Higgs EFTs: systematics and applications

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Outline

- Motivation
- Building the EFT: Power-counting criteria and operators at NLO
- Illustration (I): new physics at LHC and ILC for $\bar{f}f \to (W^+W^-)$
- Illustration (II): new physics in the angular distribution of $h \to Z\ell^+\ell^-$
- Conclusions and future prospects

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1) Mass stabilization (naturalness): Physics at the TeV scale is generally requested (but so far no signals thereof...), either **weakly-coupled** (SUSY?...) or **strongly-coupled**. Even small deviations from the SM parameters have profound implications (renormalizability and unitarization). Hints at the UV completions of the EW theory.

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2) Departures from the SM typically expected. Many alternatives to the SM Higgs in the market (composite Higgs, little Higgs, holographic Higgs, littlest Higgs, Higgs as a dilaton, etc.), mostly dealing with strongly-coupled scenarios with the Higgs as a PGB of a general SSB gauge group.

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3) **Q**: Is there a framework that contains all the composite models? Generically, the interaction is nonrenormalizable and EFTs become an essential tool. What is this EFT of the electroweak interactions?

General description of the Higgs mechanism

- **SSB à la CCWZ**: Goldstone bosons from the spontaneous breaking of a $SU(2)_L \otimes SU(2)_R$ global symmetry to $SU(2)_V$ (minimal scenario). Goldstone modes collected in a $SU(2)$ matrix U, transforming as

$$U \to g_L U g_R^\dagger, \qquad g_{L,R} \in SU(2)_{L,R} \qquad U = \exp(2i\varphi^a \tau^a / v)$$

- Gauge the $SU(2)_L \otimes U(1)_Y$ subgroup: $D_\mu U = \partial_\mu U + igW_\mu U - ig' B_\mu U \frac{\tau_3}{2}$
- Generation of gauge masses transparent in unitary gauge:

$$\mathcal{L}_{EWSB} = \frac{v^2}{4} \mathrm{tr}\left[D_\mu U^\dagger D^\mu U\right] = m_W^2 W_\mu^+ W^{\mu -} + m_Z^2 Z_\mu Z^\mu$$

- Equivalent results for the masses: NσM at leading order is equivalent to the LσM with the scalar integrated out.
- For the Higgs mechanism to work no scalar is requested. But we do have a scalar in the spectrum...

General description of the Higgs mechanism

- With the discovery of a light scalar, the minimal picture gets generalized to [Contino et al'12]

$$\mathcal{L}_{EWSB} = \frac{1}{2}\partial_\mu h \partial^\mu h - V(h) + \frac{v^2}{4}\mathrm{tr}\left[D_\mu U^\dagger D^\mu U\right] \times \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots\right)$$

- By construction, the most general parameterization of (leading) scalar effects to gauge bosons.

- Light scalar as pNGB of unspecified broken symmetry [Georgi,Kaplan'85;Agashe et al'05].

- h affects (dramatically) the properties of the QFT: renormalizability, etc. Eventually, it can unveil in which precise way EW symmetry is broken.

- The generic EW theory is **no longer renormalizable**. If phrased as an EFT, renormalizability order by order in the expansion parameter. The transition from naive effective operators to an EFT requires a consistent power-counting.

Some reflections on power-counting

- Weakly-coupled EFTs have dimensional counting ($1/\Lambda^2$ expansion). Strongly-coupled expansions have loop counting ($v^2/\Lambda^2 \sim 1/(16\pi^2)$ expansion).
- In some simplified cases the loop expansion can be cast as a dimensional expansion, *e.g.* ChPT (expansion in derivatives). Chiral dimension vs canonical dimension.
- For phenomenological effects, interactions of Goldstones and gauge bosons can be disguised as dimensional, but at the price of rather exotic chiral dimensions (couplings scaling as powers of momenta).
- The main goal is to couple also to fermions. There is no chiral dimension that makes it consistent [Nyffeler et al'99; Hirn et al'03]
- Subsets of operators worked out [Giudice et al'07, Contino et al'12, Alonso et al'12]. Intuition in many cases right, but systematics (and therefore completeness) lacking.

