Higgs Physics Beyond the SM: the non-Linear EFT approach

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In collaboration with:

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SEVENTH FRAMEWORK PROGRAMME

MARIE CURIE ACTIONS

invisibles

neutrinos, dark matter & dark energy physics

ift

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Why a non-linear EFT?

EFTs: indirect, model-independent study of new physics through its impact at the EW scale

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- applies to **weak-interacting** NP (e.g. SUSY)
- associated to an **elementary** Higgs

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linear EFT ⇝ see talk by **F. Riva**

- applies to **weak-interacting** NP (e.g. SUSY)
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non-linear EFT

- best suited for **strong-interacting** NP
- typically **composite** Higgs
- turns out to be **very general**!
  Can describe also dilaton, 2HDM . . .

The power of EFTs

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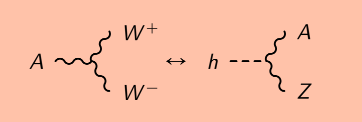

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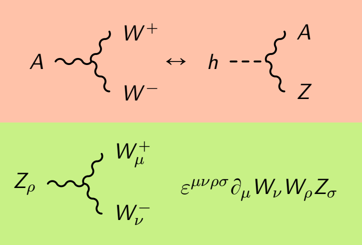

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foreseen @NNLO ($d = 8$)	allowed @NLO (4∂)

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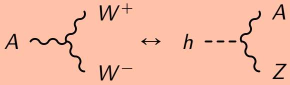
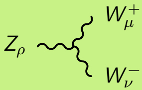
	correlated	uncorrelated in general
 $\varepsilon^{\mu\nu\rho\sigma}\partial_\mu W_\nu W_\rho Z_\sigma$	foreseen @NNLO ($d=8$)	allowed @NLO (4∂)
custodial symmetry	approximately conserved @NLO ($d=6$)	larger violating effects allowed @NLO

Non-linear construction: scalar sector

Field content

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \pi^1 + i\pi^2 \\ v + h + i\pi^3 \end{pmatrix}$$

Goldstone bosons: $\pi^i \to Z_L, W_L^\pm$

physical Higgs: h

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

Goldstone bosons:	$\mathbf{U}(x) = e^{i\pi^a(x)\sigma^a/v}$	$\mathbf{U} \mapsto L\mathbf{U}Y^\dagger$
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Building blocks for the Lagrangian:

$$\mathbf{V}_\mu = (D_\mu \mathbf{U})\mathbf{U}^\dagger \qquad \mathbf{V}_\mu \mapsto L\mathbf{V}_\mu L^\dagger$$

$$\mathbf{T} = \mathbf{U}\sigma^3\mathbf{U}^\dagger \qquad \mathbf{T} \mapsto L\mathbf{T}L^\dagger \to$$ ~~Custodial sym.~~

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in unitary gauge

$$\mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots \qquad \neq (v+h)^n$$

$$\partial_\mu\mathcal{F}(h)$$

Grinstein, Trott (PRD 76 073002)
Contino et al. (JHEP 1005 089)
Azatov et al. (JHEP 1204 127)

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unitary gauge

$\mathbf{U}$ and h independent!

$\mathbf{U}$ is adimensional

h is a singlet

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The non-linear effective Lagrangian

$$\mathscr{L} = \mathscr{L}_{\mathbf{SM}} + \boldsymbol{\Delta}\mathscr{L}$$

Leading Order: SM Lagrangian

$$\begin{aligned}\mathscr{L}_{\rm SM} =& (\text{kinetic terms for } \psi, W, Z, \mathcal{G}) + \\ &+ \frac{1}{2}\partial_\mu h \partial^\mu h - V(h) + \\ &- \frac{(v+h)^2}{4}\,\mathrm{Tr}[\mathbf{V}_\mu \mathbf{V}^\mu] + \\ &- \frac{v+h}{\sqrt{2}}\left[\bar{\psi}_L \mathbf{U} Y \psi_R + \text{h.c.}\right]\end{aligned}$$

GB kinetic terms
gauge bosons' masses

Yukawas

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The non-linear effective Lagrangian

NLO (BSM effects):

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

with a complete basis of effective operators $\{\mathcal{P}_i\}$

- allowed by SM symmetries
- with up to 4 derivatives (chiral expansion)

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☛ in this talk: bosonic, CP even

Alonso et al. (Phys.Lett.B722 330)

Brivio et al. (JHEP 1403 024)

- bosonic CP odd — Gavela et al. (JHEP 1410 44)
- bosons + fermions — Buchalla,Catà,Krause (Nucl.Phys.B880 552)

Bosonic CP even basis

Alonso, Gavela, Merlo, Rigolin, Yepes (Phys.Lett.B722 330)

$$\mathcal{P}_W = -\frac{g^2}{4} W^a_{\mu\nu} W^{a\mu\nu} \mathcal{F}_W(h)$$
$$\mathcal{P}_B = -\frac{g'^2}{4} B_{\mu\nu} B^{\mu\nu} \mathcal{F}_B(h)$$
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Bosonic sector CP even

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Alonso,Gavela,Merlo,Rigolin,Yepes (Phys.Lett.B722 330)

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

No h: ALF basis

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$$\mathcal{P}_{18} = \operatorname{Tr}(\mathbf{T}[\mathbf{V}_\mu, \mathbf{V}_\nu]) \operatorname{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_{18}(h)$$
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$$\mathcal{P}_{20} = \operatorname{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) \partial_\nu \mathcal{F}_{20}(h) \partial^\nu \mathcal{F}'_{20}(h)$$
$$\mathcal{P}_{21} = (\operatorname{Tr}(\mathbf{T}\mathbf{V}_\mu))^2 \partial_\nu \mathcal{F}_{21}(h) \partial^\nu \mathcal{F}'_{21}(h)$$
$$\mathcal{P}_{22} = \operatorname{Tr}(\mathbf{T}\mathbf{V}_\mu) \operatorname{Tr}(\mathbf{T}\mathbf{V}_\nu) \partial^\mu \mathcal{F}_{22}(h) \partial^\mu \mathcal{F}'_{22}(h)$$
$$\mathcal{P}_{23} = \operatorname{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu)(\operatorname{Tr}(\mathbf{T}\mathbf{V}_\nu))^2 \mathcal{F}_{23}(h)$$
$$\mathcal{P}_{24} = \operatorname{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu) \operatorname{Tr}(\mathbf{T}\mathbf{V}^\mu) \operatorname{Tr}(\mathbf{T}\mathbf{V}^\nu) \mathcal{F}_{24}(h)$$
$$\mathcal{P}_{25} = (\operatorname{Tr}(\mathbf{T}\mathbf{V}_\mu))^2 \partial_\nu \partial^\nu \mathcal{F}_{25}(h)$$
$$\mathcal{P}_{26} = (\operatorname{Tr}(\mathbf{T}\mathbf{V}_\mu) \operatorname{Tr}(\mathbf{T}\mathbf{V}_\nu))^2 \mathcal{F}_{26}(h)$$

Custodial symmetry imposed

Bosonic CP even basis

Alonso,Gavela,Merlo,Rigolin,Yepes (Phys.Lett.B722 330)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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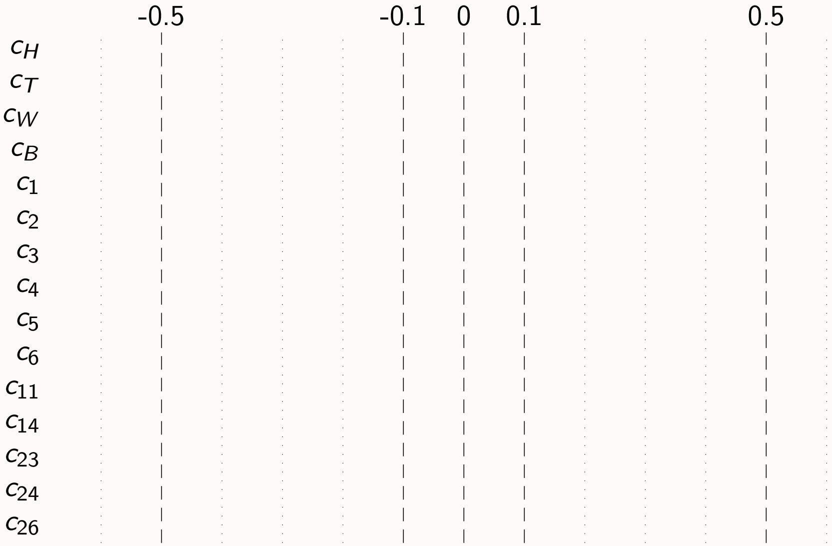
Massless fermions

