EWSB by strongly-coupled dynamics: an EFT approach

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Outline

- Motivation
- Linear vs non-linear realization of EWSB
- Organizing the expansion: Power-counting criteria
- Operators at NLO
- Back to the linear case: SM at NLO
- Conclusions and future prospects

Motivation (Why bother about strongly-coupled EWSB?)

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- **Conclusion**: Identification of the scalar (Higgs or not) can take many years... If new states at the TeV, signatures can hardly distinguish SUSY particles from strongly-coupled resonances. Strongly-coupled scenarios have a lot to say. But so far **no evidence of TeV physics**...

Linear vs non-linear EWSB

- Massless gauge and fermion sector of the SM $[SU(3)_C, SU(2)_L, U(1)_Y]$:

$$G_\mu[8,1,0], \qquad W_\mu[1,2,0], \qquad B_\mu[1,1,0]$$

$$q\left[3,2,\frac{1}{6}\right], \quad l\left[1,2,-\frac{1}{2}\right], \quad u\left[3,1,\frac{2}{3}\right], \quad d\left[3,1,-\frac{1}{3}\right], \quad e[1,1,-1]$$

organized as:

$$\mathcal{L}_4 = -\frac{1}{2}\langle G_{\mu\nu}G^{\mu\nu}\rangle - \frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$
$$+ i\bar{q}\not{D}q + i\bar{l}\not{D}l + i\bar{u}\not{D}u + i\bar{d}\not{D}d + i\bar{e}\not{D}e$$

with

$$D_\mu\psi_L = (\partial_\mu + igW_\mu + ig'Y_L B_\mu)\psi_L$$
$$D_\mu\psi_R = (\partial_\mu + ig'Y_R B_\mu)\psi_R$$

- Masses to gauge bosons and fermions through Higgs mechanism: SSB with the pattern $SU(2)_L \otimes U(1)_Y \to U(1)_Q$. But in which precise way EW symmetry is broken?

Linear sigma model: the Higgs boson

- Masses to the gauge bosons are given by a fundamental (complex) scalar doublet in a renormalizable interaction:

$$\mathcal{L}_H = D_\mu \Phi^\dagger D_\mu \Phi + \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger \Phi)^2, \qquad \Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

- SSB is achieved through picking a nontrivial vacuum

$$\Phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \qquad v = \left(\frac{\mu^2}{\lambda}\right)^{1/2} = \left(\sqrt{2} G_F\right)^{1/2} \simeq 246\,\mathrm{GeV}$$

- Goldstone bosons are converted into longitudinal components of the gauge boson, *i.e.*, they generate masses:

$$m_W = \frac{v}{2} g$$
$$m_Z = \frac{v}{2} \sqrt{g^2 + g'^2}$$
$$m_A = 0$$

- Price to pay: appearance of a fundamental scalar H with arbitrary mass $m_H = 2\lambda v^2$
- **Custodial symmetry**: accidental global $SU(2)_L \otimes SU(2)_R$ symmetry that ensures that $\rho = \frac{g^2+g'^2}{g^2} \frac{m_W^2}{m_Z^2} \simeq 1$.

Non-linear sigma model: Higgsless* scenario

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

$$U \to g_L U g_R^\dagger, \qquad g_{L,R} \in SU(2)_{L,R}$$

- Convenient realization:

$$U = \exp(2i\Phi/v), \qquad \Phi = \varphi^a \frac{\tau^a}{2} = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\varphi^0}{\sqrt{2}} & \varphi^+ \\ \varphi^- & -\frac{\varphi^0}{\sqrt{2}} \end{pmatrix}$$

with $\tau^a = \tau_a$ the generators of $SU(2)$.

- Gauge the $SU(2)_L \otimes U(1)_Y$ subgroup:

$$D_\mu U = \partial_\mu U + igW_\mu U - ig' B_\mu U \frac{\tau_3}{2}$$

- Collect the right-handed quark and lepton fields in spurion doublets $r = (u, d)^T$ and $\eta = (\nu, e)^T$.

