Effective electroweak theory for a strongly-coupled light Higgs

Oscar Catà
LMU and IAS Munich

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Outline

- Motivation: strong coupling after the Higgs discovery
- Foundations and systematics of the EFT
- The decoupling limit
- Future directions

Dynamical EWSB

- **SM Higgs** *vs* **EWSB**.

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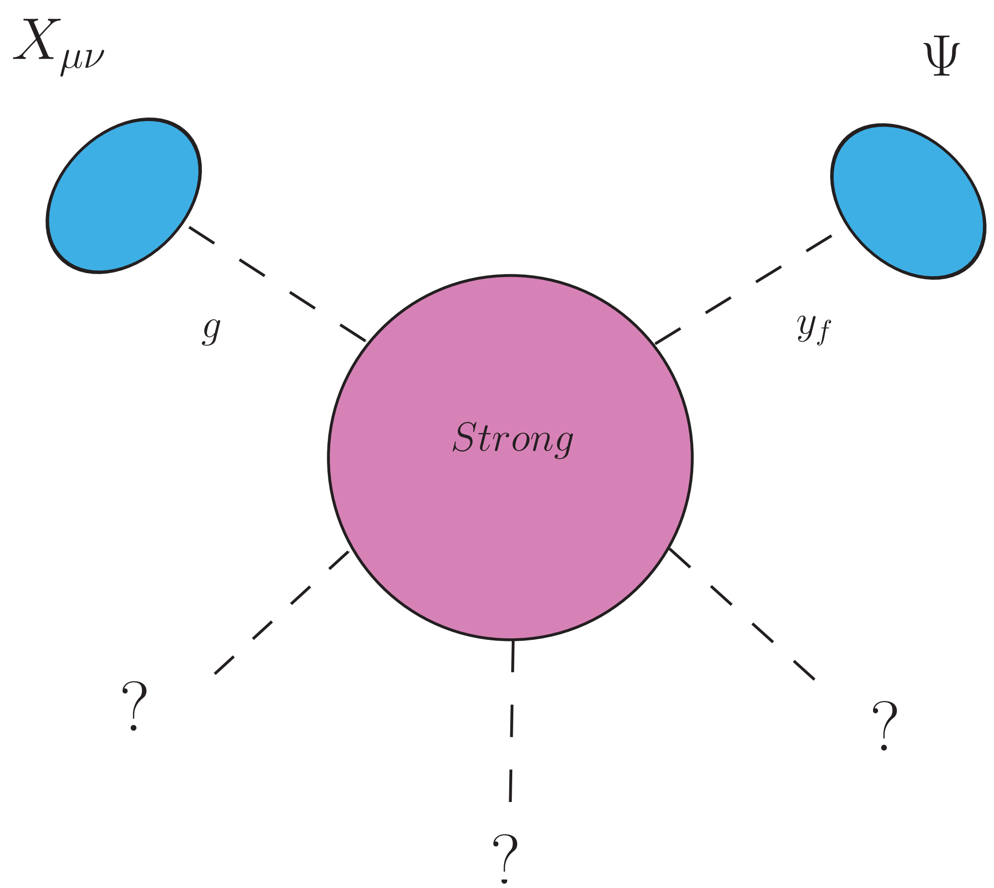
- **Q1**: What are the systematics of the EFT framework for strongly-coupled EWSB scenarios? What is this EFT of the strong electroweak interactions?

- **Q2**: If the scale of new physics is large, what are the leading deviations expected from a strongly-coupled sector?

EFT for strongly-coupled EWSB



- Combination of strong and weak sector makes the theory complicated (not a derivative expansion!).
- Framework has to reduce to a ChPT-like theory when weak couplings are switched off.

EFT for strongly-coupled EWSB

MAIN ASSUMPTIONS:

- **Strongly-coupled dynamics** at the TeV scale triggering EWSB [Longhitano'80,81; Appelquist et al'80,93]. Natural cutoff of the theory: (dynamically generated) $\Lambda \sim 4\pi v \sim 3$ TeV.

- **Minimal EWSB pattern**: $SU(2)_L \times SU(2)_R \to SU(2)_V$ with $SU(2)_L \times U(1)_Y$ gauged. Most general with the minimal particle content (3 Goldstone bosons to account for the longitudinal modes of the W and Z). Collected in a nonlinear realization inside $U(x) \to g_L U(x) g_R^\dagger$.

- **Soft custodial symmetry breaking**: T-parameter contribution at NLO.

- Gauge bosons weakly coupled to the strong sector.

- **Light scalar** h as a SM singlet (pGB of a more general symmetry group) [Ferruglio'93; Contino et al.'10]. It can always be tuned to the SM Higgs but comprises more general scenarios.

