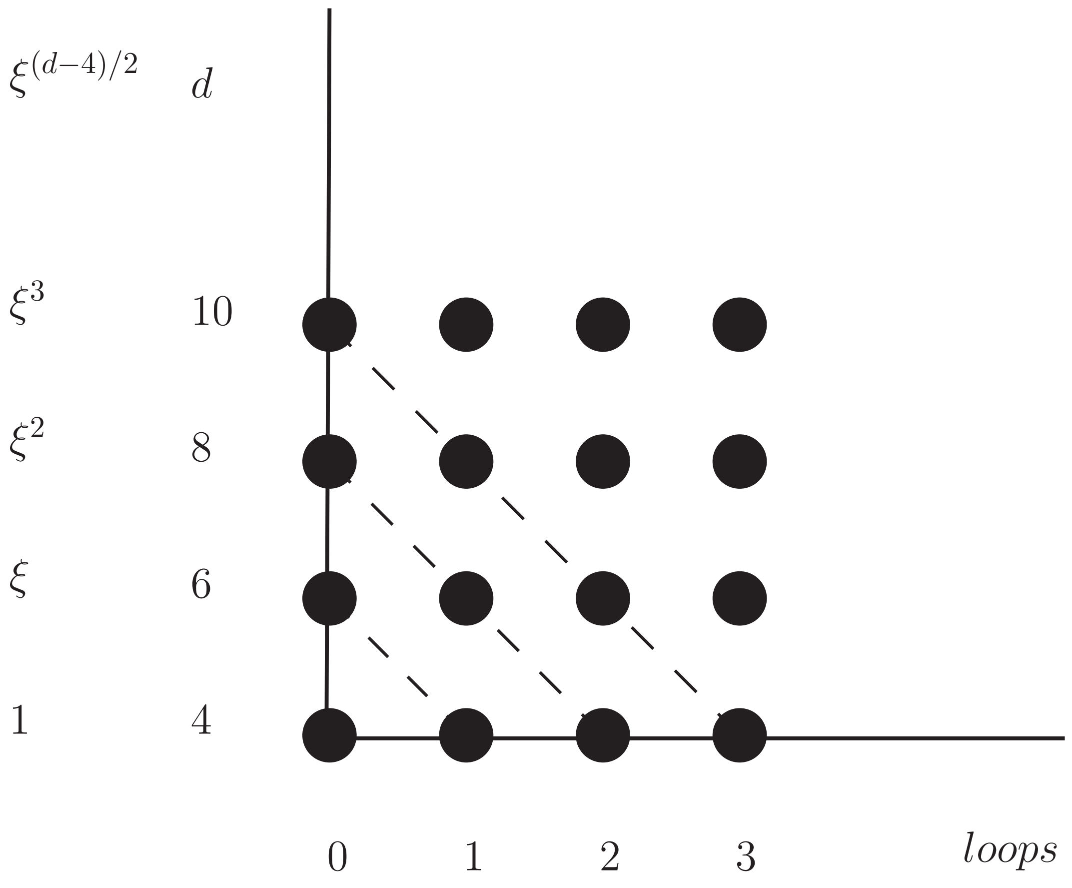
$$\Lambda = 4\pi f$$

$$f$$

$$v$$

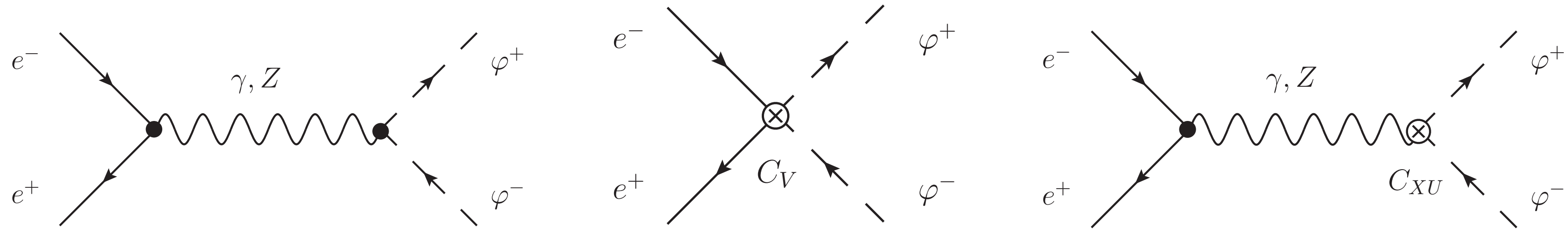
$$\xi = \frac{v^2}{f^2} \to \text{dim. exp.}$$