Organizing the expansion: power-counting

Requirements for a consistent power-counting:

- **Homogeneity of the LO Lagrangian**. Naive dimensional power-counting only applies to weakly-coupled (decoupling) scenarios.
- **Landau gauge** especially suited: ghosts and Goldstones decoupled, *i.e.* ghosts decoupled from EWSB dynamics [Appelquist et al'80-81]
- **Soft custodial symmetry breaking**: $\mathcal{O}_\beta = v^2 \langle \tau_L L_\mu \rangle^2$ subleading (loop-induced).

Leading order Lagrangian:

$$\mathcal{L}_{LO} = -\frac{1}{2}\langle G_{\mu\nu}G^{\mu\nu}\rangle - \frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \sum_{j=L,R} \bar{\psi}_j i\gamma_\mu D^\mu \psi_j$$

$$+ \frac{v^2}{4}\langle L_\mu L^\mu\rangle f_U(h) - v\left[\bar{\psi} f_\psi(h) U P_\pm \psi + \text{h.c.}\right] + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h)$$

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

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$$+ \frac{v^2}{4}\langle L_\mu L^\mu\rangle f_U(h) - v\left[\bar{\psi} f_\psi(h) U P_\pm \psi + \text{h.c.}\right] + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h)$$

Comments:

- Scalar and fermion-gauge sectors fully general.
- Gauge boson weakly coupled to the strong sector.
- All powers of h contribute at the same order. For phenomenological applications, $f_j(h)$ effectively truncated.
- EFT: expansion in v^2/Λ^2. Power counting gives a precise definition of NLO operators.

Organizing the expansion: power-counting

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

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

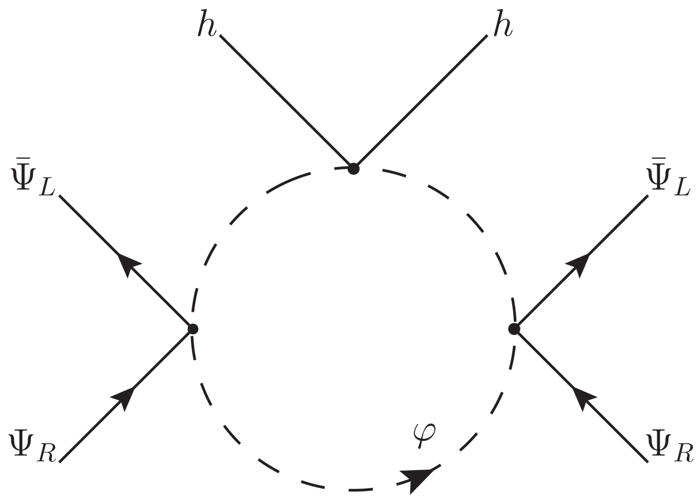
where

$$d = 2L + 2 - F/2 - G - 2\nu_h - \nu_f - \nu_g$$

- 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:

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

Organizing the expansion: power-counting



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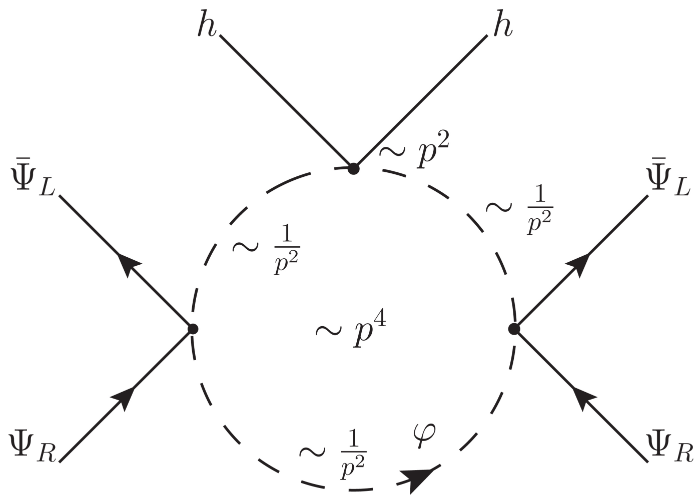

$\mathcal{O}(v^2/\Lambda^2)$ correction: Yukawa^2 operator appears at NLO.