Inclusion of a light scalar

LEADING ORDER LAGRANGIAN: [Contino et al.'10; Buchalla, O.C., Krause'13]

$$\mathcal{L}_{LO} = -\frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + i\sum_j \bar{f}_j \not{D} f_j + \frac{1}{2}\partial_\mu h \partial^\mu h$$
$$+ \frac{v^2}{4}\,\langle D_\mu U D^\mu U^\dagger\rangle f_U(h) - v\left[\bar{\psi} f_\psi(h) U P_\pm \psi + \text{h.c.}\right] - V(h)$$

with

$$f_U(h) = 1 + \sum_j a_j^U \left(\frac{h}{v}\right)^j ; \quad f_\psi(h) = \lambda_\psi + \sum_j A_j^\psi \left(\frac{h}{v}\right)^j ; \quad V(h) = \sum_{j\geq 2} a_j^V \left(\frac{h}{v}\right)^j$$

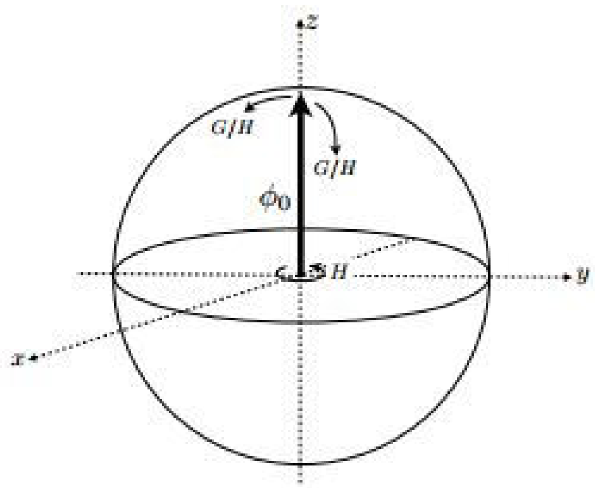
COMMENTS:

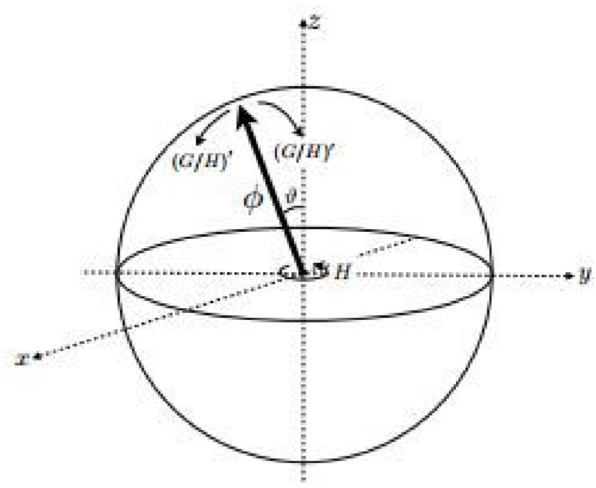
- Loop suppression of $V(h)$ essential: $v^2 \sim \Lambda^2\left(\frac{v^2}{\Lambda^2}\right)$.
- All powers of h contribute at the same order. For phenomenological applications, $f_j(h)$ effectively truncated.
- Scalar and fermion-gauge sectors fully general.

Dynamical picture: Vacuum misalignment mechanism

- $G \to H_1 \supset G_{SM}$ at the scale f, generating Goldstones and a scalar.

- Explicit breaking of G_{SM} by Yukawa interactions generates a (loop-induced) Higgs potential. True vacuum tilted away from $SU(2)_L \times U(1)_Y$. [Georgi et al'84]



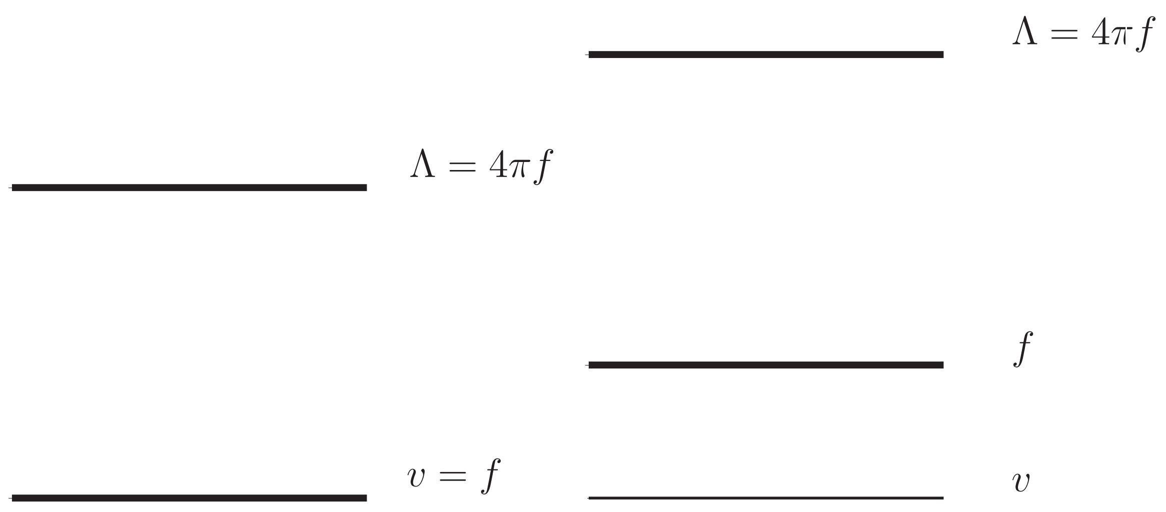


- Decoupling of v and f with Higgs as pNGB. Early alternative to technicolor.