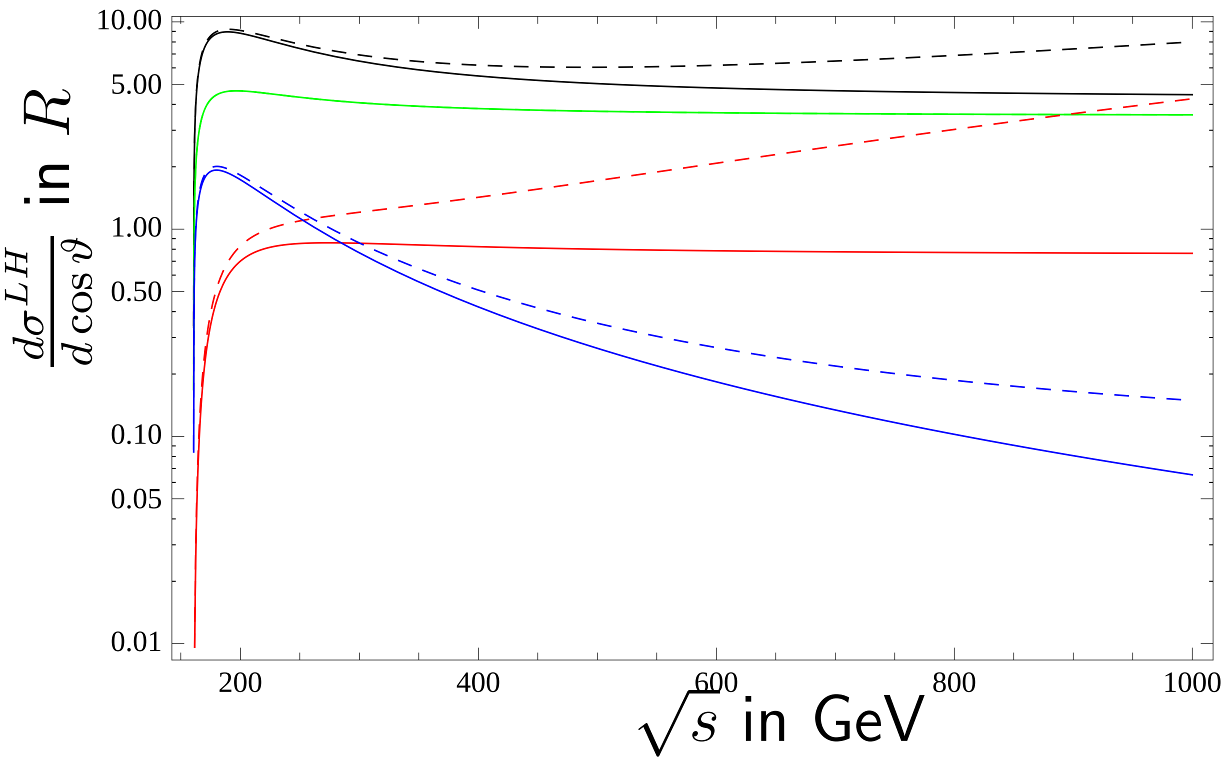
$$\frac{1}{16\pi^2} \approx \frac{f^2}{\Lambda^2} \to \text{loop exp.}$$



