Effective Chiral Lagrangian for a Light Dynamical Higgs

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S. Rigolin

Università degli Studi di Padova and INFN Padova

invisibles
neutrinos, dark matter & dark energy physics

Mainly based on	R. Alonso et al. **Phys. Lett. B722 (2013) 330-335**
	I. Brivio et al. **JHEP 1403, 024 (2014)**
	R. Alonso, I. Brivio, B. Gavela, L. Merlo and SR **in preparation**

Contents

- **The (Higgsless) Effective χ-Lagrangian;**
  - Linear vs nonlinear realization of the EW symmetry breaking (from the effective Lagrangian side);
  - The (Higgsless) effective χ-Lagrangian for the gauge-Goldstone bosons interactions (up to 4 derivatives);
- **The Dynamical Higgs Effective χ-Lagrangian;**
  - The effective χ-Lagrangian for the gauge-Goldstone-Higgs bosons interactions (up to 4 derivatives);
  - Relation with model building: the SU(5)/SO(5) example;
- **Conclusions & Outlooks**

(Linear) Effective Lagrangian

☆ The Linear ElectroWeak Symmetry Breaking

- If the resonance found @LHC is the (doublet) Higgs boson then some NP@TeV should be present to stabilize its mass

HIERARCHY PROBLEM

- In the absence of experimental indications pointing to some specific model (like i.e. MSSM) NP effects above the TEV scale can be parametrized by writing the (linear) effective Lagrangian including up to d=6 operators:

$$\boxed{\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_{i=1}^{n} c_i \mathcal{O}_i^{d=6} + O(\frac{1}{\Lambda^4})}$$

with Λ (≥ few TeV) the NP scale and $c_i = O(1)$ parameters;

The Linear (Gauge-Higgs) HISZ Basis

- The effective Lagrangian is built using the SM (weak) gauge bosons $W_{\mu\nu}, B_{\mu\nu}$ and the Higgs doublet Φ;
- The d=6 (HISZ) basis of operators describing the gauge-Higgs sector relevant for our discussion reads:

$$\mathcal{O}_{WW} = \left(\frac{g}{2}\right)^2 \Phi^\dagger W^{\mu\nu} W_{\mu\nu} \Phi \quad , \quad \mathcal{O}_{\Phi,1} = (D_\mu \Phi)^\dagger \Phi \Phi^\dagger (D_\nu \Phi)$$

$$\mathcal{O}_{BB} = \left(\frac{g'}{2}\right)^2 \Phi^\dagger B^{\mu\nu} B_{\mu\nu} \Phi \quad , \quad \mathcal{O}_{\Phi,2} = \frac{1}{2} \partial_\mu (\Phi^\dagger \Phi) \partial^\mu (\Phi^\dagger \Phi)$$

$$\mathcal{O}_{BW} = \frac{g\, g'}{4} \Phi^\dagger B^{\mu\nu} W_{\mu\nu} \Phi \quad , \quad \mathcal{O}_{\Phi,3} = \frac{1}{3} \left(\Phi^\dagger \Phi\right)^3$$

$$\mathcal{O}_W = \frac{g}{2} (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi) \quad , \quad \mathcal{O}_{\Phi,4} = (D_\mu \Phi)^\dagger (D^\mu \Phi)(\Phi^\dagger \Phi)$$

$$\mathcal{O}_B = \frac{g'}{2} (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi) \quad , \quad \mathcal{O}_{\Box\Phi} = (D^\mu D_\mu \Phi)^\dagger (D^\nu D_\nu \Phi)$$

[Buchmuller, Wyler (1984), Gradkoski, Iskrzynski, Misiak, Rosiek (2010); Hagiwara, Ishihara, Szalapski, Zeppenfeld (1993)]

Non-Linear (Higgless) Lagrangian

The Non-Linear ElectroWeak Symmetry Breaking

- Only the 3 d.o.f. are needed in the theory in order to give mass the the SM gauge bosons. They can be Goldstone bosons of a "strong chiral" symmetry breaking with $f = v$;
  [Weinberg (1979), Susskind (1979)]
- One can give masses to fermions by introducing a strong sector condensate (techni-fermions); [Dimopoulos, Susskind (1979)]
- No need to introduce a fundamental doublet in the theory. The EWSB can be realized non-linearly; [Callan, Coleman, Wess, Zumino (1980)]
- Technicolor at least in its simpler implementation is severely constrained by EW precision measurements (S,T parameters);
  [Peskin, Takeuchi (1990), Holdom, Terning (1990), Golden, Randall (1991)]

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The Underline Assumption

- Linear (weak int.) vs non-linear (strong int.) scale setup:

weak theory
(SUSY)

$\Lambda \gg v$

$$\left\{ \text{Effective Lagrangian} \right\}$$

$SU(2)_L \times U(1)_Y$

Φ
Linear

$\langle \Phi \rangle = v$

$U(1)_{em}$

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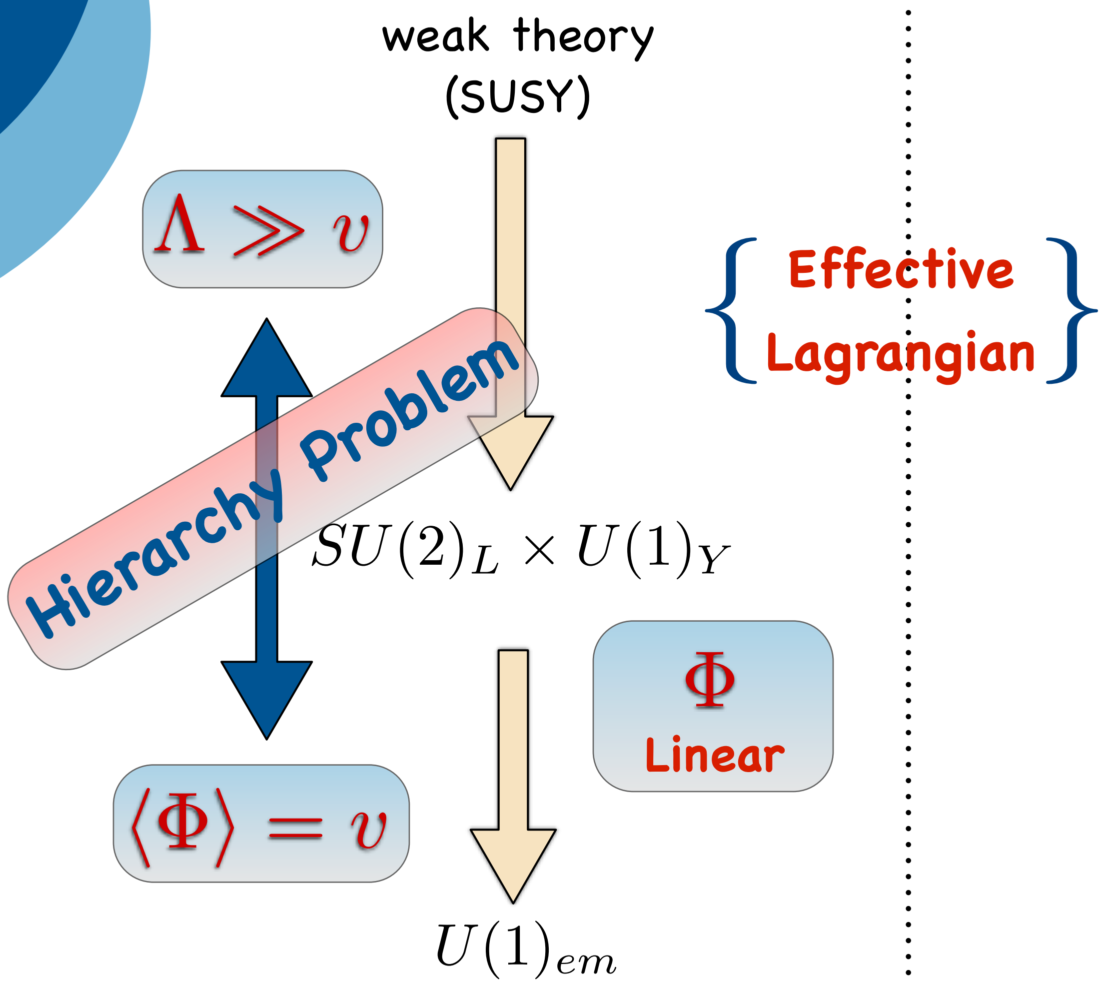