- Most popular cosets: $SO(5)/SO(4)$, $SO(6)/SO(5)$. [Agashe,Pomarol,...]

Dynamical picture: Vacuum misalignment mechanism

- Interpolating scenario between nondecoupling (composite) and decoupling (fundamental) interactions.



- The transition can be gauged with the parameter $\xi = \dfrac{v^2}{f^2}$:
  - $\xi \to 1$: purely nondecoupling limit.
  - $0 < \xi < 1$: heavy states and h balanced out to achieve unitarization.
  - $\xi \to 0$: decoupling (SM) limit, heavy states pushed up in energy.

Example: $SO(5)/SO(4)$ *model*

- $G = SO(5) \times U(1)_X$ broken to $H_1 = SO(4) \times U(1)_X$
- Isomorphism: $H_1 \sim SU(2)_L \times SU(2)_R \times U(1)_X \supset G_{SM}$
- 4 real pGB h^A transforming under the fundamental of $SO(4)$:

$$\Sigma(h^A) = \exp(\sqrt{2} i t^A h^A / f)\Sigma_0, \qquad \Sigma_0 = \begin{pmatrix} 0_4 \\ 1 \end{pmatrix}$$

- Equivalently, bidoublet of $SU(2)$ (H, H^c). Defining

$$H = h_A \lambda_A \equiv hU, \qquad \vec{\lambda} = (i\vec{\sigma}, 1_2) \Longrightarrow \quad h_A = \frac{h}{2}\langle U \lambda_A^\dagger \rangle$$

one can express $\Sigma(h, U)$:

$$\Sigma(h, U) = \begin{pmatrix} \frac{\langle U \lambda_A^\dagger \rangle}{2} \sin h/f \\ \cos h/f \end{pmatrix}$$

Example: $SO(5)/SO(4)$ *model*

- (Bosonic) leading order term:

$$\frac{f^2}{2}\langle D_\mu \Sigma^\dagger D^\mu \Sigma\rangle = \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{f^2}{4}\langle D_\mu U^\dagger D^\mu U\rangle \sin^2\frac{h}{f}$$
$$= \frac{1}{2}\partial_\mu \hat{h}\partial^\mu \hat{h} + \frac{v^2}{4}\langle D_\mu U^\dagger D^\mu U\rangle f_U(\hat{h})$$

- Upon breaking, $h = \langle h\rangle + \hat{h}$:

  (i) v **dynamically generated**. Matching to the gauge boson masses:

$$v = f \sin\frac{\langle h\rangle}{f}$$

  (ii) In this particular model

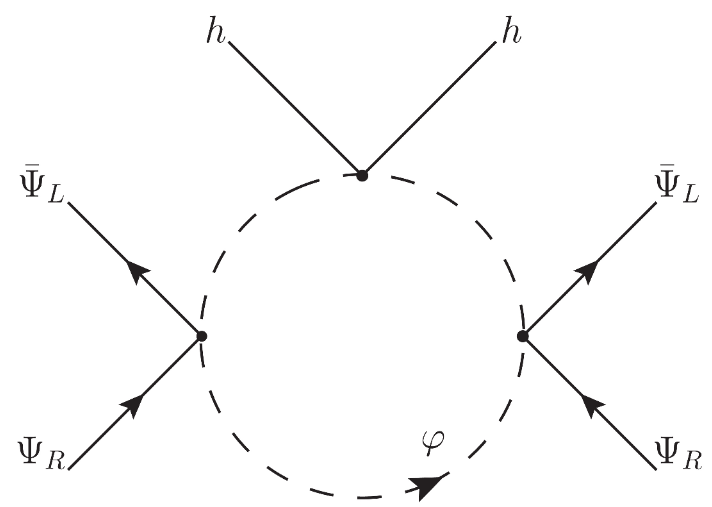
$$f_U(\hat{h}) = \cos\frac{2\hat{h}}{f} + \frac{\sqrt{1-\xi^2}}{\xi}\sin\frac{2\hat{h}}{f} + \frac{1}{\xi^2}\sin^2\frac{\hat{h}}{f}$$

  (iii) Linear and quadratic interactions:

$$f_U(\hat{h}) = 1 + 2\sqrt{1-\xi}\left(\frac{\hat{h}}{v}\right) + (1-2\xi)\left(\frac{\hat{h}}{v}\right)^2$$

Some reflections on power-counting

- Decoupling EFTs: dimensional counting ($1/\Lambda^2$ expansion).
- In some simplified cases strongly-coupled EFTs can be cast as a dimensional expansion, *e.g.* pure ChPT (expansion in derivatives).
- Non-decoupling EFTs: loop counting ($v^2/\Lambda^2 \sim 1/(16\pi^2)$ expansion).
- When weakly and strongly-coupled sectors mix, the picture gets complicated. Basic requirements of a power-counting: Homogeneity of the LO Lagrangian and essential nondecoupling divergences.