- List down to most general Lagrangian at leading order:

$$\mathcal{L}_U = \frac{v^2}{4} \langle D_\mu U^\dagger D^\mu U \rangle - v\left(\bar{q} Y_u U P_+ r + \bar{q} Y_d U P_- r + \bar{l} Y_e U P_- \eta + \text{h.c.}\right)$$

where $P_\pm$ are $SU(2)_L$ projectors:

$$P_\pm \equiv \frac{1 \pm \tau_3}{2}, \qquad P_{12} \equiv \frac{\tau_1 + i\tau_2}{2}, \qquad P_{21} \equiv \frac{\tau_1 - i\tau_2}{2}$$

- Moving to unitary gauge it is clear that masses for the gauge bosons and fermions are also generated:

$$\mathcal{L}_U = \frac{v^2}{8}\left[2g^2 W_\mu^+ W^{\mu-} + (g^2 + g'^2) Z_\mu Z^\mu\right] - v\left(\bar{q} Y_u u + \bar{q} Y_d d + \bar{l} Y_e e + \text{h.c.}\right)$$

- **No fundamental scalar** is requested. The $N\sigma M$ at leading order is equivalent to the $L\sigma M$ with the scalar integrated out.

- However, **composite scalars** can be accommodated, with natural masses at the electroweak scale. [Georgi, Kaplan, Galison'84]

- The theory is **no longer renormalizable**, but if phrased in an EFT language, renormalizability order by order can be recovered and the framework can become predictive. Power-counting essential.

A survey on strongly-coupled EWSB

- First works in early 80's [Longhitano; Appelquist, Bernard] (before NLO χPT!). LO and NLO bosonic sector with comments on the power-counting. Size of the operators estimated with technicolor models. Revisited in [Appelquist et al'93,95; Nyffeler et al'99; Grojean et al'06] with redundancies eventually eliminated.

- Fermion bilinears [Appelquist et al'85], completed in [Peccei et al'90].

- Four-fermion operators partially discussed in [Bagan et al'99].

- Mostly all work oriented to phenomenological studies with technicolor in mind. From early 90's, phenomenological studies with LEP physics. However, (i) not systematic and power-counting discussions absent; (ii) some of the technical developments ignored.

Organizing the expansion: power-counting

- Canonical dimension of operators clearly not the right expansion. $\mathcal{L}_4 + \mathcal{L}_U$ inhomogeneous...

- Landau gauge is especially suited: ghosts and Goldstones decoupled (ghosts decoupled from EWSB dynamics), so no ghost fields needed to build the effective operators.

- In the absence of fermions and gauge bosons the power-counting should reduce to the familiar χPT formula:

$$\mathcal{D} \sim \frac{v^2}{\Lambda^{2L}} p^{2L+2} \left(\frac{\varphi}{v}\right)^B$$

- The addition of fermions leads to

$$\mathcal{D} \sim \frac{(yv)^\nu}{v^{F_L+F_R-2}} \frac{p^d}{\Lambda^{2L}} \bar{\psi}_L^{F_L^1} \psi_L^{F_L^2} \bar{\psi}_R^{F_R^1} \psi_R^{F_R^2} \left(\frac{\varphi}{v}\right)^B, \qquad d = 2L + 2 - \nu - (F_L + F_R)/2$$

- Divergences, *i.e.*, $d \geq 0$ exhaust the list of counterterms.

- A more general formula can be written down to include gauge fields.

$$\mathcal{D} \sim \frac{(yv)^{\nu}(gv)^{m+2r+2x+u+z}}{v^{F_L+F_R-2}} \frac{p^d}{\Lambda^{2L}} \bar{\psi}_L^{F_L^1} \psi_L^{F_L^2} \bar{\psi}_R^{F_R^1} \psi_R^{F_R^2} \left(\frac{X_{\mu\nu}}{v}\right)^V \left(\frac{\varphi}{v}\right)^B$$

where the power of p is

$$d \equiv 2L + 2 - \nu - \frac{F_L + F_R}{2} - V - m - 2r - 2x - u - z$$

Bounded from above.

- The power-counting formula justifies that the naively LO custodial symmetry breaking operator

$$\beta_1 v^2 \langle \tau_L L_\mu \rangle^2$$

is actually NLO.