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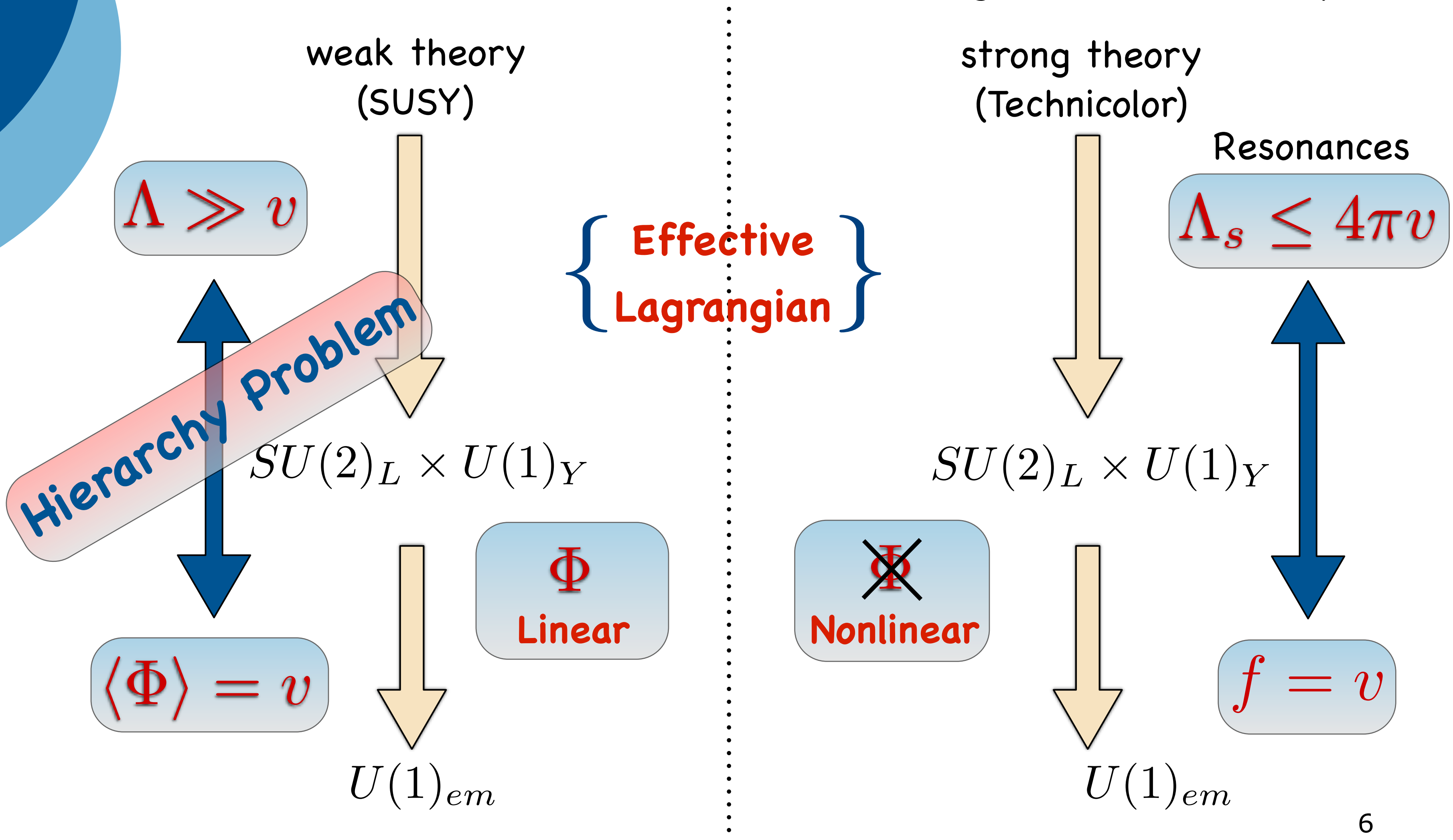

[Appelquist, Carazzone (1980); Longhitano (1980,1981), Feruglio (1993)]

Constructing the Chiral Fields

☆ The EW symmetry breaking without the "Higgs":

Let's start from the SM doublet Φ (linear σ model):

$$\mathbf{M}(x) \equiv \left(\widetilde{\Phi}\,,\,\Phi\right) \quad \overset{SU(2)_L\times U(1)_Y}{\Longrightarrow} \quad \mathbf{M}'(x) = L\,\mathbf{M}(x)R^\dagger$$

and send m_H to infinity (keeping v=const). One removes the physical Higgs from the spectrum keeping the 3 WBGBs

$$\mathbf{M}^\dagger\mathbf{M} = v^2/2 \quad \overset{m_H\to\infty,\ v=const}{\Longrightarrow} \quad \mathbf{U}(x) \equiv e^{i\sigma_a\pi^a(x)/v} \sim \mathbf{M}(x)/v$$

Writing the covariant derivative as:

$$\mathbf{D}_\mu\mathbf{U}(x) \equiv \partial_\mu\mathbf{U}(x) + \frac{ig}{2}W_\mu^a(x)\sigma_a\mathbf{U}(x) - \frac{ig'}{2}B_\mu(x)\mathbf{U}(x)\sigma_3$$

we can define the scalar and the vector LEFT chiral fields

$$\boxed{\mathbf{T}(x) \equiv \mathbf{U}\sigma_3\mathbf{U}^\dagger \qquad \mathbf{V}_\mu(x) \equiv (\mathbf{D}_\mu\mathbf{U})\,\mathbf{U}^\dagger}$$

The (Higgsless) Effective χ-Lagrangian

Making use of $\mathbf{U}(x), \mathbf{T}(x), \mathbf{V}_\mu(x)$ + **SM gauge bosons** one can build all possible $SU(2)_L \times U(1)_Y$ invariants up to 4 derivatives. The CP even gauge-Goldstone interacting Lagrangian reads:

$$\mathcal{L}^{d<4} = -\frac{v^2}{4}\mathrm{Tr}\left[\mathbf{V}^\mu \mathbf{V}_\mu\right] + c_T\,\frac{v^2}{4}\,\mathrm{Tr}\left[\mathbf{T}\mathbf{V}^\mu\right]^2 - \left(\frac{v}{\sqrt{2}}\bar{Q}_L \mathbf{U}(x)\,\mathcal{Y}\,Q_R + \mathrm{h.c.}\right)$$

$$\mathcal{L}^{d=4} = -\frac{1}{4}W^a_{\mu\nu}W_a^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \sum_{i=1}^{14} c_i\,\mathcal{A}_i$$

[Appelquist, Bernard, Phys. Rev. D22 (1980) 200]
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$\Delta\rho \equiv c_T \approx \times 10^{-3}$

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$\Longleftrightarrow$ CPeven ALF gauge-GBs interactions