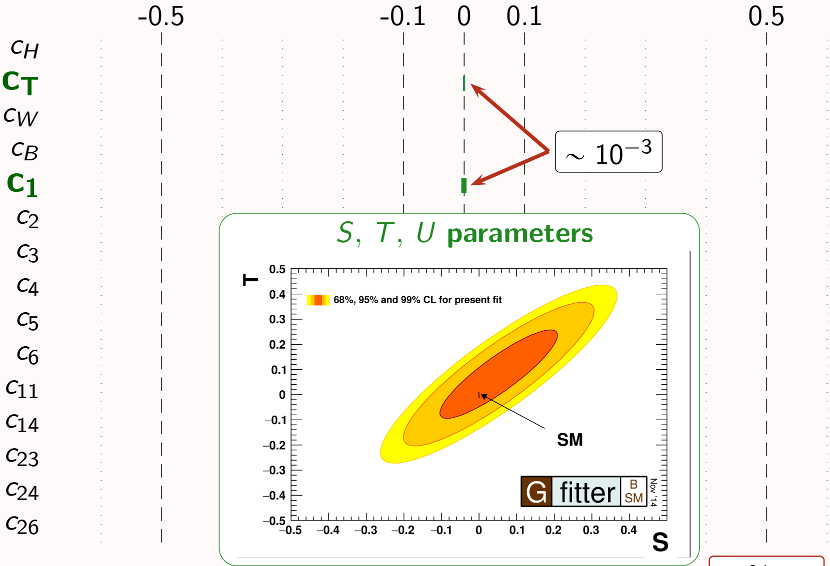
Current bounds on the chiral coefficients



Brivio,Corbett,Éboli,Gavela,Gonzalez-Fraile,Gonzalez-García,Merlo,Rigolin (JHEP 1403 024)

90% CL

Current bounds on the chiral coefficients



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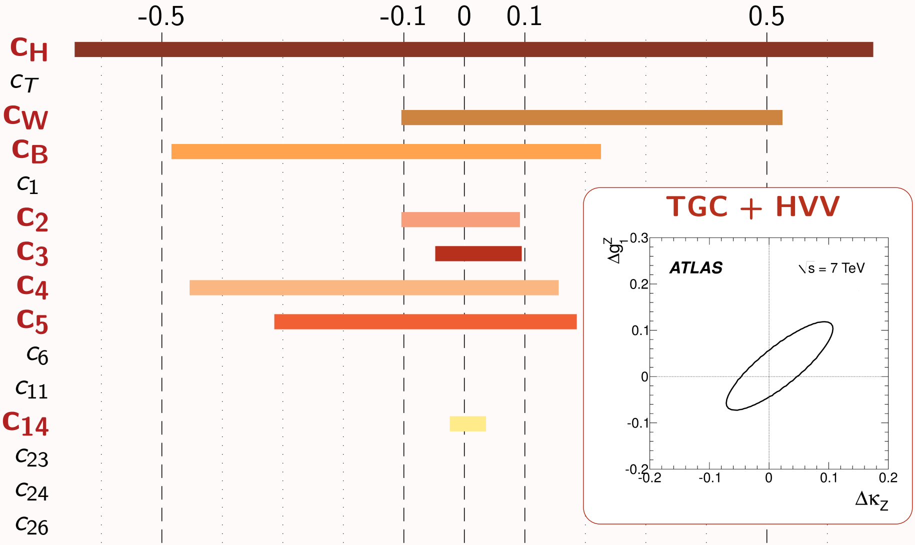

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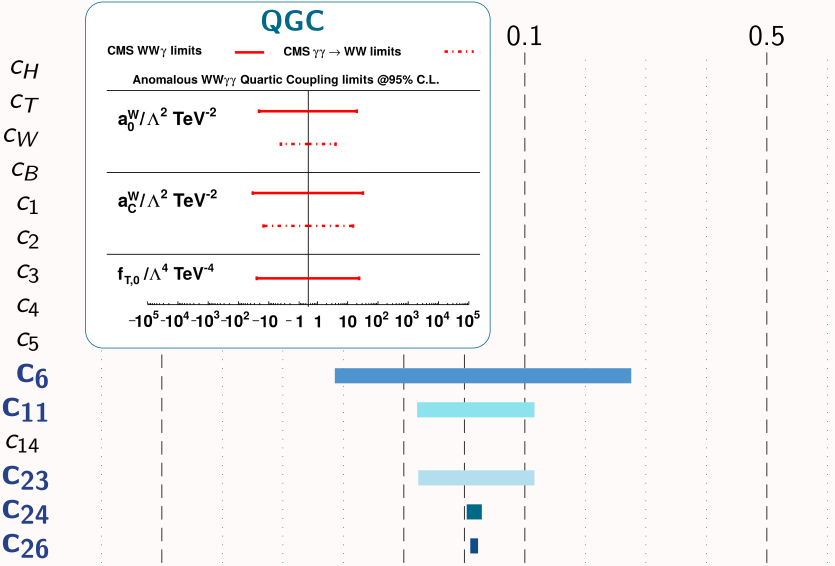

Brivio, Corbett, Éboli, Gavela, Gonzalez-Fraile, Gonzalez-García, Merlo, Rigolin (JHEP 1403 024)

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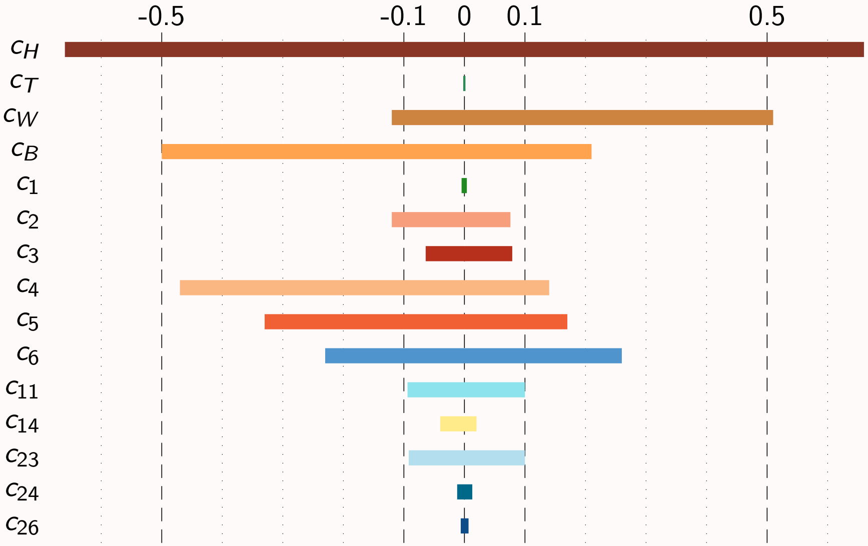
Current bounds on the chiral coefficients



Brivio,Corbett,Éboli,Gavela,Gonzalez-Fraile,Gonzalez-García,Merlo,Rigolin (JHEP 1403 024)

90% CL

Disentangling linear and non-linear

Most interesting:
what are the **characteristic signatures** of the non-linear EFT?

Strategy

- Match linear and non-linear EFTs
- Look for distinctive signals.