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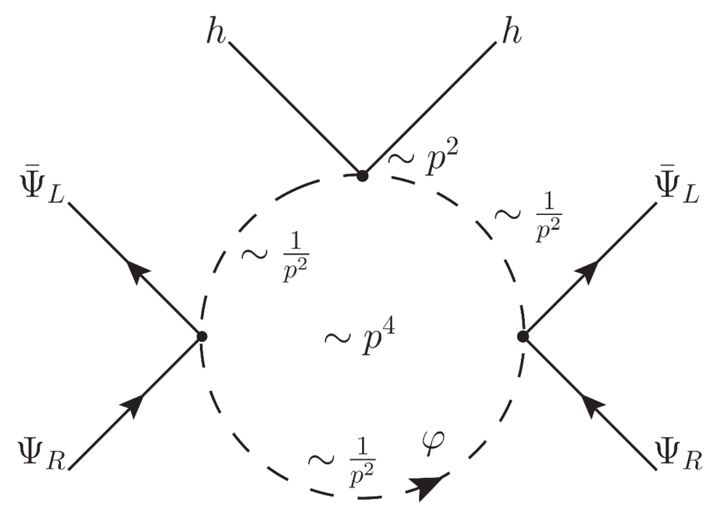

Organizing the expansion: general power-counting

The **degree of divergence** of every diagram is [Buchalla, O.C.'12;Buchalla, O.C., Krause'13]

$$\Delta = \frac{p^d}{\Lambda^{2L}} \left[(yv)^{\nu_f} \left(\frac{\Psi}{v}\right)^F \right] \left[(gv)^{\nu_g} \left(\frac{X_{\mu\nu}}{v}\right)^G \right] \left[v^2 \left(\frac{\varphi}{v}\right)^B \right] \left[(hv)^{2\nu_h} \left(\frac{h}{v}\right)^H \right]$$

where

$$d = 2L + 2 - \frac{F}{2} - G - 2\nu_h - \nu_f - \nu_g$$

- Bounded from above: number of counterterms finite (consistency check).
- The divergences of the theory should not differentiate between Goldstone bosons (h or U).
- In the absence of fermions and gauge bosons the power-counting should reduce to the familiar χPT formula:

$$\Delta = v^2 \frac{p^d}{\Lambda^{2L}} \left(\frac{\varphi}{v}\right)^B, \qquad d = 2L + 2$$

Chiral vs canonical dimension

Rewrite the loop-counting formula as

$$2L+2=d+\frac{F}{2}+G+2\nu_h+\nu_f+\nu_g$$

- Loop expansion can be cast as a dimensional expansion with [Buchalla,O.C.,Krause'13]

$$[\partial_\mu]_c=1,\quad [\varphi]_c=[h]_c=0,\quad [X_{\mu\nu}]_c=1,\quad [\psi_{L,R}]_c=\frac{1}{2},\quad [g]_c=[y]_c=1$$

- Homogeneity respected, but rather unexpectedly: $D_\mu=\partial_\mu-igW_\mu$ [Nyffeler et al'99]
- Couplings count: connection between strong and weak-coupling regimes.
- Chiral dimensions are the natural dimensions for loop expansions. Unique and consistent prescription, however not a power-counting.

$$\mathcal{L}_{LO}\supset-\frac{1}{4}B_{\mu\nu}B^{\mu\nu}+i\bar{f}_j\not{D}f_j+\frac{v^2}{4}\langle D_\mu U D^\mu U^\dagger\rangle f_U(h)-v\bar{\psi}f_\psi(h)UP_\pm\psi$$

Operators at NLO

Operator building at every order: assemble building blocks $(U, \psi, X$ and derivatives) in accordance with the power-counting formula.

- NLO: 6 classes, denoted as X^2U, XUD^2, UD^4, ψ^2UD, ψ^2UD^2 and ψ^4U.

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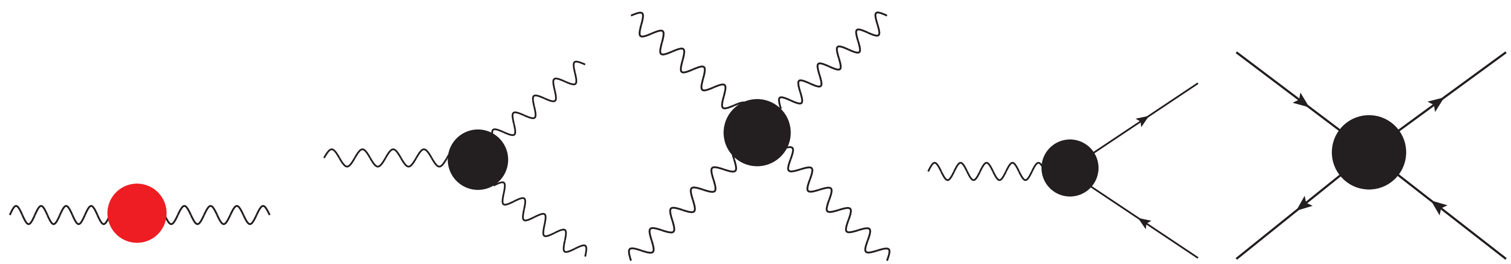

$\mathcal{O}_{XU1} = g'gB_{\mu\nu}\langle W^{\mu\nu}\tau_L\rangle$ $\mathcal{O}_{XU4} = g'g\epsilon_{\mu\nu\lambda\rho}\langle\tau_L W_{\mu\nu}\rangle B^{\lambda\rho}$ $\mathcal{O}_{XU2} = g^2\langle W^{\mu\nu}\tau_L\rangle^2$

