Unravelling the Higgs nature with EFTs

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Based on:

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In collaboration with: Alonso, Corbett, Éboli, Gavela, Gonzalez–Fraile, Gonzalez–García, Merlo, Rigolin

invisibles
neutrinos, dark matter & dark energy physics

UAM UNIVERSIDAD AUTONOMA DE MADRID

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Motivation

HEFT

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HEFT

. . . what kind of **Higgs**?

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HEFT

SM Higgs doublet

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Composite Higgs

HEFT

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Impostor

?

HEFT

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?

can **EFTs** help in this identification?

Strategy

So far data consistent with the SM → linear $SU(2)_L$ doublet

Crucial to keep looking for possible departures!

another representation?

dynamical origin?

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is the **most generic** way to couple the Higgs to the SM Goldstone bosons

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linear EW doublet
[elementary Higgs]

every BSM scenario

generic singlet
[dilaton]

pGB EW doublet
[composite Higgs]

pGB EW singlet
[exotic]

corresponds to a **specific limit** of the chiral EFT description

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different BSM signals expected!

Chiral EFT: basic formalism

Appelquist,Carazzone (1980)
Longhitano (1980,1981)

Goldstone bosons: in a bidoublet of $SU(2)_L \times U(1)_Y$

$$\mathbf{U}(x) = e^{i\pi^a(x)\sigma^a/f}\,, \qquad \mathbf{U}(x) \mapsto L\mathbf{U}(x)R^\dagger\,.$$

Higgs boson: generically a gauge singlet $h(x)$.

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Important: three scales!

- $\boldsymbol{\Lambda}$ new resonances
- $\boldsymbol{f}$ Goldstone bosons
- $\boldsymbol{v}$ EWSB

$\xi = \boldsymbol{v^2/f^2}$ **non-linearity parameter (not physical!)**

- $\xi = 1$ technicolor (non-linear EWSB)
- $\xi = 0$ linear EWSB

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Building blocks for the Lagrangian:

GBs
$$\mathbf{V}_\mu = \mathbf{D}_\mu\mathbf{U}\mathbf{U}^\dagger\,, \qquad \mathbf{V}_\mu \mapsto L\mathbf{V}_\mu L^\dagger$$
$$\mathbf{T} = \mathbf{U}\sigma^3\mathbf{U}^\dagger\,, \qquad \mathbf{T} \mapsto L\mathbf{T}L^\dagger \rightarrow$$ ~~Custodial sym.~~

Higgs
$$\mathcal{F}(\mathbf{h}) = 1 + 2a_i\frac{h}{v} + b_i\frac{h^2}{v^2} + \dots \qquad \partial_\mu\mathcal{F}(\mathbf{h})$$

Grinstein, Trott (2007)

The non-linear effective Lagrangian

With this notation, the **SM Lagrangian** reads

$$\mathscr{L}_{\text{SM}} = (\text{kinetic terms for } \psi, W, Z, \mathcal{G}) +$$

$$+ \frac{1}{2}\partial_\mu h \partial^\mu h - V(h) +$$

$$- \frac{(v+h)^2}{4} \text{Tr}[\mathbf{V}_\mu \mathbf{V}^\mu] +$$ **GB kinetic terms gauge bosons' masses**

$$- \frac{v+h}{\sqrt{2}} \left[\bar{\psi}_L \mathbf{U} Y \psi_R + \text{h.c.}\right]$$ **Yukawas**

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GB kinetic terms
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Yukawas

BSM effects: effective operators with up to 4 derivatives

$$\Delta\mathscr{L} = \sum_i c_i \mathcal{P}_i$$

The non-linear basis

Alonso, Gavela, Merlo, Rigolin, Yepes (2013)

Bosonic sector
CP even

$$\mathcal{P}_W = -\frac{g^2}{4} W^a_{\mu\nu} W^{a\mu\nu} \mathcal{F}_W(h)$$
$$\mathcal{P}_B = -\frac{g'^2}{4} B_{\mu\nu} B^{\mu\nu} \mathcal{F}_B(h)$$
$$\mathcal{P}_G = -\frac{g_s^2}{4} \mathcal{G}^A_{\mu\nu} \mathcal{G}^{A\mu\nu} \mathcal{F}_G(h)$$
$$\mathcal{P}_H = \frac{1}{2} \partial_\mu h \partial^\mu h \mathcal{F}_H(h)$$
$$\mathcal{P}_{DH} = \frac{1}{v^4} \left(\partial_\mu h \partial^\mu h\right)^2 \mathcal{F}_{DH}(h)$$
$$\mathcal{P}_{\Delta H} = \frac{1}{v^3} (\partial_\mu h \partial^\mu h) \, \Box \, \mathcal{F}_{\Delta H}(h)$$
$$\mathcal{P}_{\Box H} = \frac{1}{v^2} (\Box h)(\Box h) \mathcal{F}_{\Box H}(h)$$
$$\mathcal{P}_C = -\frac{v^2}{4} \mathrm{Tr}(\mathbf{V}^\mu \mathbf{V}_\mu) \mathcal{F}_C(h)$$
$$\mathcal{P}_T = \frac{v^2}{4} \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \mathcal{F}_T(h)$$
$$\mathcal{P}_1 = g g' B_{\mu\nu} \mathrm{Tr}(\mathbf{T} W^{\mu\nu}) \mathcal{F}_1(h)$$
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The non-linear basis

Alonso, Gavela, Merlo, Rigolin, Yepes (2013)

Appelquist, Bernard (1980)
Longhitano (1980,1981)
Feruglio (1993)

$$\mathcal{P}_W = -\frac{g^2}{4} W^a_{\mu\nu} W^{a\mu\nu} \mathcal{F}_W(h)$$
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No h: ALF basis

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Custodial symmetry imposed

The non-linear basis

Alonso, Gavela, Merlo, Rigolin, Yepes (2013)

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$$\mathcal{P}_8 = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu) \partial^\mu \mathcal{F}_8(h) \partial^\nu \mathcal{F}'_8(h)$$
~~$\mathcal{P}_9 = \mathrm{Tr}((\mathcal{D}_\mu \mathbf{V}^\mu)^2) \mathcal{F}_9(h)$~~

~~$\mathcal{P}_{10} = \mathrm{Tr}(\mathbf{V}_\nu \mathcal{D}_\mu \mathbf{V}^\mu) \partial^\nu \mathcal{F}_{10}(h)$~~
$$\mathcal{P}_{11} = (\mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu))^2 \mathcal{F}_{11}(h)$$
$$\mathcal{P}_{12} = g^2\, \mathrm{Tr}(\mathbf{T} W_{\mu\nu}))^2 \mathcal{F}_{12}(h)$$
$$\mathcal{P}_{13} = i g\, \mathrm{Tr}(\mathbf{T} W_{\mu\nu})\, \mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_{13}(h)$$
$$\mathcal{P}_{14} = g \varepsilon^{\mu\nu\rho\lambda}\, \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\, \mathrm{Tr}(\mathbf{V}_\nu W_{\rho\lambda}) \mathcal{F}_{14}(h)$$
~~$\mathcal{P}_{15} = \mathrm{Tr}(\mathbf{T}\mathcal{D}_\mu \mathbf{V}^\mu)\, \mathrm{Tr}(\mathbf{T}\mathcal{D}_\nu \mathbf{V}^\nu) \mathcal{F}_{15}(h)$~~

~~$\mathcal{P}_{16} = \mathrm{Tr}([\mathbf{T}, \mathbf{V}_\nu] \mathcal{D}_\mu \mathbf{V}^\mu)\, \mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu) \mathcal{F}_{16}(h)$~~
$$\mathcal{P}_{17} = i g\, \mathrm{Tr}(\mathbf{T} W_{\mu\nu})\, \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_{17}(h)$$
$$\mathcal{P}_{18} = \mathrm{Tr}(\mathbf{T}[\mathbf{V}_\mu, \mathbf{V}_\nu])\, \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_{18}(h)$$
~~$\mathcal{P}_{19} = \mathrm{Tr}(\mathbf{T}\mathcal{D}_\mu \mathbf{V}^\mu)\, \mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu) \partial^\nu \mathcal{F}_{19}(h)$~~
$$\mathcal{P}_{20} = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) \partial_\nu \mathcal{F}_{20}(h) \partial^\nu \mathcal{F}'_{20}(h)$$
$$\mathcal{P}_{21} = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu))^2 \partial_\nu \mathcal{F}_{21}(h) \partial^\nu \mathcal{F}'_{21}(h)$$
$$\mathcal{P}_{22} = \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\, \mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu) \partial^\mu \mathcal{F}_{22}(h) \partial^\mu \mathcal{F}'_{22}(h)$$
$$\mathcal{P}_{23} = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2 \mathcal{F}_{23}(h)$$
$$\mathcal{P}_{24} = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu)\, \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\, \mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu) \mathcal{F}_{24}(h)$$
$$\mathcal{P}_{25} = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu))^2 \partial_\nu \partial^\nu \mathcal{F}_{25}(h)$$
$$\mathcal{P}_{26} = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\, \mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2 \mathcal{F}_{26}(h)$$

Massless fermions

The non-linear basis

Alonso, Gavela, Merlo, Rigolin, Yepes (2013)

$$\mathcal{P}_W = -\frac{g^2}{4} W^a_{\mu\nu} W^{a\mu\nu} \mathcal{F}_W(h)$$
$$\mathcal{P}_B = -\frac{g'^2}{4} B_{\mu\nu} B^{\mu\nu} \mathcal{F}_B(h)$$
$$\mathcal{P}_G = -\frac{g_s^2}{4} \mathcal{G}^A_{\mu\nu} \mathcal{G}^{A\mu\nu} \mathcal{F}_G(h)$$
$$\mathcal{P}_H = \frac{1}{2} \partial_\mu h \partial^\mu h \mathcal{F}_H(h)$$
$$\mathcal{P}_{DH} = \frac{1}{v^4} \left(\partial_\mu h \partial^\mu h\right)^2 \mathcal{F}_{DH}(h)$$
$$\mathcal{P}_{\Delta H} = \frac{1}{v^3} (\partial_\mu h \partial^\mu h) \Box \mathcal{F}_{\Delta H}(h)$$
$$\mathcal{P}_{\Box H} = \frac{1}{v^2} (\Box h)(\Box h) \mathcal{F}_{\Box H}(h)$$
$$\mathcal{P}_C = -\frac{v^2}{4} \operatorname{Tr}(\mathbf{V}^\mu \mathbf{V}_\mu) \mathcal{F}_C(h)$$
$$\mathcal{P}_T = \frac{v^2}{4} \operatorname{Tr}(\mathbf{T}\mathbf{V}_\mu) \operatorname{Tr}(\mathbf{T}\mathbf{V}^\mu) \mathcal{F}_T(h)$$
$$\mathcal{P}_1 = g g' B_{\mu\nu} \operatorname{Tr}(\mathbf{T} W^{\mu\nu}) \mathcal{F}_1(h)$$
$$\mathcal{P}_2 = i g' B_{\mu\nu} \operatorname{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_2(h)$$
$$\mathcal{P}_3 = i g \operatorname{Tr}(W_{\mu\nu}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_3(h)$$
$$\mathcal{P}_4 = i g' B_{\mu\nu} \operatorname{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_4(h)$$
$$\mathcal{P}_5 = i g \operatorname{Tr}(W_{\mu\nu} \mathbf{V}^\mu) \partial^\nu \mathcal{F}_5(h)$$
$$\mathcal{P}_6 = (\operatorname{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu))^2 \mathcal{F}_6(h)$$
$$\mathcal{P}_7 = \operatorname{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) \partial_\nu \partial^\nu \mathcal{F}_7(h)$$
$$\mathcal{P}_8 = \operatorname{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu) \partial^\mu \mathcal{F}_8(h) \partial^\nu \mathcal{F}'_8(h)$$
$$\mathcal{P}_9 = \operatorname{Tr}((\mathcal{D}_\mu \mathbf{V}^\mu)^2) \mathcal{F}_9(h)$$