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	doublet Φ	**singlet h**
h couplings:	fixed by $(v+h)$ pattern	generic
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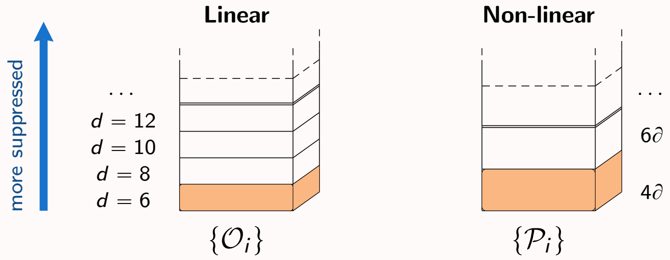
	Φ of $dim=1$	**U adimensional**
$\exists$ signals:	@NNLO (further suppressed)	@ NLO

Linear - chiral correspondence

Two towers of operators:



Correspondence $\mathcal{O}_\mathbf{i} \to \mathcal{P}_\mathbf{j}$

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

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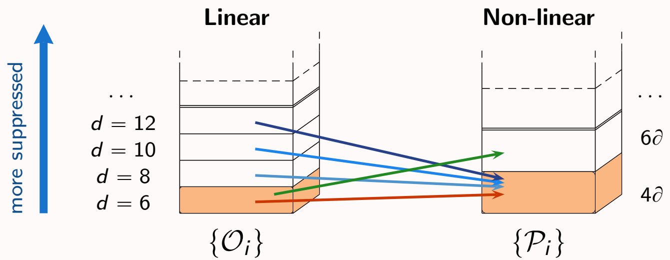

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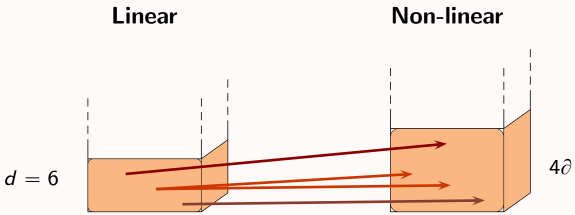
Replace in $\mathcal{O}_i$: $\quad \Phi \rightarrow \frac{v+h}{\sqrt{2}}\mathbf{U}\begin{pmatrix}0\\1\end{pmatrix}$

Correspondence between first orders



10 linear operators of $d = 6$

correspond to

17 chiral operators with 4∂

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

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

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

Example I: (De)correlation effects

For instance, consider

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

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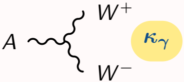
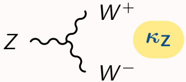
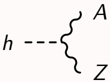
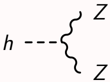
Replacing $\Phi \to \frac{v+h}{\sqrt{2}}\,\mathbf{U}\binom{0}{1}$ we get

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

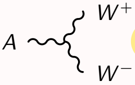
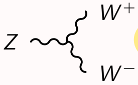
$$\mathcal{O}_W = \frac{ig}{8}\,\mathrm{Tr}(W_{\mu\nu}[\mathbf{V}^\mu,\mathbf{V}^\nu])(v+h)^2 - \frac{ig}{2}\,\mathrm{Tr}(W_{\mu\nu}\mathbf{V}^\mu)\partial^\nu h(v+h)$$
$$= v^2\left(\frac{\mathcal{P}_3}{8}-\frac{\mathcal{P}_5}{4}\right)_{\mathcal{F}_3=\mathcal{F}_5=(1+h/v)^2}$$

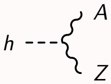
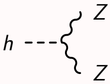
Example I: (De)correlation effects

Coupling	$A_{\mu\nu}W^{+\mu}W^{-\nu}$ 	$Z_{\mu\nu}W^{+\mu}W^{-\nu}$ 
non-linear EFT	$2c_2 + c_3$	$-t_\theta^2 2c_2 + c_3$
linear EFT	$\frac{1}{8}(c_B + c_W)$	$\frac{1}{8}(-t_\theta^2 c_B + c_W)$
Coupling	$A_{\mu\nu}Z^{\mu}\partial^{\nu}h$ 	$Z_{\mu\nu}Z^{\mu}\partial^{\nu}h$ 
non-linear EFT	$2c_4a_4 + c_5a_5$	$t_\theta^2 2c_4a_4 - c_5a_5$
linear EFT	$\frac{1}{4}(c_B - c_W)$	$\frac{1}{4}(t_\theta^2 c_B + c_W)$

Example I: (De)correlation effects

Focus on O_B *vs.* $\mathcal{P}_2$, $\mathcal{P}_4$

	$A_{\mu\nu}W^{+\mu}W^{-\nu}$	$Z_{\mu\nu}W^{+\mu}W^{-\nu}$
Coupling	 κ_γ	 κ_Z
non-linear EFT	$2c_2 + c_3$	$-t_\theta^2 2c_2 + c_3$
linear EFT	$\frac{1}{8}(c_B + c_W)$	$\frac{1}{8}(-t_\theta^2 c_B + c_W)$

	$A_{\mu\nu}Z^{\mu}\partial^{\nu}h$	$Z_{\mu\nu}Z^{\mu}\partial^{\nu}h$
Coupling		
non-linear EFT	$2c_4 a_4 + c_5 a_5$	$t_\theta^2 2c_4 a_4 - c_5 a_5$
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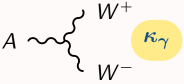
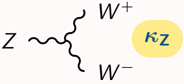
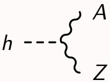
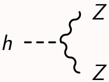
Example I: (De)correlation effects

	$A_{\mu\nu}W^{+\mu}W^{-\nu}$	$Z_{\mu\nu}W^{+\mu}W^{-\nu}$
Coupling		
non-linear EFT	$\frac{1}{8}(\Sigma_B + \Delta_B) + c_3$	$-t_\theta^2 \frac{1}{8}(\Sigma_B + \Delta_B) + c_3$
linear EFT	$\frac{1}{8}(c_B + c_W)$	$\frac{1}{8}(-t_\theta^2 c_B + c_W)$
	$A_{\mu\nu}Z^\mu\partial^\nu h$	$Z_{\mu\nu}Z^\mu\partial^\nu h$
Coupling		
non-linear EFT	$\frac{1}{4}(\Sigma_B - \Delta_B) + c_5 a_5$	$t_\theta^2 \frac{1}{4}(\Sigma_B - \Delta_B) - c_5 a_5$
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Focus on $\boxed{O_B \text{ vs. } \mathcal{P}_2, \mathcal{P}_4}$

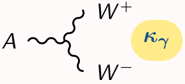
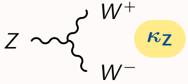
Define the combinations

$$\mathbf{\Sigma_B} \equiv 4(2c_2 + c_4 a_4) \sim \mathbf{c_B}$$
$$\mathbf{\Delta_B} \equiv 4(2c_2 - c_4 a_4)$$

$\Sigma_B \neq 0$ deviation from SM

$\Delta_B \neq 0$ TGC and HVV not aligned as in the linear case

Example I: (De)correlation effects

	$A_{\mu\nu}W^{+\mu}W^{-\nu}$	$Z_{\mu\nu}W^{+\mu}W^{-\nu}$
Coupling		
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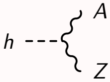
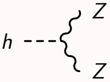
Coupling		
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smoking gun!

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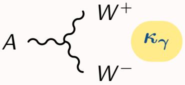
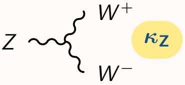
Coupling		
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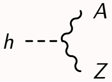
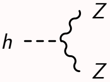
linear EFT	$\frac{1}{8}(c_B + c_W)$	$\frac{1}{8}(-t_\theta^2 c_B + c_W)$

	$A_{\mu\nu}Z^\mu\partial^\nu h$	$Z_{\mu\nu}Z^\mu\partial^\nu h$
Coupling		
non-linear EFT	$\frac{1}{4}(\Sigma_B - \Delta_B) + c_5 a_5$	$t_\theta^2 \frac{1}{4}(\Sigma_B - \Delta_B) - c_5 a_5$
linear EFT	$\frac{1}{4}(c_B - c_W)$	$\frac{1}{4}(t_\theta^2 c_B + c_W)$

Focus on O_B *vs.* $\mathcal{P}_2, \mathcal{P}_4$

Define the combinations

$$\mathbf{\Sigma_B} \equiv 4(2c_2 + c_4 a_4) \sim \mathbf{c_B}$$
$$\mathbf{\Delta_B} \equiv 4(2c_2 - c_4 a_4)$$

$\Sigma_B \neq 0$ deviation from SM

$\Delta_B \neq 0$ TGC [illegible] HVV not [illegible]d as in the linear case

smoking gun!

for $\mathcal{O}_W$ *vs.* $\mathcal{P}_3, \mathcal{P}_5$ define

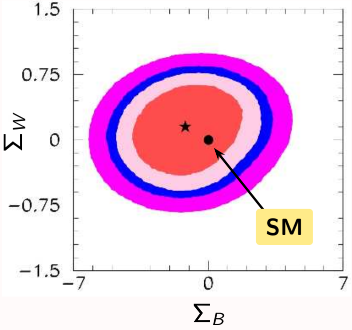
$$\begin{cases} \Sigma_W \sim c_3 \\ \Delta_W \end{cases}$$

➡ **fit**

Combining TGV + Higgs data

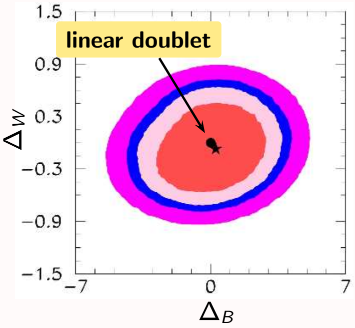
A BSM sensor

$$\Sigma_B \equiv 4(2c_2 + c_4 a_4)$$
$$\Sigma_W \equiv 2(2c_3 - c_5 a_5)$$



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+ATLAS+CMS).