Operators at NLO

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

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

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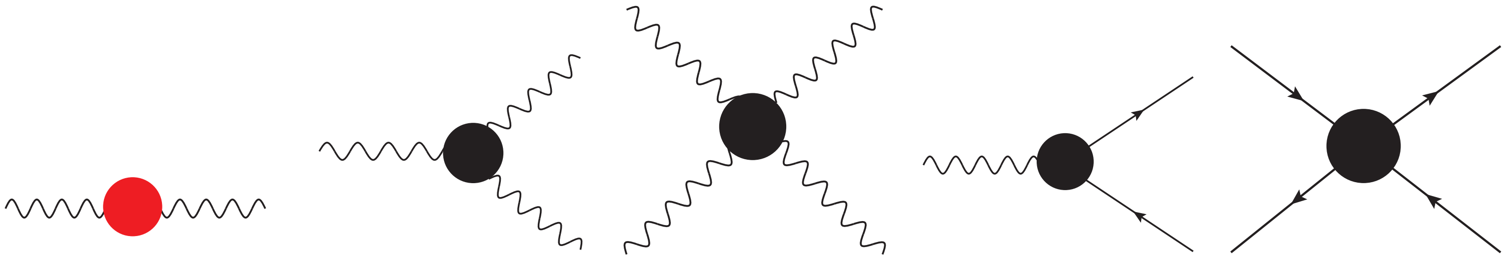

$\mathcal{O}_{XU1} = g' g B_{\mu\nu} \langle W^{\mu\nu} \tau_L \rangle \quad \mathcal{O}_{XU4} = g' g \epsilon_{\mu\nu\lambda\rho} \langle \tau_L W_{\mu\nu} \rangle B^{\lambda\rho} \quad \mathcal{O}_{XU2} = g^2 \langle W^{\mu\nu} \tau_L \rangle^2$

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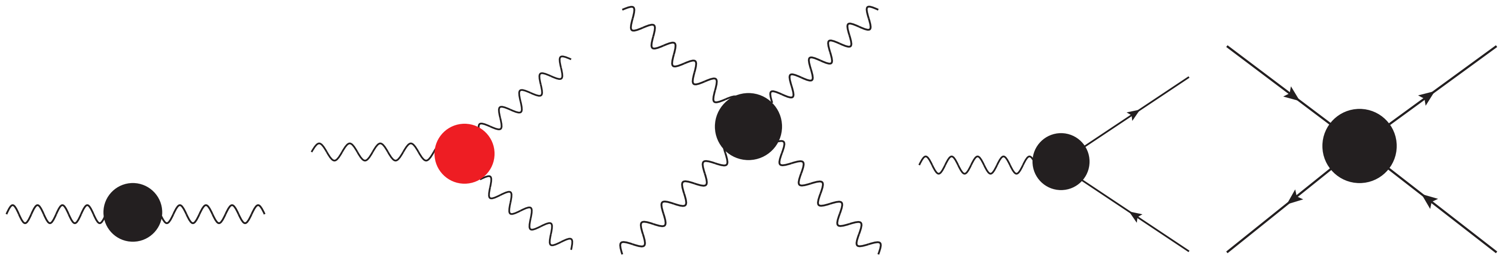

$$\mathcal{O}_{XU7} = ig' B_{\mu\nu}\langle \tau_L [L^\mu, L^\nu]\rangle \quad \mathcal{O}_{XU8} = ig\langle W_{\mu\nu}[L^\mu, L^\nu]\rangle \quad \mathcal{O}_{XU9} = ig\langle W_{\mu\nu}\tau_L\rangle\langle \tau_L[L^\mu, L^\nu]\rangle$$