Applications $e^+e^- \to W^+W^-$

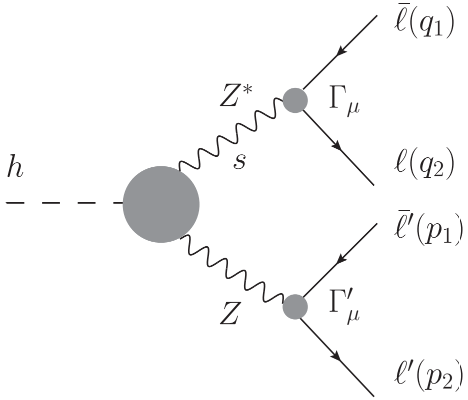
G.B., Catà, Rahn, Schlaffer

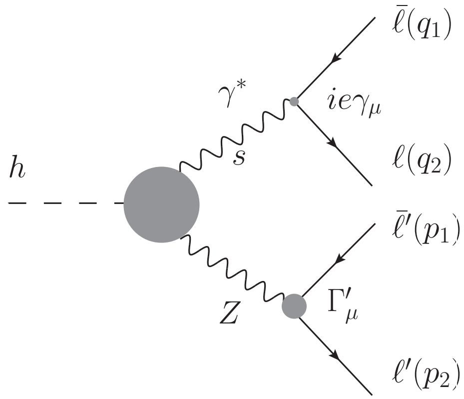


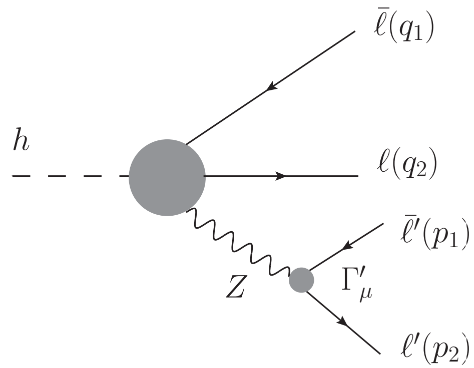


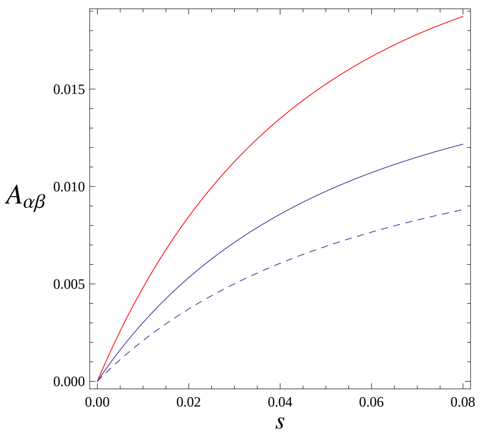
Applications $h \to Z\ell^+\ell^-$

Isidori et al.; Grinstein et al.; G.B., Catà, D'Ambrosio; Beneke et al.









$$\frac{d\Gamma}{ds\, d\cos\alpha\, d\cos\beta\, d\varphi} \sim$$

$$J_1 \frac{9}{40}(1+\cos^2\alpha\cos^2\beta) + J_2 \frac{9}{16}\sin^2\alpha\sin^2\beta$$

$$+J_3 \cos\alpha\cos\beta$$

$$+\,(J_4 \sin\alpha\sin\beta + J_5 \sin 2\alpha\sin 2\beta)\sin\varphi$$

$$+\,(J_6 \sin\alpha\sin\beta + J_7 \sin 2\alpha\sin 2\beta)\cos\varphi$$

$$+J_8 \sin^2\alpha\sin^2\beta\sin 2\varphi + J_9 \sin^2\alpha\sin^2\beta\cos 2\varphi$$

Summary

- EFT for new physics: particle content, symmetries, power counting
- $\mathcal{L}_\chi + h$ singlet: most general EFT
- includes strong EWSB with pseudo-Goldstone higgs
- loop counting: chiral dimensions
- full set of NLO operators; many applications

NLO Lagrangian

$$L_\mu \equiv iUD_\mu U^\dagger\,, \qquad \tau_L \equiv UT_3U^\dagger$$

$$\mathcal{L} = \mathcal{L}_{LO} + \mathcal{L}_{\beta_1} + \sum_i c_i \frac{v^{6-d_i}}{\Lambda^2}\,\mathcal{O}_i$$

$$\mathcal{L}_{\beta_1} = -\beta_1 v^2 \langle \tau_L L_\mu \rangle \langle \tau_L L^\mu \rangle\, F_{\beta_1}(h), \qquad F_{\beta_1}(h) = 1 + \sum_{n=1}^{\infty} f_{\beta_1,n} \left(\frac{h}{v}\right)^n$$

