Higgs-less Higgs mechanism: low-energy expansion

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Alternatives to the SM: without a Higgs

- **Higgs mechanism**: 3 GBs give masses to $W^\pm$ and $Z^0$
  - In the SM, 1 physical scalar: **Higgs boson** $\rightarrow$ renormalizable
  - Add **SUSY** $\rightarrow$ allow $\Lambda_{\text{new physics}} \rightarrow \infty$ with $m_H$ fixed, or...
  - Get rid of Higgs boson $\rightarrow$ $\Lambda_{\text{new physics}}$ finite: non-decoupling

**Familiar approach**: ideas from QCD

- (Walking) technicolor: strongly-interacting at $\sim 3$ TeV $\rightarrow$ uncomputable

**Recent approach**: weak-coupling up to 10's of TeV $\rightarrow$ new particles below TeV

- 5D Higgsless models: KK$^\text{holography}$ $\leftrightarrow$ resonances of 4D strongly-coupled thy.
  Csáki, Grojean, Murayama, Terning, Barbieri, Pomarol... 03

**Effective theory approach**: rely on symmetries

- DOFs: light particles ($m \rightarrow 0 \leftrightarrow$ symmetry $\uparrow$) $\rightarrow$ scalar sector: only the 3 GBs. No Higgs
Outline

- Introduction

- **Non-decoupling effective theories**
  - Loop expansion: Weinberg power-counting formula

- Application to EWSB without a Higgs particle
  - Difficulties at leading order: irrelevant operators from the SM

- Use **larger symmetry** $\text{SU}(2)^4 \times \text{U}(1)_{B-L}$
  - Reduced via *spurions* to $\text{SU}(2)_L \times \text{U}(1)_Y$

- Consequences
Expansion in non-decoupling effective theories

$L(\dim \leq 4)$ non-renormalizable $\implies$ expansion in $\partial_\mu/L_{\text{new physics}}$

- **Rescale** operators in $L$
  
  \[ p \mapsto tp, \quad g \mapsto tg \implies M_W \mapsto tM_W, \quad \chi \mapsto \sqrt{t} \chi \quad t \rightarrow 0 \]

  - Vertex $v$ scales as $t^{d_v}$, with **hopefully** $d_v \geq 2$
  
    $\implies$ diagram with $L$ loops scales as $t^D$ (i.e. is $O(p^D)$) with
    \[
    D = 2 + 2L + \sum_{v=1}^{V} (d_v - 2) \quad \text{Weinberg 79}
    \]

- **Precision** $D \implies L \leq D/2 - 1 \implies$ finite number of diagrams/divergences
  
  - $O(p^2)$: tree diagrams with $L_{O(p^2)}$
  
  - $O(p^4)$: one-loop diagrams with $L_{O(p^2)}$, renormalized by $L_{O(p^4)}$ trees

- Renormalized and unitarized **order-by-order** Gasser, Leutwyler 84
  
  - Finite scale-independent results: no cut-off
Direct application to Higgs-less EWSB

\[ \text{SU}(2)_L \times \text{U}(1)_Y \rightarrow \text{U}(1)_{\text{em}} : 3 \text{ GBs} \implies \Sigma \in \text{SU}(2): \quad \Sigma \leftrightarrow G \Sigma e^{i \alpha_0 \tau^3 / 2} \]

- Compare Higgs doublet \( \Phi \equiv (\phi_c, \phi) \):
  \[ \Sigma \leftrightarrow \Phi / \sqrt{\det \Phi} \]
  \[ \nu \approx 246 \text{ GeV of the SM} \rightarrow \text{GB decay constant} \rightarrow \Lambda_{\text{new physics}} \approx 3 \text{ TeV} \]

