Disentangling a Dynamical Higgs

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IB, Corbett, Éboli, Gavela, Gonzalez–Fraile, Gonzalez–García, Merlo, Rigolin

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invisibles
neutrinos, dark matter & dark energy physics

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Motivation

Is the Higgs elementary or composite?

A crucial, urgent question!

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- collider searches (SUSY particles, heavy fermionic resonances)
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Indirect approach:

- look for deviations from SM predictions at low energy

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Direct approach:

- kinematical studies: *WW* scattering
- collider searches (SUSY particles, heavy fermionic resonances)

Indirect approach:

model-independent parameterization via an **Effective Lagrangian**

Strategy

elementary Higgs	▸	linear EWSB	▸	**linear** effective Lagrangian
composite Higgs	▸	non-linear (dynamical) EWSB	▸	**non-linear (chiral)** effective Lagrangian

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Focus:

- first order in the operator expansion
- **bosonic** sector (gauge & gauge-Higgs), **CP even**

Strategy

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composite Higgs	▸	non-linear (dynamical) EWSB	▸	**non-linear (chiral)** effective Lagrangian

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Idea:

- they give different predictions! → distinctive **signatures**
- is the LHC sensitive enough?

The linear effective Lagrangian

standard Higgs doublet Φ → Expansion in canonical dimensions

$$\mathscr{L}_{\text{linear}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda^2} \sum_i c_i \mathcal{O}_i$$

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$$\mathscr{L}_{\text{linear}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i$$

$$(d=4) \qquad \mathscr{L}_{\text{SM}} = -\frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}\mathcal{G}^A_{\mu\nu}\mathcal{G}^{A\mu\nu} + \\ + (D_\mu\Phi)^\dagger(D^\mu\Phi) + \\ + i\bar\psi \not{D}\psi - \left[\bar\psi_L \Phi Y \psi_R + \text{h.c.}\right]$$

$$(d=6) \qquad \text{basis } \{\mathcal{O}_i\}$$

⇝ see talk by **J. Gonzalez-Fraile**

Linear basis $d = 6$

Bosonic sector, CP even
(HISZ basis)

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

see talk by **J. Gonzalez-Fraile**

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

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

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

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

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

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

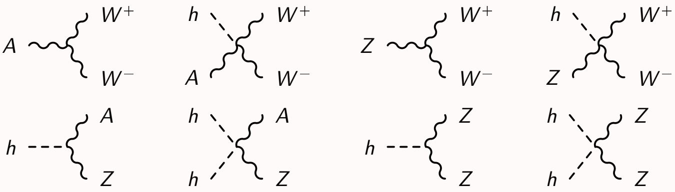
Grzadkowski,Iskrzynski,Misiak,Rosiek (2010)

Example: $\mathcal{O}_\mathrm{B}$

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

$$= \frac{eg^2}{8}A_{\mu\nu}W^{-\mu}W^{+\nu}(v+h)^2 - \frac{ie^2g}{4c_\theta}Z_{\mu\nu}W^{-\mu}W^{+\nu}(v+h)^2 +$$

$$-\frac{ge}{4c_\theta}A_{\mu\nu}Z^\mu\partial^\nu h(v+h) + \frac{e^2}{4c_\theta^2}Z_{\mu\nu}Z^\mu\partial^\nu h(v+h)$$



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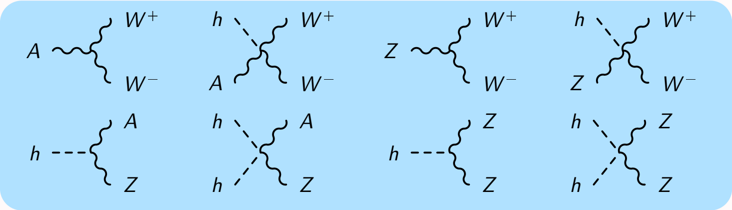
same coefficient with fixed relative weights!