$$\mathcal{P}_{10} = \operatorname{Tr}(\mathbf{V}_\nu \mathcal{D}_\mu \mathbf{V}^\mu) \partial^\nu \mathcal{F}_{10}(h)$$
$$\mathcal{P}_{11} = (\operatorname{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu))^2 \mathcal{F}_{11}(h)$$
$$\mathcal{P}_{12} = g^2 \operatorname{Tr}(\mathbf{T} W_{\mu\nu}))^2 \mathcal{F}_{12}(h)$$
$$\mathcal{P}_{13} = i g \operatorname{Tr}(\mathbf{T} W_{\mu\nu}) \operatorname{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_{13}(h)$$
$$\mathcal{P}_{14} = g \varepsilon^{\mu\nu\rho\lambda} \operatorname{Tr}(\mathbf{T}\mathbf{V}_\mu) \operatorname{Tr}(\mathbf{V}_\nu W_{\rho\lambda}) \mathcal{F}_{14}(h)$$
$$\mathcal{P}_{15} = \operatorname{Tr}(\mathbf{T}\mathcal{D}_\mu \mathbf{V}^\mu) \operatorname{Tr}(\mathbf{T}\mathcal{D}_\nu \mathbf{V}^\nu) \mathcal{F}_{15}(h)$$
$$\mathcal{P}_{16} = \operatorname{Tr}([\mathbf{T}, \mathbf{V}_\nu] \mathcal{D}_\mu \mathbf{V}^\mu) \operatorname{Tr}(\mathbf{T}\mathbf{V}^\nu) \mathcal{F}_{16}(h)$$
$$\mathcal{P}_{17} = i g \operatorname{Tr}(\mathbf{T} W_{\mu\nu}) \operatorname{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_{17}(h)$$
$$\mathcal{P}_{18} = \operatorname{Tr}(\mathbf{T}[\mathbf{V}_\mu, \mathbf{V}_\nu]) \operatorname{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_{18}(h)$$
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$$\mathcal{P}_{22} = \operatorname{Tr}(\mathbf{T}\mathbf{V}_\mu) \operatorname{Tr}(\mathbf{T}\mathbf{V}_\nu) \partial^\mu \mathcal{F}_{22}(h) \partial^\mu \mathcal{F}'_{22}(h)$$
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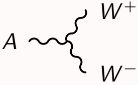
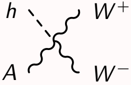
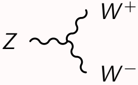
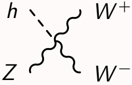
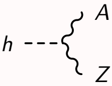
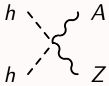
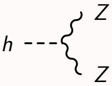
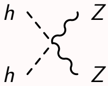
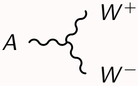
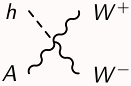
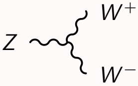
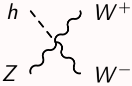
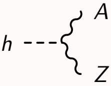
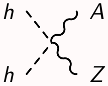
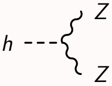
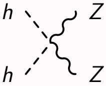
$$\mathcal{P}_{24} = \operatorname{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu) \operatorname{Tr}(\mathbf{T}\mathbf{V}^\mu) \operatorname{Tr}(\mathbf{T}\mathbf{V}^\nu) \mathcal{F}_{24}(h)$$
$$\mathcal{P}_{25} = (\operatorname{Tr}(\mathbf{T}\mathbf{V}_\mu))^2 \partial_\nu \partial^\nu \mathcal{F}_{25}(h)$$
$$\mathcal{P}_{26} = (\operatorname{Tr}(\mathbf{T}\mathbf{V}_\mu) \operatorname{Tr}(\mathbf{T}\mathbf{V}_\nu))^2 \mathcal{F}_{26}(h)$$

Example I

Coupling	$A_{\mu\nu} W^{+\mu} W^{-\nu}$	$A_{\mu\nu} W^{+\mu} W^{-\nu} h$	$Z_{\mu\nu} W^{+\mu} W^{-\nu}$	$Z_{\mu\nu} W^{+\mu} W^{-\nu} h$
				
generic singlet	$2c_2 + c_3$	$2c_2 a_2 + c_3 a_3$	$-2t_\theta^2 c_2 + c_3$	$-2t_\theta^2 c_2 a_2 + c_3 a_3$

Coupling	$A_{\mu\nu} Z^{\mu} \partial^{\nu} h$	$A_{\mu\nu} Z^{\mu} h \partial^{\nu} h$	$Z_{\mu\nu} Z^{\mu} \partial^{\nu} h$	$Z_{\mu\nu} Z^{\mu} h \partial^{\nu} h$
				
generic singlet	$2c_4 a_4 + c_5 a_5$	$2c_4 b_4 + c_5 b_5$	$2t_\theta c_4 a_4 - c_5 a_5$	$2t_\theta c_4 b_4 - c_5 b_5$

Example I

Coupling	$A_{\mu\nu}W^{+\mu}W^{-\nu}$ 	$A_{\mu\nu}W^{+\mu}W^{-\nu}h$ 	$Z_{\mu\nu}W^{+\mu}W^{-\nu}$ 	$Z_{\mu\nu}W^{+\mu}W^{-\nu}h$ 
generic singlet	$2c_2 + c_3$	$2c_2a_2 + c_3a_3$	$-2t_\theta^2 c_2 + c_3$	$-2t_\theta^2 c_2a_2 + c_3a_3$
Coupling	$A_{\mu\nu}Z^\mu\partial^\nu h$ 	$A_{\mu\nu}Z^\mu h\partial^\nu h$ 	$Z_{\mu\nu}Z^\mu\partial^\nu h$ 	$Z_{\mu\nu}Z^\mu h\partial^\nu h$ 
generic singlet	$2c_4a_4 + c_5a_5$	$2c_4b_4 + c_5b_5$	$2t_\theta c_4a_4 - c_5a_5$	$2t_\theta c_4b_4 - c_5b_5$

Decorrelations:
- $\mathcal{P}_{2,3,4,5}$ are independent
- $\mathcal{F}_{2,3,4,5}(h)$ are arbitrary

If the Higgs is an elementary $SU(2)_L$ doublet

How is the linear $SU(2)$ doublet described in the chiral formalism?

- The chiral expansion shall converge to the linear one

If the Higgs is an elementary $SU(2)_L$ doublet

How is the linear $SU(2)$ doublet described in the chiral formalism?

- The chiral expansion shall converge to the linear one

For example:

HISZ linear basis

Buchmüller, Wyler (1986)
Hagiwara,Ishihara,Szalapski,Zeppenfeld (1993)

$$\mathcal{O}_{GG} = -\frac{g_s^2}{4}\Phi^\dagger\Phi G_{\mu\nu}G^{\mu\nu} \qquad \mathcal{O}_{WW} = -\frac{g^2}{4}\Phi^\dagger W_{\mu\nu}W^{\mu\nu}\Phi$$

$$\mathcal{O}_{BB} = -\frac{g'^2}{4}\Phi^\dagger B_{\mu\nu}B^{\mu\nu}\Phi \qquad \mathcal{O}_{BW} = -\frac{gg'}{4}\Phi^\dagger B_{\mu\nu}W^{\mu\nu}\Phi$$

$$\mathcal{O}_{W} = \frac{ig}{2}(\mathbf{D}_\mu\Phi)^\dagger W^{\mu\nu}(\mathbf{D}_\nu\Phi) \qquad \mathcal{O}_{B} = \frac{ig'}{2}(\mathbf{D}_\mu\Phi)^\dagger B^{\mu\nu}(\mathbf{D}_\nu\Phi)$$

$$\mathcal{O}_{\Phi 1} = (\mathbf{D}_\mu\Phi)^\dagger\,\Phi\;\Phi^\dagger\,(\mathbf{D}^\mu\Phi) \qquad \mathcal{O}_{\Phi 2} = \frac{1}{2}\partial^\mu\left(\Phi^\dagger\Phi\right)\partial_\mu\left(\Phi^\dagger\Phi\right)$$

$$\mathcal{O}_{\Phi 3} = \frac{1}{3}\left(\Phi^\dagger\Phi\right)^3 \qquad \mathcal{O}_{\Phi 4} = (\mathbf{D}_\mu\Phi)^\dagger(\mathbf{D}^\mu\Phi)\left(\Phi^\dagger\Phi\right)$$

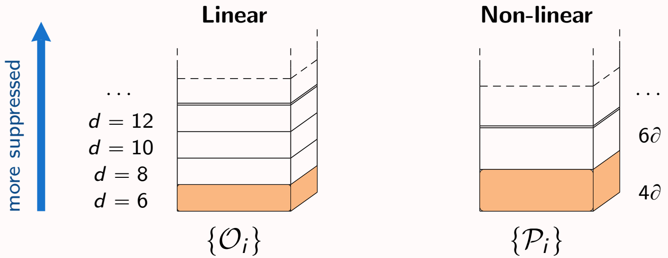
$$\mathcal{O}_{\Box\Phi} = (D_\mu D^\mu\Phi)^\dagger(D_\nu D^\nu\Phi)$$

Grzadkowski,Iskrzynski,Misiak,Rosiek (2010)

⇝ see talk by **J. Gonzalez-Fraile**

Linear - chiral correspondence

Two towers of operators:

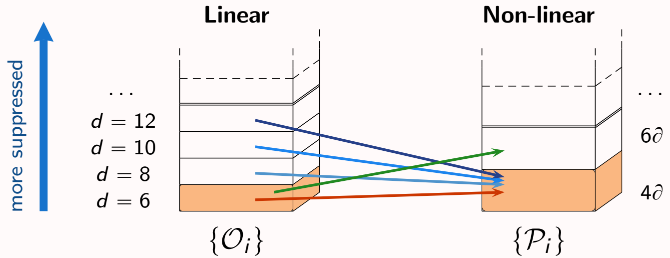


Correspondence $\mathcal{O}_i \to \mathcal{P}_j$

Replace in $\mathcal{O}_i$: $\quad \Phi \to \dfrac{v+h}{\sqrt{2}} \mathbf{U} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

Linear - chiral correspondence

Two towers of operators:



Correspondence $\mathcal{O}_i \to \mathcal{P}_j$

Replace in $\mathcal{O}_i$: $\quad \Phi \to \frac{v+h}{\sqrt{2}}\mathbf{U}\begin{pmatrix}0\\1\end{pmatrix}$

The non-linear basis

$$\mathcal{P}_W = -\frac{g^2}{4} W^a_{\mu\nu} W^{a\mu\nu} \mathcal{F}_W(h)$$
$$\mathcal{P}_B = -\frac{g'^2}{4} B_{\mu\nu} B^{\mu\nu} \mathcal{F}_B(h)$$
$$\mathcal{P}_G = -\frac{g_s^2}{4} \mathcal{G}^A_{\mu\nu} \mathcal{G}^{A\mu\nu} \mathcal{F}_G(h)$$
$$\mathcal{P}_H = \frac{1}{2} \partial_\mu h \partial^\mu h \mathcal{F}_H(h)$$
$$\mathcal{P}_{DH} = \frac{1}{v^4} (\partial_\mu h \partial^\mu h)^2 \mathcal{F}_{DH}(h)$$
$$\mathcal{P}_{\Delta H} = \frac{1}{v^3} (\partial_\mu h \partial^\mu h) \Box \mathcal{F}_{\Delta H}(h)$$
$$\mathcal{P}_{\Box H} = \frac{1}{v^2} (\Box h)(\Box h) \mathcal{F}_{\Box H}(h)$$
$$\mathcal{P}_C = -\frac{v^2}{4} \mathrm{Tr}(\mathbf{V}^\mu \mathbf{V}_\mu) \mathcal{F}_C(h)$$
$$\mathcal{P}_T = \frac{v^2}{4} \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \mathcal{F}_T(h)$$
$$\mathcal{P}_1 = gg' B_{\mu\nu} \mathrm{Tr}(\mathbf{T} W^{\mu\nu}) \mathcal{F}_1(h)$$
$$\mathcal{P}_2 = ig' B_{\mu\nu} \mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_2(h)$$
$$\mathcal{P}_3 = ig \mathrm{Tr}(W_{\mu\nu} [\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_3(h)$$
$$\mathcal{P}_4 = ig' B_{\mu\nu} \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_4(h)$$
$$\mathcal{P}_5 = ig \mathrm{Tr}(W_{\mu\nu} \mathbf{V}^\mu) \partial^\nu \mathcal{F}_5(h)$$
$$\mathcal{P}_6 = (\mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu))^2 \mathcal{F}_6(h)$$
$$\mathcal{P}_7 = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) \partial_\nu \partial^\nu \mathcal{F}_7(h)$$
$$\mathcal{P}_8 = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu) \partial^\mu \mathcal{F}_8(h) \partial^\nu \mathcal{F}'_8(h)$$
$$\mathcal{P}_9 = \mathrm{Tr}((\mathcal{D}_\mu \mathbf{V}^\mu)^2) \mathcal{F}_9(h)$$