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The ALF CP even basis

Basis of CPeven gauge-Goldstone operators up to 4 derivatives:

$$\mathcal{A}_1 = g\, g'\, B_{\mu\nu} \mathrm{Tr}\left(\mathbf{T}\, W^{\mu\nu}\right)$$
$$\mathcal{A}_2 = i\, g'\, B_{\mu\nu} \mathrm{Tr}\left(\mathbf{T}\left[\mathbf{V}^\mu, \mathbf{V}^\nu\right]\right)$$
$$\mathcal{A}_3 = i\, g\, \mathrm{Tr}\left(W_{\mu\nu}\left[\mathbf{V}^\mu, \mathbf{V}^\nu\right]\right)$$
$$\mathcal{A}_4 = \left(\mathrm{Tr}\left(\mathbf{V}_\mu\, \mathbf{V}^\mu\right)\right)^2$$
$$\mathcal{A}_5 = \left(\mathrm{Tr}\left(\mathbf{V}_\mu\, \mathbf{V}_\nu\right)\right)^2$$
$$\mathcal{A}_6 = g^2\, \left(\mathrm{Tr}\left(\mathbf{T}\, W^{\mu\nu}\right)\right)^2$$

$$\mathcal{A}_7 = i\, g\, \mathrm{Tr}\left(\mathbf{T}\, W_{\mu\nu}\right) \mathrm{Tr}\left(\mathbf{T}\left[\mathbf{V}^\mu, \mathbf{V}^\nu\right]\right)$$
$$\mathcal{A}_8 = g\, \epsilon^{\mu\nu\rho\lambda} \mathrm{Tr}\left(\mathbf{T}\mathbf{V}_\mu\right) \mathrm{Tr}\left(\mathbf{V}_\nu\, W_{\rho\lambda}\right)$$
$$\mathcal{A}_9 = \mathrm{Tr}\left(\mathbf{V}_\mu \mathbf{V}^\mu\right) \left(\mathrm{Tr}\left(\mathbf{T}\mathbf{V}_\nu\right)\right)^2$$
$$\mathcal{A}_{10} = \mathrm{Tr}\left(\mathbf{V}_\mu \mathbf{V}_\nu\right) \mathrm{Tr}\left(\mathbf{T}\mathbf{V}^\mu\right) \mathrm{Tr}\left(\mathbf{T}\mathbf{V}^\nu\right)$$
$$\mathcal{A}_{11} = \left(\mathrm{Tr}\left(\mathbf{T}\mathbf{V}_\mu\right) \mathrm{Tr}\left(\mathbf{T}\mathbf{V}_\nu\right)\right)^2$$

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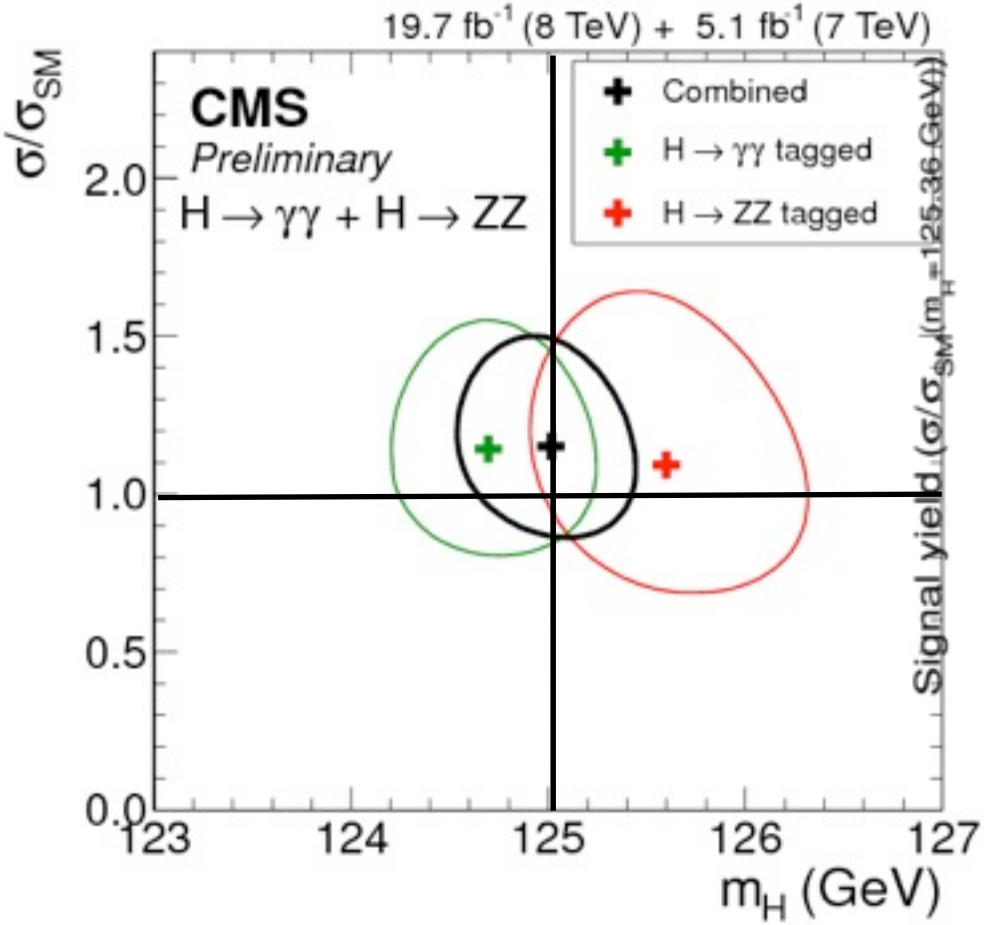
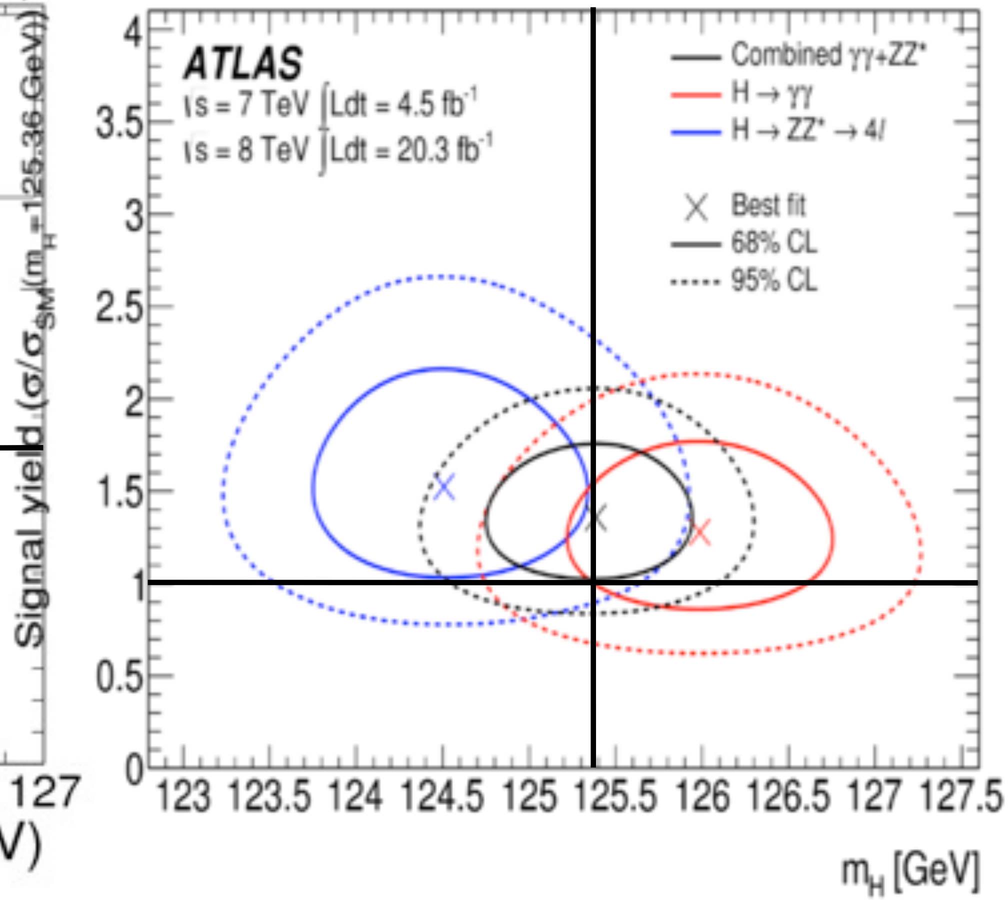
If $m_f = 0$ these ops are not independent from $\mathcal{A}_1 - \mathcal{A}_{11}$!
If $m_f \neq 0$ can eventually be traded by fermionic ops !