Operators at NLO

- The general effective Lagrangian reads:

$$\mathcal{L} = \mathcal{L}_4 + \mathcal{L}_U + \mathcal{L}_{\beta_1} + \sum_i c_i \frac{v^{6-d_i}}{\Lambda^2} \mathcal{O}_i$$

- Classes of operators $\mathcal{O}_i$:

UD^4 :	$\langle D_\mu U^\dagger D^\mu U \rangle$	(5)
XUD^2 :	$\langle U^\dagger W_{\mu\nu} D^\mu U \rangle \langle U^\dagger D^\nu U \tau_3 \rangle$	(2)
$X^2 U$:	$B_{\mu\nu} \langle U^\dagger W^{\mu\nu} U \tau_3 \rangle$	(4)
$\psi^2 UD$:	$i\bar{e}\gamma_\mu e \langle U^\dagger D^\mu U \tau_3 \rangle$	(10)
$\psi^2 UD^2$	$\bar{l} U P_- \eta \langle D_\mu U^\dagger D^\mu U \rangle$	(15)
$\psi^4 U$	$\bar{l}\gamma_\mu U \tau_3 U^\dagger l \bar{e}\gamma^\mu e$	(64)

- Potential classes $[UD^6, XUD^4, X^2UD^2, X^3U, \psi^2UD^3, \psi^2UXD, \psi^2UX]$ can be shown to be subleading (NNLO).

- Notation: to simplify the operators I will work with $L_\mu = UD_\mu U^\dagger$ and $\tau_L = U\tau_3 U^\dagger$.

Operators at NLO: UD^4

- Pure Goldstone sector [Longhitano'80-81]

$$\begin{aligned}
\mathcal{O}_{D1} &= \langle L_\mu L^\mu \rangle \langle L_\nu L^\nu \rangle \\
\mathcal{O}_{D2} &= \langle L_\mu L_\nu \rangle \ \langle L^\mu L^\nu \rangle \\
\mathcal{O}_{D3} &= \langle \tau_L L^\mu \rangle^2 \langle \tau_L L^\nu \rangle^2 \\
\mathcal{O}_{D4} &= \langle \tau_L L^\mu \rangle \langle \tau_L L_\mu \rangle \langle L_\nu L^\nu \rangle \\
\mathcal{O}_{D5} &= \langle \tau_L L^\mu \rangle \langle \tau_L L_\nu \rangle \langle L_\mu L^\nu \rangle
\end{aligned}$$

- In unitary gauge they correspond to all the possible quartic contractions of gauge bosons:

$$Z_\mu Z^\mu Z_\nu Z^\nu, \quad W_\mu^+ W^{\mu +} W_\nu^- W^{\nu -}, \quad W_\mu^+ W^{\mu -} W_\nu^+ W^{\nu -},$$
$$Z_\mu Z^\mu W_\mu^+ W^{\mu -}, \quad Z_\mu Z^\nu W_\nu^+ W^{\mu -}$$

- They correspond to the usual χPT operators at NLO.

Operators at NLO: XUD^2 and X^2U

- CP even and CP odd operators: [Longhitano'80-81, Appelquist et al'93]

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

$$\mathcal{O}_{XU2} = g^2\langle W^{\mu\nu}\tau_L\rangle^2 \qquad \mathcal{O}_{XU5} = g^2\epsilon_{\mu\nu\lambda\rho}\langle\tau_L W^{\mu\nu}\rangle\langle\tau_L W^{\lambda\rho}\rangle$$

$$\mathcal{O}_{XU3} = g\epsilon^{\mu\nu\lambda\rho}\langle W^{\mu\nu}L_\lambda\rangle\langle\tau_L L_\rho\rangle \qquad \mathcal{O}_{XU6} = g\langle W_{\mu\nu}L^\mu\rangle\langle\tau_L L^\nu\rangle$$

$$\mathcal{O}_{XU7} = ig'B_{\mu\nu}\langle\tau_L[L^\mu, L^\nu]\rangle \qquad \mathcal{O}_{XU10} = ig'\epsilon_{\mu\nu\lambda\rho}B^{\mu\nu}\langle\tau_L[L^\lambda, L^\rho]\rangle$$

$$\mathcal{O}_{XU8} = ig\langle W_{\mu\nu}[L^\mu, L^\nu]\rangle \qquad \mathcal{O}_{XU11} = ig\epsilon_{\mu\nu\lambda\rho}\langle W^{\mu\nu}[L^\lambda, L^\rho]\rangle$$

$$\mathcal{O}_{XU9} = ig\langle W_{\mu\nu}\tau_L\rangle\langle\tau_L[L^\mu, L^\nu]\rangle \qquad \mathcal{O}_{XU12} = ig\epsilon_{\mu\nu\lambda\rho}\langle W^{\mu\nu}\tau_L\rangle\langle\tau_L[L^\lambda, L^\rho]\rangle$$