ξ

$$\mathcal{P}_{10} = \mathrm{Tr}(\mathbf{V}_\nu \mathcal{D}_\mu \mathbf{V}^\mu) \partial^\nu \mathcal{F}_{10}(h)$$
$$\mathcal{P}_{11} = (\mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu))^2 \mathcal{F}_{11}(h)$$
$$\mathcal{P}_{12} = g^2 \mathrm{Tr}(\mathbf{T} W_{\mu\nu}))^2 \mathcal{F}_{12}(h)$$
$$\mathcal{P}_{13} = ig \mathrm{Tr}(\mathbf{T} W_{\mu\nu}) \mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_{13}(h)$$
$$\mathcal{P}_{14} = g\varepsilon^{\mu\nu\rho\lambda} \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) \mathrm{Tr}(\mathbf{V}_\nu W_{\rho\lambda}) \mathcal{F}_{14}(h)$$
$$\mathcal{P}_{15} = \mathrm{Tr}(\mathbf{T}\mathcal{D}_\mu \mathbf{V}^\mu) \mathrm{Tr}(\mathbf{T}\mathcal{D}_\nu \mathbf{V}^\nu) \mathcal{F}_{15}(h)$$
$$\mathcal{P}_{16} = \mathrm{Tr}([\mathbf{T}, \mathbf{V}_\nu] \mathcal{D}_\mu \mathbf{V}^\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu) \mathcal{F}_{16}(h)$$
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$$\mathcal{P}_{18} = \mathrm{Tr}(\mathbf{T}[\mathbf{V}_\mu, \mathbf{V}_\nu]) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_{18}(h)$$
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$$\mathcal{P}_{20} = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) \partial_\nu \mathcal{F}_{20}(h) \partial^\nu \mathcal{F}'_{20}(h)$$
$$\mathcal{P}_{21} = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu))^2 \partial_\nu \mathcal{F}_{21}(h) \partial^\nu \mathcal{F}'_{21}(h)$$
$$\mathcal{P}_{22} = \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu) \partial^\mu \mathcal{F}_{22}(h) \partial^\mu \mathcal{F}'_{22}(h)$$
$$\mathcal{P}_{23} = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2 \mathcal{F}_{23}(h)$$
$$\mathcal{P}_{24} = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu) \mathcal{F}_{24}(h)$$
$$\mathcal{P}_{25} = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu))^2 \partial_\nu \partial^\nu \mathcal{F}_{25}(h)$$

ξ^2

$$\mathcal{P}_{26} = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2 \mathcal{F}_{26}(h)$$

ξ^4

Expected ξ weights

The non-linear basis

$\mathcal{P}_W = -\frac{g^2}{4} W^a_{\mu\nu} W^{a\mu\nu} \mathcal{F}_W(h)$

$\mathcal{P}_B = -\frac{g'^2}{4} B_{\mu\nu} B^{\mu\nu} \mathcal{F}_B(h)$

$\mathcal{P}_G = -\frac{g_s^2}{4} \mathcal{G}^A_{\mu\nu} \mathcal{G}^{A\mu\nu} \mathcal{F}_G(h)$

$\mathcal{P}_H = \frac{1}{2} \partial_\mu h \partial^\mu h \mathcal{F}_H(h)$

$\mathcal{P}_{DH} = \frac{1}{v^4} (\partial_\mu h \partial^\mu h)^2 \mathcal{F}_{DH}(h)$

$\mathcal{P}_{\Delta H} = \frac{1}{v^3} (\partial_\mu h \partial^\mu h) \square \mathcal{F}_{\Delta H}(h)$

ξ

$\mathcal{P}_{\square H} = \frac{1}{v^2} (\square h)(\square h) \mathcal{F}_{\square H}(h)$

$\mathcal{P}_C = -\frac{v^2}{4} \operatorname{Tr}(\mathbf{V}^\mu \mathbf{V}_\mu) \mathcal{F}_C(h)$

$\mathcal{P}_T = \frac{v^2}{4} \operatorname{Tr}(\mathbf{T}\mathbf{V}_\mu) \operatorname{Tr}(\mathbf{T}\mathbf{V}^\mu) \mathcal{F}_T(h)$

$\mathcal{P}_1 = g g' B_{\mu\nu} \operatorname{Tr}(\mathbf{T} W^{\mu\nu}) \mathcal{F}_1(h)$

$\mathcal{P}_2 = i g' B_{\mu\nu} \operatorname{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_2(h)$

$\mathcal{P}_3 = i g \operatorname{Tr}(W_{\mu\nu} [\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_3(h)$

$\mathcal{P}_4 = i g' B_{\mu\nu} \operatorname{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_4(h)$

$\mathcal{P}_5 = i g \operatorname{Tr}(W_{\mu\nu} \mathbf{V}^\mu) \partial^\nu \mathcal{F}_5(h)$

$\mathcal{P}_6 = (\operatorname{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu))^2 \mathcal{F}_6(h)$

$\mathcal{P}_7 = \operatorname{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) \partial_\nu \partial^\nu \mathcal{F}_7(h)$

$\mathcal{P}_8 = \operatorname{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu) \partial^\mu \mathcal{F}_8(h) \partial^\nu \mathcal{F}'_8(h)$

$\mathcal{P}_9 = \operatorname{Tr}((\mathcal{D}_\mu \mathbf{V}^\mu)^2) \mathcal{F}_9(h)$

$\mathcal{P}_{10} = \operatorname{Tr}(\mathbf{V}_\nu \mathcal{D}_\mu \mathbf{V}^\mu) \partial^\nu \mathcal{F}_{10}(h)$

Corresponding to linear $d = 6$

ξ^2

$\mathcal{P}_{11} = (\operatorname{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu))^2 \mathcal{F}_{11}(h)$

$\mathcal{P}_{12} = g^2 \operatorname{Tr}(\mathbf{T} W_{\mu\nu})^2 \mathcal{F}_{12}(h)$

$\mathcal{P}_{13} = i g \operatorname{Tr}(\mathbf{T} W_{\mu\nu}) \operatorname{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_{13}(h)$

$\mathcal{P}_{14} = g \varepsilon^{\mu\nu\rho\lambda} \operatorname{Tr}(\mathbf{T}\mathbf{V}_\mu) \operatorname{Tr}(\mathbf{V}_\nu W_{\rho\lambda}) \mathcal{F}_{14}(h)$

$\mathcal{P}_{15} = \operatorname{Tr}(\mathbf{T}\mathcal{D}_\mu \mathbf{V}^\mu) \operatorname{Tr}(\mathbf{T}\mathcal{D}_\nu \mathbf{V}^\nu) \mathcal{F}_{15}(h)$

$\mathcal{P}_{16} = \operatorname{Tr}([\mathbf{T}, \mathbf{V}_\nu] \mathcal{D}_\mu \mathbf{V}^\mu) \operatorname{Tr}(\mathbf{T}\mathbf{V}^\nu) \mathcal{F}_{16}(h)$

$\mathcal{P}_{17} = i g \operatorname{Tr}(\mathbf{T} W_{\mu\nu}) \operatorname{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_{17}(h)$

$\mathcal{P}_{18} = \operatorname{Tr}(\mathbf{T}[\mathbf{V}_\mu, \mathbf{V}_\nu]) \operatorname{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_{18}(h)$

$\mathcal{P}_{19} = \operatorname{Tr}(\mathbf{T}\mathcal{D}_\mu \mathbf{V}^\mu) \operatorname{Tr}(\mathbf{T}\mathbf{V}_\nu) \partial^\nu \mathcal{F}_{19}(h)$

$\mathcal{P}_{20} = \operatorname{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) \partial_\nu \mathcal{F}_{20}(h) \partial^\nu \mathcal{F}'_{20}(h)$

$\mathcal{P}_{21} = (\operatorname{Tr}(\mathbf{T}\mathbf{V}_\mu))^2 \partial_\nu \mathcal{F}_{21}(h) \partial^\nu \mathcal{F}'_{21}(h)$

$\mathcal{P}_{22} = \operatorname{Tr}(\mathbf{T}\mathbf{V}_\mu) \operatorname{Tr}(\mathbf{T}\mathbf{V}_\nu) \partial^\mu \mathcal{F}_{22}(h) \partial^\mu \mathcal{F}'_{22}(h)$

$\mathcal{P}_{23} = \operatorname{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) (\operatorname{Tr}(\mathbf{T}\mathbf{V}_\nu))^2 \mathcal{F}_{23}(h)$

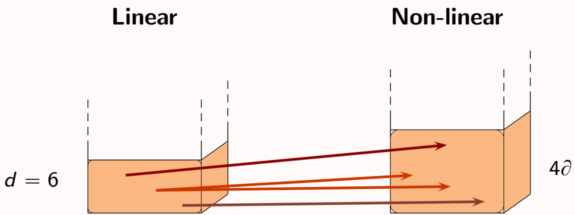
$\mathcal{P}_{24} = \operatorname{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu) \operatorname{Tr}(\mathbf{T}\mathbf{V}^\mu) \operatorname{Tr}(\mathbf{T}\mathbf{V}^\nu) \mathcal{F}_{24}(h)$

$\mathcal{P}_{25} = (\operatorname{Tr}(\mathbf{T}\mathbf{V}_\mu))^2 \partial_\nu \partial^\nu \mathcal{F}_{25}(h)$

ξ^4

$\mathcal{P}_{26} = (\operatorname{Tr}(\mathbf{T}\mathbf{V}_\mu) \operatorname{Tr}(\mathbf{T}\mathbf{V}_\nu))^2 \mathcal{F}_{26}(h)$

Correspondence between first orders



10 linear operators of $d = 6$

correspond to

17 chiral operators with 4∂

Linear doublet *vs* generic singlet

Already at LO the linear EFT has fewer parameters than the chiral one!