The light scalar discovery





[CMS & ATLAS Collaborations (2014)];

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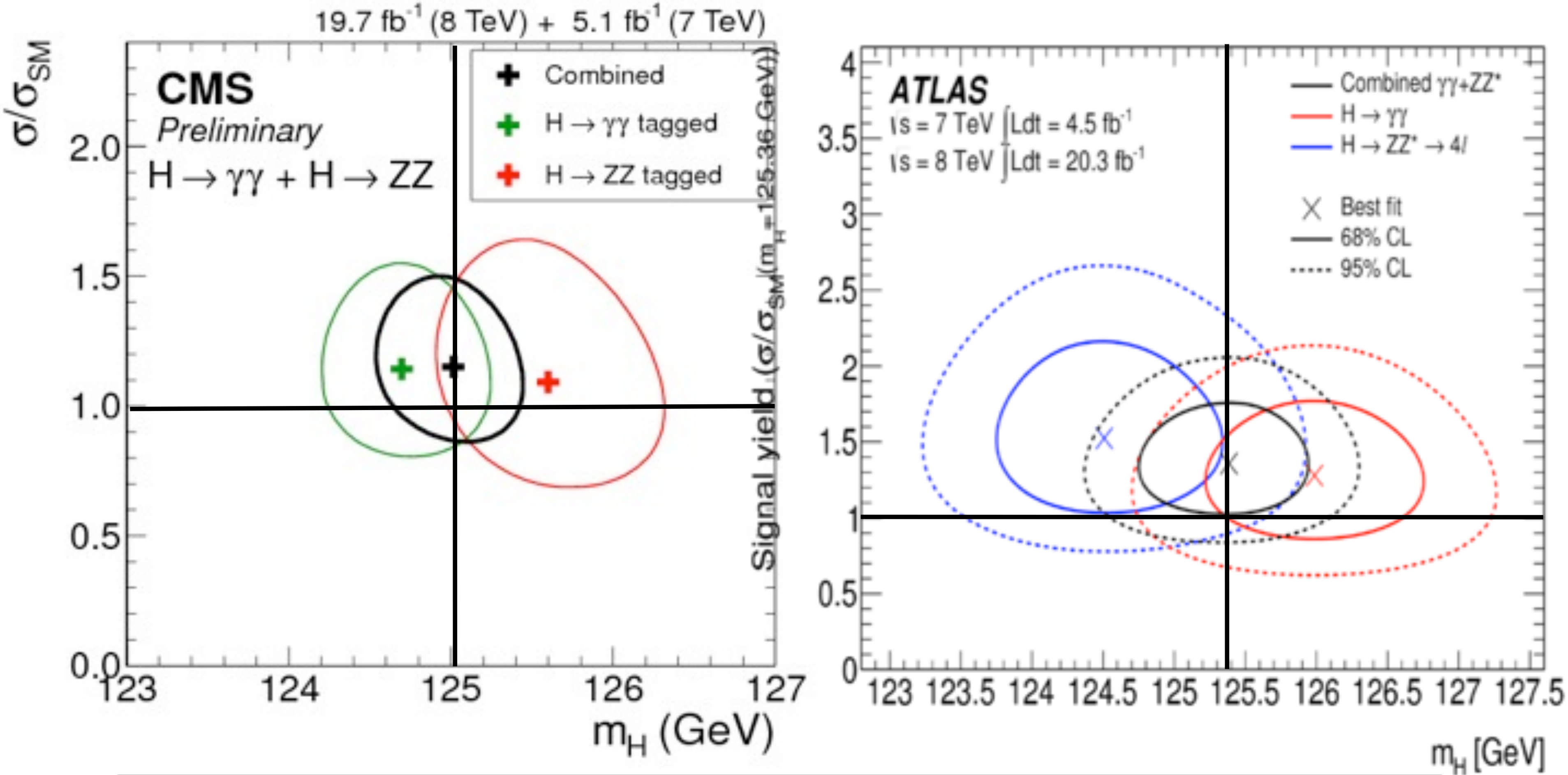

Is this resonance the SM-like Higgs particle (doublet)?

Which effective Lagrangian ?

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☆ YES - EWSB is linearly realized!

- New physics effects are produced by some **WEAK** interacting physics with $\Lambda_{EW} \gtrsim 1$ TeV;
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The (light) dynamical Higgs scenario

- The presence of the new light scalar resonance h should be included. Extension of the ALF (Higgless) chiral Lagrangian;
- One can introduce h as a generic SM "singlet" (whose couplings do not coincide necessarily with the ones of the σ component of the linear model, i.e. doublet);

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Composite Higgs

[Georgi, Kaplan (1984); Dimopoulos, Georgi, Kaplan (1984); Galison, Georgi, Kaplan (1984); Dugan, Georgi, Kaplan (1985)]

- the new scalar h is light because is the GB of a global $\mathcal{G}/\mathcal{H}$ symmetry breaking (4 in SO(5)/SO(4)); [Agashe, Contino, Pomarol (2005)]
- the GB dynamics with a typical the scale $f \geq v$ will induce the (non linear) EWSB $v = v(f, \langle h \rangle)$;

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But not only | **Composite Higgs** | But not only

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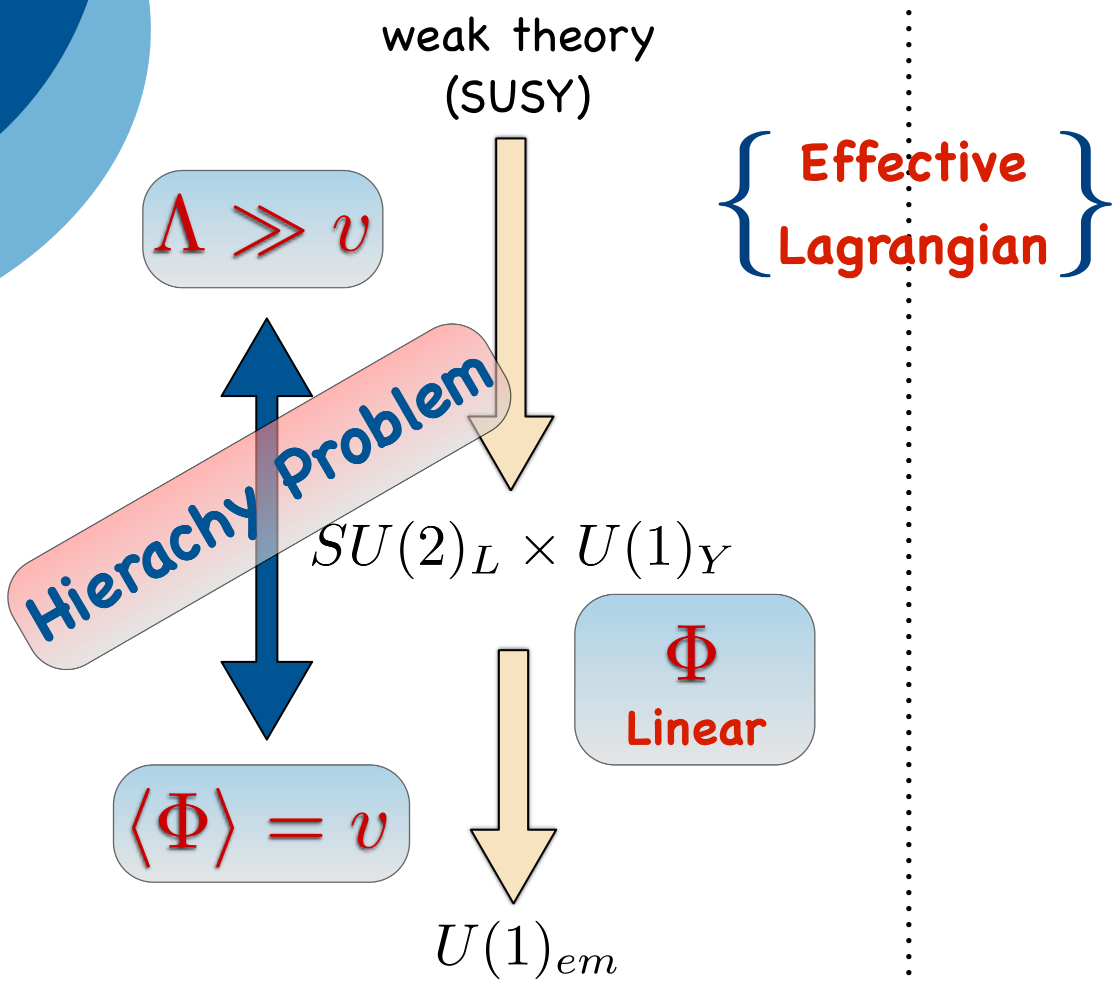