The chiral formalism

$\rightsquigarrow$ see talk by **S. Rigolin**

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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U adimensional → insertions of GB fields do not add suppression factors

h singlet → more possible invariants

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Building blocks for the Lagrangian:

GBs	$\mathbf{V}_\mu = \mathbf{D}_\mu\mathbf{U}\mathbf{U}^\dagger\,,$	$\mathbf{V}_\mu \mapsto L\mathbf{V}_\mu L^\dagger$
	$\mathbf{T} = \mathbf{U}\sigma^3\mathbf{U}^\dagger\,,$	$\mathbf{T} \mapsto L\mathbf{T}L^\dagger \rightarrow$ ~~Custodial sym.~~
Higgs	$\mathcal{F}(\mathbf{h})$	$\partial_\mu\mathcal{F}(\mathbf{h})$

The non-linear effective Lagrangian

U is adimensional → expansion in derivatives

In a phenomenological approach:

⇝ see talk by **S. Rigolin**

$$\mathscr{L}_{\text{chiral}} = \mathscr{L}_{\text{SM}} + \sum_i c_i \mathcal{P}_i$$

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

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$$\mathscr{L}_{\text{chiral}} = \mathscr{L}_{\text{SM}} + \sum_i c_i \mathcal{P}_i$$

$$\begin{aligned}\mathscr{L}_{\text{SM}} = &-\frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}\mathcal{G}^A_{\mu\nu}\mathcal{G}^{A\mu\nu} + i\bar{\psi}\not{D}\psi + \\ &+ \frac{1}{2}\partial_\mu h\partial^\mu h - V(h) - \frac{(v+h)^2}{4}\text{Tr}[\mathbf{V}_\mu\mathbf{V}^\mu] + \\ &- \frac{v+h}{\sqrt{2}}\left[\bar{\psi}_L\mathbf{U}Y\psi_R + \text{h.c.}\right]\end{aligned}$$

GB kinetic terms
gauge bosons' masses

Yukawas

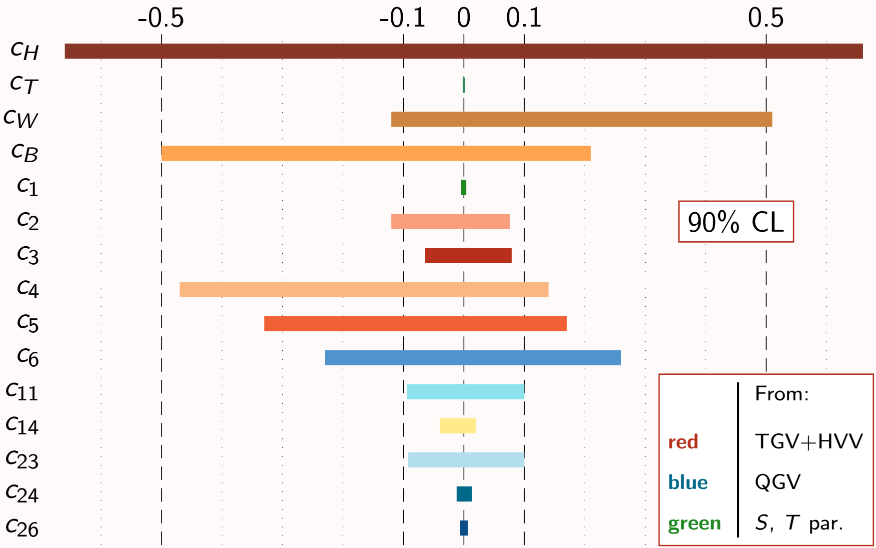
$\{\mathcal{P}_i\}$ operators with up to 4 derivatives