Linear doublet *vs* generic singlet

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Requirements:

1. Linearity of EWSB ▸ $\boldsymbol{\xi \to 0}$

linear op. $d=6$ $\to$	chiral op. weighted by	ξ
$d=8$ $\to$		ξ^2
$d=10$ $\to$		ξ^4

▸ $\mathcal{F}(h) = (1+h/v)^n$ $\Rightarrow$ constraint on a_i , b_i

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▸ $\mathcal{F}(h) = (1 + h/v)^n$ $\Rightarrow$ constraint on a_i , b_i

2. Gauge structure: $\Phi = \frac{v+h}{\sqrt{2}}\mathbf{U}\begin{pmatrix}0\\1\end{pmatrix}$

- fixes the **relative weight** of some operators to reproduce the structure of $D_\mu\Phi \propto (v+h)\,D_\mu\mathbf{U} + \partial_\mu h\,\mathbf{U}$ $\Rightarrow$ constraint on c_i

Linear doublet *vs* generic singlet

For instance, consider

$$\mathcal{O}_B = \frac{ig'}{2}(\mathbf{D}^\mu\Phi)^\dagger B_{\mu\nu}(\mathbf{D}^\nu\Phi)$$
$$\mathcal{O}_W = \frac{ig}{2}(\mathbf{D}^\mu\Phi)^\dagger W_{\mu\nu}(\mathbf{D}^\nu\Phi)$$

Linear doublet *vs* generic singlet

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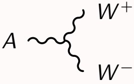
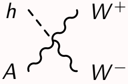
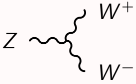
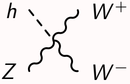
Replacing $\Phi \to \frac{v+h}{\sqrt{2}}\,\mathbf{U}\binom{0}{1}$ we get

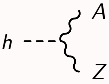
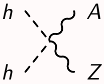
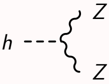
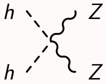
$$\mathcal{O}_B = \frac{ig'}{16}B_{\mu\nu}\,\mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu,\mathbf{V}^\nu])(v+h)^2 + \frac{ig'}{4}B_{\mu\nu}\,\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu h(v+h)$$
$$= v^2\left(\frac{\mathcal{P}_2}{16}+\frac{\mathcal{P}_4}{8}\right)_{\mathcal{F}_2=\mathcal{F}_4=(1+h/v)^2}$$

$$\mathcal{O}_W = \frac{ig}{8}\,\mathrm{Tr}(W_{\mu\nu}[\mathbf{V}^\mu,\mathbf{V}^\nu])(v+h)^2 - \frac{ig}{2}\,\mathrm{Tr}(W_{\mu\nu}\mathbf{V}^\mu)\partial^\nu h(v+h)$$
$$= v^2\left(\frac{\mathcal{P}_3}{8}-\frac{\mathcal{P}_5}{4}\right)_{\mathcal{F}_3=\mathcal{F}_5=(1+h/v)^2} \quad\Rightarrow$$

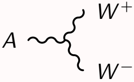
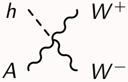
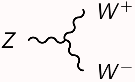
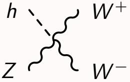
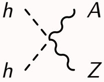
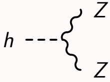
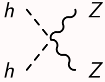
$$2c_2 = c_4 \qquad (= c_B/8)$$
$$2c_3 = -c_5 \qquad (= c_W/4)$$
$$a_i = b_i = 1$$

Back to example I

Coupling	$A_{\mu\nu}W^{+\mu}W^{-\nu}$	$A_{\mu\nu}W^{+\mu}W^{-\nu}h$	$Z_{\mu\nu}W^{+\mu}W^{-\nu}$	$Z_{\mu\nu}W^{+\mu}W^{-\nu}h$
				
generic singlet	$2c_2 + c_3$	$2c_2a_2 + c_3a_3$	$-2t_\theta^2c_2 + c_3$	$-2t_\theta^2c_2a_2 + c_3a_3$
linear doublet	$\frac{1}{8}(c_B + c_W)$	$\frac{1}{8}(c_B + c_W)$	$\frac{1}{8}(-t_\theta^2 c_B + c_W)$	$\frac{1}{8}(-t_\theta^2 c_B + c_W)$

Coupling	$A_{\mu\nu}Z^\mu\partial^\nu h$	$A_{\mu\nu}Z^\mu h\partial^\nu h$	$Z_{\mu\nu}Z^\mu\partial^\nu h$	$Z_{\mu\nu}Z^\mu h\partial^\nu h$
				
generic singlet	$2c_4a_4 + c_5a_5$	$2c_4b_4 + c_5b_5$	$2t_\theta^2c_4a_4 - c_5a_5$	$2t_\theta^2c_4b_4 - c_5b_5$
linear doublet	$\frac{1}{4}(c_B - c_W)$	$\frac{1}{4}(c_B - c_W)$	$\frac{1}{4}(t_\theta^2 c_B + c_W)$	$\frac{1}{4}(t_\theta^2 c_B + c_W)$

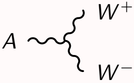
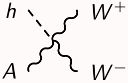
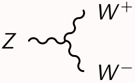
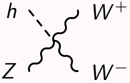
Back to example I

Coupling	$A_{\mu\nu} W^{+\mu} W^{-\nu}$ 	$A_{\mu\nu} W^{+\mu} W^{-\nu} h$ 	$Z_{\mu\nu} W^{+\mu} W^{-\nu}$ 	$Z_{\mu\nu} W^{+\mu} W^{-\nu} h$ 
generic singlet	$2c_2 + c_3$	$2c_2 a_2 + c_3 a_3$	$-2t_\theta^2 c_2 + c_3$	$-2t_\theta^2 c_2 a_2 + c_3 a_3$
linear doublet	$\frac{1}{8}(c_B + c_W)$	$\frac{1}{8}(c_B + c_W)$	$\frac{1}{8}(-t_\theta^2 c_B + c_W)$	$\frac{1}{8}(-t_\theta^2 c_B + c_W)$
		$A_{\mu\nu} Z^\mu h \partial^\nu h$ 	$Z_{\mu\nu} Z^\mu \partial^\nu h$ 	$Z_{\mu\nu} Z^\mu h \partial^\nu h$ 
generic singlet	$2c_4 a_4 + c_5 a_5$	$2c_4 b_4 + c_5 b_5$	$2t_\theta^2 c_4 a_4 - c_5 a_5$	$2t_\theta^2 c_4 b_4 - c_5 b_5$
linear doublet	$\frac{1}{4}(c_B - c_W)$	$\frac{1}{4}(c_B - c_W)$	$\frac{1}{4}(t_\theta^2 c_B + c_W)$	$\frac{1}{4}(t_\theta^2 c_B + c_W)$

Complete equivalence for

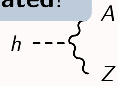
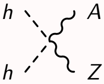
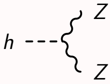
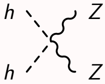
$$2c_2 = c_4 = c_B/8$$
$$2c_3 = -c_5 = c_W/4$$
$$a_i = b_i = 1$$

Back to example I

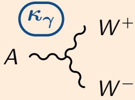
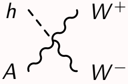
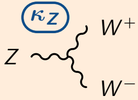
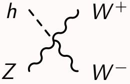
Coupling	$A_{\mu\nu}W^{+\mu}W^{-\nu}$ 	$A_{\mu\nu}W^{+\mu}W^{-\nu}h$ 	$Z_{\mu\nu}W^{+\mu}W^{-\nu}$ 	$Z_{\mu\nu}W^{+\mu}W^{-\nu}h$ 
generic singlet	$2c_2 + c_3$	$2c_2a_2 + c_3a_3$	$-2t_\theta^2c_2 + c_3$	$-2t_\theta^2c_2a_2 + c_3a_3$
linear doublet	$\frac{1}{8}(c_B + c_W)$	$\frac{1}{8}(c_B + c_W)$	$\frac{1}{8}(-t_\theta^2 c_B + c_W)$	$\frac{1}{8}(-t_\theta^2 c_B + c_W)$

linear doublet:

couplings **correlated**!

	h 	$A_{\mu\nu}Z^\mu h\partial^\nu h$ 	$Z_{\mu\nu}Z^\mu\partial^\nu h$ 	$Z_{\mu\nu}Z^\mu h\partial^\nu h$ 
generic singlet	$2c_4a_4 + c_5a_5$	$2c_4b_4 + c_5b_5$	$2t_\theta^2c_4a_4 - c_5a_5$	$2t_\theta^2c_4b_4 - c_5b_5$
linear doublet	$\frac{1}{4}(c_B - c_W)$	$\frac{1}{4}(c_B - c_W)$	$\frac{1}{4}(t_\theta^2 c_B + c_W)$	$\frac{1}{4}(t_\theta^2 c_B + c_W)$

Back to example I

Coupling	$A_{\mu\nu}W^{+\mu}W^{-\nu}$ 	$A_{\mu\nu}W^{+\mu}W^{-\nu}h$ 	$Z_{\mu\nu}W^{+\mu}W^{-\nu}$ 	$Z_{\mu\nu}W^{+\mu}W^{-\nu}h$ 
generic singlet	$2c_2 + c_3$	$2c_2a_2 + c_3a_3$	$-2t_\theta^2 c_2 + c_3$	$-2t_\theta^2 c_2 a_2 + c_3 a_3$
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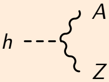
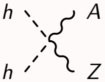
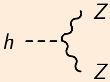
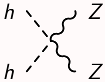
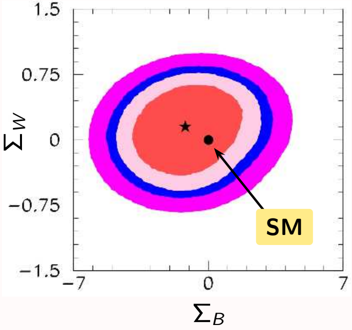
Coupling	$A_{\mu\nu}Z^{\mu}\partial^{\nu}h$ 	$A_{\mu\nu}Z^{\mu}h\partial^{\nu}h$ 	$Z_{\mu\nu}Z^{\mu}\partial^{\nu}h$ 	$Z_{\mu\nu}Z^{\mu}h\partial^{\nu}h$ 
generic singlet	$2c_4a_4 + c_5a_5$	$2c_4b_4 + c_5b_5$	$2t_\theta^2 c_4 a_4 - c_5 a_5$	$2t_\theta^2 c_4 b_4 - c_5 b_5$
linear doublet	$\frac{1}{4}(c_B - c_W)$	$\frac{1}{4}(c_B - c_W)$	$\frac{1}{4}(t_\theta^2 c_B + c_W)$	$\frac{1}{4}(t_\theta^2 c_B + c_W)$

Combining TGV + Higgs data

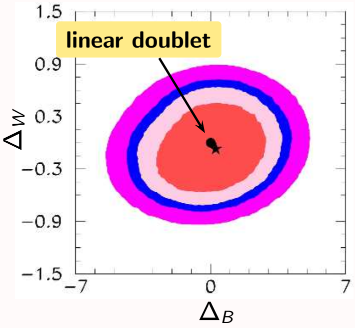
A BSM sensor

$$\Sigma_B \equiv 4(2c_2 + c_2 a_4)$$
$$\Sigma_W \equiv 2(2c_3 - c_5 a_5)$$



A linear vs non-linear discriminator

$$\Delta_B \equiv 4(2c_2 - c_4 a_4)$$
$$\Delta_W \equiv 2(2c_3 + c_5 a_5)$$



χ^2 dependence after marginalizing over the other chiral parameters

Datasets: TGV (LEP) and HVV couplings (D0+CDF+LHC7+LHC8).

Colored areas: 68, 90, 95, 99% CL

Example II

In the **linear** Lagrangian

$$\mathcal{O}_{\Box\Phi} = \left(D_\mu D^\mu \Phi\right)^\dagger \left(D_\nu D^\nu \Phi\right)$$

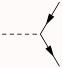
Example II

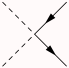
In the **linear** Lagrangian

$$\mathcal{O}_{\Box\Phi} = \left(D_\mu D^\mu \Phi\right)^\dagger \left(D_\nu D^\nu \Phi\right)$$

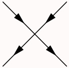
Applying the EOM for Φ ▸ $c_{\Box\Phi}$ contributes to

Yukawa couplings

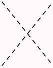


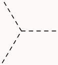


4-fermions



scalar potential





Example II

In the **chiral** Lagrangian

$$\mathcal{O}_{\Box h} = \frac{1}{v^2}\left(\partial_\mu \partial^\mu h\right)\left(\partial_\nu \partial^\nu h\right)$$

Applying the EOM for h ▸ $c_{\Box h}$ contributes to

Yukawa couplings

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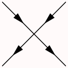
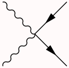
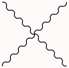


scalar potential

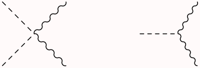
fermion-gauge



4-gauge



gauge-Higgs



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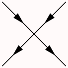
Applying the EOM for h ▸ $c_{\Box h}$ contributes to

also from $c_{\Box\Phi}$ {

Yukawa couplings

4-fermions



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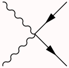

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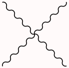

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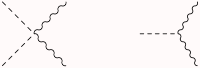

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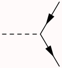
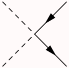
different pattern! →

Yukawa couplings





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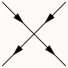

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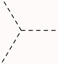
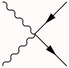


fermion-gauge



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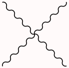
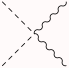
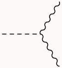


gauge-Higgs





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Yukawa couplings

also from $c_{\Box\Phi}$

different pattern! → 4-fermions

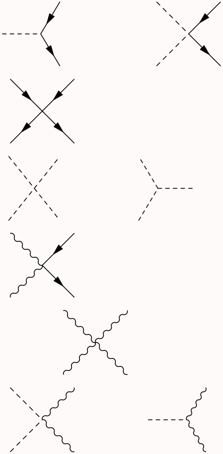
scalar potential

fermion-gauge

no contribution in the linear EFT!