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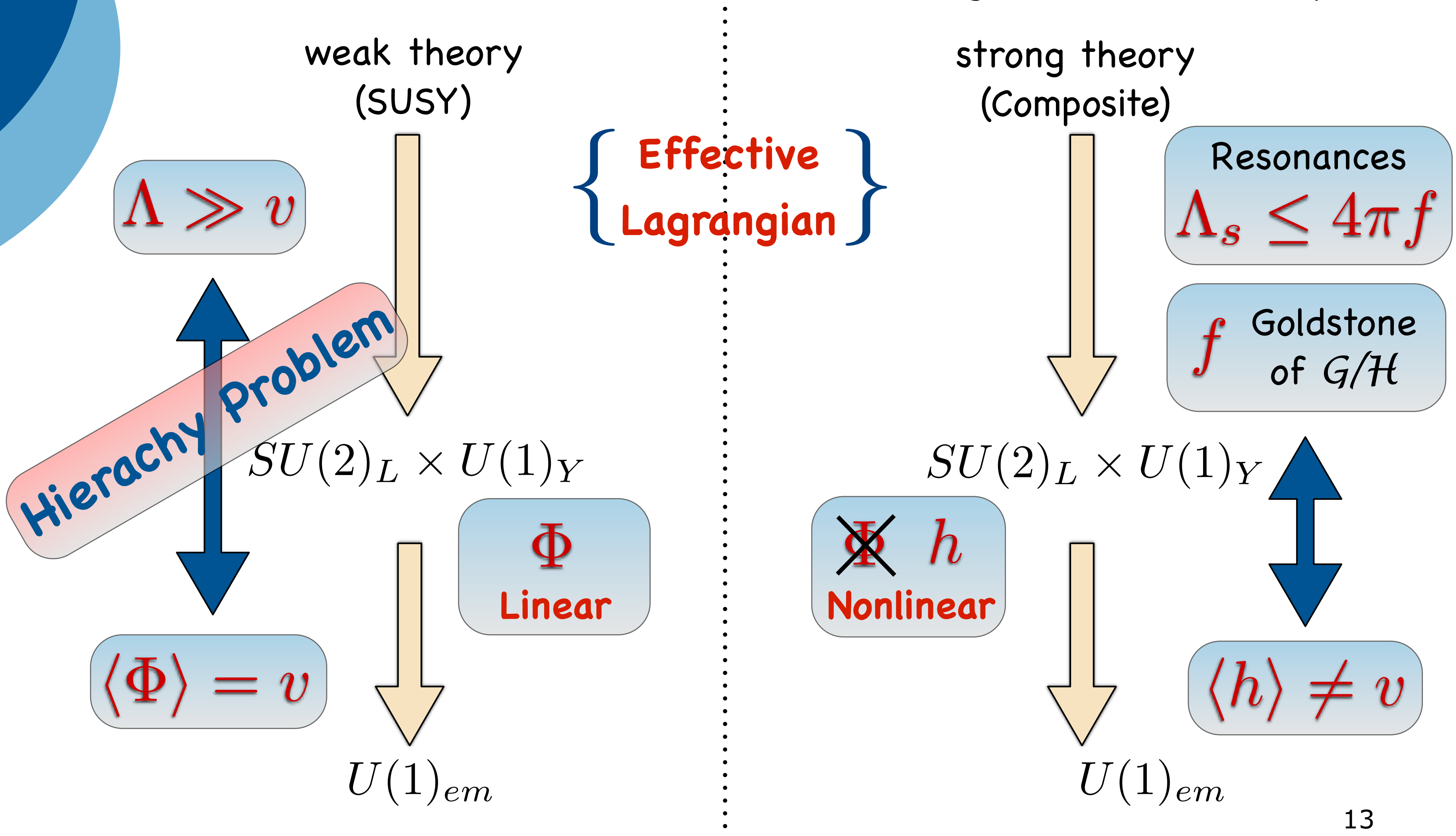

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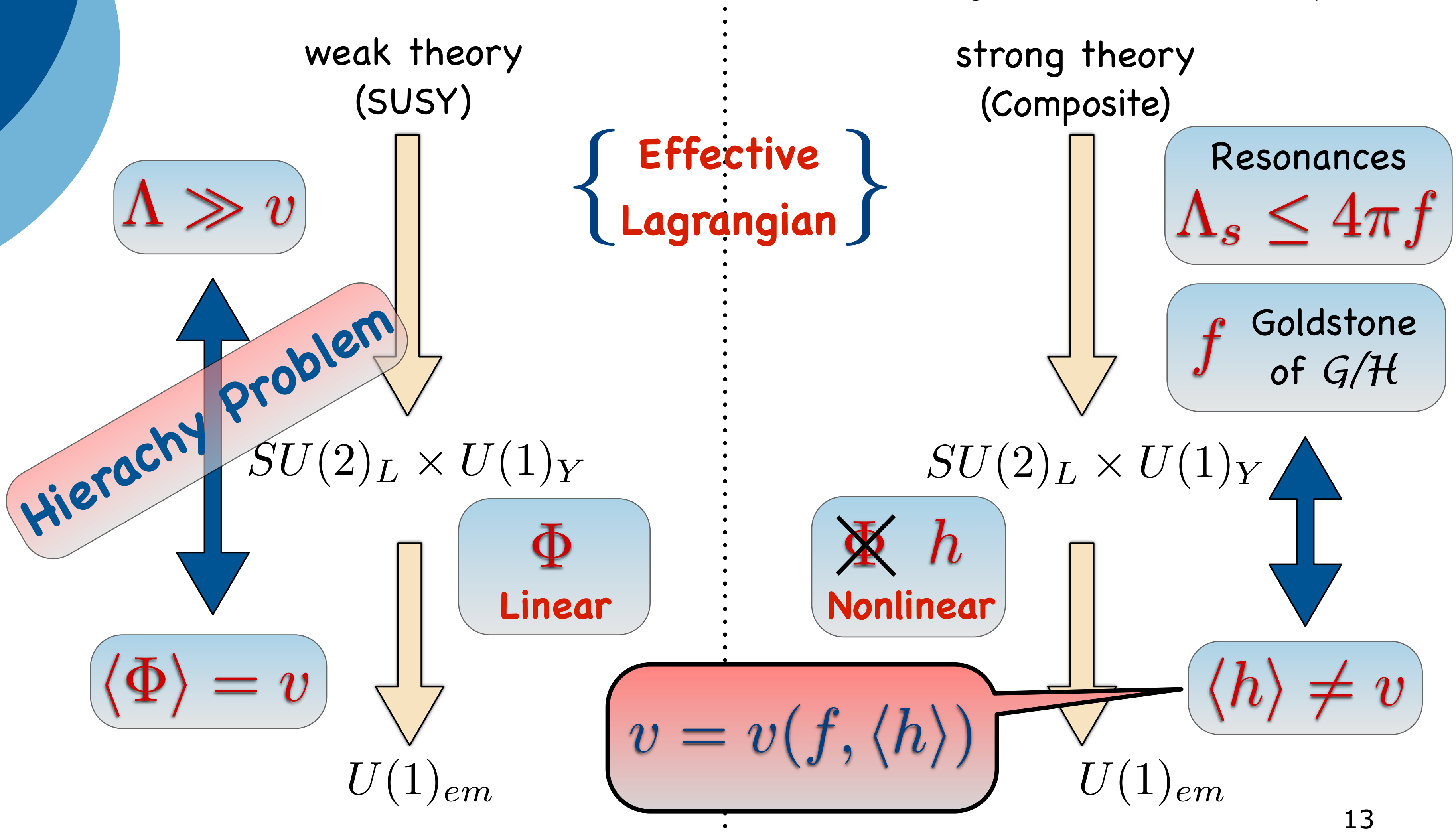