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

Example II: Cancellations

Another linear operator corresponds to **6** non-linear ones:

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

IB,Éboli,Gavela,Gonzalez-García,Merlo,Rigolin (JHEP 1412 004)

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

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

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

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

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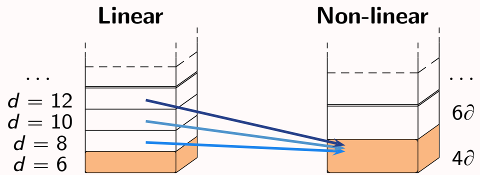
- interesting **cancellation effects** in the linear case compared to chiral
- a possible non-linear signature: $\mathbf{h}^* \to \mathbf{ZZ}$ or $\mathbf{W}^+\mathbf{W}^-$ from $\mathcal{P}_7$
- box operators associated to **Lee-Wick partner** for the Higgs
  $\to$ alternative solution to the hierarchy problem

Grinstein, O'Connell, Wise (Phys.Rev. D77 (2008) 025012)

Example III: Characteristic signals



Effects that are expected to be

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

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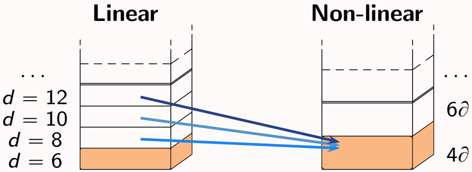

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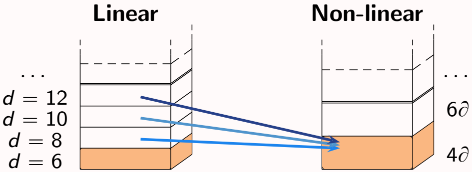
$$\varepsilon^{\mu\nu\rho\lambda}\left(\Phi^\dagger \overleftrightarrow{\mathbf{D}}_\rho \Phi\right)\left(\Phi^\dagger \sigma_i \overleftrightarrow{\mathbf{D}}_\lambda \Phi\right) W^i_{\mu\nu} \qquad d = 8$$

▼

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

Example III: Characteristic signals



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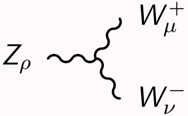
$\mathcal{P}_{14}$ ➔ 

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

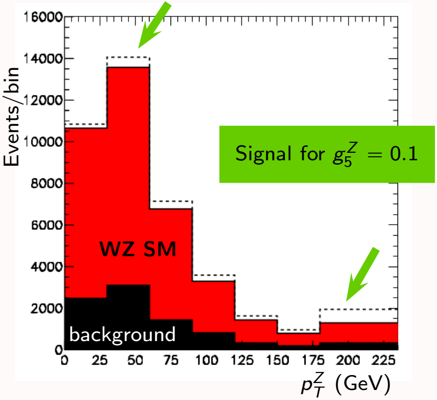
Warning: this operator breaks custodial symmetry.

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

Current best bound at 95% CL

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

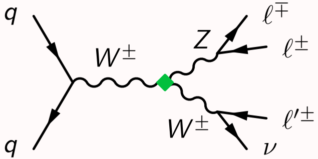
Dawson,Valencia (1994)



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

Simulation analysis

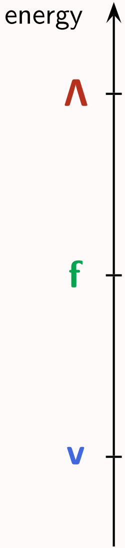
- WZ pair production



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

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

Matching on specific CH models



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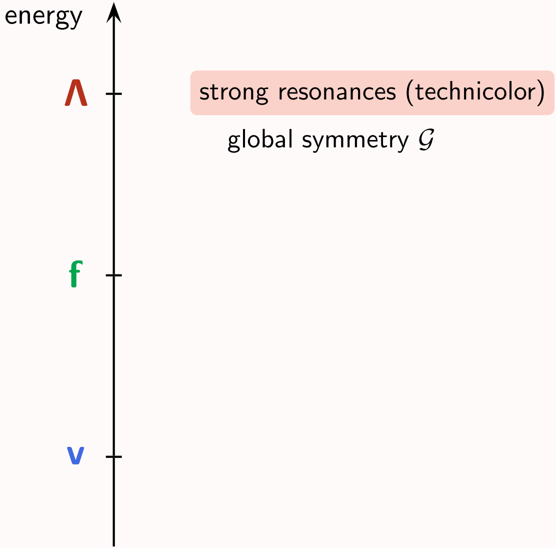

Matching on specific CH models

energy

Λ — strong resonances (technicolor)

global symmetry $\mathcal{G}$

f — Goldstone bosons characteristic scale **$4\pi f \geqslant \Lambda$**

condensates $\supseteq \{\pi^a, h\}$

$\mathcal{G}$ spontaneously broken in $\mathcal{H} \supseteq SU(2)_L \times U(1)_Y$

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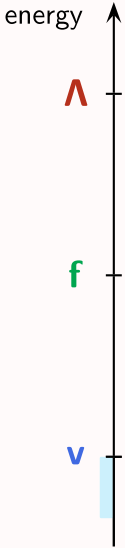
v — electroweak scale

$SU(2)_L \times U(1)_Y \to U(1)_{em}$ breaking

$\boldsymbol{\xi = v^2/f^2 \in [0,1]}$
non-linearity
parameter

Two effective Lagrangians

Alonso,Brivio,Gavela,Merlo,Rigolin (JHEP 1412 034)



$\mathcal{L}_{\text{low}}$

- invariant under SM group, EW sym. in the broken phase
- fields: $\mathbf{V}_\mu\,,\mathbf{T}\,,h\,,W_{\mu\nu}\,,B_{\mu\nu}$

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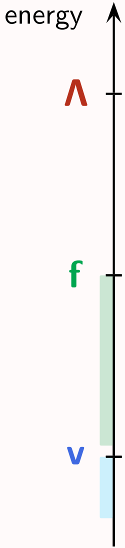

$\mathcal{L}_{\text{high}}$

- chiral Lagrangian invariant under $\mathcal{G}$ → EW unbroken
- fields: $\Sigma \supseteq \{\pi^i, \varphi\}\,, \tilde{\mathbf{V}}_\mu = (D_\mu\Sigma)\Sigma^\dagger\,, \tilde{\mathbf{W}}_{\mu\nu}\,, \tilde{\mathbf{B}}_{\mu\nu}$

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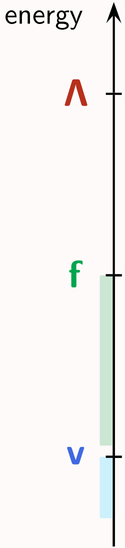

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EWSB: $\boldsymbol{\Sigma}$ $\supset$ $\varphi = \langle\varphi\rangle + \mathbf{h}$

$\mathcal{L}_{\text{low}}$

- invariant under SM group, EW sym. in the broken phase
- fields: $\mathbf{V}_\mu\,, \mathbf{T}\,, h\,, W_{\mu\nu}\,, B_{\mu\nu}$

$\mathscr{L}_{\text{high}}$ basis

The high energy basis contains only up to **13** independent operators
independently of the choice of $\mathcal{G}/\mathcal{H}$
(provided the coset is symmetric)

$$\tilde{\mathcal{A}}_C = -\frac{f^2}{4}\,\mathrm{Tr}\left(\tilde{\mathbf{V}}_\mu \tilde{\mathbf{V}}^\mu\right)$$

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- at most **10** independent low-energy parameters!

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In the example $\boxed{\mathcal{G}/\mathcal{H} = SO(5)/SO(4)}$

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$\tilde{\mathcal{A}}_7\,,\tilde{\mathcal{A}}_8$ are not independent

- only **8** independent low-energy parameters!