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

The non-linear basis

$$\mathcal{P}_W = -\frac{g^2}{4} W^a_{\mu\nu} W^{a\mu\nu} \mathcal{F}_W(h)$$
$$\mathcal{P}_B = -\frac{g'^2}{4} B_{\mu\nu} B^{\mu\nu} \mathcal{F}_B(h)$$
$$\mathcal{P}_G = -\frac{g_s^2}{4} \mathcal{G}^A_{\mu\nu} \mathcal{G}^{A\mu\nu} \mathcal{F}_G(h)$$
$$\mathcal{P}_H = \frac{1}{2} \partial_\mu h \partial^\mu h \mathcal{F}_H(h)$$
$$\mathcal{P}_C = -\frac{v^2}{4} \mathrm{Tr}(\mathbf{V}^\mu \mathbf{V}_\mu) \mathcal{F}_C(h)$$
$$\mathcal{P}_T = \frac{v^2}{4} \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \mathcal{F}_T(h)$$
$$\mathcal{P}_1 = gg' B_{\mu\nu} \mathrm{Tr}(\mathbf{T} W^{\mu\nu}) \mathcal{F}_1(h)$$
$$\mathcal{P}_2 = ig' B_{\mu\nu} \mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_2(h)$$
$$\mathcal{P}_3 = ig \mathrm{Tr}(W_{\mu\nu}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_3(h)$$
$$\mathcal{P}_4 = ig' B_{\mu\nu} \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_4(h)$$
$$\mathcal{P}_5 = ig \mathrm{Tr}(W_{\mu\nu} \mathbf{V}^\mu) \partial^\nu \mathcal{F}_5(h)$$
$$\mathcal{P}_6 = (\mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu))^2 \mathcal{F}_6(h)$$
$$\mathcal{P}_7 = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) \partial_\nu \partial^\nu \mathcal{F}_7(h)$$
$$\mathcal{P}_8 = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu) \partial^\mu \mathcal{F}_8(h) \partial^\nu \mathcal{F}'_8(h)$$
$$\mathcal{P}_9 = \mathrm{Tr}((\mathcal{D}_\mu \mathbf{V}^\mu)^2) \mathcal{F}_9(h)$$
$$\mathcal{P}_{10} = \mathrm{Tr}(\mathbf{V}_\nu \mathcal{D}_\mu \mathbf{V}^\mu) \partial^\nu \mathcal{F}_{10}(h)$$
$$\mathcal{P}_{11} = (\mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu))^2 \mathcal{F}_{11}(h)$$
$$\mathcal{P}_{12} = g^2 \mathrm{Tr}(\mathbf{T} W_{\mu\nu}))^2 \mathcal{F}_{12}(h)$$
$$\mathcal{P}_{13} = ig \mathrm{Tr}(\mathbf{T} W_{\mu\nu}) \mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_{13}(h)$$
$$\mathcal{P}_{14} = g\varepsilon^{\mu\nu\rho\lambda} \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) \mathrm{Tr}(\mathbf{V}_\nu W_{\rho\lambda}) \mathcal{F}_{14}(h)$$
$$\mathcal{P}_{15} = \mathrm{Tr}(\mathbf{T}\mathcal{D}_\mu \mathbf{V}^\mu) \mathrm{Tr}(\mathbf{T}\mathcal{D}_\nu \mathbf{V}^\nu) \mathcal{F}_{15}(h)$$
$$\mathcal{P}_{16} = \mathrm{Tr}([\mathbf{T}, \mathbf{V}_\nu] \mathcal{D}_\mu \mathbf{V}^\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu) \mathcal{F}_{16}(h)$$
$$\mathcal{P}_{17} = ig \mathrm{Tr}(\mathbf{T} W_{\mu\nu}) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_{17}(h)$$
$$\mathcal{P}_{18} = \mathrm{Tr}(\mathbf{T}[\mathbf{V}_\mu, \mathbf{V}_\nu]) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_{18}(h)$$
$$\mathcal{P}_{19} = \mathrm{Tr}(\mathbf{T}\mathcal{D}_\mu \mathbf{V}^\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu) \partial^\nu \mathcal{F}_{19}(h)$$
$$\mathcal{P}_{20} = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) \partial_\nu \mathcal{F}_{20}(h) \partial^\nu \mathcal{F}'_{20}(h)$$
$$\mathcal{P}_{21} = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu))^2 \partial_\nu \mathcal{F}_{21}(h) \partial^\nu \mathcal{F}'_{21}(h)$$
$$\mathcal{P}_{22} = \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu) \partial^\mu \mathcal{F}_{22}(h) \partial^\mu \mathcal{F}'_{22}(h)$$
$$\mathcal{P}_{23} = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2 \mathcal{F}_{23}(h)$$
$$\mathcal{P}_{24} = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu) \mathcal{F}_{24}(h)$$
$$\mathcal{P}_{25} = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu))^2 \partial_\nu \partial^\nu \mathcal{F}_{25}(h)$$
$$\mathcal{P}_{26} = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2 \mathcal{F}_{26}(h)$$