related work: *Contino et al., Alonso et al.*

NLO operators UhD^4

CP even: $(F_{Di} = F_{Di}(h))$

$$\mathcal{O}_{D1} = \langle L_\mu L^\mu \rangle^2 \; F_{D1}$$
$$\mathcal{O}_{D2} = \langle L_\mu L_\nu \rangle \; \langle L^\mu L^\nu \rangle \; F_{D2}$$
$$\mathcal{O}_{D3} = (\langle \tau_L L_\mu \rangle \; \langle \tau_L L^\mu \rangle)^2 \; F_{D3}$$
$$\mathcal{O}_{D4} = \langle \tau_L L_\mu \rangle \; \langle \tau_L L^\mu \rangle \; \langle L_\nu L^\nu \rangle \; F_{D4}$$
$$\mathcal{O}_{D5} = \langle \tau_L L_\mu \rangle \; \langle \tau_L L_\nu \rangle \; \langle L^\mu L^\nu \rangle \; F_{D5}$$
$$\mathcal{O}_{D6} = i \langle \tau_L L_\mu L_\nu \rangle \; \langle \tau_L L^\mu \rangle \; \frac{\partial^\nu h}{v} F_{D6}$$
$$\mathcal{O}_{D7} = \langle L_\mu L^\mu \rangle \; \frac{\partial_\nu h \, \partial^\nu h}{v^2} F_{D7}$$
$$\mathcal{O}_{D8} = \langle L_\mu L_\nu \rangle \; \frac{\partial^\mu h \, \partial^\nu h}{v^2} F_{D8}$$
$$\mathcal{O}_{D9} = \langle \tau_L L_\mu \rangle \; \langle \tau_L L^\mu \rangle \; \frac{\partial_\nu h \, \partial^\nu h}{v^2} F_{D9}$$
$$\mathcal{O}_{D10} = \langle \tau_L L_\mu \rangle \; \langle \tau_L L_\nu \rangle \; \frac{\partial^\mu h \, \partial^\nu h}{v^2} F_{D10}$$
$$\mathcal{O}_{D11} = \frac{(\partial_\mu h \, \partial^\mu h)^2}{v^4} F_{D11}$$

(and 4 CP odd operators)

NLO operators X^2Uh, $XUhD^2$

$$\mathcal{O}_{Xh1} = g'^2 B_{\mu\nu} B^{\mu\nu}\, F_{Xh1}(h)$$

$$\mathcal{O}_{Xh2} = g^2 \langle W_{\mu\nu} W^{\mu\nu} \rangle\, F_{Xh2}(h)$$

$$\mathcal{O}_{Xh3} = g_s^2 \langle G_{\mu\nu} G^{\mu\nu} \rangle\, F_{Xh3}(h)$$

$$\mathcal{O}_{XU1} = g' g B_{\mu\nu} \langle W^{\mu\nu} \tau_L \rangle\, (1 + F_{XU1}(h))$$

$$\mathcal{O}_{XU2} = g^2 \langle W_{\mu\nu} \tau_L \rangle^2\, (1 + F_{XU2}(h))$$

$$\mathcal{O}_{XU3} = g \varepsilon_{\mu\nu\lambda\rho} \langle W^{\mu\nu} L^\lambda \rangle \langle \tau_L L^\rho \rangle\, (1 + F_{XU3}(h))$$

$$\mathcal{O}_{XU7} = i g' B_{\mu\nu} \langle \tau_L [L^\mu, L^\nu] \rangle\, F_{XU7}(h)$$

$$\mathcal{O}_{XU8} = i g \langle W_{\mu\nu} [L^\mu, L^\nu] \rangle\, F_{XU8}(h)$$

$$\mathcal{O}_{XU9} = i g \langle W_{\mu\nu} \tau_L \rangle \langle \tau_L [L^\mu, L^\nu] \rangle\, F_{XU9}(h)$$

(and 9 CP odd operators)