- Relevant for EWPT: oblique parameters and triple gauge vertices.
- Caveat for phenomenology: redundancies such as

$$\langle W_{\mu\nu}[L^\mu, L^\nu]\rangle = g\bar{\psi}_L\gamma_\mu L^\mu\psi_L - \frac{ig}{2}v^2\langle L_\mu L^\mu\rangle + ig'B^{\mu\nu}\langle\tau_L W_{\mu\nu}\rangle - ig\langle W_{\mu\nu}W^{\mu\nu}\rangle$$

$$\varepsilon_{\mu\nu\lambda\rho}\langle W^{\mu\nu}[L^\lambda, L^\rho]\rangle = ig'\varepsilon_{\mu\nu\lambda\rho}B^{\mu\nu}\langle\tau_L W^{\lambda\rho}\rangle$$

not taken into account in phenomenological studies!

Operators at NLO: $\psi^2 UD$

- Operators involving a fermionic vector current: [Appelquist et al'93]

$$\mathcal{O}_{\psi V1} = i\bar{q}\gamma^\mu q\,\langle \tau_L L_\mu\rangle, \qquad \mathcal{O}_{\psi V4} = i\bar{u}\gamma^\mu u\,\langle \tau_L L_\mu\rangle$$

$$\mathcal{O}_{\psi V2} = i\bar{q}\gamma^\mu \tau_L q\,\langle \tau_L L_\mu\rangle, \qquad \mathcal{O}_{\psi V5} = i\bar{d}\gamma^\mu d\,\langle \tau_L L_\mu\rangle$$

$$\mathcal{O}_{\psi V3} = i\bar{q}\gamma^\mu P_{12}^L q\,\langle L_\mu P_{21}^L\rangle \quad \text{(h.c.)}, \qquad \mathcal{O}_{\psi V6} = i\bar{u}\gamma^\mu d\,\langle L_\mu P_{21}^L\rangle \quad \text{(h.c.)}$$

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

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

$$\mathcal{O}_{\psi V9} = i\bar{l}\gamma^\mu P_{12}^L l\,\langle L_\mu P_{21}^L\rangle \quad \text{(h.c.)}$$

Operators at NLO: $\psi^2 U D^2$

- Operators involving a fermionic scalar and tensor current: [Peccei et al'90; Buchalla, O.C.'12]

$$
\begin{aligned}
\mathcal{O}_{\psi S1,2} &= \bar{q} U P_\pm r \, \langle L_\mu L^\mu \rangle \\
\mathcal{O}_{\psi S3,4} &= \bar{q} U P_\pm r \, \langle \tau_L L_\mu \rangle^2 \\
\mathcal{O}_{\psi S5} &= \bar{q} U P_{12} r \, \langle L_\mu P_{21}^L \rangle \, \langle \tau_L L^\mu \rangle \\
\mathcal{O}_{\psi S6} &= \bar{q} U P_{21} r \, \langle L_\mu P_{12}^L \rangle \, \langle \tau_L L^\mu \rangle \\
\mathcal{O}_{\psi S7} &= \bar{l} U P_- \eta \, \langle L_\mu L^\mu \rangle \\
\mathcal{O}_{\psi S8} &= \bar{l} U P_- \eta \, \langle \tau_L L_\mu \rangle^2 \\
\mathcal{O}_{\psi S9} &= \bar{l} U P_{12} \eta \, \langle L_\mu P_{21}^L \rangle \, \langle \tau_L L^\mu \rangle
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{O}_{\psi T1} &= \bar{q} \sigma^{\mu\nu} U P_{12} r \, \langle L_\mu P_{21}^L \rangle \langle \tau_L L_\nu \rangle \\
\mathcal{O}_{\psi T2} &= \bar{q} \sigma^{\mu\nu} U P_{21} r \, \langle L_\mu P_{12}^L \rangle \langle \tau_L L_\nu \rangle \\
\mathcal{O}_{\psi T3,4} &= \bar{q} \sigma^{\mu\nu} U P_\pm r \, \langle L_\mu P_{12}^L \rangle \langle L_\nu P_{21}^L \rangle \\
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\end{aligned}
$$