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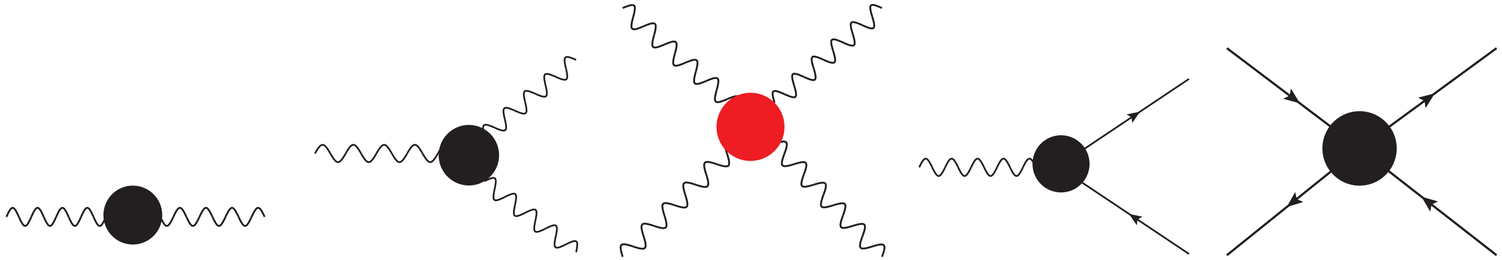

$$\mathcal{O}_{D1} = \langle L_\mu L^\mu \rangle \langle L_\nu L^\nu \rangle \qquad \mathcal{O}_{D5} = \langle \tau_L L^\mu \rangle \langle \tau_L L_\nu \rangle \langle L_\mu L^\nu \rangle$$

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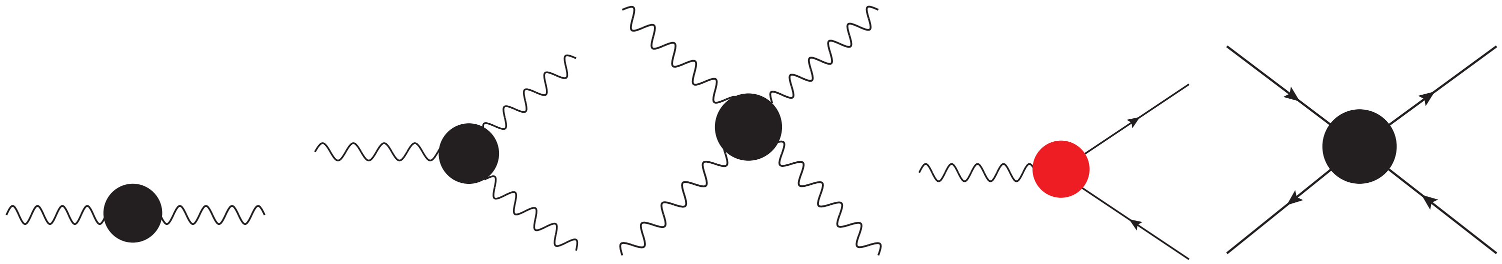

$$\mathcal{O}_{\psi V7} = i\bar{l}\gamma^\mu l\ \langle\tau_L L_\mu\rangle \quad \mathcal{O}_{\psi V8} = i\bar{l}\gamma^\mu\tau_L l\ \langle\tau_L L_\mu\rangle \quad \mathcal{O}_{\psi V10} = i\bar{e}\gamma^\mu e\ \langle\tau_L L_\mu\rangle$$

