# Disentangling a Dynamical Higgs

**Ilaria Brivio**

Universidad Autónoma de Madrid

Planck14, May 2014, Paris

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

**JHEP 1403 (2014) 024**
**arXiv:hep-ph/1311.1823**

inVisibles
neutrinos, dark matter & dark energy physics

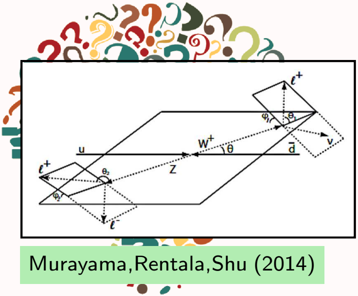
UAM UNIVERSIDAD AUTONOMA DE MADRID

# Motivation

**Is the Higgs elementary or composite?**

A crucial, urgent question!

# Motivation




Murayama,Rentala,Shu (2014)

**Is the Higgs elementary or composite?**

A crucial, urgent question!

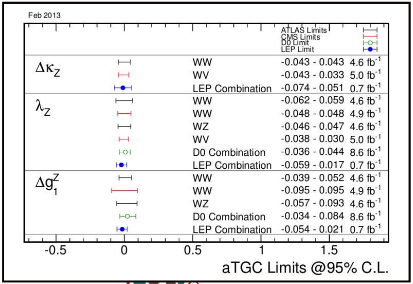
Direct approach:

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

Ilaria Brivio
UAM/IFT Madrid



# Motivation




LEP+LHC (2013)

**Is the Higgs**
**elementary or composite?**

A crucial, urgent question!

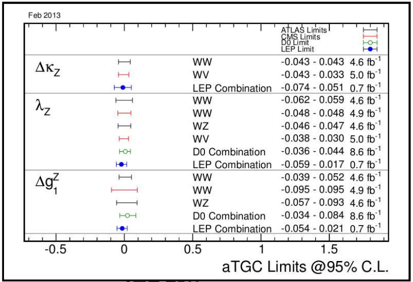
Direct approach:

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

Indirect approach:

- look for deviations from SM predictions at low energy

# Motivation




LEP+LHC (2013)

**Is the Higgs**
**elementary or composite?**

A crucial, urgent question!

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 |

# Strategy

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

Focus:

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

# Strategy

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

Focus:

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

Idea:

- they give different predictions! $\rightarrow$ distinctive **signatures**
- is the LHC sensitive enough?

# The linear effective Lagrangian

standard Higgs doublet $\Phi \rightarrow$ Expansion in canonical dimensions

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

# The linear effective Lagrangian

standard Higgs doublet $\Phi \rightarrow$ Expansion in canonical dimensions

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

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

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

# Linear basis $d = 6$

Bosonic sector, CP even
(HISZ 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 basis $d = 6$

Bosonic sector, CP even (HISZ basis)

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

**10** independent gauge & gauge-$h$ operators

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

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

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

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

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

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

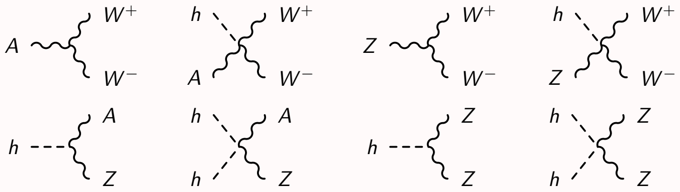
Grzadkowski, Iskrzynski, Misiak, Rosiek (2010)

# Example: $\mathcal{O}_B$

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

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

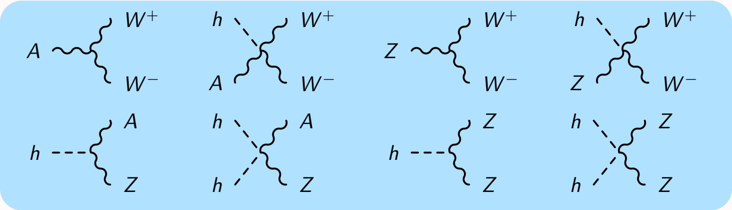
$$-\frac{ge}{4c_\theta}A_{\mu\nu}Z^\mu\partial^\nu h(v+h) + \frac{e^2}{4c_\theta^2}Z_{\mu\nu}Z^\mu\partial^\nu h(v+h)$$