Operators at NLO: $\psi^4 U$

[Buchmüller et al'86; Bagan et al'99; Buchalla, O.C.'12]

- $\bar{L}L\bar{L}L$ operators (16):

$$\mathcal{O}_{LL6} = \bar{q}\gamma^\mu \tau_L q\, \bar{q}\gamma_\mu \tau_L q\,, \qquad \mathcal{O}_{LL7} = \bar{q}\gamma^\mu \tau_L q\, \bar{q}\gamma_\mu q$$

$$\mathcal{O}_{LL8} = \bar{q}_\alpha\gamma^\mu \tau_L q_\beta\, \bar{q}_\beta\gamma_\mu \tau_L q_\alpha\,, \qquad \mathcal{O}_{LL9} = \bar{q}_\alpha\gamma^\mu \tau_L q_\beta\, \bar{q}_\beta\gamma_\mu q_\alpha$$

$$\mathcal{O}_{LL10} = \bar{q}\gamma^\mu \tau_L q\, \bar{l}\gamma_\mu \tau_L l$$

$$\mathcal{O}_{LL11} = \bar{q}\gamma^\mu \tau_L q\, \bar{l}\gamma_\mu l\,, \qquad \mathcal{O}_{LL12} = \bar{q}\gamma^\mu q\, \bar{l}\gamma_\mu \tau_L l$$

$$\mathcal{O}_{LL13} = \bar{q}\gamma^\mu \tau_L l\, \bar{l}\gamma_\mu \tau_L q\,, \qquad \mathcal{O}_{LL14} = \bar{q}\gamma^\mu \tau_L l\, \bar{l}\gamma_\mu q$$

$$\mathcal{O}_{LL15} = \bar{l}\gamma^\mu \tau_L l\, \bar{l}\gamma_\mu \tau_L l\,, \qquad \mathcal{O}_{LL16} = \bar{l}\gamma^\mu \tau_L l\, \bar{l}\gamma_\mu l$$

- $\bar{R}R\bar{R}R$ operators without U fields (7).
- $\bar{L}L\bar{R}R$ operators (18):

$$\mathcal{O}_{LR10} = \bar{q}\gamma^\mu U T_3 U^\dagger q\, \bar{u}\gamma_\mu u\,, \qquad \mathcal{O}_{LR11} = \bar{q}\gamma^\mu T^A \tau_L q\, \bar{u}\gamma_\mu T^A u$$

$$\mathcal{O}_{LR12} = \bar{q}\gamma^\mu \tau_L q\, \bar{d}\gamma_\mu d\,, \qquad \mathcal{O}_{LR13} = \bar{q}\gamma^\mu T^A \tau_L q\, \bar{d}\gamma_\mu T^A d$$

$$\mathcal{O}_{LR14} = \bar{u}\gamma^\mu u\, \bar{l}\gamma_\mu \tau_L l\,, \qquad \mathcal{O}_{LR15} = \bar{d}\gamma^\mu d\, \bar{l}\gamma_\mu \tau_L l$$

$$\mathcal{O}_{LR16} = \bar{q}\gamma^\mu \tau_L q\, \bar{e}\gamma_\mu e\,, \qquad \mathcal{O}_{LR17} = \bar{l}\gamma^\mu \tau_L l\, \bar{e}\gamma_\mu e$$

$$\mathcal{O}_{LR18} = \bar{q}\gamma^\mu \tau_L l\, \bar{e}\gamma_\mu d$$

- $\bar{L}R\bar{L}R$ operators (12):

$$\mathcal{O}_{ST5} = \bar{q}UP_{+}r\,\bar{q}UP_{-}r\,, \qquad \mathcal{O}_{ST6} = \bar{q}UP_{21}r\,\bar{q}UP_{12}r$$

$$\mathcal{O}_{ST7} = \bar{q}UP_{+}T^{A}r\,\bar{q}UP_{-}T^{A}r\,, \qquad \mathcal{O}_{ST8} = \bar{q}UP_{21}T^{A}r\,\bar{q}UP_{12}T^{A}r$$

$$\mathcal{O}_{ST9} = \bar{q}UP_{+}r\,\bar{l}UP_{-}\eta\,, \qquad \mathcal{O}_{ST10} = \bar{q}UP_{21}r\,\bar{l}UP_{12}\eta$$

$$\mathcal{O}_{ST11} = \bar{q}\sigma^{\mu\nu}UP_{+}r\,\bar{l}\sigma_{\mu\nu}UP_{-}\eta\,, \qquad \mathcal{O}_{ST12} = \bar{q}\sigma^{\mu\nu}UP_{21}r\,\bar{l}\sigma_{\mu\nu}UP_{12}\eta$$