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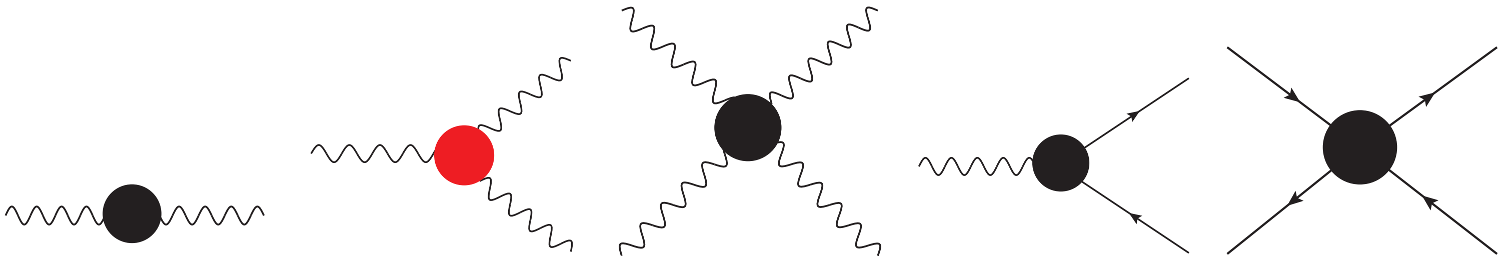

$$\mathcal{O}_{XU7} = ig' B_{\mu\nu}\langle\tau_L[L^\mu, L^\nu]\rangle \quad \mathcal{O}_{XU8} = ig\langle W_{\mu\nu}[L^\mu, L^\nu]\rangle \quad \mathcal{O}_{XU9} = ig\langle W_{\mu\nu}\tau_L\rangle\langle\tau_L[L^\mu, L^\nu]\rangle$$

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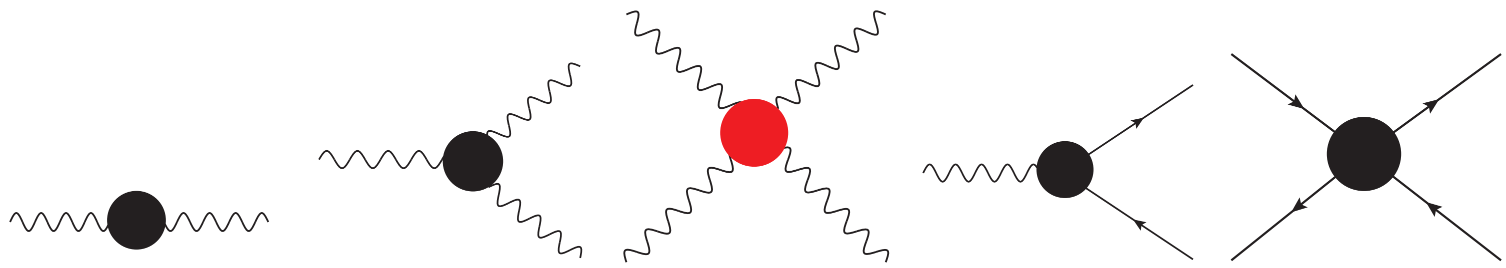

$\mathcal{O}_{D1} = \langle L_\mu L^\mu \rangle \langle L_\nu L^\nu \rangle \qquad \mathcal{O}_{D5} = \langle \tau_L L^\mu \rangle \langle \tau_L L_\nu \rangle \langle L_\mu L^\nu \rangle$

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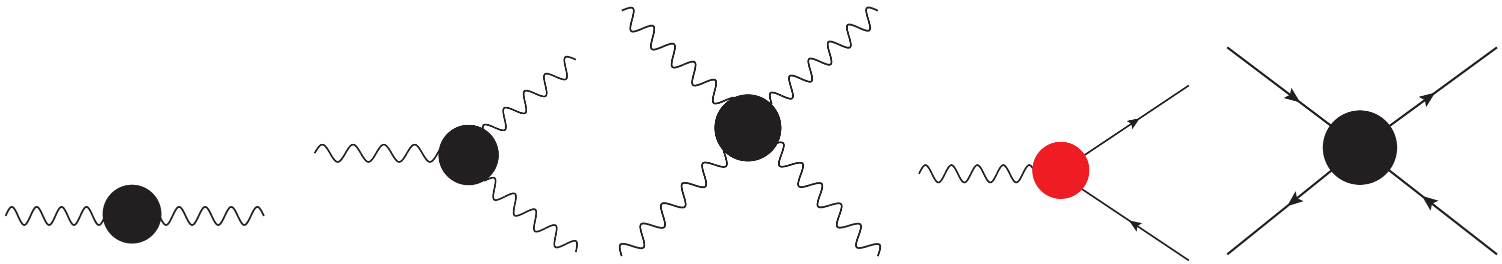

$$\mathcal{O}_{\psi V7} = i\bar{l}\gamma^\mu l \, \langle \tau_L L_\mu \rangle \quad \mathcal{O}_{\psi V8} = i\bar{l}\gamma^\mu \tau_L l \, \langle \tau_L L_\mu \rangle \quad \mathcal{O}_{\psi V10} = i\bar{e}\gamma^\mu e \, \langle \tau_L L_\mu \rangle$$