# Example: $\mathcal{O}_\text{B}$

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

**same coefficient with fixed relative weights!**



# The chiral formalism

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

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

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

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

# The chiral formalism

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

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

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

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

Can describe the linear limit

$$\Phi = \frac{v+h}{\sqrt{2}}\,\mathbf{U}\begin{pmatrix}0\\1\end{pmatrix}$$

# The chiral formalism

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

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

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

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

$\mathbf{U}$ adimensional → insertions of GB fields do not add suppression factors

$h$ singlet → more possible invariants

# The chiral formalism

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

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

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

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

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 $\rightarrow$ expansion in derivatives

In a phenomenological approach:

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

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

# The non-linear effective Lagrangian

**U** is adimensional $\rightarrow$ expansion in derivatives

In a phenomenological approach:

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

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

**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

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

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

Expanding in unitary gauge:

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

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

▼

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

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

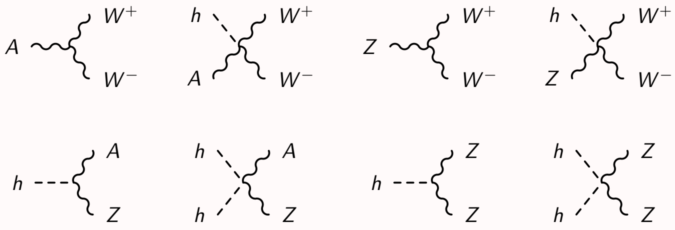
# Example: $\mathcal{P}_2$, $\mathcal{P}_4$ vs. $\mathcal{O}_B$

Expanding in unitary gauge:

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

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

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



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

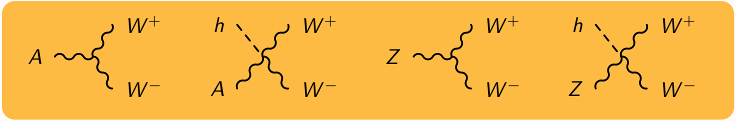
Expanding in unitary gauge:

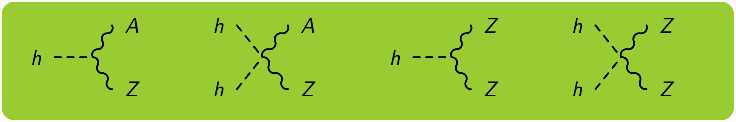
$$\mathcal{O}_B \to \frac{\mathcal{P}_2}{16} + \frac{\mathcal{P}_4}{8}$$

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

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

**Different coefficients and arbitrary weights!**



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

Expanding in unitary gauge:

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

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

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

Indeed, in concrete models:

$$SU(5)/SO(5)\,, SO(5)/SO(4)\,, SU(3)/SU(2)\times U(1)\ldots$$

the coefficients $\mathbf{c_2}\,,\mathbf{c_4}$ and the functions $\boldsymbol{\mathcal{F}_2(h)}\,,\boldsymbol{\mathcal{F}_4(h)}$ are **specified** and their pattern **differs from the linear** one

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

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

Expanding in unitary gauge:

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

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

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

An analogous splitting is found for

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

►

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

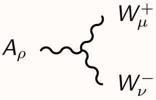
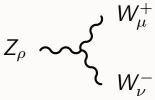
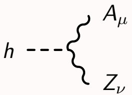
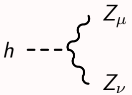
$$\mathcal{P}_5 = ig\, \mathrm{Tr}(W_{\mu\nu}\mathbf{V}^\mu)\partial^\nu \mathcal{F}_5(h)$$

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

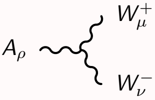
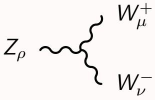
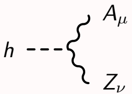
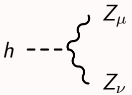
Ilaria Brivio
UAM/IFT Madrid