4-gauge

gauge-Higgs



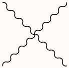
Example II

Replacing $\Phi \rightarrow \frac{v+h}{\sqrt{2}}\,\mathbf{U}\binom{0}{1}$:

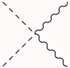
$$\mathcal{O}_{\Box\Phi} \rightarrow \mathcal{P}_{\Box h} + v^2\left(\frac{1}{8}\mathcal{P}_6 + \frac{1}{4}\mathcal{P}_7 - \mathcal{P}_8 - \frac{1}{4}\mathcal{P}_9 - \frac{1}{2}\mathcal{P}_{10}\right)$$

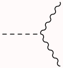
where:

$c_6\,,\, c_9 \quad \rightarrow \quad$ 4-gauge



$c_7\,,\, c_8\,,\, c_9\,,\, c_{10} \quad \rightarrow \quad$ gauge-Higgs





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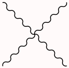

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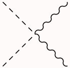
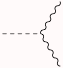




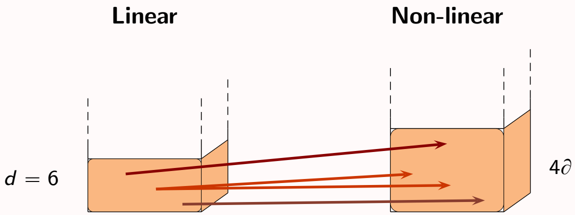
The chiral description is physically equivalent to the linear one *iff*:

$$v^2 c_{\Box h} = 8c_6 = 4c_7 = -c_8 = -4c_9 = -2c_{10}$$
$$a_i = b_i = 1\,, \qquad i = 6,\ldots,10$$

contributions to **QGV**, **gauge-Higgs** and **gauge-fermion** couplings
signal deviations from the $SU(2)_L$ doublet structure

- *e.g.* impact on <u>off-shell</u> $\quad gg \to h^* \to VV \quad$ from $\mathcal{P}_7 = \mathrm{Tr}[\mathbf{V}_\mu\mathbf{V}^\mu]\partial_\nu\partial^\nu\mathcal{F}_7(h)$

Correspondence between first orders



10 linear operators of $d = 6$

correspond to

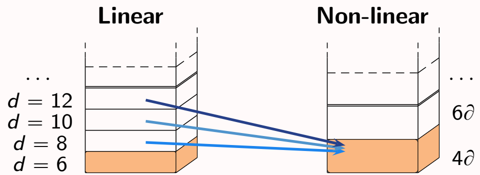
17 chiral operators with 4∂

$$\mathcal{O}_B \rightarrow \frac{\mathcal{P}_2}{16} + \frac{\mathcal{P}_4}{8}$$

$$\mathcal{O}_W \rightarrow \frac{\mathcal{P}_3}{8} - \frac{\mathcal{P}_5}{4}$$

$$\mathcal{O}_{\Box\Phi} \rightarrow \mathcal{P}_{\Box h} + \frac{\mathcal{P}_6}{8} + \frac{\mathcal{P}_7}{4} - \mathcal{P}_8 - \frac{\mathcal{P}_9}{4} - \frac{\mathcal{P}_{10}}{2}$$

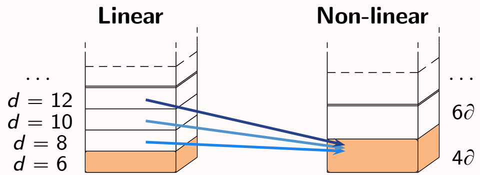
Example III



Effects that are expected to be

- leading-order corrections in the most general non-linear expansion
- higher-order corrections in the linear series

Example III



Effects that are expected to be

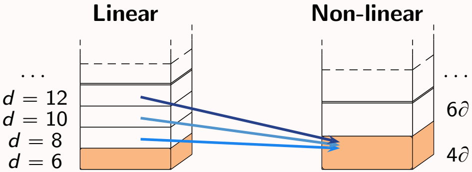
- leading-order corrections in the most general non-linear expansion
- higher-order corrections in the linear series

$$\varepsilon^{\mu\nu\rho\lambda}\left(\Phi^\dagger \overleftrightarrow{\mathbf{D}}_\rho \Phi\right)\left(\Phi^\dagger \sigma_i \overleftrightarrow{\mathbf{D}}_\lambda \Phi\right) W^i_{\mu\nu} \qquad d=8$$

▾

$$\mathcal{P}_{14} = g\varepsilon^{\mu\nu\rho\lambda}\,\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\,\mathrm{Tr}(\mathbf{V}_\nu W_{\rho\lambda})\mathcal{F}_{14}(h) \qquad 4\partial$$

Example III



Effects that are expected to be

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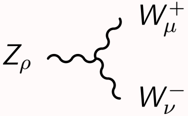
$\mathcal{P}_{14}$ ➔



$$-\frac{g^3 c_{14}}{2c_\theta}\varepsilon^{\mu\nu\rho\lambda}\partial_\mu W_\nu^+ W_\rho^- Z_\lambda + \text{h.c.}$$

Warning: this operator breaks custodial symmetry.

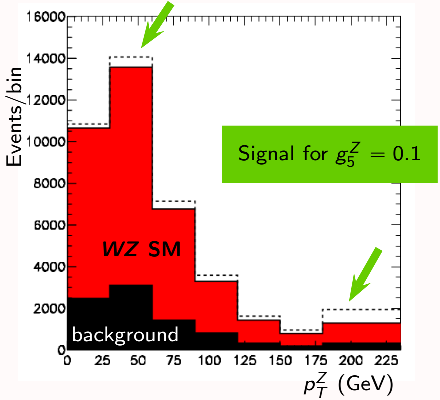
Expected LHC sensitivity

$$g_5^Z = g^2 c_{14} / 2 c_\theta^2$$

Current best bound at 95% CL

$$g_5^Z \in [-0.08, 0.04]$$

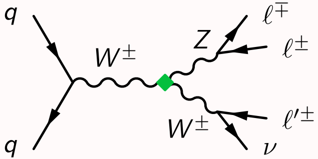
Dawson,Valencia (1994)



dataset: 7+8+14 TeV
($4.7+19.6+300$ fb^{-1})

Simulation analysis

- WZ pair production



- binned analysis of p_T^Z distribution
- Result (95% CL)

$$g_5^Z \in [-0.033, 0.028]$$

If the Higgs is a pGB embedded in a doublet

So far we have compared the phenomenology of the Higgs as a

linear $SU(2)_L$ doublet vs. **generic singlet**

But what if the Higgs is a **pseudo Goldstone boson** ?

If the Higgs is a pGB embedded in a doublet

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linear $SU(2)_L$ doublet vs. **generic singlet**

But what if the Higgs is a **pseudo Goldstone boson** ?

General expectations:

1. the functions $\mathcal{F}(h)$ contain an infinite series of $\frac{h}{f} = \sqrt{\xi}\frac{h}{v}$

e.g. trigonometric

2. if h embedded in a $SU(2)_L$ doublet $\Rightarrow$ in concrete models, the linear expansion is recovered for $\xi \to 0$

Results from specific CH models

In specific models:

$\boldsymbol{SU(5)/SO(5)}$ and $\boldsymbol{SO(5)/SO(4)}$

Georgi, Kaplan (1984)
Agashe,Contino,Pomarol (2004)

$$c_2\mathcal{F}_2(h) = \tilde{c}_2 \;\sin^2\frac{\varphi}{2f}$$

$$c_4\mathcal{F}_4(h) = 2\,\tilde{c}_2 \;\sin^2\frac{\varphi}{2f}$$

Alonso,IB,Gavela,Merlo,Rigolin (2014)
[hep-ph/1409.1589]

⇝ see talk by **R. Alonso**

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- $\mathcal{F}_2(h) = \mathcal{F}_4(h) \neq (1 + h/v)^2$

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⟿ see talk by **R. Alonso**

- $\mathcal{F}_2(h) = \mathcal{F}_4(h) \neq (1+h/v)^2$
- expanding:

$$\sin^2\frac{\varphi}{2f} = \frac{\xi}{4}\left[1 + \frac{2h}{v}\sqrt{1-\frac{\xi}{4}} + \frac{h^2}{v^2}\left(1-\frac{\xi}{2}\right)\right] + \mathcal{O}(h^3) = \frac{\xi}{4}\frac{(v+h)^2}{v^2} + \mathcal{O}(\xi^2)$$

  - ξ is a parameter of the model
  - $\mathcal{F}(h) \to \xi(1+h/v)^2$ for $\xi \to 0$

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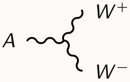
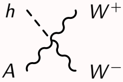
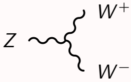
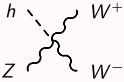
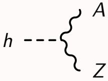
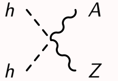
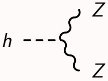
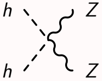
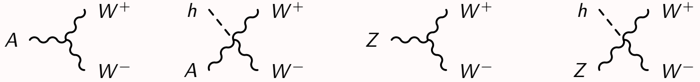
  - ξ is a parameter of the model
  - $\mathcal{F}(h) \to \xi(1 + h/v)^2$ for $\xi \to 0$
- the condition $2c_2 = c_4$ is verified exactly

Back again to example I

Coupling	$A_{\mu\nu}W^{+\mu}W^{-\nu}$	$A_{\mu\nu}W^{+\mu}W^{-\nu}h$	$Z_{\mu\nu}W^{+\mu}W^{-\nu}$	$Z_{\mu\nu}W^{+\mu}W^{-\nu}h$
				
generic singlet	a $2c_2 + c_3$	$2c_2a_2 + c_3a_3$	$-2t_\theta^2 c_2 + c_3$	$-2t_\theta^2 c_2 a_2 + c_3 a_3$
linear doublet	$\frac{1}{8}(c_B + c_W)$	$\frac{1}{8}(c_B + c_W)$	$\frac{1}{8}(-t_\theta^2 c_B + c_W)$	$\frac{1}{8}(-t_\theta^2 c_B + c_W)$
pGB doublet	$\frac{1}{2}(2\tilde{c}_2 + \tilde{c}_3)$	$\frac{1}{2}(2\tilde{c}_2 + \tilde{c}_3)\sqrt{\mathbf{1-\frac{\xi}{4}}}$	$\frac{1}{2}(-2t_\theta^2\tilde{c}_2 + \tilde{c}_3)$	$\frac{1}{2}(-2t_\theta^2\tilde{c}_2 + \tilde{c}_3)\sqrt{\mathbf{1-\frac{\xi}{4}}}$

Coupling	$A_{\mu\nu}Z^\mu\partial^\nu h$	$A_{\mu\nu}Z^\mu h\partial^\nu h$	$Z_{\mu\nu}Z^\mu\partial^\nu h$	$Z_{\mu\nu}Z^\mu h\partial^\nu h$
				
generic singlet	$2c_4a_4 + c_5a_5$	$2c_4b_4 + c_5b_5$	$2t_\theta^2 c_4 a_4 - c_5 a_5$	$2t_\theta^2 c_4 b_4 - c_5 b_5$
linear doublet	$\frac{1}{4}(c_B - c_W)$	$\frac{1}{4}(c_B - c_W)$	$\frac{1}{4}(t_\theta^2 c_B + c_W)$	$\frac{1}{4}(t_\theta^2 c_B + c_W)$
pGB doublet	$(2\tilde{c}_2 - \tilde{c}_3)\sqrt{\mathbf{1-\frac{\xi}{4}}}$	$(2\tilde{c}_2 - \tilde{c}_3)\left(\mathbf{1-\frac{\xi}{2}}\right)$	$(2t_\theta^2\tilde{c}_2 + \tilde{c}_3)\sqrt{\mathbf{1-\frac{\xi}{4}}}$	$(2t_\theta^2\tilde{c}_2 + \tilde{c}_3)\left(\mathbf{1-\frac{\xi}{2}}\right)$