- Four-quark operators with $Y_f \neq 0$ (11):

$$\mathcal{O}_{FY1} = \bar{q}UP_{+}r\,\bar{q}UP_{+}r\,, \qquad \mathcal{O}_{FY2} = \bar{q}UP_{+}T^{A}r\,\bar{q}UP_{+}T^{A}r$$

$$\mathcal{O}_{FY3} = \bar{q}UP_{-}r\,\bar{q}UP_{-}r\,, \qquad \mathcal{O}_{FY4} = \bar{q}UP_{-}T^{A}r\,\bar{q}UP_{-}T^{A}r$$

$$\mathcal{O}_{FY5} = \bar{q}UP_{-}r\,\bar{r}P_{+}U^{\dagger}q\,, \qquad \mathcal{O}_{FY6} = \bar{q}UP_{-}T^{A}r\,\bar{r}P_{+}U^{\dagger}T^{A}q$$

$$\mathcal{O}_{FY7} = \bar{q}UP_{-}r\,\bar{l}UP_{-}\eta\,, \qquad \mathcal{O}_{FY8} = \bar{q}\sigma^{\mu\nu}UP_{-}r\,\bar{l}\sigma_{\mu\nu}UP_{-}\eta$$

$$\mathcal{O}_{FY9} = \bar{l}UP_{-}\eta\,\bar{r}P_{+}U^{\dagger}q$$

$$\mathcal{O}_{FY10} = \bar{l}UP_{-}\eta\,\bar{l}UP_{-}\eta$$

$$\mathcal{O}_{FY11} = \bar{l}UP_{-}r\,\bar{r}P_{+}U^{\dagger}l$$

Dynamical scales

The power-counting formula is useful to identify the classes of operators associated with physics of electroweak symmetry breaking. These are counterterms needed to renormalize the theory order by order. However, some operators are unrelated to EWSB processes. A full renormalization program is in any case needed.

- Electroweak scale: $\Lambda_{EW} = 4\pi v \sim (2:3)$ TeV
- Lepton number violating scale:

$$Q_{LV} = l^T C U^* P_+ U^\dagger l$$

  Operator of dimension-3 giving Majorana mass to the neutrinos. $\Lambda_\nu \sim$ TeV-GUT scale (?).
- Baryon number breaking scale:

$$\epsilon^{abc}[d_a^T C u_b][u_c^T C e]$$

  Dimension-6 operators responsible for proton decay. $\Lambda_{BV} \sim$ GUT scale (?).
- Flavor mass scale: $\Lambda_Y \ldots$
- Generic new physics: $\bar{\psi}_L \psi_L \bar{\psi}_L \psi_L$ can be mediated with with heavy vector exchange (Z'). $\Lambda_{NP} \sim$ TeV-GUT scale (?)

Back to the linear case: SM at NLO

- Replace $U \to H/v = 1/v(\tilde{\phi}, \phi)$ in the basis operators.
- The theory will become renormalizable and so the electroweak and new physics scale decouple: $v/\Lambda \to 0$. The power-counting becomes the naive dimensional one.
- $H^\dagger H \neq 1$, so those factors have to be added in all places possible. This trivially generates $d = 4$ terms

$$(\phi^\dagger\phi)^3, \qquad (\phi^\dagger\phi)\partial^2(\phi^\dagger\phi)$$

$$(\phi^\dagger\phi)\bar{l}e\phi, \qquad (\phi^\dagger\phi)\bar{q}d\phi, \qquad (\phi^\dagger\phi)\bar{q}u\tilde{\phi}$$

$$(\phi^\dagger\phi)X_{\mu\nu}X^{\mu\nu}, \qquad (\phi^\dagger\phi)\tilde{X}_{\mu\nu}X^{\mu\nu}$$

$$(D_\mu\phi^\dagger\phi)(\phi^\dagger D^\mu\phi), \qquad B_{\mu\nu}\phi^\dagger W^{\mu\nu}\phi$$