The Dynamical Higgs χ-Lagrangian

- The effective χ-Lagrangian for the pure gauge and gauge-h interaction can now be built from the SM gauge boson +

$$\begin{cases} \mathbf{U}(x) = e^{i\sigma_a \pi^a(x)/v} \\ \mathbf{T}(x) \equiv \mathbf{U}\sigma_3\mathbf{U}^\dagger \; , \; \mathbf{V}_\mu(x) \equiv (\mathbf{D}_\mu \mathbf{U})\, \mathbf{U}^\dagger \end{cases} + \begin{cases} h(x) \\ \partial_\mu h(x) \end{cases}$$

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The complete gauge-Goldstone-Higgs interaction basis has been derived: the dynamical-h equivalent of the ALF basis

[Alonso et al, Phys.Lett. B722 (2013) 330-335]

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- The total Lagrangian can be split as: $\mathcal{L}_{DH} = \mathcal{L}_{SM} + \Delta\mathcal{L}^h_{\chi\leq 4}$

$$\begin{aligned} \mathcal{L}_{SM} = &+ \frac{1}{2}(\partial_\mu h)(\partial^\mu h) - \frac{1}{4} W^a_{\mu\nu} W^{\mu\nu}_a - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \\ &- V(h) - \frac{v^2}{4}\mathrm{Tr}\left[\mathbf{V}^\mu \mathbf{V}_\mu\right]\left(1+\frac{h}{v}\right)^2 + \\ &- \frac{v}{\sqrt{2}}\bar{Q}_L \mathbf{U}(x)\,\mathcal{Y}\,Q_R\left(1+\frac{h}{v}\right) + \mathrm{h.c.} \end{aligned}$$

Modification of the SM Lagrangian

Basis of gauge-Goldstone-Higgs operators up to 4 derivatives:

$$\Delta\mathcal{L}^h_{\chi\leq 4} = \xi\left[c_W\mathcal{P}_W + c_B\mathcal{P}_B + c_C\mathcal{P}_C + c_T\mathcal{P}_T + c_H\mathcal{P}_H\right] + \\ + \sum_{i=1} \xi^{n_i} c_{H_i}\mathcal{P}_{H_i} + \xi\sum_{i=1}^{10} c_i\mathcal{P}_i + \xi^2\sum_{i=11}^{25} c_i\,\mathcal{P}_i + \xi^4\, c_{26}\,\mathcal{P}_{26}$$

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The first line shows the modification of the gauge-h and h ops. of the SM Lagrangian + custodial breaking (d=2) term:

$$\mathcal{P}_W = -\frac{g^2}{2}\mathrm{Tr}(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu})\,\mathcal{F}_W(h) \qquad \mathcal{P}_B = -\frac{g'^2}{4}B_{\mu\nu}B^{\mu\nu}\mathcal{F}_B(h)$$

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

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

Modification to the SM Lagrangian

The functions $\mathcal{F}_i(h)$ encode the dependence on h and are assumed to be generic polynomials in h. In general one has

$$\mathcal{F}_i(h) = 1 + 2\,\alpha_i \frac{h}{v} + \beta_i \frac{h^2}{v^2} + \dots$$

with the coefficients α_i , β_i generic functions of $\xi \equiv \dfrac{v^2}{f^2}$

In this notation the connection between our convention and the one often used in the literature:

$$\mathcal{L} \ni -\frac{v^2}{4}\mathrm{Tr}(\mathbf{V}^\mu \mathbf{V}_\mu)\left(1 + 2\,a\frac{h}{v} + b\frac{h^2}{v^2}\right) - \frac{v}{\sqrt{2}}\bar{Q}_L \mathbf{U} \mathcal{Y} Q_R \left(1 + c\frac{h}{v}\right)$$

reads:

$$a = 1 + \xi\frac{c_C(2\alpha_C - 1) - c_H}{2}$$

$$c = 1 - \xi\frac{c_H}{2}$$

[R. Contino, C. Grojean, M. Moretti, F. Piccinini and R. Rattazzi (2010)]
[Azatov, Contino, Galloway (2012)]

[Alonso et al, Phys.Lett. B722 (2013) 330-335]

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The second line shows the new Higgs, gauge-Goldstone-Higgs operators for a light dynamical scalar field;

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The sec see Kanshin talk he new Higgs, gauge-Goldstone-Higgs operator ynamical scalar field;

[Alonso et al, Phys.Lett. B722 (2013) 330-335]

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Extended gauge-GBs-Higgs EW effective chiral Lagrangian (EALF)

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$\xi \equiv v^2/f^2$

Basis of gauge ggs operators up to 4 derivatives:

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Beware: it is NOT an expansion in ξ !

Just a useful tool to connect with the linear case

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Extension of the ALF basis of CP-even operators for the gauge and gauge-Higgs sector up to four derivatives:

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

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

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

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

$$\mathcal{P}_7(h) = (\mathrm{Tr}\,(\mathbf{T}\,\mathbf{V}_\mu))^2\,\partial_\nu\partial^\nu\mathcal{F}_7(h)$$

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

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

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

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$$\mathcal{P}_{11}(h) = \left(\mathrm{Tr}\left(\mathbf{V}_\mu\, \mathbf{V}_\nu\right)\right)^2 \mathcal{F}_{11}(h)$$
$$\mathcal{P}_{12}(h) = g^2 \left(\mathrm{Tr}\left(\mathbf{T}\, W^{\mu\nu}\right)\right)^2 \mathcal{F}_{12}(h)$$
$$\mathcal{P}_{13}(h) = i\, g\, \mathrm{Tr}\left(\mathbf{T}\, W_{\mu\nu}\right) \mathrm{Tr}\left(\mathbf{T}\, [\mathbf{V}^\mu, \mathbf{V}^\nu]\right) \mathcal{F}_{13}(h)$$
$$\mathcal{P}_{14}(h) = g\, \epsilon^{\mu\nu\rho\lambda} \mathrm{Tr}\left(\mathbf{T}\mathbf{V}_\mu\right) \mathrm{Tr}\left(\mathbf{V}_\nu\, W_{\rho\lambda}\right) \mathcal{F}_{14}(h)$$
$$\mathcal{P}_{15}(h) = \mathrm{Tr}(\mathbf{T}\, \mathcal{D}_\mu \mathbf{V}^\mu)\, \mathrm{Tr}(\mathbf{T}\, \mathcal{D}_\nu \mathbf{V}^\nu)\, \mathcal{F}_{15}(h)$$
$$\mathcal{P}_{16}(h) = \mathrm{Tr}([\mathbf{T}\, , \mathbf{V}_\nu]\, \mathcal{D}_\mu \mathbf{V}^\mu)\, \mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu) \mathcal{F}_{16}(h)$$
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$$\mathcal{P}_{19}(h) = \mathrm{Tr}(\mathbf{T}\, \mathcal{D}_\mu \mathbf{V}^\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu)\, \partial^\nu \mathcal{F}_{19}(h)$$
$$\mathcal{P}_{20}(h) = \mathrm{Tr}\left(\mathbf{V}_\mu\, \mathbf{V}^\mu\right) \partial_\nu \mathcal{F}_{20}(h) \partial^\nu \mathcal{F}'_{20}(h)$$
$$\mathcal{P}_{21}(h) = \mathrm{Tr}\left(\mathbf{T}\mathbf{V}_\mu\right)^2 \partial^\nu \mathcal{F}_{21}(h) \partial^\nu \mathcal{F}'_{21}(h)$$
$$\mathcal{P}_{22}(h) = \mathrm{Tr}\left(\mathbf{T}\mathbf{V}_\mu\right) \mathrm{Tr}\left(\mathbf{T}\mathbf{V}_\nu\right) \partial^\mu \mathcal{F}_{22}(h) \partial^\nu \mathcal{F}'_{22}(h)$$
$$\mathcal{P}_{23}(h) = \mathrm{Tr}\left(\mathbf{V}_\mu \mathbf{V}^\mu\right) \left(\mathrm{Tr}\left(\mathbf{T}\mathbf{V}_\nu\right)\right)^2 \mathcal{F}_{23}(h)$$
$$\mathcal{P}_{24}(h) = \mathrm{Tr}\left(\mathbf{V}_\mu \mathbf{V}_\nu\right) \mathrm{Tr}\left(\mathbf{T}\mathbf{V}^\mu\right) \mathrm{Tr}\left(\mathbf{T}\mathbf{V}^\nu\right) \mathcal{F}_{24}(h)$$
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$$\mathcal{P}_{26}(h) = \left(\mathrm{Tr}\left(\mathbf{T}\mathbf{V}_\mu\right) \mathrm{Tr}\left(\mathbf{T}\mathbf{V}_\nu\right)\right)^2 \mathcal{F}_{26}(h)$$