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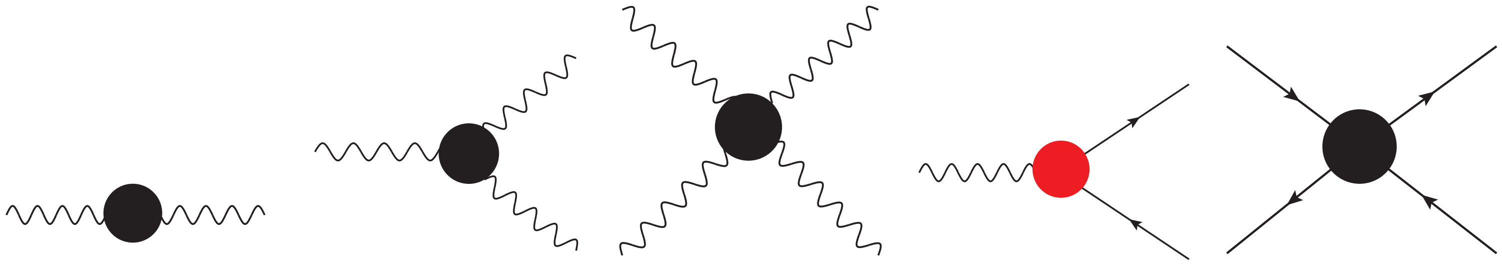

$\mathcal{O}_{\psi S7} = \bar{l}UP\_l \; \langle L^\mu L_\mu \rangle \quad \mathcal{O}_{\psi S8} = \bar{l}UP\_l \; \langle \tau_L L_\mu \rangle^2$

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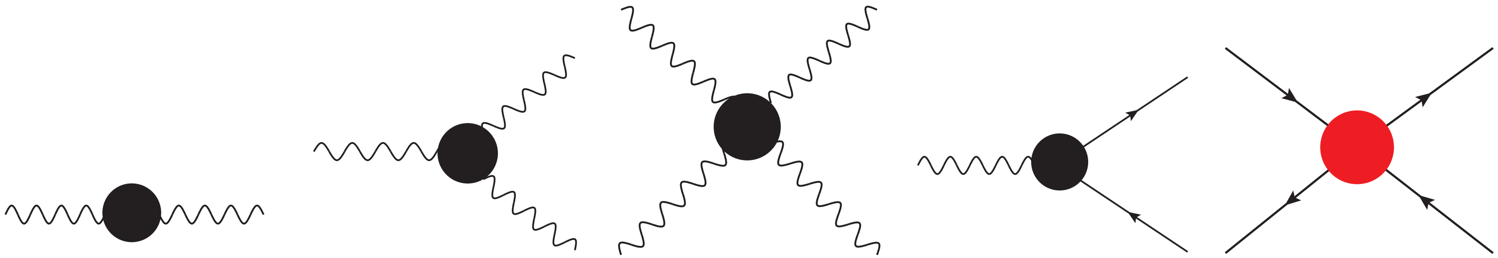


$\mathcal{O}_{LR8} = \bar{l}\gamma_\mu l\bar{e}\gamma^\mu e \quad \mathcal{O}_{FY10} = \bar{l}UP\_l\bar{l}UP\_l$

The route to completeness

Avoid missing operators and eliminate redundancies.

- No fail-proof algorithm, but useful tools: E.O.M., Integration by parts, $SU(2)$ relations, Bianchi identities, ...
- Guiding principles (for us): build the basis with the minimal number of derivatives. ChPT tradition, also in [Grzadkowski et al'10]
- Redundancies sometimes hard to spot...[Nyffeler et al'99,Grojean et al'06, Buchalla, O.C.'12]

$$\mathcal{O}_{XU1} = g'gB_{\mu\nu}\langle W^{\mu\nu}\tau_L\rangle \qquad \mathcal{O}_{XU7} = ig'B_{\mu\nu}\langle\tau_L[L^\mu, L^\nu]\rangle$$

$$\mathcal{O}_{XU2} = g^2\langle W^{\mu\nu}\tau_L\rangle^2 \qquad \mathcal{O}_{XU8} = ig\langle W_{\mu\nu}[L^\mu, L^\nu]\rangle$$

$$\mathcal{O}_{XU3} = g\epsilon^{\mu\nu\lambda\rho}\langle W^{\mu\nu}L_\lambda\rangle\langle\tau_L L_\rho\rangle \qquad \mathcal{O}_{XU9} = ig\langle W_{\mu\nu}\tau_L\rangle\langle\tau_L[L^\mu, L^\nu]\rangle$$