# Correlation / decorrelation effects

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

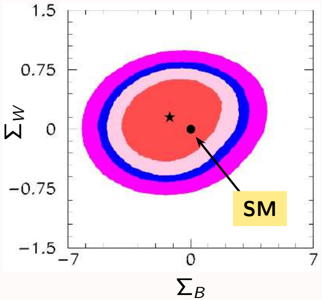
# Correlation / decorrelation effects

| Vertex | Operator | 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

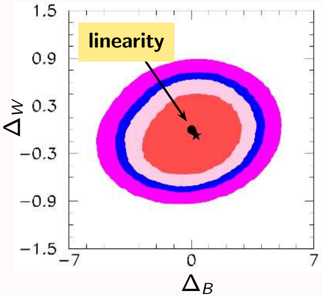
A BSM sensor

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




A linear vs non-linear discriminator

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



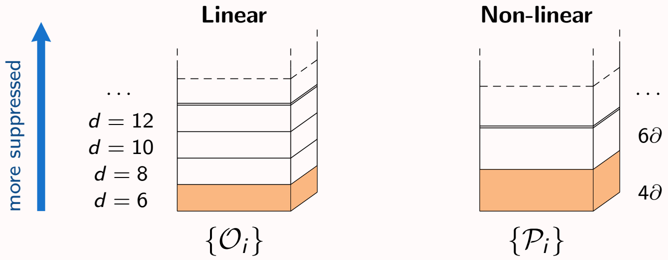

$\chi^2$ dependence after marginalizing over the other chiral parameters

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:

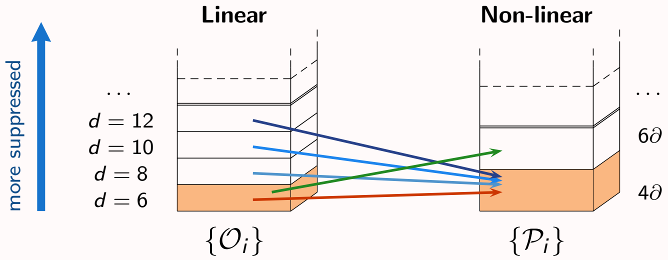



**Correspondence $\mathcal{O}_i \to \mathcal{P}_j$**

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

# Generalizing: linear - chiral correspondence

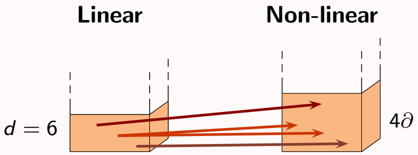
Two towers of operators:




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

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

# Correspondence between first orders

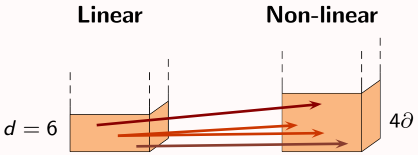



**10** linear operators of $d = 6$

correspond to

**17** chiral operators with $4\partial$

# Correspondence between first orders



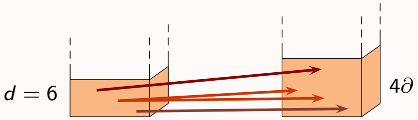

$\mathcal{P}_2\,,\mathcal{P}_4 \to \mathcal{O}_B$ and $\mathcal{P}_3\,,\mathcal{P}_5 \to \mathcal{O}_W$

**10** linear operators of $d = 6$

correspond to

**17** chiral operators with $4\partial$

# Correspondence between first orders




**10** linear operators of $d = 6$

correspond to

**17** chiral operators with $4\partial$

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

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

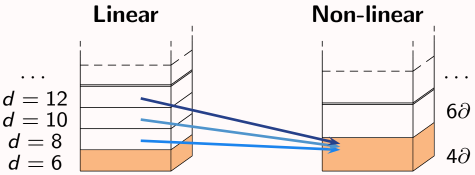
An interesting effect also is seen in

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

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

- Lee-Wick partner for the Higgs

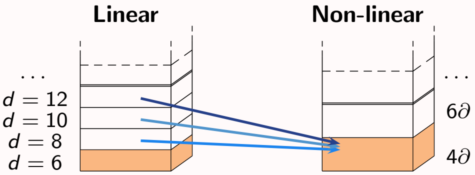
# Characteristic signatures of a dynamical EWSB




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

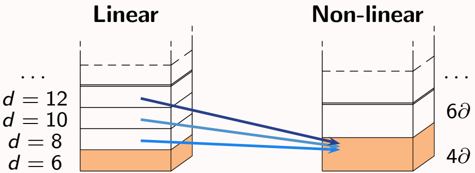
- leading-order corrections in the non-linear expansion
- higher-order corrections in the linear series

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

▼

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

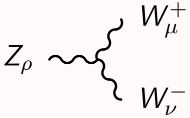
# Characteristic signatures of a dynamical EWSB