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BLUE

in the limit $\mathcal{F}_i(h) = 1$ reduce to the ALF gauge-GB basis

[Alonso et al, Phys.Lett. B722 (2013) 330-335]

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$$\mathcal{P}_7(h) = \left(\mathrm{Tr}\left(\mathbf{T}\,\mathbf{V}_\mu\right)\right)^2\partial_\nu\partial^\nu\mathcal{F}_7(h)$$

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

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

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

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

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

[Alonso et al, Phys.Lett. B722 (2013) 330-335]

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RED

new operators with derivatives of the light scalar field (some already in Azatov, Contino, Galloway (2012))

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$$\mathcal{P}_3(h) \quad \ldots \quad h)$$

$$\mathcal{P}_4(h)$$

$$\mathcal{P}_5(h)$$

not independent in the m$_f$ = 0 limit, or traded by fermions

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

$$\mathcal{P}_7(h) = \left(\mathrm{Tr}\left(\mathbf{T}\, \mathbf{V}_\mu\right)\right)^2 \partial_\nu \partial^\nu \mathcal{F}_7(h)$$

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$$\boxed{\xi\,\mathcal{P}_2(h)} \qquad \boxed{\xi\,\mathcal{P}_4(h)}$$

- The power of ξ in front of each operator tells us at which order the sibling appears in the linear expansion;
- Disentangling between Linear and Non-Linear expansions;

see Brivio talk

CH models vs Low Energy ξ powers

ξ dependence and degrees of non-linearity

- We have introduce the ξ-powers in front of our basis operators based on the dimension of their siblings;
- Check the correctness of this assumption at least in a well motivated framework: Composite Higgs models;

Composite Higgs models on $\mathcal{G}/\mathcal{H}$ coset

- The Higgs and the 3WBGS are GBs of the $\mathcal{G}/\mathcal{H}$ breaking (4 in the SO(5)/SO(4) MCHM case); [Agashe, Contino, Pomarol (2005)]
- The GB dynamics related to the scale $f \geq v$ has something to do with the EWSB $v = v(f, \langle h \rangle)$ (model dependent way);

[Georgi, Kaplan (1984); Dimopoulos, Georgi, Kaplan (1984); Galison, Georgi, Kaplan (1984); Dugan, Georgi, Kaplan (1985)]

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SU(5)/SO(5) example

- Instead of $SU(2)_L \times SU(2)_R / SU(2)_V$ global breaking of the EW effective χ-Lagrangian (Higgsless ALF) one can consider:

$$\mathcal{G}/\mathcal{H} = SU(5)/SO(5) \qquad\qquad \Phi(x) \subset SU(5)/SO(5)$$

- To the Goldstone field $\mathbf{U}(x)$ one replaces the non-linear field $\mathbf{\Theta}(x)$ belonging to the coset of SU(5)/SO(5):

$$\boxed{\mathbf{\Theta}(x) = e^{i\frac{\alpha(x)}{f}\mathcal{X}(x)} = 1 + i\sin\alpha\,\mathcal{X}(x) + (\cos\alpha - 1)\,\mathcal{X}^2(x)} \qquad \left(\alpha(x) = \frac{h(x) + \langle h \rangle}{f}\right)$$

$$\mathcal{X}(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & \mathbf{U}(x)e_1 \\ 0 & 0 & \mathbf{U}(x)e_2 \\ (\mathbf{U}(x)e_1)^\dagger & (\mathbf{U}(x)e_2)^\dagger & 0 \end{pmatrix} \quad \text{with} \quad e_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad e_2 = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

- SU(5)/SO(5) effective χ-Lagrangian building blocks:

$$\boxed{\widetilde{\mathbf{W}}_{\mu\nu}\,, \quad \tilde{\mathbf{B}}_{\mu\nu}\,, \quad \mathbf{\Theta}\,, \quad \tilde{\mathbf{V}}_\mu = (\mathbf{D}_\mu \mathbf{\Theta})\,\mathbf{\Theta}^\dagger}$$

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3 SM WBGBs

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“Higgs” scalar

$$\begin{pmatrix} & & \mathbf{U}(x)e_1 \\ & & \mathbf{U}(x)e_2 \\ (\mathbf{U}(x)e_1)^\dagger & (\mathbf{U}(x)e_2)^\dagger & 0 \end{pmatrix} \quad \text{with} \quad e_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad e_2 = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

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[Alonso, Brivio, Gavela, Merlo and SR in preparation]

SU(5)/SO(5) EW χ-Lagrangian (custodial)

- Basis of CP-even gauge-Goldstone operators up to 4 derivatives

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

$$\widetilde{\mathcal{A}}_B = -\frac{1}{4}\mathrm{Tr}\left(\widetilde{\mathbf{B}}_{\mu\nu}\widetilde{\mathbf{B}}^{\mu\nu}\right)$$

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$$\widetilde{\mathcal{A}}_1 = g\,g'\,\mathrm{Tr}\left(\Theta\widetilde{\mathbf{B}}_{\mu\nu}\Theta^\dagger\widetilde{\mathbf{W}}^{\mu\nu}\right)$$

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$\widetilde{\mathcal{A}}_1$

$\widetilde{\mathcal{A}}_2$

not independent in the $m_f = 0$ limit, or traded by fermions

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SU(5)/SO(5) decomposition example

- Decomposing the high energy operators in terms of the low energy gauge and chiral structures one obtains for example

$$\tilde{\mathcal{A}}_2 = i\,g'\mathrm{Tr}\left(\tilde{\mathbf{B}}_{\mu\nu}\left[\tilde{\mathbf{V}}^\mu,\tilde{\mathbf{V}}^\nu\right]\right) = \mathcal{P}_2(h) + 2\,\mathcal{P}_4(h)$$

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

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

$$\mathcal{F}(h) = \sin^2\left(\frac{h+\langle h\rangle}{2f}\right)$$

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$$\mathcal{F}(h) = \sin^2\left(\frac{h + \langle h \rangle}{2f}\right)$$

- In the $\xi \ll 1$ limit one recover the linear d=6 operator:

$$\tilde{A}_2 \approx \frac{\xi}{4}\left(\underbrace{i\, g'\, B_{\mu\nu} \mathrm{Tr}(\mathbf{T}\,[\mathbf{V}^\mu, \mathbf{V}^\nu])\left(1 + \frac{h}{v}\right)^2}_{\xi\,\mathcal{P}_2(h)} + \underbrace{2\, i\, g'\, B_{\mu\nu} \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu \left(1 + \frac{h}{v}\right)^2}_{\xi\,\mathcal{P}_4(h)}\right)$$

as expected as a doublet is embedded in SU(5) representation.