Back again to example I



Coupling	$A_{\mu\nu}W^{+\mu}W^{-\nu}$	$A_{\mu\nu}W^{+\mu}W^{-\nu}h$	$Z_{\mu\nu}W^{+\mu}W^{-\nu}$	$Z_{\mu\nu}W^{+\mu}W^{-\nu}h$
generic singlet	a $2c_2+c_3$	$2c_2a_2+c_3a_3$	$-2t_\theta^2c_2+c_3$	$-2t_\theta^2c_2a_2+c_3a_3$
linear doublet	$\frac{1}{8}(c_B+c_W)$	$\frac{1}{8}(c_B+c_W)$	$\frac{1}{8}(-t_\theta^2c_B+c_W)$	$\frac{1}{8}(-t_\theta^2c_B+c_W)$
pGB doublet	$\frac{1}{2}(2\tilde{c}_2+\tilde{c}_3)$	$\frac{1}{2}(2\tilde{c}_2+\tilde{c}_3)\sqrt{\mathbf{1-\frac{\xi}{4}}}$	$\frac{1}{2}(-2t_\theta^2\tilde{c}_2+\tilde{c}_3)$	$\frac{1}{2}(-2t_\theta^2\tilde{c}_2+\tilde{c}_3)\sqrt{\mathbf{1-\frac{\xi}{4}}}$

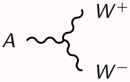
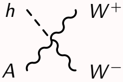
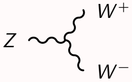
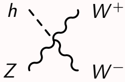
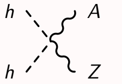
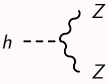
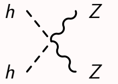
pGB constraints

$$2c_2=c_4=\tilde{c}_2 \qquad a_2=a_3=a_4=a_5=\sqrt{1-\frac{\xi}{4}}$$

$$2c_3=-c_5=\tilde{c}_3 \qquad b_4=b_5=1-\frac{\xi}{2}$$

			$Z_{\mu\nu}Z^\mu\partial^\nu h$	$Z_{\mu\nu}Z^\mu h\partial^\nu h$
generic singlet	$2c_4a_4+c_5a_5$	$2c_4b_4+c_5b_5$	$2t_\theta^2c_4a_4-c_5a_5$	$2t_\theta^2c_4b_4-c_5b_5$
linear doublet	$\frac{1}{4}(c_B-c_W)$	$\frac{1}{4}(c_B-c_W)$	$\frac{1}{4}(t_\theta^2c_B+c_W)$	$\frac{1}{4}(t_\theta^2c_B+c_W)$
pGB doublet	$(2\tilde{c}_2-\tilde{c}_3)\sqrt{\mathbf{1-\frac{\xi}{4}}}$	$(2\tilde{c}_2-\tilde{c}_3)\left(\mathbf{1-\frac{\xi}{2}}\right)$	$(2t_\theta^2\tilde{c}_2+\tilde{c}_3)\sqrt{\mathbf{1-\frac{\xi}{4}}}$	$(2t_\theta^2\tilde{c}_2+\tilde{c}_3)\left(\mathbf{1-\frac{\xi}{2}}\right)$

Back again to example I

Coupling	$A_{\mu\nu} W^{+\mu} W^{-\nu}$ 	$A_{\mu\nu} W^{+\mu} W^{-\nu} h$ 	$Z_{\mu\nu} W^{+\mu} W^{-\nu}$ 	$Z_{\mu\nu} W^{+\mu} W^{-\nu} h$ 
generic singlet	a $2c_2 + c_3$	$2c_2 a_2 + c_3 a_3$	$-2t_\theta^2 c_2 + c_3$	$-2t_\theta^2 c_2 a_2 + c_3 a_3$
linear doublet	$\frac{1}{8}(c_B + c_W)$	$\frac{1}{8}(c_B + c_W)$	$\frac{1}{8}(-t_\theta^2 c_B + c_W)$	$\frac{1}{8}(-t_\theta^2 c_B + c_W)$
pGB doublet	$\frac{1}{2}(2\tilde{c}_2 + \tilde{c}_3)$	$\frac{1}{2}(2\tilde{c}_2 + \tilde{c}_3)\sqrt{\mathbf{1 - \frac{\xi}{4}}}$	$\frac{1}{2}(-2t_\theta^2 \tilde{c}_2 + \tilde{c}_3)$	$\frac{1}{2}(-2t_\theta^2 \tilde{c}_2 + \tilde{c}_3)\sqrt{\mathbf{1 - \frac{\xi}{4}}}$
		$A_{\mu\nu} Z^{\mu} h \partial^\nu h$ 	$Z_{\mu\nu} Z^{\mu} \partial^\nu h$ 	$Z_{\mu\nu} Z^{\mu} h \partial^\nu h$ 
generic singlet	$2c_4 a_4 + c_5 a_5$	$2c_4 b_4 + c_5 b_5$	$2t_\theta^2 c_4 a_4 - c_5 a_5$	$2t_\theta^2 c_4 b_4 - c_5 b_5$
linear doublet	$\frac{1}{4}(c_B - c_W)$	$\frac{1}{4}(c_B - c_W)$	$\frac{1}{4}(t_\theta^2 c_B + c_W)$	$\frac{1}{4}(t_\theta^2 c_B + c_W)$
pGB doublet	$(2\tilde{c}_2 - \tilde{c}_3)\sqrt{\mathbf{1 - \frac{\xi}{4}}}$	$(2\tilde{c}_2 - \tilde{c}_3)\left(\mathbf{1 - \frac{\xi}{2}}\right)$	$(2t_\theta^2 \tilde{c}_2 + \tilde{c}_3)\sqrt{\mathbf{1 - \frac{\xi}{4}}}$	$(2t_\theta^2 \tilde{c}_2 + \tilde{c}_3)\left(\mathbf{1 - \frac{\xi}{2}}\right)$

pGB doublet: all couplings **correlated**!

extra h legs are weighted by a factor containing ξ

Summary

The chiral EFT is a powerful tool to study the Higgs nature:
every scenario corresponds to a specific region of the parameter space

Disentangling a **linear $SU(2)_L$ doublet** from a **generic singlet** Higgs:

- **correlation/decorrelation** of TGV, HVV and HHVV
- the op. $\mathcal{O}_{\Box\Phi}$ **does not affect** QGV, gauge-Higgs or gauge-fermion couplings, the op. $\mathcal{P}_{\Box h}$ **does**
- the g_5^Z coupling is a **NNLO (d=8)/NLO (4∂)** effect

How to recognize a **pGB Higgs embedded as a $SU(2)_L$ doublet**:

- vertices with **different number of h legs** have characteristic relative weights that depend on ξ
- if $f \gg v$ there may be no visible difference from the linear scenario

Backup slides

Triple gauge vertices

$$\begin{aligned}\mathscr{L}_{WWV} = &- ig_{WWV}\Big\{g_1^V\Big(W^+_{\mu\nu}W^{-\,\mu}V^\nu - W^+_\mu V_\nu W^{-\,\mu\nu}\Big) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu}\\ &- ig_5^V\varepsilon^{\mu\nu\rho\sigma}\left(W^+_\mu\partial_\rho W^-_\nu - W^-_\nu\partial_\rho W^+_\mu\right)V_\sigma +\\ &+ g_6^V\left(\partial_\mu W^{+\mu}W^{-\nu} - \partial_\mu W^{-\mu}W^{+\nu}\right)V_\nu\Big\}\end{aligned}$$

$g_{WWZ} = g\cos\theta\,,\quad g_{WW\gamma} = e$

	Coeff. $\times e^2/s^2_\theta$	Chiral	Linear $\times v^2$
$\Delta\kappa_\gamma$	1	$-2c_1 + 2c_2 + c_3 - 4c_{12} + 2c_{13}$	$\frac{1}{8}(c_W + c_B - 2c_{BW})$
Δg_6^γ	1	$-c_9$	–
Δg_1^Z	$\frac{1}{c^2_\theta}$	$\frac{s^2_{2\theta}}{4e^2c_{2\theta}}c_T + \frac{2s^2_\theta}{c_{2\theta}}c_1 + c_3$	$\frac{1}{8}c_W + \frac{s^2_\theta}{4c_{2\theta}}c_{BW} - \frac{s^2_{2\theta}}{16e^2c_{2\theta}}c_{\Phi,1}$
$\Delta\kappa_Z$	1	$\frac{s^2_\theta}{e^2c_{2\theta}}c_T + \frac{4s^2_\theta}{c_{2\theta}}c_1 - \frac{2s^2_\theta}{ct^2}c_2 + c_3 - 4c_{12} + 2c_{13}$	$\frac{1}{8}c_W - \frac{s^2_\theta}{8ct^2}c_B + \frac{s^2_\theta}{2c_{2\theta}}c_{BW} - \frac{s^2_\theta}{4e^2c_{2\theta}}c_{\Phi,1}$
Δg_5^Z	$\frac{1}{c^2_\theta}$	c_{14}	–
Δg_6^Z	$\frac{1}{c^2_\theta}$	$s^2_\theta c_9 - c_{16}$	–

HVV vertices

$$
\begin{aligned}
\mathscr{L}_{\rm HVV} \equiv & g_{Hgg}\, G^a_{\mu\nu} G^{a\mu\nu} h + g_{H\gamma\gamma}\, A_{\mu\nu} A^{\mu\nu} h + g^{(1)}_{HZ\gamma}\, A_{\mu\nu} Z^{\mu} \partial^{\nu} h + g^{(2)}_{HZ\gamma}\, A_{\mu\nu} Z^{\mu\nu} h \\
& + g^{(1)}_{HZZ}\, Z_{\mu\nu} Z^{\mu} \partial^{\nu} h + g^{(2)}_{HZZ}\, Z_{\mu\nu} Z^{\mu\nu} h + g^{(3)}_{HZZ}\, Z_{\mu} Z^{\mu} h + g^{(4)}_{HZZ}\, Z_{\mu} Z^{\mu} \square h \\
& + g^{(5)}_{HZZ}\, \partial_{\mu} Z^{\mu} Z_{\nu} \partial^{\nu} h + g^{(6)}_{HZZ}\, \partial_{\mu} Z^{\mu} \partial_{\nu} Z^{\nu} h \\
& + g^{(1)}_{HWW}\, \left(W^{+}_{\mu\nu} W^{-\,\mu} \partial^{\nu} h + \text{h.c.} \right) + g^{(2)}_{HWW}\, W^{+}_{\mu\nu} W^{-\,\mu\nu} h + g^{(3)}_{HWW}\, W^{+}_{\mu} W^{-\,\mu} h \\
& + g^{(4)}_{HWW}\, W^{+}_{\mu} W^{-\mu} \square h + g^{(5)}_{HWW}\, \left(\partial_{\mu} W^{+\mu} W^{-}_{\nu} \partial^{\nu} h + \text{h.c.} \right) + g^{(6)}_{HWW}\, \partial_{\mu} W^{+\mu} \partial_{\nu} W^{-\nu} h
\end{aligned}
$$