Effects that are expected to be

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

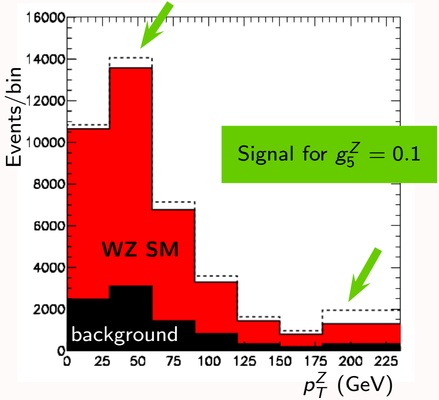
$\mathcal{P}_{14}$ →




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

# 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
  $pp \to W^\pm Z \to \ell'^\pm \ell^+ \ell^- E_T^{\text{miss}}$
- 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

# Conclusions

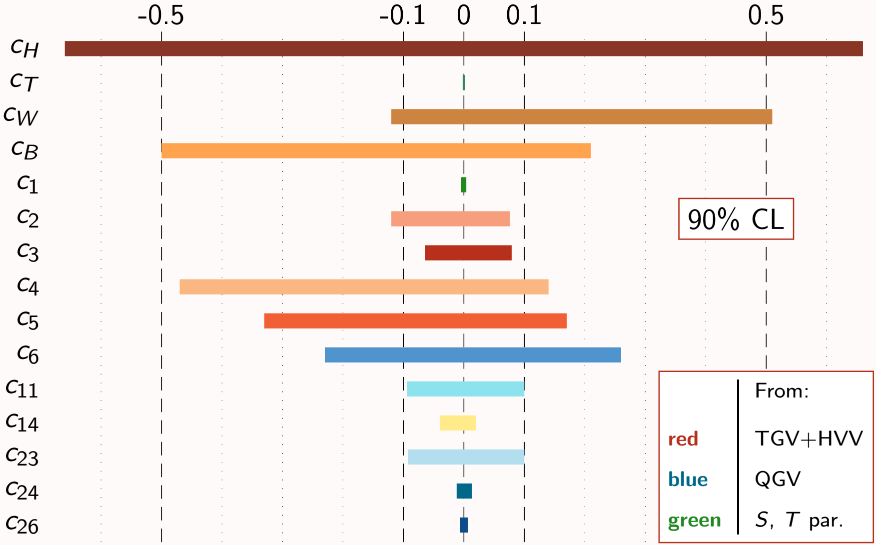
- New physics effects at low-energy can be properly described by an Effective Lagrangian
  - **linear** if the Higgs is elementary
  - **chiral** if the Higgs is composite
- The two descriptions give significantly different predictions!
  - **correlation/decorrelation effects**
  - distinct **characterizing signals**

# 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

# Best bounds on the chiral coefficients



# Triple gauge vertices

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

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

| | Coeff. $\times e^2/s^2_\theta$ | Chiral | Linear $\times v^2$ |
|---|---|---|---|
| $\Delta\kappa_\gamma$ | 1 | $-2c_1 + 2c_2 + c_3 - 4c_{12} + 2c_{13}$ | $\frac{1}{8}(c_W + c_B - 2c_{BW})$ |
| $\Delta g_6^\gamma$ | 1 | $-c_9$ | – |
| $\Delta g_1^Z$ | $\frac{1}{c^2_\theta}$ | $\frac{s^2_{2\theta}}{4e^2 c_{2\theta}} c_T + \frac{2s^2_\theta}{c_{2\theta}} c_1 + c_3$ | $\frac{1}{8} c_W + \frac{s^2_\theta}{4c_{2\theta}} c_{BW} - \frac{s^2_{2\theta}}{16e^2 c_{2\theta}} c_{\Phi,1}$ |
| $\Delta\kappa_Z$ | 1 | $\frac{s^2_\theta}{e^2 c_{2\theta}} c_T + \frac{4s^2_\theta}{c_{2\theta}} c_1 - \frac{2s^2_\theta}{ct^2} c_2 + c_3 - 4c_{12} + 2c_{13}$ | $\frac{1}{8} c_W - \frac{s^2_\theta}{8ct^2} c_B + \frac{s^2_\theta}{2c_{2\theta}} c_{BW} - \frac{s^2_\theta}{4e^2 c_{2\theta}} c_{\Phi,1}$ |
| $\Delta g_5^Z$ | $\frac{1}{c^2_\theta}$ | $c_{14}$ | – |
| $\Delta g_6^Z$ | $\frac{1}{c^2_\theta}$ | $s^2_\theta c_9 - c_{16}$ | – |