Comparison of explicit CH models

$c_i\mathcal{F}_i(h)$	SU(5)/SO(5) SO(5)/SO(4)	SU(3)/SU(2) × U(1)	linear d = 6
$c_2\mathcal{F}_2(h)$	$\tilde{c}_2\sin^2\frac{\varphi}{2f}$	$\frac{\tilde{c}_2}{4}\sin^2\frac{\varphi}{f}$	$\frac{(v+h)^2}{8\Lambda^2}c_B$
$c_4\mathcal{F}_4(h)$	$\tilde{c}_2\sqrt{\xi}\sin\frac{\varphi}{f}$	$\frac{\tilde{c}_2}{2}\sqrt{\xi}\sin\frac{2\varphi}{f}$	$\frac{v(v+h)}{2\Lambda^2}c_B$
$c_3\mathcal{F}_3(h)$	$2\tilde{c}_3\sin^2\frac{\varphi}{2f}$	$\frac{\tilde{c}_3}{2}\sin^2\frac{\varphi}{f}$	$\frac{(v+h)^2}{8\Lambda^2}c_W$
$c_5\mathcal{F}_5(h)$	$-2\tilde{c}_3\sqrt{\xi}\sin\frac{\varphi}{f}$	$-2\tilde{c}_3\sqrt{\xi}\sin\frac{\varphi}{f}$	$-\frac{v(v+h)}{2\Lambda^2}c_W$
$c_{\Box H}\mathcal{F}_{\Box H}(h)$	$-2\tilde{c}_6\xi$	$-2\tilde{c}_6\xi$	$\frac{v^2}{2\Lambda^2}c_{\Box\Phi}$
$c_6\mathcal{F}_6(h)$	$16\tilde{c}_4\sin^4\frac{\varphi}{2f}-\frac{1}{2}\tilde{c}_6\sin^2\frac{\varphi}{f}$	$8(2\tilde{c}_4+\tilde{c}_7)\sin^4\frac{\varphi}{2f}-\frac{1}{2}\tilde{c}_6\sin^2\frac{\varphi}{f}$	$\frac{(v+h)^2}{8\Lambda^2}c_{\Box\Phi}$
$c_7\mathcal{F}_7(h)$	$-2\tilde{c}_6\sqrt{\xi}\sin\frac{\varphi}{f}$	$-2\tilde{c}_6\sqrt{\xi}\sin\frac{\varphi}{f}$	$\frac{v(v+h)}{2\Lambda^2}c_{\Box\Phi}$
$c_8\mathcal{F}_8(h)$	$-16\tilde{c}_5\xi\sin^2\frac{\varphi}{2f}+4\tilde{c}_6\xi\cos^2\frac{\varphi}{2f}$	$-4(4\tilde{c}_5+\tilde{c}_7)\xi\sin^2\frac{\varphi}{2f}+4\tilde{c}_6\xi\cos^2\frac{\varphi}{2f}$	$-\frac{v^2}{\Lambda^2}c_{\Box\Phi}$
$c_9\mathcal{F}_9(h)$	$4\tilde{c}_6\sin^2\frac{\varphi}{2f}$	$4\tilde{c}_6\sin^2\frac{\varphi}{2f}$	$-\frac{(v+h)^2}{4\Lambda^2}c_{\Box\Phi}$
$c_{10}\mathcal{F}_{10}(h)$	$4\tilde{c}_6\sqrt{\xi}\sin\frac{\varphi}{f}$	$4\tilde{c}_6\sqrt{\xi}\sin\frac{\varphi}{f}$	$-\frac{v(v+h)}{\Lambda^2}c_{\Box\Phi}$

Comparison of explicit CH models

$\mathbf{c_i \mathcal{F}_i(h)}$	$\mathbf{SU(5)/SO(5)}$ $\mathbf{SO(5)/SO(4)}$	$\mathbf{SU(3)/SU(2) \times U(1)}$	**linear** $\mathbf{d = 6}$
$c_2\mathcal{F}_2(h)$	$\tilde{c}_2 \sin^2 \frac{\varphi}{2f}$	$\tilde{c}_2 \sin^2 \frac{\varphi}{}$ [illegible]	$\frac{(v+h)^2}{}$ [illegible] c_B
$c_4\mathcal{F}_4(h)$	$\tilde{c}_2\sqrt{\xi} \sin \frac{\varphi}{f}$	[illegible]	[illegible] B
$c_3\mathcal{F}_3(h)$	$2\tilde{c}_3 \sin^2 \frac{\varphi}{2f}$	[illegible]	[illegible] W
$c_5\mathcal{F}_5(h)$	$-2\tilde{c}_3\sqrt{\xi} \sin \frac{\varphi}{f}$	$-2\tilde{c}_3\sqrt{\xi} \sin \frac{\varphi}{f}$	$-\frac{v(v+h)}{2\Lambda^2} c_W$
$c_{\Box H}\mathcal{F}_{\Box H}(h)$	$-2\tilde{c}_6\xi$	$-2\tilde{c}_6\xi$	$\frac{v^2}{2\Lambda^2} c_{\Box\Phi}$
$c_6\mathcal{F}_6(h)$	$16\tilde{c}_4 \sin^4 \frac{\varphi}{2f} - \frac{1}{2}\tilde{c}_6 \sin^2 \frac{\varphi}{f}$	$8(2\tilde{c}_4 + \tilde{c}_7) \sin^4 \frac{\varphi}{2f} - \frac{1}{2}\tilde{c}_6 \sin^2 \frac{\varphi}{f}$	$\frac{(v+h)^2}{8\Lambda^2} c_{\Box\Phi}$
$c_7\mathcal{F}_7(h)$	$-2\tilde{c}_6\sqrt{\xi} \sin \frac{\varphi}{f}$	$-2\tilde{c}_6\sqrt{\xi} \sin \frac{\varphi}{f}$	$\frac{v(v+h)}{2\Lambda^2} c_{\Box\Phi}$
$c_8\mathcal{F}_8(h)$	$-16\tilde{c}_5\xi \sin^2 \frac{\varphi}{2f} + 4\tilde{c}_6\xi \cos^2 \frac{\varphi}{2f}$	$-4(4\tilde{c}_5 + \tilde{c}_7)\xi \sin^2 \frac{\varphi}{2f} + 4\tilde{c}_6\xi \cos^2 \frac{\varphi}{2f}$	$-\frac{v^2}{\Lambda^2} c_{\Box\Phi}$
$c_9\mathcal{F}_9(h)$	$4\tilde{c}_6 \sin^2 \frac{\varphi}{2f}$	$4\tilde{c}_6 \sin^2 \frac{\varphi}{2f}$	$-\frac{(v+h)^2}{4\Lambda^2} c_{\Box\Phi}$
$c_{10}\mathcal{F}_{10}(h)$	$4\tilde{c}_6\sqrt{\xi} \sin \frac{\varphi}{f}$	$4\tilde{c}_6\sqrt{\xi} \sin \frac{\varphi}{f}$	$-\frac{v(v+h)}{\Lambda^2} c_{\Box\Phi}$

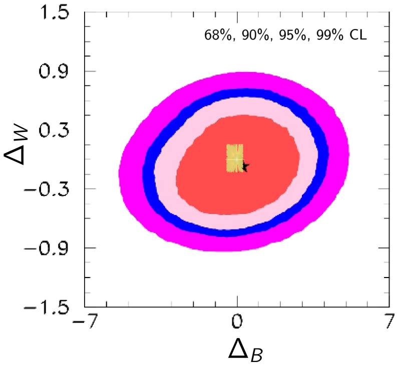
- Less free parameters
- the functions $\mathcal{F}(h)$ are fixed

Comparison of explicit CH models

$c_i\mathcal{F}_i(h)$	SU(5)/SO(5) SO(5)/SO(4)	[illegible]	[illegible]
$c_2\mathcal{F}_2(h)$	$\tilde{c}_2 \sin^2 \frac{\varphi}{2f}$		
$c_4\mathcal{F}_4(h)$	$\tilde{c}_2\sqrt{\xi} \sin \frac{\varphi}{f}$		
$c_3\mathcal{F}_3(h)$	$2\tilde{c}_3 \sin^2 \frac{\varphi}{2f}$		
$c_5\mathcal{F}_5(h)$	$-\,2\tilde{c}_3\sqrt{\xi} \sin \frac{\varphi}{f}$		
$c_{\Box H}\mathcal{F}_{\Box H}(h)$	$-2\tilde{c}_6\xi$		
$c_6\mathcal{F}_6(h)$	$16\tilde{c}_4 \sin^4 \frac{\varphi}{2f} - \frac{1}{2}\tilde{c}_6 \sin^2 \frac{\varphi}{f}$		
$c_7\mathcal{F}_7(h)$	$-2\tilde{c}_6\sqrt{\xi} \sin \frac{\varphi}{f}$		
$c_8\mathcal{F}_8(h)$	$-16\tilde{c}_5\xi \sin^2 \frac{\varphi}{2f} + 4\tilde{c}_6\xi \cos^2 \frac{\varphi}{2f}$	[illegible]	
$c_9\mathcal{F}_9(h)$	$4\tilde{c}_6 \sin^2 \frac{\varphi}{2f}$		
$c_{10}\mathcal{F}_{10}(h)$	$4\tilde{c}_6\sqrt{\xi} \sin \frac{\varphi}{f}$	$4\tilde{c}_6\sqrt{\xi} \sin \frac{\varphi}{f}$	[illegible] $c_{\Box\Phi}$