HVV vertices

	Coeff. $\times e^2/4v$	Chiral	Linear $\times v^2$
Δg_{Hgg}	$\frac{g_s^2}{e^2}$	$-2c_G a_G$	$-4c_{GG}$
$\Delta g_{H\gamma\gamma}$	1	$-2(c_B a_B + c_W a_W) + 8c_1 a_1 + 8c_{12} a_{12}$	$-(c_{BB} + c_{WW}) + c_{BW}$
$\Delta g^{(1)}_{HZ\gamma}$	$\frac{1}{s_{2\theta}}$	$-8(c_5 a_5 + 2c_4 a_4) - 16c_{17} a_{17}$	$2(c_W - c_B)$
$\Delta g^{(2)}_{HZ\gamma}$	$\frac{c_\theta}{s_\theta}$	$4\frac{s_\theta^2}{c_\theta^2} c_B a_B - 4c_W a_W + 8\frac{c_{2\theta}}{c_\theta^2} c_1 a_1 + 16c_{12} a_{12}$	$2\frac{s_\theta^2}{c_\theta^2} c_{BB} - 2c_{WW} + \frac{c_{2\theta}}{c_\theta^2} c_{BW}$
$\Delta g^{(1)}_{HZZ}$	$\frac{1}{c_\theta^2}$	$-4\frac{c_\theta^2}{s_\theta^2} c_5 a_5 + 8c_4 a_4 - 8\frac{c_\theta^2}{s_\theta^2} c_{17} a_{17}$	$\frac{c_\theta^2}{s_\theta^2} c_W + c_B$
$\Delta g^{(2)}_{HZZ}$	$-\frac{c_\theta^2}{s_\theta^2}$	$2\frac{s_\theta^4}{c_\theta^4} c_B a_B + 2c_W a_W + 8\frac{s_\theta^2}{c_\theta^2} c_1 a_1 - 8c_{12} a_{12}$	$\frac{s_\theta^4}{c_\theta^4} c_{BB} + c_{WW} + \frac{s_\theta^2}{c_\theta^2} c_{BW}$
$\Delta g^{(3)}_{HZZ}$	$\frac{m_Z^2}{e^2}$	$-2c_H + 2c_C(2a_C - 1) - 8c_T(a_T - 1) - 4m_h^2 c_{\Box h}$	$c_{\Phi,1} + 2c_{\Phi,4} - 2c_{\Phi,2}$
$\Delta g^{(4)}_{HZZ}$	$-\frac{1}{s_{2\theta}^2}$	$16c_7 a_7 + 32c_{25} a_{25}$	–
$\Delta g^{(5)}_{HZZ}$	$-\frac{1}{s_{2\theta}^2}$	$16c_{10} a_{10} + 32c_{19} a_{19}$	–
$\Delta g^{(6)}_{HZZ}$	$-\frac{1}{s_{2\theta}^2}$	$16c_9 a_9 + 32c_{15} a_{15}$	–
$\Delta g^{(1)}_{HWW}$	$\frac{1}{s_\theta^2}$	$-4c_5 a_5$	c_W
$\Delta g^{(2)}_{HWW}$	$\frac{1}{s_\theta^2}$	$-4c_W a_W$	$-2c_{WW}$
$\Delta g^{(3)}_{HWW}$	$\frac{m_Z^2 c_\theta^2}{e^2}$	$-4c_H + 4c_C(2a_C - 1) + \frac{32e^2}{c_{2\theta}} c_1 + \frac{16c_\theta^2}{c_{2\theta}} c_T - 8m_h^2 c_{\Box h} - \frac{32e^2}{s_\theta^2} c_{12}$	$\frac{-2(3c_\theta^2 - s_\theta^2)}{c_{2\theta}} c_{\Phi,1} + 4c_{\Phi,4} - 4c_{\Phi,2} + \frac{4e^2}{c_{2\theta}} c_{BW}$
$\Delta g^{(4)}_{HWW}$	$-\frac{1}{s_\theta^2}$	$8c_7 a_7$	–
$\Delta g^{(5)}_{HWW}$	$-\frac{1}{s_\theta^2}$	$4c_{10} a_{10}$	–
$\Delta g^{(6)}_{HWW}$	$-\frac{1}{s_\theta^2}$	$8c_9 a_9$	–

Quartic gauge vertices

$$\mathscr{L}_{4X} \equiv g^2 \Big\{ g^{(1)}_{ZZ} (Z_\mu Z^\mu)^2 + g^{(1)}_{WW} W^+_\mu W^{+\mu} W^-_\nu W^{-\nu} - g^{(2)}_{WW} (W^+_\mu W^{-\mu})^2 + g^{(3)}_{VV'} W^{+\mu} W^{-\nu} \left(V_\mu V'_\nu + V'_\mu V_\nu \right) - g^{(4)}_{VV'} W^+_\nu W^{-\nu} V^\mu V'_\mu + i g^{(5)}_{VV'} e^{\mu\nu\rho\sigma} W^+_\mu W^-_\nu V_\rho V'_\sigma \Big\}$$

	Coeff. $\times e^2/4s^2_\theta$	Chiral	Linear $\times v^2$
$\Delta g^{(1)}_{WW}$	1	$\frac{s^2_{2\theta}}{e^2 c_{2\theta}} c_T + \frac{8 s^2_\theta}{c_{2\theta}} c_1 + 4c_3 + 2c_{11} - 16c_{12} + 8c_{13}$	$\frac{c_W}{2} + \frac{s^2_\theta}{c_{2\theta}} c_{BW} - \frac{s^2_{2\theta}}{4c_{2\theta} e^2} c_{\Phi 1}$
$\Delta g^{(2)}_{WW}$	1	$\frac{s^2_{2\theta}}{e^2 c_{2\theta}} c_T + \frac{8 s^2_\theta}{c_{2\theta}} c_1 + 4c_3 - 4c_6 - \frac{v^2}{2} c_{\Box h} - 2c_{11} - 16c_{12} + 8c_{13}$	$\frac{c_W}{2} + \frac{s^2_\theta}{c_{2\theta}} c_{BW} - \frac{s^2_{2\theta}}{4c_{2\theta} e^2} c_{\Phi 1}$
$\Delta g^{(1)}_{ZZ}$	$\frac{1}{c^4_\theta}$	$c_6 + \frac{v^2}{8} c_{\Box h} + c_{11} + 2c_{23} + 2c_{24} + 4c_{26}$	–
$\Delta g^{(3)}_{ZZ}$	$\frac{1}{c^2_\theta}$	$\frac{s^2_{2\theta} c^2_\theta}{e^2 c_{2\theta}} c_T + \frac{2 s^2_{2\theta}}{c_{2\theta}} c_1 + 4c^2_\theta c_3 - 2s^4_\theta c_9 + 2c_{11} + 4s^2_\theta c_{16} + 2c_{24}$	$\frac{c_W c^2_\theta}{2} + \frac{s^2_{2\theta}}{4c_{2\theta}} c_{BW} - \frac{s^2_{2\theta} c^2_\theta}{4e^2 c_{2\theta}} c_{\Phi 1}$
$\Delta g^{(4)}_{ZZ}$	$\frac{1}{c^2_\theta}$	$\frac{2 s^2_{2\theta} c^2_\theta}{e^2 c_{2\theta}} c_T + \frac{4 s^2_{2\theta}}{c_{2\theta}} c_1 + 8c^2_\theta c_3 - 4c_6 - \frac{v^2}{2} c_{\Box h} - 4c_{23}$	$c_W c^2_\theta + 2\frac{s^2_{2\theta}}{4c_{2\theta}} c_{BW} - \frac{s^2_{2\theta} c^2_\theta}{2e^2 c_{2\theta}} c_{\Phi 1}$
$\Delta g^{(3)}_{\gamma\gamma}$	s^2_θ	$-2c_9$	–
$\Delta g^{(3)}_{\gamma Z}$	$\frac{s_\theta}{c_\theta}$	$\frac{s^2_{2\theta}}{e^2 c_{2\theta}} c_T + \frac{8 s^2_\theta}{c_{2\theta}} c_1 + 4c_3 + 4s^2_\theta c_9 - 4c_{16}$	$\frac{c_W}{2} + \frac{s^2_\theta}{c_{2\theta}} c_{BW} - \frac{s^2_{2\theta}}{4c_{2\theta} e^2} c_{\Phi 1}$
$\Delta g^{(4)}_{\gamma Z}$	$\frac{s_\theta}{c_\theta}$	$\frac{2 s^2_{2\theta}}{e^2 c_{2\theta}} c_T + \frac{16 s^2_\theta}{c_{2\theta}} c_1 + 8c_3$	$c_W + 2\frac{s^2_\theta}{c_{2\theta}} c_{BW} - \frac{s^2_{2\theta}}{2c_{2\theta} e^2} c_{\Phi 1}$
$\Delta g^{(5)}_{\gamma Z}$	$\frac{s_\theta}{c_\theta}$	$8c_{14}$	–

Coefficients of custodial preserving operators

$c_i\mathcal{F}_i(h)$	$SU(5)/SO(5)$	$SU(3)/SU(2)\times U(1)$	linear $d=6$
$\mathcal{F}_B(h)$	$1-4g'^2\tilde{c}_{B\Sigma}\cos^2\frac{\varphi}{2f}$	$1-g'^2\frac{\tilde{c}_{B\Sigma}}{6}\left(1+3\cos\frac{2\varphi}{f}\right)$	$1+\frac{(v+h)^2}{2}g'^2c_{BB}$
$\mathcal{F}_W(h)$	$1-4g^2\tilde{c}_{W\Sigma}\cos^2\frac{\varphi}{2f}$	$1-2g^2\tilde{c}_{W\Sigma}\cos\frac{\varphi}{f}$	$1+\frac{(v+h)^2}{2}g^2c_{WW}$
$c_{\Box H}\mathcal{F}_{\Box H}(h)$	$-2\tilde{c}_6\xi$	$-2\tilde{c}_6\xi$	$\frac{v^2}{2}c_{\Box\Phi}$
$c_{\Delta H}\mathcal{F}_{\Delta H}(h)$	–	–	–
$c_{DH}\mathcal{F}_{DH}(h)$	$4\left(\tilde{c}_4+\tilde{c}_5\right)\xi^2$	$2\left(2\tilde{c}_4+2\tilde{c}_5+\tilde{c}_7\right)\xi^2$	–
$c_1\mathcal{F}_1(h)$	$\tilde{c}_1\sin^2\frac{\varphi}{2f}$	$\frac{\tilde{c}_1}{4}\sin^2\frac{\varphi}{f}$	$\frac{(v+h)^2}{4}c_{BW}$
$c_2\mathcal{F}_2(h)$	$\tilde{c}_2\sin^2\frac{\varphi}{2f}$	$\frac{\tilde{c}_2}{4}\sin^2\frac{\varphi}{f}$	$\frac{(v+h)^2}{8}c_B$
$c_3\mathcal{F}_3(h)$	$2\tilde{c}_3\sin^2\frac{\varphi}{2f}$	$\frac{\tilde{c}_3}{2}\sin^2\frac{\varphi}{f}$	$\frac{(v+h)^2}{8}c_W$
$c_4\mathcal{F}_4(h)$	$\tilde{c}_2\sqrt{\xi}\sin\frac{\varphi}{f}$	$\frac{\tilde{c}_2}{2}\sqrt{\xi}\sin\frac{2\varphi}{f}$	$\frac{v(v+h)}{2}c_B$
$c_5\mathcal{F}_5(h)$	$-2\tilde{c}_3\sqrt{\xi}\sin\frac{\varphi}{f}$	$-2\tilde{c}_3\sqrt{\xi}\sin\frac{\varphi}{f}$	$-\frac{v(v+h)}{2}c_W$
$c_6\mathcal{F}_6(h)$	$16\tilde{c}_4\sin^4\frac{\varphi}{2f}-\frac{1}{2}\tilde{c}_6\sin^2\frac{\varphi}{f}$	$8(2\tilde{c}_4+\tilde{c}_7)\sin^4\frac{\varphi}{2f}-\frac{1}{2}\tilde{c}_6\sin^2\frac{\varphi}{f}$	$\frac{(v+h)^2}{8}c_{\Box\Phi}$
$c_7\mathcal{F}_7(h)$	$-2\tilde{c}_6\sqrt{\xi}\sin\frac{\varphi}{f}$	$-2\tilde{c}_6\sqrt{\xi}\sin\frac{\varphi}{f}$	$\frac{v(v+h)}{2}c_{\Box\Phi}$
$c_8\mathcal{F}_8(h)$	$-16\tilde{c}_5\xi\sin^2\frac{\varphi}{2f}+4\tilde{c}_6\xi\cos^2\frac{\varphi}{2f}$	$-4(4\tilde{c}_5+\tilde{c}_7)\xi\sin^2\frac{\varphi}{2f}+4\tilde{c}_6\xi\cos^2\frac{\varphi}{2f}$	$-v^2c_{\Box\Phi}$
$c_9\mathcal{F}_9(h)$	$4\tilde{c}_6\sin^2\frac{\varphi}{2f}$	$4\tilde{c}_6\sin^2\frac{\varphi}{2f}$	$-\frac{(v+h)^2}{4}c_{\Box\Phi}$
$c_{10}\mathcal{F}_{10}(h)$	$4\tilde{c}_6\sqrt{\xi}\sin\frac{\varphi}{f}$	$4\tilde{c}_6\sqrt{\xi}\sin\frac{\varphi}{f}$	$-v(v+h)c_{\Box\Phi}$
$c_{11}\mathcal{F}_{11}(h)$	$16\tilde{c}_5\sin^4\frac{\varphi}{2f}$	$16\tilde{c}_5\sin^4\frac{\varphi}{2f}$	–
$c_{20}\mathcal{F}_{20}(h)$	$-16\tilde{c}_4\xi\sin^2\frac{\varphi}{2f}$	$-4(4\tilde{c}_4+\tilde{c}_7)\xi\sin^2\frac{\varphi}{2f}$	–