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

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

Ilaria Brivio
UAM/IFT Madrid



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

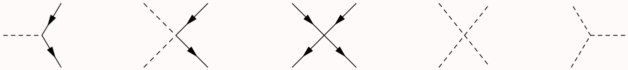
In the linear basis: $\mathcal{O}_{\Box\Phi} = (D_\mu D^\mu \Phi)^\dagger (D_\nu D^\nu \Phi)$

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

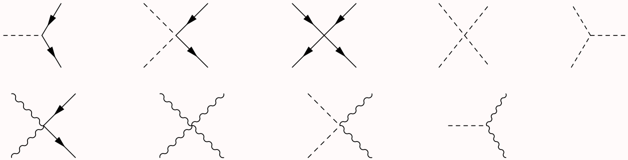
IB,Éboli,Gavela,Gonzalez-Garcia,Merlo, Rigolin (2014) [hep-ph/1405.5412]

Applying the EOMs:

$\mathcal{O}_{\Box\Phi}$ ▶



$\mathcal{P}_{\Box h}$ ▶



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

Defining

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

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

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

| **model** | $\mathbf{c_2\mathcal{F}_2(h)}$ | $\mathbf{c_4\mathcal{F}_4(h)}$ |
|---:|---|---|
| linear | $\frac{c_B}{\Lambda^2}\frac{1}{16}(v+h)^2$ | $\frac{c_B}{\Lambda^2}\frac{1}{4}v(v+h)$ |
| $SU(5)/SO(5)$<br>$SO(5)/SO(4)$ | $\tilde{c}_2\sqrt{2}\sin^2\left[\frac{\varphi}{2f}\right]$ | $\tilde{c}_2\sqrt{2\xi}\sin\left[\frac{\varphi}{f}\right]$ |
| $SU(3)/SU(2)\times U(1)$ | $\frac{\tilde{c}_2}{2}\sin^2\left[\frac{\varphi}{f}\right]$ | $\tilde{c}_2\sqrt{\xi}\sin\left[\frac{2\varphi}{f}\right]$ |

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

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

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

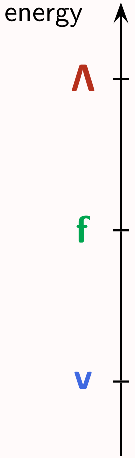
Alonso,IB,Gavela,Merlo,Rigolin
*to appear very soon!*

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

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

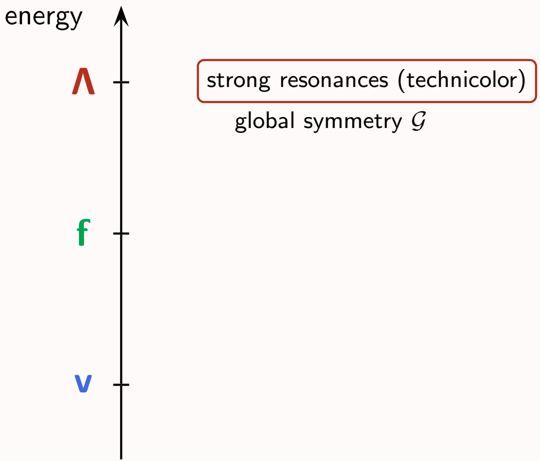
$$\sin\left[\frac{\varphi}{f}\right]=\frac{1}{f}\sqrt{1-\frac{\xi}{4}}\left(v+h\frac{1-\xi/2}{\sqrt{1-\xi/4}}+\dots\right)$$

# Basic idea for a composite Higgs



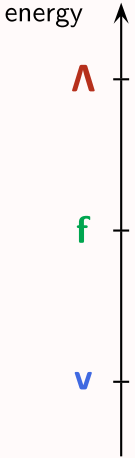

Georgi,Kaplan (1984)
Dimopoulos,Georgi,Kaplan (1984)
Galison,Georgi,Kaplan (1984)
Banks (1984)
Dugan,Georgi,Kaplan (1985)
Agashe,Contino,Pomarol (2005)
Gripaios,Pomarol,Riva,Serra (2009)
...

# Basic idea for a composite Higgs




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)
. . .

# Basic idea for a composite Higgs




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)
...

**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 $\mathcal{H} \supseteq SU(2) \times U(1)$

**v**

# 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

$\mathbf{4\pi f \geqslant \Lambda}$

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