Non-linearity sensors

$$\Delta_B = \tilde{c}_2\,\xi^2$$
$$\Delta_W = \tilde{c}_3\,\xi^2$$



Comparison of explicit CH models

$c_i\mathcal{F}_i(h)$	SU(5)/SO(5) SO(5)/SO(4)	SU(3)/SU(2) × U(1)	linear d = 6
$c_2\mathcal{F}_2(h)$	$\tilde{c}_2 \sin^2\frac{\varphi}{2f}$	$\frac{\tilde{c}_2}{4}\sin^2\frac{\varphi}{f}$	$\frac{(v+h)^2}{8\Lambda^2}c_B$
$c_4\mathcal{F}_4(h)$	$\tilde{c}_2\sqrt{\xi}\sin\frac{\varphi}{f}$	$\frac{\tilde{c}_2}{2}\sqrt{\xi}\sin\frac{2\varphi}{f}$	$\frac{v(v+h)}{2\Lambda^2}c_B$
$c_3\mathcal{F}_3(h)$	$2\tilde{c}_3\sin^2\frac{\varphi}{2f}$	$\frac{\tilde{c}_3}{2}\sin^2\frac{\varphi}{f}$	$\frac{(v+h)^2}{8\Lambda^2}c_W$
$c_5\mathcal{F}_5(h)$	$-2\tilde{c}_3\sqrt{\xi}\sin\frac{\varphi}{f}$	$-2\tilde{c}_3\sqrt{\xi}\sin\frac{\varphi}{f}$	$-\frac{v(v+h)}{2\Lambda^2}c_W$
$c_{\Box H}\mathcal{F}_{\Box H}(h)$	$-2\tilde{c}_6$		$\frac{v^2}{2\Lambda^2}c_{\Box\Phi}$
$c_6\mathcal{F}_6(h)$	$16\tilde{c}_4\sin^4\frac{\varphi}{2f}-\frac{1}{2}\tilde{c}_6\sin^2\frac{\varphi}{f}$	$8(2\tilde{c}_4+\tilde{c}_7)\sin^4\frac{\varphi}{2f}-\frac{1}{2}\tilde{c}_6\sin^2\frac{\varphi}{f}$	$\frac{(v+h)^2}{8\Lambda^2}c_{\Box\Phi}$
$c_7\mathcal{F}_7(h)$	$-2\tilde{c}_6\sqrt{\xi}\sin\frac{\varphi}{f}$	$-2\tilde{c}_6\sqrt{\xi}\sin\frac{\varphi}{f}$	$\frac{v(v+h)}{2\Lambda^2}c_{\Box\Phi}$
$c_8\mathcal{F}_8(h)$	$-16\tilde{c}_5\xi\sin^2\frac{\varphi}{2f}+4\tilde{c}_6\xi\cos^2\frac{\varphi}{2f}$	$-4(4\tilde{c}_5+\tilde{c}_7)\xi\sin^2\frac{\varphi}{2f}+4\tilde{c}_6\xi\cos^2\frac{\varphi}{2f}$	$-\frac{v^2}{\Lambda^2}c_{\Box\Phi}$
$c_9\mathcal{F}_9(h)$	$4\tilde{c}_6\sin^2\frac{\varphi}{2f}$	$4\tilde{c}_6\sin^2\frac{\varphi}{2f}$	$-\frac{(v+h)^2}{4\Lambda^2}c_{\Box\Phi}$
$c_{10}\mathcal{F}_{10}(h)$	$4\tilde{c}_6\sqrt{\xi}\sin\frac{\varphi}{f}$	$4\tilde{c}_6\sqrt{\xi}\sin\frac{\varphi}{f}$	$-\frac{v(v+h)}{\Lambda^2}c_{\Box\Phi}$

Universality of the functions $\mathcal{F}(\mathbf{h})$

Summary

The **non-linear EFT** is one of the best-suited tools to study the Higgs if the new physics behind EWSB is strong-interacting

key: Goldstone bosons and Higgs are independent fields
U adimensional, h singlet

Disentangling a **linear EFT** from a **non-linear EFT**:

- **correlation/decorrelation** of TGV, HVV and HHVV
- cancellation effects from $\boldsymbol{\mathcal{O}_{\Box\Phi}}$ **vs** $\boldsymbol{\mathcal{P}_{\Box h}}$ $\rightarrow$ Non-linearity signal: $h^* \rightarrow VV$
- anomalous WWZ ($\mathbf{g_5^Z}$) and WWZγ couplings appearing
  @ NNLO (d=8) vs @ NLO (4∂)

When considering **specific composite Higgs models**:

- the number of parameters is considerably reduced
- **h couplings** have characteristic weights depending on ξ

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

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

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

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

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

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

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

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)

Linear - chiral correspondence

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

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

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

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

$$\mathcal{P}_{DH}(h)\,,\mathcal{P}_{20}(h) \to \left[\mathbf{D}_\mu\Phi^\dagger\mathbf{D}^\mu\Phi\right]^2$$

$$\mathcal{P}_{11}(h)\,,\mathcal{P}_{18}(h)\,,\mathcal{P}_{21}(h)\,,\mathcal{P}_{22}(h)\,,\mathcal{P}_{23}(h)\,,\mathcal{P}_{24}(h) \to \left[\mathbf{D}^\mu\Phi^\dagger\mathbf{D}^\nu\Phi\right]^2$$

$$\mathcal{P}_{12}(h) \to \left(\Phi^\dagger W^{\mu\nu}\Phi\right)^2$$

$$\mathcal{P}_{13}(h)\,,\mathcal{P}_{17}(h) \to \left(\Phi^\dagger W^{\mu\nu}\Phi\right)\mathbf{D}_\mu\Phi^\dagger\mathbf{D}_\nu\Phi$$

$$\mathcal{P}_{14}(h) \to \varepsilon^{\mu\nu\rho\lambda}\left(\Phi^\dagger\overleftrightarrow{\mathbf{D}}_\rho\Phi\right)\left(\Phi^\dagger\sigma_i\overleftrightarrow{\mathbf{D}}_\lambda\Phi\right)W^i_{\mu\nu}$$

$$\mathcal{P}_{15}(h)\,,\mathcal{P}_{19}(h) \to \left[\Phi^\dagger\mathbf{D}_\mu\mathbf{D}^\mu\Phi - \mathbf{D}_\mu\mathbf{D}^\mu\Phi^\dagger\Phi\right]^2$$

$$\mathcal{P}_{16}(h)\,,\mathcal{P}_{25}(h) \to \left(\mathbf{D}^\nu\Phi^\dagger\mathbf{D}_\mu\mathbf{D}^\mu\Phi - \mathbf{D}_\mu\mathbf{D}^\mu\Phi^\dagger\mathbf{D}^\nu\Phi\right)\left(\Phi^\dagger\overleftrightarrow{\mathbf{D}}_\nu\Phi\right)$$

$$\mathcal{P}_{26}(h) \to \left[\left(\Phi^\dagger\overleftrightarrow{\mathbf{D}}_\mu\Phi\right)\left(\Phi^\dagger\overleftrightarrow{\mathbf{D}}_\nu\Phi\right)\right]^2$$

Linear - chiral correspondence (SILH)

$$\mathcal{O}_g^{\rm SILH} = \Phi^\dagger\Phi\, G^a_{\mu\nu}G^{a\mu\nu}$$

$$\mathcal{O}_B^{\rm SILH} = \left(\Phi^\dagger \overleftrightarrow{\mathbf{D}}_\mu \Phi\right)\partial_\nu \hat{B}^{\mu\nu}$$

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

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

$$\mathcal{O}_6^{\rm SILH} = \frac{1}{3}\left(\Phi^\dagger\Phi\right)^3$$

$$\mathcal{O}_\gamma^{\rm SILH} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi$$