- Some dimensional reshuffling (different power-counting): some classes get relegated to NNLO (UD^4, $\psi^4 U$, $\psi^2 UD^2$).
- We recover the SM at NLO. [Buchmüller et al'86; Grzadkowski et al'10]

Applications

Realistic models that accommodate existing experimental data hard to find. EFT approach can be a common ground where possible UV completions can be easily tested, for instance for EWPT or top physics.

- **Oblique parameters** (S, T, U). They test deviations in the gauge sector for two-point functions.

$$\mathcal{L}_{VP} = -\frac{1}{2} W_\mu^3 \Pi_{33}^{\mu\nu}(q^2) W_\nu^3 - \frac{1}{2} B_\mu \Pi_{00}^{\mu\nu}(q^2) B_\nu - W_\mu^3 \Pi_{30}^{\mu\nu}(q^2) B_\nu - W_\mu^+ \Pi_{WW}^{\mu\nu}(q^2) W_\nu^-$$

$$\hat{S} = \left(\frac{g}{g'}\right) \Pi'_{30}(0) \quad \hat{T} = \frac{\Pi_{33}(0) - \Pi_{WW}(0)}{m_W^2} \quad \hat{U} = \Pi'_{33}(0) - \Pi'_{WW}(0)$$

and involve only 3 operators of our basis, namely

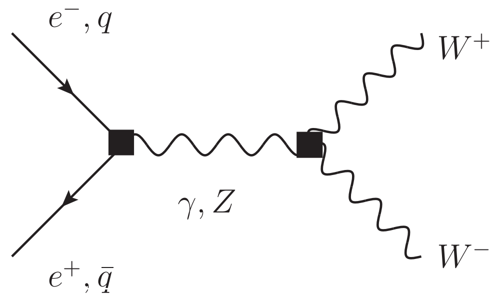
$$\mathcal{O}_\beta = v^2 \langle L_\mu \tau_L \rangle^2$$
$$\mathcal{O}_{XU1} = g' g \; B_{\mu\nu} \; \langle W^{\mu\nu} \tau_L \rangle$$
$$\mathcal{O}_{XU2} = g^2 \; \langle W_{\mu\nu} \tau_L \rangle \langle W^{\mu\nu} \tau_L \rangle$$

Then,

$$\hat{S} = -16\pi\alpha_1 \qquad \hat{T} = 2\beta_1 \qquad \hat{U} = -16\pi\alpha_2$$

The coefficients can be determined from experimental fits and then used to constrain UV completion scenarios.

- **Triple gauge vertices** (revisited)



Our effective operator basis can be matched onto the general vertex parametrization

$$\mathcal{L}_{WWV} = i\kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} + i\tilde{\kappa}_V W_\mu^+ W_\nu^- \tilde{V}^{\mu\nu} + ig_1^V (W_{\mu\nu}^+ W^{\mu -} - W_{\mu\nu}^- W^{\mu +}) V^\nu$$
$$+ g_4^V (W_{\mu\nu}^+ W^{\mu -} + W_{\mu\nu}^- W^{\mu +}) V^\nu - g_5^V (\tilde{W}_{\mu\nu}^+ W^{\mu -} + \tilde{W}_{\mu\nu}^- W^{\mu +}) V^\nu$$

where $\kappa_V = \kappa_V^0 + \Delta\kappa_V(\alpha_1, \alpha_2, ..., \beta_1)$.

- Triple gauge vertices loosely constrained (LEP). However, in combination with the oblique parameters (and LHC data?) bounds might get tighter, especially when redundancies are eliminated. EFT language really fits that purpose.

Conclusions

- An EFT description of a strongly-coupled EWSB scenario in general is useful even in the presence of a light scalar.
- For the first time we have a systematic and complete basis of operators at NLO.
- Future prospects for phenomenological applications: EWPT, top physics, etc.
- So far only the minimal setting worked out (several phenomenological applications are Higgs-insensitive). However, a light scalar can (should!) be added with a consistent power-counting.