NLO operators $\psi^2 UhD$

$$\mathcal{O}_{\psi V1} = -\bar{q}\gamma^\mu q \, \langle \tau_L L_\mu \rangle \, F_{\psi V1}(h)$$
$$\mathcal{O}_{\psi V2} = -\bar{q}\gamma^\mu \tau_L q \, \langle \tau_L L_\mu \rangle \, F_{\psi V2}(h)$$
$$\mathcal{O}_{\psi V3} = -\bar{q}\gamma^\mu U P_{12} U^\dagger q \, \langle L_\mu U P_{21} U^\dagger \rangle \, F_{\psi V3}(h), \qquad \mathcal{O}^\dagger_{\psi V3}$$

$$\mathcal{O}_{\psi V4} = -\bar{u}\gamma^\mu u \, \langle \tau_L L_\mu \rangle \, F_{\psi V4}(h)$$
$$\mathcal{O}_{\psi V5} = -\bar{d}\gamma^\mu d \, \langle \tau_L L_\mu \rangle \, F_{\psi V5}(h)$$
$$\mathcal{O}_{\psi V6} = -\bar{u}\gamma^\mu d \, \langle L_\mu U P_{21} U^\dagger \rangle \, F_{\psi V6}(h), \qquad \mathcal{O}^\dagger_{\psi V6}$$

(similar operators with leptons)

NLO operators $\psi^2 UhD^2$, $\psi^4 Uh$

$$\mathcal{O}_{\psi S1} = \bar{q} U P_+ r \langle L_\mu L^\mu \rangle F_{\psi S1}$$
$$\mathcal{O}_{\psi S2} = \bar{q} U P_- r \langle L_\mu L^\mu \rangle F_{\psi S2}$$

$$\mathcal{O}_{\psi S3} = \bar{q} U P_+ r \langle \tau_L L_\mu \rangle \langle \tau_L L^\mu \rangle F_{\psi S3}$$
$$\mathcal{O}_{\psi S4} = \bar{q} U P_- r \langle \tau_L L_\mu \rangle \langle \tau_L L^\mu \rangle F_{\psi S4}$$

$$\mathcal{O}_{\psi S5} = \bar{q} U P_{12} r \langle \tau_L L_\mu \rangle \langle U P_{21} U^\dagger L^\mu \rangle F_{\psi S5}$$
$$\mathcal{O}_{\psi S6} = \bar{q} U P_{21} r \langle \tau_L L_\mu \rangle \langle U P_{12} U^\dagger L^\mu \rangle F_{\psi S6}$$

$$\mathcal{O}_{\psi S10} = \bar{q} U P_+ r \langle \tau_L L_\mu \rangle \frac{\partial^\mu h}{v} F_{\psi S10}$$
$$\mathcal{O}_{\psi S11} = \bar{q} U P_- r \langle \tau_L L_\mu \rangle \frac{\partial^\mu h}{v} F_{\psi S11}$$

$$\mathcal{O}_{\psi S12} = \bar{q} U P_{12} r \langle U P_{21} U^\dagger L_\mu \rangle \frac{\partial^\mu h}{v} F_{12}$$
$$\mathcal{O}_{\psi S13} = \bar{q} U P_{21} r \langle U P_{12} U^\dagger L_\mu \rangle \frac{\partial^\mu h}{v} F_{13}$$

$$\mathcal{O}_{\psi S14} = \bar{q} U P_+ r \frac{\partial_\mu h}{v} \frac{\partial^\mu h}{v} F_{\psi S14}$$
$$\mathcal{O}_{\psi S15} = \bar{q} U P_- r \frac{\partial_\mu h}{v} \frac{\partial^\mu h}{v} F_{\psi S15}$$

$\psi^4 U h$ operators: $\mathcal{O}_{4\psi Uh,i} = \mathcal{O}_{4\psi U,i} \, F_{4\psi i}(h)$

e.g. $\bar{\psi}_L U \psi_R \, \bar{\psi}_L U \psi_R \, F(h)$

Comparison with linearly realized Higgs

$\mathcal{L}_\chi$:	LO	LO	X^2Uh $XUhD^2$	ψ^2UhD	ψ^4Uh	UhD^4	ψ^2UhD^2	NNLO	NNLO
$\mathcal{L}_{BW}$:	φ^6 φ^4D^2	$\psi^2\varphi^3$	$X^2\varphi^2$	$\psi^2\varphi^2D$	ψ^4	NNLO	NNLO	X^3	$\psi^2X\varphi$

linear in $\xi = \frac{v^2}{f^2}$ from $\mathcal{L}_\chi \leftrightarrow$ dimension 6 from $\mathcal{L}_{BW}$

Buchmüller, Wyler; Grzadkowski et al.

SILH

Giudice et al.