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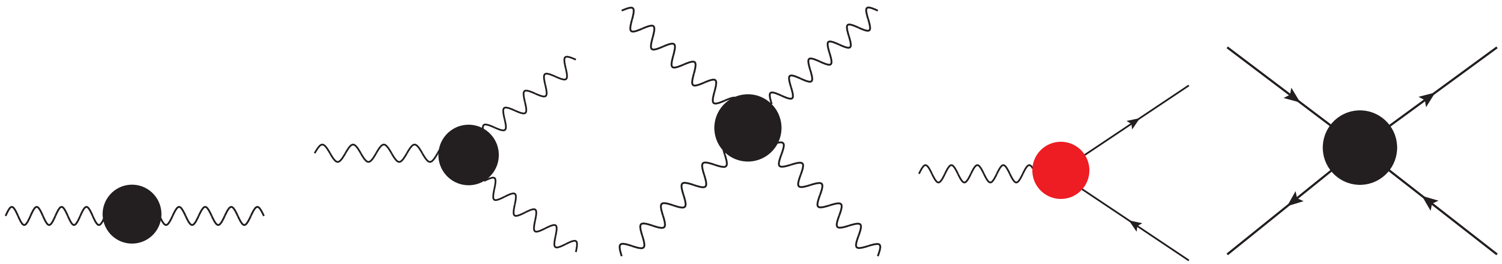

$$\mathcal{O}_{\psi S7} = \bar{l} U P\_l \, \langle L^\mu L_\mu \rangle \quad \mathcal{O}_{\psi S8} = \bar{l} U P\_l \, \langle \tau_L L_\mu \rangle^2$$

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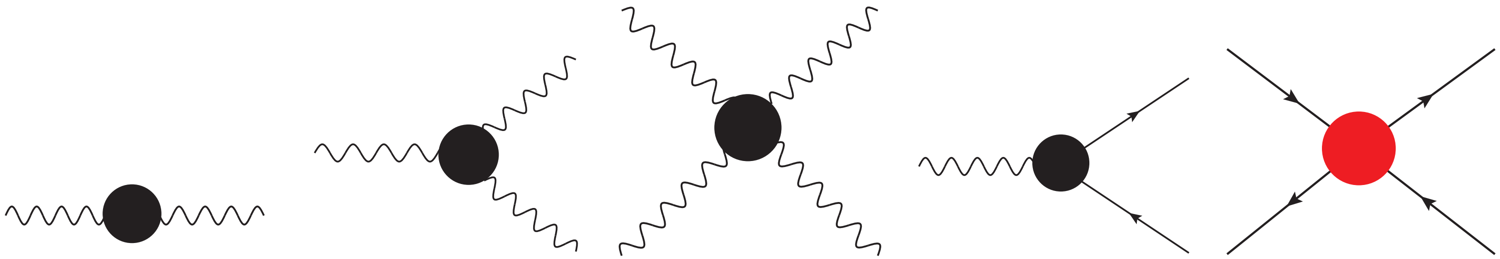
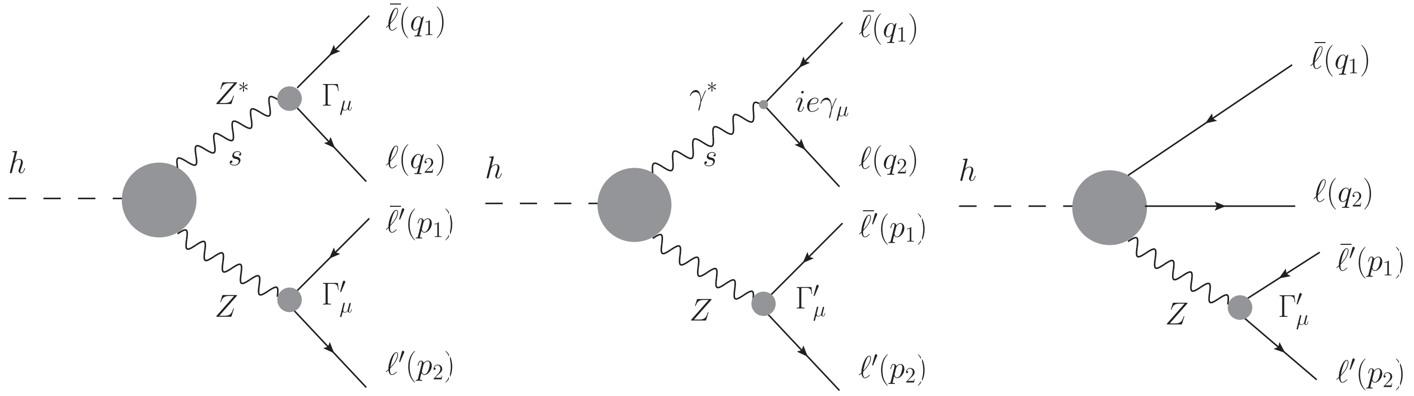


$$\mathcal{O}_{LR8} = \bar{l}\gamma_\mu l\bar{e}\gamma^\mu e \quad \mathcal{O}_{FY10} = \bar{l}UP\_l\bar{l}UP\_l$$

Application: New physics in $h \to Z\ell^+\ell^-$



[Buchalla,O.C.,D'Ambrosio'13]

- A priori not a promising channel (induced at tree level in the SM).
- However, clean and kinematically rich (4-body decay into lepton pairs).
- Information in the angular distribution complementary to the dilepton mass distribution [Isidori et al'13; Grinstein et al'13]
- Sources of corrections: $\delta g_{V,A}$ (LEP data), δg_{hXX} (α_{em}-suppressed), $h_{V,A}$ (possibly enhanced).