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

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

$$\mathcal{O}_H^{\rm SILH} = \frac{1}{2}\partial^\mu\left(\Phi^\dagger\Phi\right)\partial_\mu\left(\Phi^\dagger\Phi\right)$$

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

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

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

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

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

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

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

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

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

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

Expected xi weights

ξ

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

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

ξ^2

$$\mathcal{P}_{11} = (\mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu))^2 \mathcal{F}_{11}(h)$$
$$\mathcal{P}_{12} = g^2 \mathrm{Tr}(\mathbf{T} W_{\mu\nu}))^2 \mathcal{F}_{12}(h)$$
$$\mathcal{P}_{13} = i g \mathrm{Tr}(\mathbf{T} W_{\mu\nu}) \mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_{13}(h)$$
$$\mathcal{P}_{14} = g \varepsilon^{\mu\nu\rho\lambda} \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) \mathrm{Tr}(\mathbf{V}_\nu W_{\rho\lambda}) \mathcal{F}_{14}(h)$$
$$\mathcal{P}_{15} = \mathrm{Tr}(\mathbf{T}\mathcal{D}_\mu \mathbf{V}^\mu) \mathrm{Tr}(\mathbf{T}\mathcal{D}_\nu \mathbf{V}^\nu) \mathcal{F}_{15}(h)$$
$$\mathcal{P}_{16} = \mathrm{Tr}([\mathbf{T}, \mathbf{V}_\nu] \mathcal{D}_\mu \mathbf{V}^\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu) \mathcal{F}_{16}(h)$$
$$\mathcal{P}_{17} = i g \mathrm{Tr}(\mathbf{T} W_{\mu\nu}) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_{17}(h)$$
$$\mathcal{P}_{18} = \mathrm{Tr}(\mathbf{T}[\mathbf{V}_\mu, \mathbf{V}_\nu]) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_{18}(h)$$
$$\mathcal{P}_{19} = \mathrm{Tr}(\mathbf{T}\mathcal{D}_\mu \mathbf{V}^\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu) \partial^\nu \mathcal{F}_{19}(h)$$
$$\mathcal{P}_{20} = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) \partial_\nu \mathcal{F}_{20}(h) \partial^\nu \mathcal{F}'_{20}(h)$$
$$\mathcal{P}_{21} = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu))^2 \partial_\nu \mathcal{F}_{21}(h) \partial^\nu \mathcal{F}'_{21}(h)$$
$$\mathcal{P}_{22} = \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu) \partial^\mu \mathcal{F}_{22}(h) \partial^\mu \mathcal{F}'_{22}(h)$$
$$\mathcal{P}_{23} = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2 \mathcal{F}_{23}(h)$$
$$\mathcal{P}_{24} = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu) \mathcal{F}_{24}(h)$$
$$\mathcal{P}_{25} = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu))^2 \partial_\nu \partial^\nu \mathcal{F}_{25}(h)$$

ξ^4

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

Expected xi weights

Corresponding to linear d = 6

$$\mathcal{P}_W = -\frac{g^2}{4} W^a_{\mu\nu} W^{a\mu\nu} \mathcal{F}_W(h)$$
$$\mathcal{P}_B = -\frac{g'^2}{4} B_{\mu\nu} B^{\mu\nu} \mathcal{F}_B(h)$$
$$\mathcal{P}_G = -\frac{g_s^2}{4} \mathcal{G}^A_{\mu\nu} \mathcal{G}^{A\mu\nu} \mathcal{F}_G(h)$$
$$\mathcal{P}_H = \frac{1}{2} \partial_\mu h \partial^\mu h \mathcal{F}_H(h)$$

$$\mathcal{P}_{DH} = \frac{1}{v^4} (\partial_\mu h \partial^\mu h)^2 \mathcal{F}_{DH}(h)$$
$$\mathcal{P}_{\Delta H} = \frac{1}{v^3} (\partial_\mu h \partial^\mu h) \Box \mathcal{F}_{\Delta H}(h)$$

ξ

$$\mathcal{P}_{\Box H} = \frac{1}{v^2} (\Box h)(\Box h) \mathcal{F}_{\Box H}(h)$$
$$\mathcal{P}_C = -\frac{v^2}{4} \mathrm{Tr}(\mathbf{V}^\mu \mathbf{V}_\mu) \mathcal{F}_C(h)$$
$$\mathcal{P}_T = \frac{v^2}{4} \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \mathcal{F}_T(h)$$
$$\mathcal{P}_1 = g g' B_{\mu\nu} \mathrm{Tr}(\mathbf{T} W^{\mu\nu}) \mathcal{F}_1(h)$$
$$\mathcal{P}_2 = i g' B_{\mu\nu} \mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_2(h)$$
$$\mathcal{P}_3 = i g \mathrm{Tr}(W_{\mu\nu} [\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_3(h)$$
$$\mathcal{P}_4 = i g' B_{\mu\nu} \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_4(h)$$
$$\mathcal{P}_5 = i g \mathrm{Tr}(W_{\mu\nu} \mathbf{V}^\mu) \partial^\nu \mathcal{F}_5(h)$$
$$\mathcal{P}_6 = (\mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu))^2 \mathcal{F}_6(h)$$
$$\mathcal{P}_7 = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) \partial_\nu \partial^\nu \mathcal{F}_7(h)$$
$$\mathcal{P}_8 = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu) \partial^\mu \mathcal{F}_8(h) \partial^\nu \mathcal{F}'_8(h)$$
$$\mathcal{P}_9 = \mathrm{Tr}((\mathcal{D}_\mu \mathbf{V}^\mu)^2) \mathcal{F}_9(h)$$
$$\mathcal{P}_{10} = \mathrm{Tr}(\mathbf{V}_\nu \mathcal{D}_\mu \mathbf{V}^\mu) \partial^\nu \mathcal{F}_{10}(h)$$

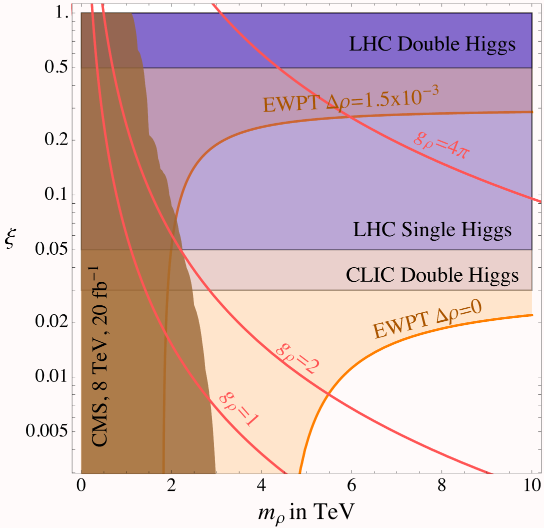
ξ^2

$$\mathcal{P}_{11} = (\mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu))^2 \mathcal{F}_{11}(h)$$
$$\mathcal{P}_{12} = g^2 \mathrm{Tr}(\mathbf{T} W_{\mu\nu})^2 \mathcal{F}_{12}(h)$$
$$\mathcal{P}_{13} = i g \mathrm{Tr}(\mathbf{T} W_{\mu\nu}) \mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_{13}(h)$$
$$\mathcal{P}_{14} = g \varepsilon^{\mu\nu\rho\lambda} \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) \mathrm{Tr}(\mathbf{V}_\nu W_{\rho\lambda}) \mathcal{F}_{14}(h)$$
$$\mathcal{P}_{15} = \mathrm{Tr}(\mathbf{T}\mathcal{D}_\mu \mathbf{V}^\mu) \mathrm{Tr}(\mathbf{T}\mathcal{D}_\nu \mathbf{V}^\nu) \mathcal{F}_{15}(h)$$
$$\mathcal{P}_{16} = \mathrm{Tr}([\mathbf{T}, \mathbf{V}_\nu] \mathcal{D}_\mu \mathbf{V}^\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu) \mathcal{F}_{16}(h)$$
$$\mathcal{P}_{17} = i g \mathrm{Tr}(\mathbf{T} W_{\mu\nu}) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_{17}(h)$$
$$\mathcal{P}_{18} = \mathrm{Tr}(\mathbf{T}[\mathbf{V}_\mu, \mathbf{V}_\nu]) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_{18}(h)$$
$$\mathcal{P}_{19} = \mathrm{Tr}(\mathbf{T}\mathcal{D}_\mu \mathbf{V}^\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu) \partial^\nu \mathcal{F}_{19}(h)$$
$$\mathcal{P}_{20} = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) \partial_\nu \mathcal{F}_{20}(h) \partial^\nu \mathcal{F}'_{20}(h)$$
$$\mathcal{P}_{21} = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu))^2 \partial_\nu \mathcal{F}_{21}(h) \partial^\nu \mathcal{F}'_{21}(h)$$
$$\mathcal{P}_{22} = \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu) \partial^\mu \mathcal{F}_{22}(h) \partial^\nu \mathcal{F}'_{22}(h)$$
$$\mathcal{P}_{23} = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2 \mathcal{F}_{23}(h)$$
$$\mathcal{P}_{24} = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu) \mathcal{F}_{24}(h)$$
$$\mathcal{P}_{25} = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu))^2 \partial_\nu \partial^\nu \mathcal{F}_{25}(h)$$