Best bounds on the chiral coefficients



Example: $\mathcal{P}_2$, $\mathcal{P}_4$ vs. $\mathcal{O}_B$

Expanding in unitary gauge:

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

$$\mathcal{O}_B = \frac{eg^2}{8} A_{\mu\nu} W^{-\mu} W^{+\nu} (v+h)^2 - \frac{ie^2 g}{4c_\theta} Z_{\mu\nu} W^{-\mu} W^{+\nu} (v+h)^2 + \\ - \frac{ge}{4c_\theta} A_{\mu\nu} Z^\mu \partial^\nu h (v+h) + \frac{e^2}{4c_\theta^2} Z_{\mu\nu} Z^\mu \partial^\nu h (v+h)$$

▼

$$\mathcal{P}_2 = eg^2 A_{\mu\nu} W^{-\mu} W^{+\nu} \mathcal{F}_2(h) - 2\frac{ie^2 g}{c_\theta} Z_{\mu\nu} W^{-\mu} W^{+\nu} \mathcal{F}_2(h)$$

$$\mathcal{P}_4 = -\frac{ge}{c_\theta} A_{\mu\nu} Z^\mu \partial^\nu \mathcal{F}_4(h) + \frac{e^2}{c_\theta^2} Z_{\mu\nu} Z^\mu \partial^\nu \mathcal{F}_4(h)$$

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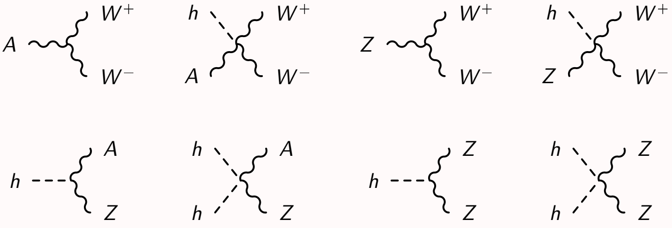

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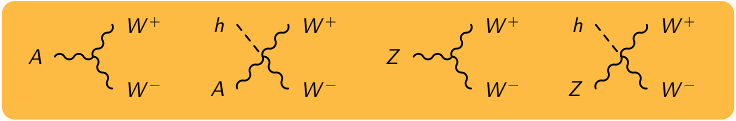
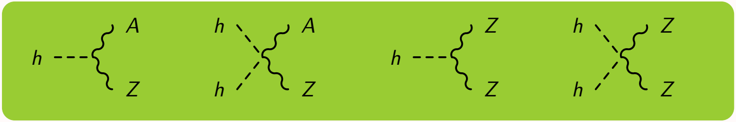
Different coefficients and unrelated weights!