$$\mathcal{O}_{XU7} = \frac{g'^2}{2}B_{\mu\nu}B^{\mu\nu} + g'^2\mathcal{O}_{\beta_1} - \mathcal{O}_{XU1} - g'^2\mathcal{O}_{\psi V7} - 2g'^2\mathcal{O}_{\psi V10}$$

$$\mathcal{O}_{XU8} = g^2\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{g^2}{2}v^2\langle L_\mu L^\mu\rangle - \mathcal{O}_{XU1} - 2g^2\mathcal{O}_{\psi V8} - 2g^2\mathcal{O}_{\psi V9}$$

$$\mathcal{O}_{XU9} = \frac{g^2}{4}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{g^2}{8}v^2\langle L_\mu L^\mu\rangle - \frac{g^2}{4}\mathcal{O}_{\beta_1} - \frac{1}{2}\mathcal{O}_{XU2} - \frac{g^2}{2}\mathcal{O}_{\psi V9}$$

Application I: New physics in $\bar{f} f \to W^+W^-$

Number of **independent EFT operators** [Buchalla, O.C. Rahn, Schlaffer'13]:

$$\mathcal{L}_{NLO} = \sum_j \lambda_j \mathcal{O}_{Xj} + \sum_j \eta_j \mathcal{O}_{Vj} + \beta \mathcal{O}_\beta + \eta_{4f} \mathcal{O}_{4f}$$

where $\mathcal{O}_\beta = v^2 \langle \tau_L L_\mu \rangle^2$ and

$$\mathcal{O}_{X1} = g' g B_{\mu\nu} \langle W^{\mu\nu} \tau_L \rangle \qquad \mathcal{O}_{X4} = g' g \epsilon^{\mu\nu\lambda\rho} \langle \tau_L W_{\mu\nu} \rangle B_{\lambda\rho}$$
$$\mathcal{O}_{X2} = g^2 \langle W^{\mu\nu} \tau_L \rangle^2 \qquad \mathcal{O}_{X5} = g^2 \epsilon^{\mu\nu\lambda\rho} \langle \tau_L W_{\mu\nu} \rangle \langle \tau_L W_{\lambda\rho} \rangle$$
$$\mathcal{O}_{X3} = g \epsilon^{\mu\nu\lambda\rho} \langle W_{\mu\nu} L_\lambda \rangle \langle \tau_L L_\rho \rangle \qquad \mathcal{O}_{X6} = g \langle W_{\mu\nu} L^\mu \rangle \langle \tau_L L^\nu \rangle$$

are oblique and triple-gauge corrections ($L_\mu = iUD_\mu U^\dagger$, $\tau_L = UT_3U^\dagger$),

$$\mathcal{O}_{V1} = -\bar{q}\gamma^\mu q \ \langle L_\mu \tau_L \rangle; \qquad \mathcal{O}_{V7} = -\bar{l}\gamma^\mu l \ \langle L_\mu \tau_L \rangle$$
$$\mathcal{O}_{V2} = -\bar{q}\gamma^\mu \tau_L q \ \langle L_\mu \tau_L \rangle; \qquad \mathcal{O}_{V8} = -\bar{l}\gamma^\mu \tau_L l \ \langle L_\mu \tau_L \rangle$$
$$\mathcal{O}_{V4} = -\bar{u}\gamma^\mu u \ \langle L_\mu \tau_L \rangle; \qquad \mathcal{O}_{V9} = -\bar{l}\gamma^\mu \tau_{12} l \ \langle L_\mu \tau_{21} \rangle$$
$$\mathcal{O}_{V5} = -\bar{d}\gamma^\mu d \ \langle L_\mu \tau_L \rangle; \qquad \mathcal{O}_{V10} = -\bar{e}\gamma^\mu e \ \langle L_\mu \tau_L \rangle$$

are gauge-fermion new physics contributions ($\tau_{12,21} = T_1 \pm iT_2$) and

$$\mathcal{O}_{4f} = \frac{1}{2}(\mathcal{O}_{LL5} - 4\mathcal{O}_{LL15}) = (\bar{e}_L \gamma_\rho \mu_L)(\bar{\nu}_\mu \gamma^\rho \nu_e)$$