Application: New physics in $h \to Z\ell^+\ell^-$

- Can be seen as a factorized 3-body ($h \to Z\ell^+\ell^-$) times 2-body ($Z \to \ell'^+\ell'^-$) decay

$$\mathcal{M}_{3,\mu} \sim \bar{u}(q_2)\left[2F_1\gamma_\mu(G_V - G_A\gamma_5) + \frac{q_\mu}{M_h^2}\not{k}(H_V - H_A\gamma_5) + \frac{\epsilon_{\alpha\mu\beta\lambda}}{M_h^2}p^\alpha q^\beta \gamma^\lambda(K_V - K_A\gamma_5)\right]v(q_1)$$

- Differential decay rate proportional to

$$\begin{aligned} J(r,s,\alpha,\beta,\phi) &= J_1\frac{9}{40}(1+\cos^2\alpha\cos^2\beta) + J_2\frac{9}{16}\sin^2\alpha\sin^2\beta + J_3\cos\alpha\cos\beta \\ &+ (J_4\sin\alpha\sin\beta + J_5\sin 2\alpha\sin 2\beta)\sin\phi \\ &+ (J_6\sin\alpha\sin\beta + J_7\sin 2\alpha\sin 2\beta)\cos\phi \\ &+ J_8\sin^2\alpha\sin^2\beta\sin 2\phi + J_9\sin^2\alpha\sin^2\beta\cos 2\phi \end{aligned}$$

- Collects the contribution to the decay rate, remaining CP even and CP odd contributions.
- The J_i can be expressed in terms of the EFT coefficients.

Application: New physics in $h \to Z\ell^+\ell^-$

To a very good approximation

$$G_j \sim g_j + \frac{h_j}{2}\frac{s - m_Z^2}{m_Z^2}; \qquad H_j \sim 0; \qquad K_j \sim 0$$

and consequently

$$J_{1,2},\, J_{7,9} \to (G_V^2 + G_A^2) \qquad J_{3,6} \to G_V G_A \qquad J_{4,5,8} \to 0$$

Interesting asymmetries:

- forward-backward asymmetry $A_{\alpha\beta}$ in α and β:

$$A_{\alpha\beta} = \left(\frac{d\Gamma}{ds}\right)^{-1} \int_{-1}^{1} dc_\alpha \,\mathrm{sgn}(c_\alpha) \int_{-1}^{1} dc_\beta \,\mathrm{sgn}(c_\beta) \frac{d\Gamma}{ds\, dc_\alpha\, dc_\beta} = \frac{J_3}{J_1 + J_2}$$

- Azimutal asymmetry B_ϕ:

$$B_\phi = \left(\frac{d\Gamma}{ds}\right)^{-1} \int_{0}^{2\pi} d\phi \,\mathrm{sgn}(\cos\phi) \frac{d\Gamma}{ds d\phi} = \frac{\pi}{2}\frac{J_6}{J_1 + J_2}$$

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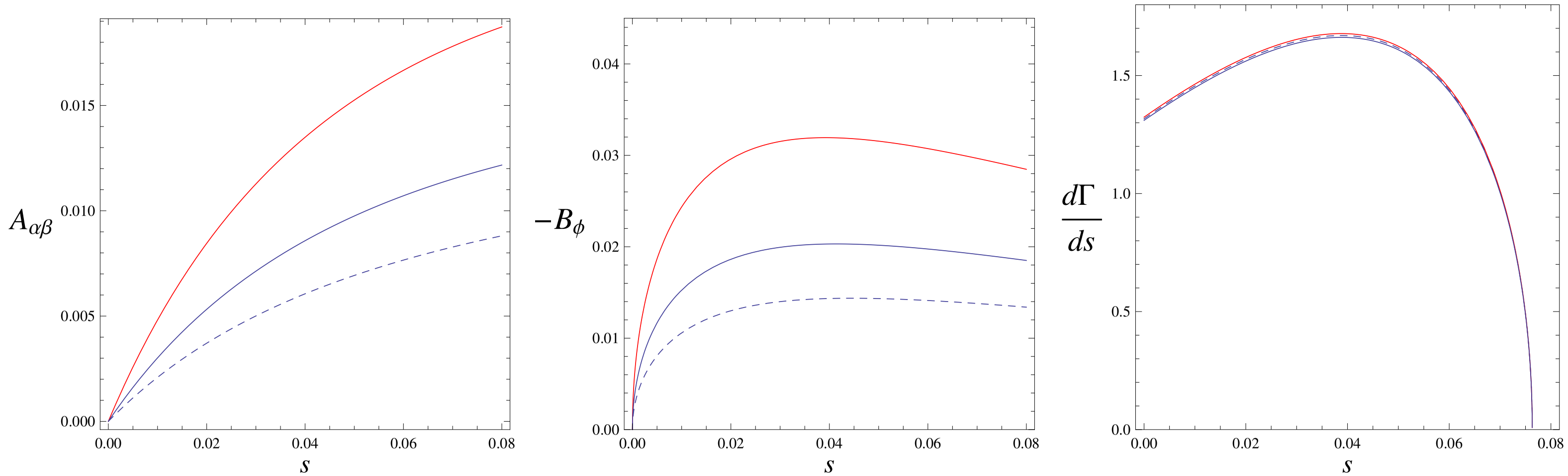