PRELIMINARY

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STAY TUNED

Backup

See Brivio talk

[Brivio et al. JHEP 1403 (2014) 024]

Linear HISZ vs nonlinear basis

Mapping between d=6 linear vs O(ξ) nonlinear operators:

$$\mathcal{O}_{WW} = g^2\Phi^\dagger W^{\mu\nu}W_{\mu\nu}\Phi/4 \longrightarrow \mathcal{P}_W(h) = -g^2\mathrm{Tr}(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu})\,\mathcal{F}_W(h)/2$$

$$\mathcal{O}_{BB} = g'\Phi^\dagger B^{\mu\nu}B_{\mu\nu}\Phi/4 \longrightarrow \mathcal{P}_B(h) = -g'^2 B_{\mu\nu}B^{\mu\nu}\mathcal{F}_B(h)/4$$

$$\mathcal{O}_{BW} = g\,g'\,\Phi^\dagger B^{\mu\nu}W_{\mu\nu}\Phi/4 \longrightarrow \mathcal{P}_1(h) = g\,g'\,B_{\mu\nu}\mathrm{Tr}\left(\mathbf{T}\,W^{\mu\nu}\right)\,\mathcal{F}_1(h)$$

$$\mathcal{O}_B = g'\,(D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)/2$$

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

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

$$\mathcal{O}_W = g\,(D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)/2$$

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

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

$$\mathcal{O}_{\Phi,1} = (D_\mu\Phi)^\dagger\Phi\Phi^\dagger(D_\nu\Phi)$$

$$\mathcal{O}_{\Phi,2} = \partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi)/2$$

$$\mathcal{O}_{\Phi,4} = (D_\mu\Phi)^\dagger(D^\mu\Phi)(\Phi^\dagger\Phi)$$

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

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

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

See Brivio talk

[Brivio et al. JHEP 1403 (2014) 024]

Linear vs Nonlinear basis

Different predictions for gauge vs Higgs-derivative couplings:

$$\mathcal{O}_B = g'\,(D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)/2 \;\longrightarrow\; c_B\Big(A^{\mu\nu}W^+_\mu W^-_\nu(1,h,h^2) + A^{\mu\nu}Z_\mu\partial_\nu h(1,h)\Big)$$

nonlinear siblings

$$\mathcal{P}_2(h) = i\,g'\,B_{\mu\nu}\mathrm{Tr}\left(\mathbf{T}\left[\mathbf{V}^\mu,\mathbf{V}^\nu\right]\right)\mathcal{F}_2(h) \qquad \mathcal{P}_4(h) = i\,g' B_{\mu\nu}\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\,\partial^\nu\mathcal{F}_4(h)$$

$$c_2\,A^{\mu\nu}W^+_\mu W^-_\nu(1,h,h^2) \qquad c_4\,A^{\mu\nu}Z_\mu\partial_\nu h(1,h)$$

c_2 and c_4 in general are not correlated (differently from the linear expansion case);

[Giudice, Grojean, Pomarol, Rattazzi (2007)]

Linear basis: HISZ vs SILH

Mapping between d=6 linear vs SILH operators:

$$\mathcal{O}_{WW} = g^2 \Phi^\dagger W^{\mu\nu} W_{\mu\nu} \Phi/4$$

$$\mathcal{O}_{BW} = g\, g'\, \Phi^\dagger B^{\mu\nu} W_{\mu\nu} \Phi/4$$

$$\mathcal{O}_{B} = g'\, (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi)/2$$

$$\mathcal{O}_{W} = g\, (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi)/2$$

$$\mathcal{O}_{BB} = g' \Phi^\dagger B^{\mu\nu} B_{\mu\nu} \Phi/4$$

$$\mathcal{O}_W^{SILH} = (\Phi^\dagger \sigma_i \overleftrightarrow{D}_\mu \Phi)(D_\nu W_i^{\mu\nu})/2$$

$$\mathcal{O}_B^{SILH} = (\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)(\partial_\nu B^{\mu\nu})/2$$

$$\mathcal{O}_{HB}^{SILH} = (D^\mu \Phi)^\dagger (D^\nu \Phi) B^{\mu\nu}/2$$

$$\mathcal{O}_{HW}^{SILH} = (D^\mu \Phi)^\dagger \sigma_i (D^\nu \Phi) W_i^{\mu\nu}/2$$

$$\mathcal{O}_\gamma^{SILH} = (\Phi^\dagger \Phi) B^{\mu\nu} B_{\mu\nu}$$

$$\mathcal{O}_{\Phi,1} = (D_\mu \Phi)^\dagger \Phi \Phi^\dagger (D_\nu \Phi)$$

$$\mathcal{O}_{\Phi,2} = \partial_\mu (\Phi^\dagger \Phi) \partial^\mu (\Phi^\dagger \Phi)/2$$

$$\mathcal{O}_{\Phi,3} = (\Phi^\dagger \Phi)^3/3$$

$$\mathcal{O}_{\Phi,4} = (D_\mu \Phi)^\dagger (D^\mu \Phi)(\Phi^\dagger \Phi)$$

$$\mathcal{O}_T^{SILH} = (\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)/2$$

$$\mathcal{O}_H^{SILH} = \partial_\mu (\Phi^\dagger \Phi) \partial^\mu (\Phi^\dagger \Phi)/2$$

$$\mathcal{O}_6^{SILH} = (\Phi^\dagger \Phi)^3/3$$

$$\mathcal{O}_y^{SILH} = (\Phi^\dagger \Phi) Q_L \Phi Q_R + h.c.$$

SILH

$$\mathcal{L}_{\rm SILH} = \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)$$
$$-\frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.}\right)$$
$$+\frac{ic_W g}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{ic_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})$$
$$+\frac{ic_{HW} g}{16\pi^2 f^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{ic_{HB} g'}{16\pi^2 f^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$+\frac{c_\gamma g'^2}{16\pi^2 f^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g g_S^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$$

[Giudicea,Grojeana,Pomarolc&Rattazzi, arXiv:hep-ph0703164]

$$\begin{aligned}
\mathcal{L}_{SILH} \;=\; \xi\Big\{ & \frac{c_H}{2}(\partial_\mu h)(\partial^\mu h)\,\mathcal{F}(h) + \frac{c_T}{2}\frac{v^2}{4}\mathrm{Tr}\left[\mathbf{T}\mathbf{V}^\mu\right]\mathrm{Tr}\left[\mathbf{T}\mathbf{V}_\mu\right]\mathcal{F}(h)^2 + \\
& - c_6\lambda\frac{v^4}{8}\mathcal{F}(h)^3 + \left(c_y\frac{v}{2\sqrt{2}}\bar{Q}_L\mathbf{U}\,\mathrm{diag}(\mathbf{y}_U,\mathbf{y}_D)\,Q_R\,\mathcal{F}(h)^{3/2} + \text{h.c.}\right) + \\
& - i\frac{c_W g}{2m_\rho^2}\frac{f^2}{2}\left(\mathcal{D}_\mu W^{\mu\nu}\right)_i \mathrm{Tr}\left[\sigma_i\,\mathbf{V}_\nu\right]\,\mathcal{F}(h) + i\frac{c_B g'}{2m_\rho^2}\frac{f^2}{2}\left(\partial_\mu B^{\mu\nu}\right)\mathrm{Tr}\left[\mathbf{T}\,\mathbf{V}_\nu\right]\,\mathcal{F}(h) + \\
& + i\frac{c_{HW} g}{16\pi^2}W_i^{\mu\nu}\left(\frac{1}{4}\mathrm{Tr}\left[\sigma_i\,\mathbf{V}_\mu\mathbf{V}_\nu\right]\,\mathcal{F}(h) - \frac{1}{4}\mathrm{Tr}\left[\sigma_i\,\mathbf{V}_\mu\right]\,\partial_\nu\mathcal{F}(h)\right) + \\
& + i\frac{c_{HB} g'}{16\pi^2}B^{\mu\nu}\left(\frac{1}{4}\mathrm{Tr}\left[\mathbf{T}\,\mathbf{V}_\mu\mathbf{V}_\nu\right]\,\mathcal{F}(h) + \frac{1}{4}\mathrm{Tr}\left[\mathbf{T}\,\mathbf{V}_\mu\right]\,\partial_\nu\mathcal{F}(h)\right) + \\
& + \frac{c_\gamma g'^2}{16\pi^2}\frac{g^2}{g_\rho^2}\frac{1}{2}B_{\mu\nu}B^{\mu\nu}\,\mathcal{F}(h) + \frac{c_g g_S^2}{16\pi^2}\frac{y_t^2}{g_\rho^2}\frac{1}{2}G^a_{\mu\nu}G^{a\mu\nu}\,\mathcal{F}(h)\Big\}
\end{aligned}$$

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

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

Defining

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

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

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

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

PRELIMINARY

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

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

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

PRELIMINARY