Phenomenology at large energies

Main motivation for EFT: large energy gap between the electroweak and new physics scales. For LHC and linear colliders, aimed energy window: $\sqrt{s} \sim (0.6 - 1)$ TeV. In this energy regime $v^2 \ll s \ll \Lambda^2$ and

- Cross sections can be expanded in powers of v^2/s;
- Good convergence of the EFT expansion (in s/Λ^2) is expected.

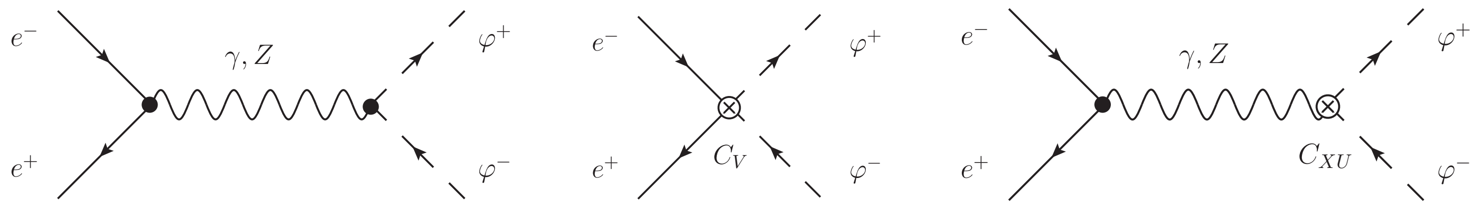
For $e^+e^- \to W^+W^-$ one finds [Buchalla, O.C., Rahn, Schlaffer'13]:

$$\frac{d\sigma_{WW}^R}{d\cos\theta} = \frac{\pi\alpha^2\sin^2\theta}{8s_W^2c_W^2}\frac{1}{m_W^2}\eta_R; \qquad \frac{d\sigma_{WW}^L}{d\cos\theta} = \frac{\pi\alpha^2\sin^2\theta}{16c_W^2s_W^4}\frac{1}{m_W^2}\eta_L$$

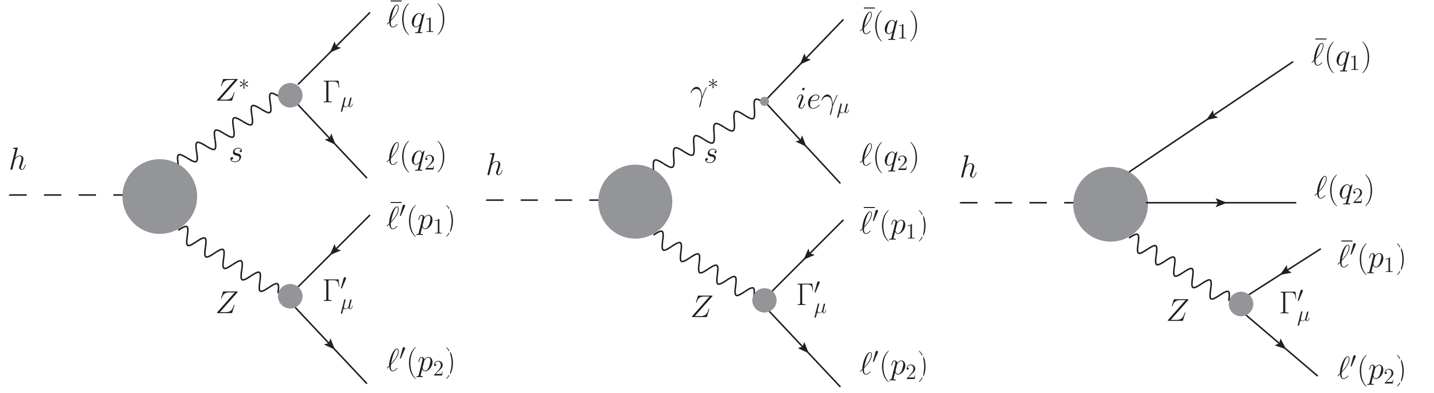
New physics signals dominated by gauge-fermion operators!...