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The same couplings also receive a contribution from $\mathcal{O}_W$:

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

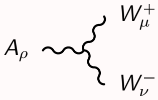
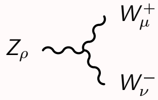
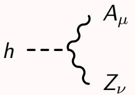
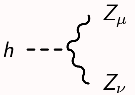
▸

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

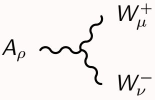
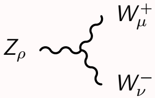
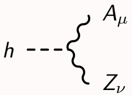
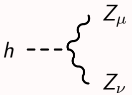
$$\mathcal{P}_5 = ig\,\mathrm{Tr}(W_{\mu\nu}\mathbf{V}^\mu)\partial^\nu \mathcal{F}_5(h)$$

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

Correlation / decorrelation effects

		④ in $\mathscr{L}$ chiral	in $\mathscr{L}$ linear ②
	$A_{\mu\nu}W^{+\mu}W^{-\nu}$	$-\frac{ieg^2}{8}(16\,c_2 + 8\,c_3)$	$-\frac{ieg^2}{8}\frac{v^2}{\Lambda^2}(c_B + c_W)$
	$Z_{\mu\nu}W^{+\mu}W^{-\nu}$	$-\frac{g^3}{8c_\theta}(-16s^2_\theta\,c_2 + 8c^2_\theta\,c_3)$	$-\frac{g^3}{8c_\theta}\frac{v^2}{\Lambda^2}(-s^2_\theta\,c_B + c^2_\theta\,c_W)$
	$A_{\mu\nu}Z^\mu\partial^\nu h$	$-\frac{eg}{4c_\theta v}(8\,a_4 + 4\,a_5)$	$-\frac{eg}{4c_\theta v}\frac{v^2}{\Lambda^2}(c_B - c_W)$
	$Z_{\mu\nu}Z^\mu\partial^\nu h$	$-\frac{g^2}{4vc_\theta}(8s_\theta\,a_4 - 4c_\theta\,a_5)$	$-\frac{g^2}{4vc_\theta}\frac{v^2}{\Lambda^2}(s_\theta\,c_B - c_\theta\,c_W)$

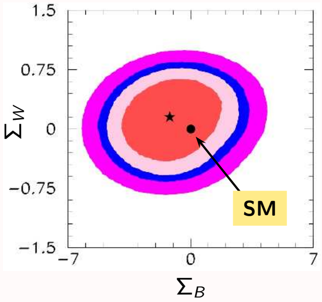
Correlation / decorrelation effects

		Decorrelated!	Correlated!
	$A_{\mu\nu}W^{+\mu}W^{-\nu}$	$-\frac{ieg^2}{8}(16\,c_2 + 8\,c_3)$	$-\frac{ieg^2}{8}\frac{v^2}{\Lambda^2}(c_B + c_W)$
	$Z_{\mu\nu}W^{+\mu}W^{-\nu}$	$-\frac{g^3}{8c_\theta}(-16s_\theta^2\,c_2 + 8c_\theta^2\,c_3)$	$-\frac{g^3}{8c_\theta}\frac{v^2}{\Lambda^2}(-s_\theta^2\,c_B + c_\theta^2\,c_W)$
	$A_{\mu\nu}Z^\mu\partial^\nu h$	$-\frac{eg}{4c_\theta v}(8\,a_4 + 4\,a_5)$	$-\frac{eg}{4c_\theta v}\frac{v^2}{\Lambda^2}(c_B - c_W)$
	$Z_{\mu\nu}Z^\mu\partial^\nu h$	$-\frac{g^2}{4vc_\theta}(8s_\theta\,a_4 - 4c_\theta\,a_5)$	$-\frac{g^2}{4vc_\theta}\frac{v^2}{\Lambda^2}(s_\theta\,c_B - c_\theta\,c_W)$