Coefficients of custodial breaking operators

$c_i\mathcal{F}_i(h)$	$SU(3)/(SU(2)\times U(1))$	$c_i\mathcal{F}_i(h)$	$SU(3)/(SU(2)\times U(1))$
$c_{12}\mathcal{F}_{12}(h)$	$\tilde{c}_{W\Sigma}\sin^4\frac{\varphi}{2f}$	$c_{21}\mathcal{F}_{21}(h)$	$8\tilde{c}_4\xi\sin^4\frac{\varphi}{2f}-2\tilde{c}_7\xi\cos\frac{\varphi}{f}\sin^2\frac{\varphi}{2f},$
$c_{13}\mathcal{F}_{13}(h)$	$2\tilde{c}_3\sin^4\frac{\varphi}{2f}$	$c_{22}\mathcal{F}_{22}(h)$	$8\tilde{c}_5\xi\sin^4\frac{\varphi}{2f}+2\xi\tilde{c}_7\sin^2\frac{\varphi}{2f}-2\tilde{c}_6\xi\sin^2\frac{\varphi}{2f}\left(1+2\cos\frac{\varphi}{f}\right)$
$c_{15}\mathcal{F}_{15}(h)$	$-2\tilde{c}_6\sin^4\frac{\varphi}{2f}$	$c_{23}\mathcal{F}_{23}(h)$	$-16\tilde{c}_4\sin^6\frac{\varphi}{2f}+\tilde{c}_6\sin^2\frac{\varphi}{2f}\sin^2\frac{\varphi}{f}+$ $2\tilde{c}_7\sin^4\frac{\varphi}{2f}\left(\cos\frac{\varphi}{f}-3\right)$
$c_{16}\mathcal{F}_{16}(h)$	$4\tilde{c}_6\sin^4\frac{\varphi}{2f}$		
$c_{17}\mathcal{F}_{17}(h)$	$2\tilde{c}_3\sqrt{\xi}\sin^2\frac{\varphi}{2f}\sin\frac{\varphi}{f}$	$c_{24}\mathcal{F}_{24}(h)$	$-4(4\tilde{c}_5+\tilde{c}_6)\sin^6\frac{\varphi}{2f}+\tilde{c}_7\sin^2\frac{\varphi}{2f}\sin^2\frac{\varphi}{f}$
$c_{18}\mathcal{F}_{18}(h)$	$2(\tilde{c}_6-\tilde{c}_7)\sqrt{\xi}\sin^2\frac{\varphi}{2f}\sin\frac{\varphi}{f}$	$c_{25}\mathcal{F}_{25}(h)$	$2\tilde{c}_6\sqrt{\xi}\sin^2\frac{\varphi}{2f}\sin\frac{\varphi}{f}$
$c_{19}\mathcal{F}_{19}(h)$	$-4\tilde{c}_6\sqrt{\xi}\sin^2\frac{\varphi}{2f}\sin\frac{\varphi}{f}$	$c_{26}\mathcal{F}_{26}(h)$	$2(2(\tilde{c}_4+\tilde{c}_5)+\tilde{c}_6+\tilde{c}_7)\sin^8\frac{\varphi}{2f}$

Linear - chiral correspondence

$$\mathcal{O}_{BB} = \frac{v^2}{2}\mathcal{P}_B(h) \qquad \mathcal{O}_{WW} = \frac{v^2}{2}\mathcal{P}_W(h) \qquad \mathcal{O}_{GG} = -\frac{2v^2}{g_s^2}\mathcal{P}_G(h)$$

$$\mathcal{O}_{BW} = \frac{v^2}{8}\mathcal{P}_1(h) \qquad \mathcal{O}_B = \frac{v^2}{16}\mathcal{P}_2(h) + \frac{v^2}{8}\mathcal{P}_4(h) \qquad \mathcal{O}_W = \frac{v^2}{8}\mathcal{P}_3(h) - \frac{v^2}{4}\mathcal{P}_5(h)$$

$$\mathcal{O}_{\Phi,1} = \frac{v^2}{2}\mathcal{P}_H(h) - \frac{v^2}{4}\mathcal{F}(h)\mathcal{P}_T(h) \qquad \mathcal{O}_{\Phi,2} = v^2\mathcal{P}_H(h) \qquad \mathcal{O}_{\Phi,4} = \frac{v^2}{2}\mathcal{P}_H(h) + \frac{v^2}{2}\mathcal{F}(h)\mathcal{P}_C(h)$$

$$\mathcal{O}_{\Box\Phi} = \frac{v^2}{2}\mathcal{P}_{\Box H}(h) + \frac{v^2}{8}\mathcal{P}_6(h) + \frac{v^2}{4}\mathcal{P}_7(h) - v^2\mathcal{P}_8(h) - \frac{v^2}{4}\mathcal{P}_9(h) - \frac{v^2}{2}\mathcal{P}_{10}(h)$$

$$\begin{aligned}
\mathcal{P}_{DH}(h)\,,\mathcal{P}_{20}(h) &\to \left[\mathbf{D}_\mu\Phi^\dagger\mathbf{D}^\mu\Phi\right]^2\\
\mathcal{P}_{11}(h)\,,\mathcal{P}_{18}(h)\,,\mathcal{P}_{21}(h)\,,\mathcal{P}_{22}(h)\,,\mathcal{P}_{23}(h)\,,\mathcal{P}_{24}(h) &\to \left[\mathbf{D}^\mu\Phi^\dagger\mathbf{D}^\nu\Phi\right]^2\\
\mathcal{P}_{12}(h) &\to \left(\Phi^\dagger W^{\mu\nu}\Phi\right)^2\\
\mathcal{P}_{13}(h)\,,\mathcal{P}_{17}(h) &\to \left(\Phi^\dagger W^{\mu\nu}\Phi\right)\mathbf{D}_\mu\Phi^\dagger\mathbf{D}_\nu\Phi\\
\mathcal{P}_{14}(h) &\to \varepsilon^{\mu\nu\rho\lambda}\left(\Phi^\dagger\overleftrightarrow{\mathbf{D}}_\rho\Phi\right)\left(\Phi^\dagger\sigma_i\overleftrightarrow{\mathbf{D}}_\lambda\Phi\right)W^i_{\mu\nu}\\
\mathcal{P}_{15}(h)\,,\mathcal{P}_{19}(h) &\to \left[\Phi^\dagger\mathbf{D}_\mu\mathbf{D}^\mu\Phi - \mathbf{D}_\mu\mathbf{D}^\mu\Phi^\dagger\Phi\right]^2\\
\mathcal{P}_{16}(h)\,,\mathcal{P}_{25}(h) &\to \left(\mathbf{D}^\nu\Phi^\dagger\mathbf{D}_\mu\mathbf{D}^\mu\Phi - \mathbf{D}_\mu\mathbf{D}^\mu\Phi^\dagger\mathbf{D}^\nu\Phi\right)\left(\Phi^\dagger\overleftrightarrow{\mathbf{D}}_\nu\Phi\right)\\
\mathcal{P}_{26}(h) &\to \left[\left(\Phi^\dagger\overleftrightarrow{\mathbf{D}}_\mu\Phi\right)\left(\Phi^\dagger\overleftrightarrow{\mathbf{D}}_\nu\Phi\right)\right]^2
\end{aligned}$$

Linear - chiral correspondence (SILH)

$$\mathcal{O}_g^{\rm SILH} = \Phi^\dagger\Phi\, G^a_{\mu\nu}G^{a\mu\nu} \qquad \mathcal{O}_\gamma^{\rm SILH} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi$$

$$\mathcal{O}_B^{\rm SILH} = \left(\Phi^\dagger \overleftrightarrow{\mathbf{D}}_\mu\Phi\right)\partial_\nu \hat{B}^{\mu\nu} \qquad \mathcal{O}_W^{\rm SILH} = \frac{ig}{2}\left(\Phi^\dagger\sigma^i \overleftrightarrow{\mathbf{D}}_\mu\Phi\right)\mathbf{D}_\nu W_i^{\mu\nu}$$

$$\mathcal{O}_{HB}^{\rm SILH} = (\mathbf{D}_\mu\Phi)^\dagger(\mathbf{D}_\nu\Phi)\hat{B}^{\mu\nu} \qquad \mathcal{O}_{HW}^{\rm SILH} = (\mathbf{D}_\mu\Phi)^\dagger\hat{W}^{\mu\nu}(\mathbf{D}_\nu\Phi)$$

$$\mathcal{O}_T^{\rm SILH} = \frac{1}{2}\left(\Phi^\dagger \overleftrightarrow{\mathbf{D}}_\mu\Phi\right)\left(\Phi^\dagger \overleftrightarrow{\mathbf{D}}^\mu\Phi\right) \qquad \mathcal{O}_H^{\rm SILH} = \frac{1}{2}\partial^\mu\left(\Phi^\dagger\Phi\right)\partial_\mu\left(\Phi^\dagger\Phi\right)$$

$$\mathcal{O}_6^{\rm SILH} = \frac{1}{3}\left(\Phi^\dagger\Phi\right)^3 \qquad \mathcal{O}_y^{\rm SILH} = \left(\Phi^\dagger\Phi\right) f_L\Phi\mathcal{Y}f_R + \text{h.c.}$$

$$\mathcal{O}_g^{\rm SILH} = \frac{v^2}{2g_s^2}\partial_G(h) \qquad \mathcal{O}_\gamma^{\rm SILH} = \frac{v^2}{2}\partial_B(h)$$

$$\mathcal{O}_B^{\rm SILH} = \frac{v^2}{8}(\mathcal{P}_2(h)+2\mathcal{P}_4(h)) + \frac{v^2}{8}\mathcal{P}_1(h) + \frac{v^2}{2}\mathcal{P}_B(h) \qquad \mathcal{O}_{HB}^{\rm SILH} = \frac{v^2}{16}(\mathcal{P}_2(h)+2\mathcal{P}_4(h))$$

$$\mathcal{O}_W^{\rm SILH} = \frac{v^2}{4}(\mathcal{P}_3(h)-2\mathcal{P}_5(h)) + \frac{v^2}{8}\mathcal{P}_1(h) + \frac{v^2}{2}\mathcal{P}_W(h) \qquad \mathcal{O}_{HW}^{\rm SILH} = \frac{v^2}{8}(\mathcal{P}_3(h)-2\mathcal{P}_5(h))$$

$$\mathcal{O}_T^{\rm SILH} = \frac{v^2}{2}\mathcal{F}(h)\mathcal{P}_T(h) \qquad \mathcal{O}_H^{\rm SILH} = v^2\mathcal{P}_H(h)$$

$$\mathcal{O}_y^{\rm SILH} = 3v^2\mathcal{P}_H(h) + v^2\mathcal{F}(h)\mathcal{P}_C(h) - \frac{(v+h)^3}{2}\frac{\delta V(h)}{\delta h}$$

Best bounds on the chiral coefficients