ξ^4

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

Current constraints on the ξ parameter

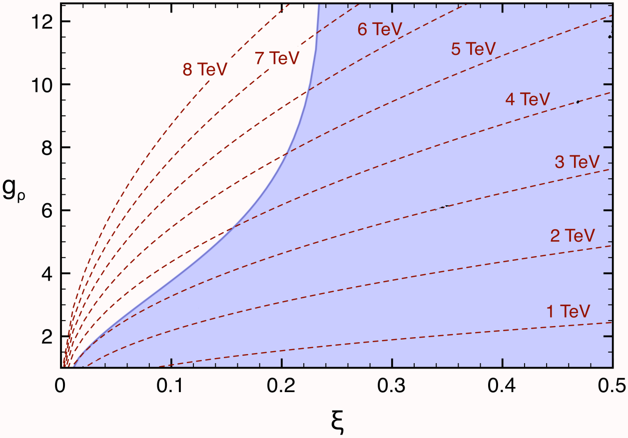


Current constraints and future sensitivities at CLIC and LHC for theories **SO(5)/SO(4)**

$\mathbf{m}_\rho$ mass of the lightest resonances

Contino et al. (JHEP 1402 006)

Current bounds on the ξ parameter



Constraints on ξ and the coupling constant g_ρ in theories **SO(5)/SO(4)**

Colored area: excluded @ 99% CL by LEP

Dashed curves: constant resonance mass m_ρ

Contino (1005.4269)

Results from specific CH models

In specific models:

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

SU(5)/SO(5) and **SO(5)/SO(4)**

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

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

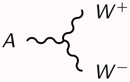
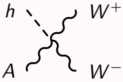
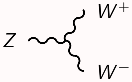
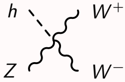
Alonso,IB,Gavela,Merlo,Rigolin (2014) (JHEP 1412 034)

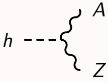
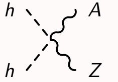
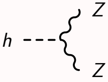
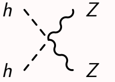
- $\mathcal{F}_2(h) = \mathcal{F}_4(h) \neq (1+h/v)^2$
- expanding:

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

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

(De)correlation effects

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	$\frac{1}{2}(2\tilde{c}_2 + \tilde{c}_3)$	$\frac{1}{2}(2\tilde{c}_2 + \tilde{c}_3)\sqrt{\mathbf{1 - \frac{\xi}{4}}}$	$\frac{1}{2}(-2t_\theta^2 \tilde{c}_2 + \tilde{c}_3)$	$\frac{1}{2}(-2t_\theta^2 \tilde{c}_2 + \tilde{c}_3)\sqrt{\mathbf{1 - \frac{\xi}{4}}}$

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	$2c_4 a_4 + c_5 a_5$	$2c_4 b_4 + c_5 b_5$	$2t_\theta^2 c_4 a_4 - c_5 a_5$	$2t_\theta^2 c_4 b_4 - c_5 b_5$
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	$(2\tilde{c}_2 - \tilde{c}_3)\sqrt{\mathbf{1 - \frac{\xi}{4}}}$	$(2\tilde{c}_2 - \tilde{c}_3)\left(\mathbf{1 - \frac{\xi}{2}}\right)$	$(2t_\theta^2 \tilde{c}_2 + \tilde{c}_3)\sqrt{\mathbf{1 - \frac{\xi}{4}}}$	$(2t_\theta^2 \tilde{c}_2 + \tilde{c}_3)\left(\mathbf{1 - \frac{\xi}{2}}\right)$

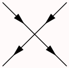
Example II: Cancellations

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

Non-linear Lagrangian ▸ applying the EOM for h, $\mathbf{V}_\mu$:

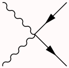
$\mathcal{P}_{\Box h} \to$ Yukawa couplings

$\mathcal{P}_{\Box h}$, $\mathcal{P}_9 \to$ 4-fermions

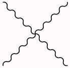


$\mathcal{P}_{\Box h} \to$ scalar potential

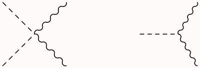
$\mathcal{P}_{\Box h}$, $\mathcal{P}_9 \to$ fermion-gauge



$\mathcal{P}_{\Box h}$, $\mathcal{P}_6 \to$ 4-gauge



$\mathcal{P}_{\Box h}$, $\mathcal{P}_6$, $\mathcal{P}_7$, $\mathcal{P}_8$, $\mathcal{P}_9$, $\mathcal{P}_{10} \to$ gauge-Higgs



Example II: Cancellations

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

Non-linear Lagrangian ▸ applying the EOM for h, $\mathbf{V}_\mu$:

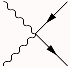
$\mathcal{P}_{\Box h} \to$ Yukawa couplings

$\mathcal{P}_{\Box h}, \mathcal{P}_9 \to$ 4-fermions

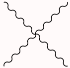
the linear EFT is recovered for
$$v^2 c_{\Box h} = 8c_6 = 4c_7 = -c_8 = -4c_9 = -2c_{10}$$
$$a_i = 1,\ b_i = 1$$

$\mathcal{P}_{\Box h} \to$ scalar potential

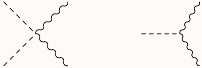
$\mathcal{P}_{\Box h}, \mathcal{P}_9 \to$ fermion-gauge



$\mathcal{P}_{\Box h}, \mathcal{P}_6 \to$ 4-gauge



$\mathcal{P}_{\Box h}, \mathcal{P}_6, \mathcal{P}_7, \mathcal{P}_8, \mathcal{P}_9, \mathcal{P}_{10} \to$ gauge-Higgs



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

Non-linear Lagrangian ▸ applying the EOM for h, $\mathbf{V}_\mu$:

$\mathcal{P}_{\Box h} \to$ Yukawa couplings

different pattern

$\mathcal{P}_{\Box h}, \mathcal{P}_9 \to$ 4-fermions

the linear EFT is recovered for
$v^2 c_{\Box h} = 8c_6 = 4c_7 = -c_8 = -4c_9 = -2c_{10}$
$a_i = 1,\ b_i = 1$

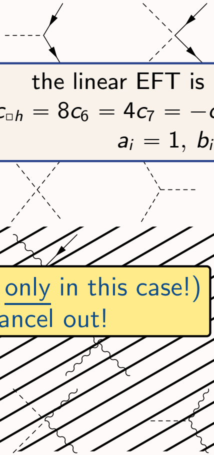
$\mathcal{P}_{\Box h} \to$ scalar potential

$\mathcal{P}_{\Box h}, \mathcal{P} \to$ fermion-gauge

in the linear limit (and only in this case!)
these effects cancel out!

$\mathcal{P}_{\Box h}, \mathcal{P}_6 \to$ 4-gauge

$\mathcal{P}_{\Box h}, \mathcal{P}_6, \mathcal{P}_7, \mathcal{P}_8, \mathcal{P}_9, \mathcal{P}_{10} \to$ gauge-Higgs



Example II: Cancellations

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

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contributions to

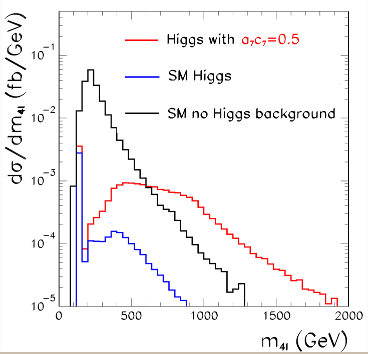
QGV, **gauge-Higgs** and **gauge-fermion** couplings

signal deviations from the $SU(2)_L$ doublet structure

a possible signal:

off-shell $gg \to h^* \to ZZ$ or WW

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



Simulation for $ZZ \to \mu^+\mu^-e^+e^-$ @LHC13