From TGV + Higgs data

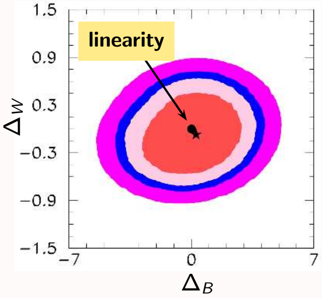
A BSM sensor

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



A linear vs non-linear discriminator

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



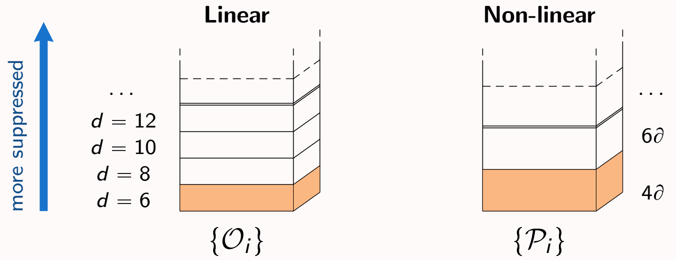
χ^2 dependence after marginalizing over the other chiral parameters

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

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

Generalizing: 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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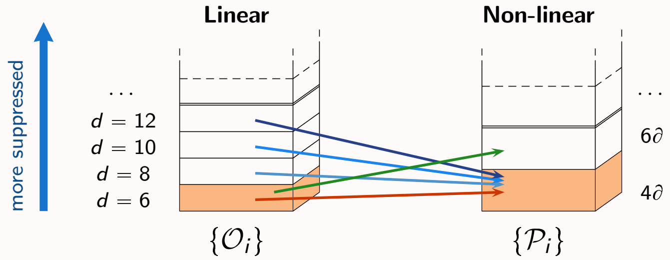
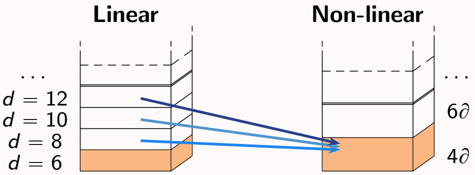
Two towers of operators:



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

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

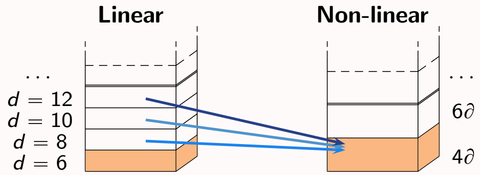
Characteristic signatures of a dynamical EWSB



Effects that are expected to be

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

Characteristic signatures of a dynamical EWSB



Effects that are expected to be

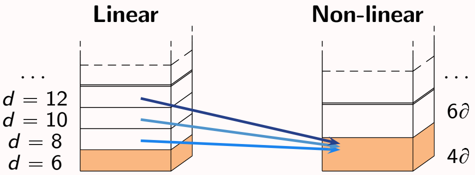
- leading-order corrections in the non-linear expansion
- higher-order corrections in the linear series

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

▼

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

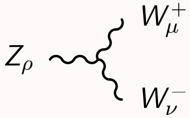
Characteristic signatures of a dynamical EWSB



Effects that are expected to be

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

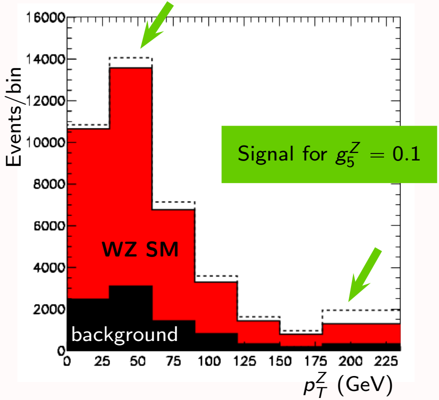
$\mathcal{P}_{14}$ →



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

Expected LHC sensitivity

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



Current best bound at 95% CL

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

Dawson, Valencia (1994)

Simulation analysis

- WZ pair production
  $pp \to W^\pm Z \to \ell'^\pm \ell^+ \ell^- E_T^{miss}$
- binned analysis of p_T^Z distribution
- dataset: 7+8+14 TeV
  ($4.64+19.6+300\,\text{fb}^{-1}$)
- Result (95% CL)

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

Conclusions

- New physics effects at low-energy can be properly described by an Effective Lagrangian
  - **linear** if the Higgs is elementary
  - **chiral** if the Higgs is composite
- The two descriptions give significantly different predictions!
  - **correlation/decorrelation effects**
  - distinct **characterizing signals**
- The next LHC run may already have something to say about the nature of the Higgs boson!