Two observations to understand the result:

- The dominant piece above comes entirely from $W_L^+W_L^-$ polarizations. The result should be equivalent to $e^+e^- \to \varphi^+\varphi^-$ in Landau gauge.



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



- 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]

Application II: 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.

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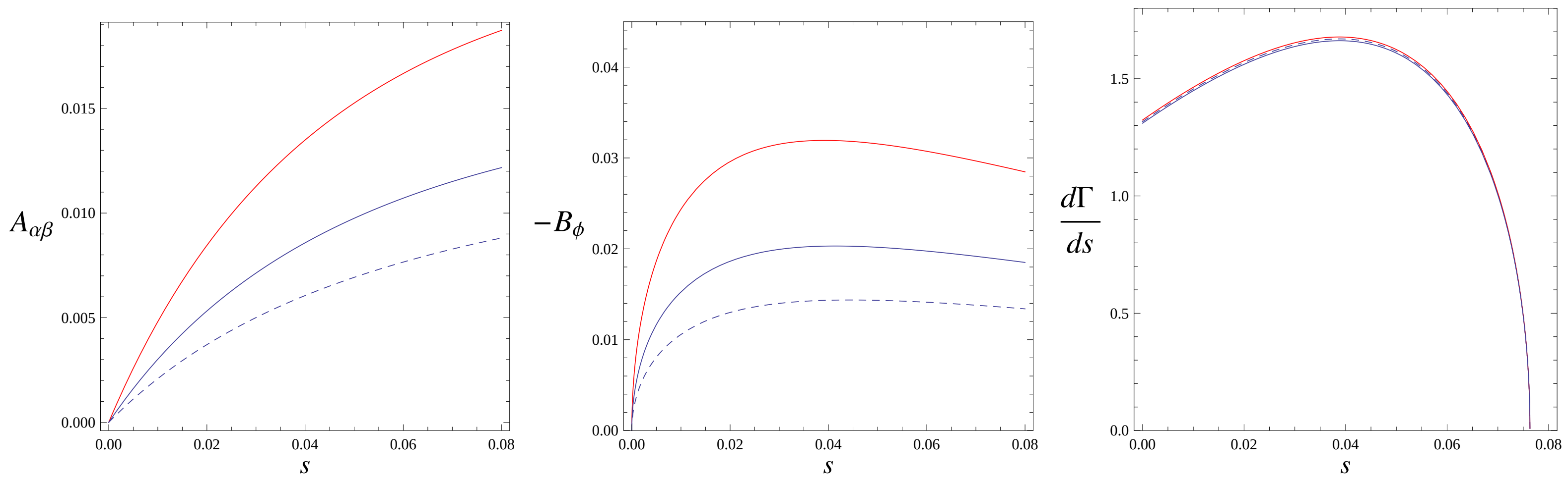

- Chosen scenario: we assume main NP contributions coming from the contact term (heavy 1 TeV vector). Thus, $\delta g_{V,A}$ negligible (LEP data) and also $\delta g_{h\gamma}, \delta g_{hZZ}$ (naive EFT power-counting). Choice of parameters: $(h_V, h_A) = v^2/\Lambda^2(-6, 0.3)$.
- Asymmetries most sensitive to new physics: double forward-backward $A_{\alpha\beta} \sim J_3$ and $B_\phi \sim J_6$ (favored by g_V being suppressed in the SM).
- Qualitative picture: h_V controls asymmetries, h_A the differential mass distribution (uncorrelated effects).

Conclusions and future outlook

- EFT for generic scenarios with pNGB Higgs. Systematics and complete NLO operators.
- Illustrations: $\bar{f}f \to WW, \gamma Z, ZZ$ and $h \to Z\ell^+\ell^-$. Complete EFT treatment yet still very informative.