- Chosen scenario: main NP contributions from the contact term $h_{V,A}$ (heavy 1 TeV vector). $\delta g_{V,A}$ (LEP data) and $\delta g_{h\gamma}, \delta g_{hZZ}$ (naive EFT power-counting) negligible. Choice of parameters: $(h_V, h_A) = v^2/\Lambda^2(-2, 0.3)$, $(h_V, h_A) = v^2/\Lambda^2(-6, 0.3)$.
- Qualitative picture: h_V controls asymmetries, h_A the differential mass distribution (uncorrelated effects).
- Asymmetries most sensitive to NP favored by g_V being suppressed. At 14 TeV and 3000 fb^{-1}, expected $1 - 2\%$ sensitivity...

The decoupling limit

[Buchalla,O.C.,Krause, in preparation]

- The EW Lagrangian is a loop (v^2/Λ^2) expansion:

$$\mathcal{L}_{\chi EW} = \mathcal{L}_{LO}^{(\xi)} + \mathcal{L}_{NLO}^{(\xi)} + \mathcal{O}\left(\frac{v^4}{\Lambda^4}\right)$$

In the small ξ limit one recovers a dimensional expansion.

$$\lim_{\xi\to 0} \mathcal{L}_{\chi EW} = \mathcal{L}_{(0)} + \xi\mathcal{L}_{(1)} + \mathcal{O}(\xi^2) \equiv \mathcal{L}_{SM} + \xi\mathcal{L}_1 + \mathcal{O}(\xi^2)$$

- The subleading effects to the SM result from a double expansion. By dimensional analysis,

$$\mathcal{L}_{(n)} = \frac{1}{\xi^n n!}\left[\frac{d^n}{d\xi^n}\sum_{j=0}^{n}\mathcal{L}_{N^jLO}^{(\xi)}\right]_{\xi\to 0} \quad \Longrightarrow \quad \mathcal{L}_{(1)} \sim \frac{d}{d\xi}\left[\mathcal{L}_{LO}^{(\xi\to 0)} + \mathcal{L}_{NLO}^{(\xi\to 0)}\right]$$

- In practice, catalog all the $d = 6$ operators and rewrite them in the nonlinear basis using

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

The decoupling limit

$$\mathcal{L}_{(1)} = V_1(h;a_1,a_2) + \frac{v^2}{4}\langle L_\mu L^\mu\rangle F_U(h;a_1,a_2) - v\left[\bar{\Psi}\mathcal{F}_{Y\psi}(h,Y_\psi;a_1,a_2,\delta Y_\psi)UP_\pm\psi\right]$$
$$-\beta_1 v^2\langle L_\mu\tau_L\rangle^2\left(1+\frac{h}{v}\right)^4 - \frac{c_X}{4}X^a_{\mu\nu}X^{\mu\nu a}\left[1-\left(1+\frac{h}{v}\right)^2\right] + \alpha g g'\langle W_{\mu\nu}\tau_L\rangle B^{\mu\nu}\left(1+\frac{h}{v}\right)^2$$
$$+ c_{\psi Vj}(\bar{\Psi}_j\gamma^\mu\Psi_j)\langle L_\mu\tau_L\rangle\left(1+\frac{h}{v}\right)^2 + c_{\psi V6}(\bar{u}\gamma^\mu d)\langle P_{21}U^\dagger L_\mu U\rangle\left(1+\frac{h}{v}\right)^2 + \mathcal{L}_{\Psi^4}$$

- Different from $d=6$ basis (additional loop expansions).
- Traces of the double expansion:

$$\xi = \frac{v^2}{f^2}; \qquad \frac{\xi}{16\pi^2} = \frac{v^2}{f^2}\left(\frac{f^2}{\Lambda^2}\right); \qquad \xi^2 = \frac{v^2}{f^2}\left(\frac{v^2}{f^2}\right)$$

In certain cases, $\mathcal{L}_{LO}(\xi^2)$ more important than $\mathcal{L}_{NLO}(\xi)$. Strong dynamics does not follow a dimensional expansion...

- Similarities with SILH, but general (model-independent) construction and framework for systematic ξ expansion.

Conclusions

- Systematics of the EWChPT: generic framework to explore nonstandard Higgs scenarios in different regimes. Provides a solid way to learn about EWSB.

- Strong coupling EWSB has appealing features: naturalness (when pGB). Masses of all particle species small due to symmetries.