Backup slides

Triple gauge vertices

$$\begin{aligned}\mathscr{L}_{WWV} = -\, i g_{WWV}\Big\{ & g_1^V\left(W^+_{\mu\nu}W^{-\,\mu}V^{\nu} - W^+_{\mu}V_{\nu}W^{-\,\mu\nu}\right) + \kappa_V W^+_{\mu}W^-_{\nu}V^{\mu\nu} \\ & - i g_5^V \varepsilon^{\mu\nu\rho\sigma}\left(W^+_{\mu}\partial_{\rho}W^-_{\nu} - W^-_{\nu}\partial_{\rho}W^+_{\mu}\right)V_{\sigma} + \\ & + g_6^V\left(\partial_{\mu}W^{+\mu}W^{-\nu} - \partial_{\mu}W^{-\mu}W^{+\nu}\right)V_{\nu}\Big\}\end{aligned}$$

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

	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	$\frac{1}{c^2_\theta}$	$\frac{s^2_{2\theta}}{4e^2 c_{2\theta}}c_T + \frac{2s^2_\theta}{c_{2\theta}}c_1 + c_3$	$\frac{1}{8}c_W + \frac{s^2_\theta}{4c_{2\theta}}c_{BW} - \frac{s^2_{2\theta}}{16e^2 c_{2\theta}}c_{\Phi,1}$
$\Delta\kappa_Z$	1	$\frac{s^2_\theta}{e^2 c_{2\theta}}c_T + \frac{4s^2_\theta}{c_{2\theta}}c_1 - \frac{2s^2_\theta}{ct^2}c_2 + c_3 - 4c_{12} + 2c_{13}$	$\frac{1}{8}c_W - \frac{s^2_\theta}{8ct^2}c_B + \frac{s^2_\theta}{2c_{2\theta}}c_{BW} - \frac{s^2_\theta}{4e^2 c_{2\theta}}c_{\Phi,1}$
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

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

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

$\mathcal{P}_2\,,\mathcal{P}_4$ in explicit CH models

Defining

Alonso,IB,Gavela,Merlo,Rigolin
to appear very soon!

$$\mathcal{A}_2 = ig' B_{\mu\nu}\,\mathrm{Tr}\left(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]\right)\,, \qquad \mathcal{A}_4 = ig' B_{\mu\nu}\,\mathrm{Tr}\left(\mathbf{T}\mathbf{V}^\mu\right)\partial^\nu h/v$$

$$\mathscr{L} \supset c_2\mathcal{F}_2(h)\mathcal{A}_2 + c_4\mathcal{F}_4(h)\mathcal{A}_4$$

model	$\mathbf{c_2\mathcal{F}_2(h)}$	$\mathbf{c_4\mathcal{F}_4(h)}$
linear	$\frac{c_B}{\Lambda^2}\frac{1}{16}(v+h)^2$	$\frac{c_B}{\Lambda^2}\frac{1}{4}v\,(v+h)$
$SU(5)/SO(5)$ $SO(5)/SO(4)$	$\tilde{c}_2\sqrt{2}\sin^2\frac{\varphi}{2f}$	$\tilde{c}_2\sqrt{2\xi}\sin\frac{\varphi}{f}$
$SU(3)/SU(2)\times U(1)$	$\frac{\tilde{c}_2}{2}\sin^2\frac{\varphi}{f}$	$\tilde{c}_2\sqrt{\xi}\sin\frac{2\varphi}{f}$

$$\varphi = \langle\varphi\rangle + h \qquad\qquad \xi = v^2/f^2 \in [0,1]$$

$\mathcal{P}_2\,,\mathcal{P}_4$ in explicit CH models

In $SU(5)/SO(5)$:

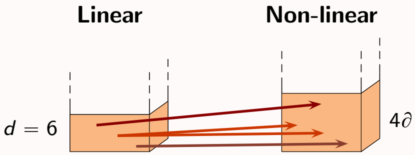
Alonso,IB,Gavela,Merlo,Rigolin
to appear very soon!

model	$\mathbf{c_2\mathcal{F}_2(h)}$	$\mathbf{c_4\mathcal{F}_4(h)}$
linear	$\frac{c_B}{\Lambda^2}\frac{1}{16}(v+h)^2$	$\frac{c_B}{\Lambda^2}\frac{1}{4}v\,(v+h)$
$SU(5)/SO(5)$ $SO(5)/SO(4)$	$\tilde{c}_2\sqrt{2}\sin^2\left[\frac{\varphi}{2f}\right]$	$\tilde{c}_2\sqrt{2\xi}\sin\left[\frac{\varphi}{f}\right]$

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

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

Correspondence between first orders



$$\mathcal{P}_2\,,\mathcal{P}_4 \;\rightarrow\; \mathcal{O}_B \quad \text{and} \quad \mathcal{P}_3\,,\mathcal{P}_5 \;\rightarrow\; \mathcal{O}_W$$

10 linear operators of $d = 6$

correspond to

17 chiral operators with 4∂

IB,Éboli,Gavela,Gonzalez-Garcia,Merlo, Rigolin (2014) [hep-ph/1405.5412]

An interesting effect also is seen in

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

$$\mathcal{O}_{\Box\Phi} = (D_\mu D^\mu \Phi)^\dagger\,(D_\nu D^\nu \Phi)$$
$$\mathcal{P}_{\Box h} = \frac{1}{2}(\partial_\mu\partial^\mu h)(\partial_\nu\partial^\nu h)$$

- Lee-Wick partner for the Higgs

$\mathcal{O}_{\Box\Phi}$ vs. $\mathcal{P}_{\Box h}$

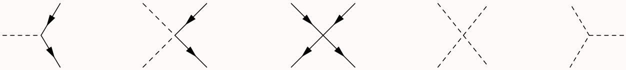
In the linear basis: $\mathcal{O}_{\Box\Phi} = (D_\mu D^\mu \Phi)^\dagger (D_\nu D^\nu \Phi)$

In the chiral basis: $\mathcal{P}_{\Box h} = \frac{1}{2}(\partial_\mu \partial^\mu h)(\partial_\nu \partial^\nu h)$

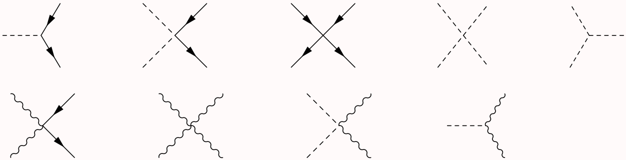
IB, Éboli, Gavela, Gonzalez-Garcia, Merlo, Rigolin (2014) [hep-ph/1405.5412]

Applying the EOMs:

$\mathcal{O}_{\Box\Phi}$ ▸



$\mathcal{P}_{\Box h}$ ▸



Basic idea for a composite Higgs

energy

Λ — strong resonances (technicolor)

global symmetry $\mathcal{G}$

Georgi,Kaplan (1984)
Dimopoulos,Georgi,Kaplan (1984)
Galison,Georgi,Kaplan (1984)
Banks (1984)
Dugan,Georgi,Kaplan (1985)
Agashe,Contino,Pomarol (2005)
Gripaios,Pomarol,Riva,Serra (2009)
...

f — Goldstone bosons characteristic scale

$4\pi f \geqslant \Lambda$

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

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

v — electroweak scale

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