**Conflict with phenomenology:** unwanted operators at \( \mathcal{O}(p^2) \) (irrelevant in SM)

\[ b^{0}_{\mu \nu} \left< G^{\mu \nu} \Sigma \tau^3 \Sigma^\dagger \right> \implies S \quad \text{Holdom, Terning 90} \]

\[ \Lambda^2 \left< \tau^3 \Sigma D_\mu \Sigma \right>^2 \implies T \quad \text{Longhitano 80} \]

\[ i \overline{\chi_L} \gamma^\mu (D_\mu \Sigma)^\dagger \chi_L \implies \delta_L \quad \text{Appelquist et al. 80} \]

\[ i \overline{\chi_R} \gamma^\mu (\Sigma^\dagger D_\mu \Sigma) \chi_R \implies \delta_R \quad \text{Peccei, Zhang 95} \]

Consider scenarios where suppression is automatic: larger symmetry \( S_{\text{natural}} \)

**Danger for consistency of expansion:** operators with \( d_\nu < 2 \)

- Fermion masses and LNV appear at \( \mathcal{O}(p^1) \)
  \[ \Lambda \overline{\chi_L} \Sigma \chi_R = \mathcal{O}(p^1) \]
  \[ \Lambda \overline{\ell_L} \Sigma^\dagger \tau^- \Sigma (\ell_L)^c = \mathcal{O}(p^1) \]
Larger symmetry $S_{\text{natural}} = \text{SU}(2)^4 \times \text{U}(1)$

Elementary sector:

- Elementary $\text{SU}(2)_{GL} \times \text{SU}(2)_{GR} \times \text{U}(1)_{B-L}$ gauge fields
  \[ g_L G^a_{L\mu}, \quad g_R G^a_{R\mu}, \quad g_B G_{B\mu} \]

- Left and right fermion doublets (right isospin $\implies$ custodial symmetry)
  \[ \chi_L \leftrightarrow G_L e^{-i \frac{B-L}{2} \alpha} \chi_L \]
  \[ \chi_R \leftrightarrow G_R e^{-i \frac{B-L}{2} \alpha} \chi_R \]
  introduced $\nu_R$

Composite sector:

- 3 GBs of spontaneous $\text{SU}(2)_{\Gamma_L} \times \text{SU}(2)_{\Gamma_R} \rightarrow \text{SU}(2)_{\Gamma_L+\Gamma_R}$
  \[ \Sigma \leftrightarrow \Gamma_L \Sigma \Gamma_R^\dagger \]

- Ward ids of global sym. $\leftrightarrow$ local invariance $\Rightarrow$ connections $\Gamma^a_{L\mu}, \Gamma^a_{R\mu}$
Spurions & constraints

Identification up to a gauge:

\[ \Gamma_L = \Omega_L g_L G_{L \mu} \Omega_L^\dagger + i \Omega_L \partial_\mu \Omega_L^\dagger \]

- Imagine that \( \Omega_L \mapsto G_L \Omega_L \Gamma_L^\dagger \) is a field
Spurions & constraints

Identification up to a gauge: \( D_\mu \Omega_L = 0 \)

- Imagine that \( \Omega_L \mapsto \mathcal{G}_L \Omega_L \Gamma^\dagger_L \) is a field
Spurions & constraints

Identification up to a gauge: \( D_\mu \Omega_L = 0 \)

- Imagine that \( \Omega_L \mapsto G_L \Omega_L \Gamma_L^{\dagger} \) is a field
- But, \( \Omega_L \) unitary \( \Rightarrow \) redundant \( \Rightarrow \) need to introduce constant in front \( \Rightarrow \xi U_L \)

Spurions: field \( X(x) \mapsto G_L X \Gamma_L^{\dagger} \) (reality cond. \( \tau^2 X^\ast \tau^2 = X \))

- Impose constraint \( D_\mu X = 0 \) \( \Rightarrow \) no kinetic term \( \Rightarrow \) does not propagate
  - To solve constraint: choose appropriate gauge & find
    \[
    \Gamma_{L\mu} = g_L G_{L\mu} \quad X = \xi 1 \quad \text{with} \quad \partial_\mu \xi = 0
    \]

- Generic spurions \( Y_u \) selects & identifies \( U(1) \) subgroups of \( \Gamma_R \) & \( G_R \)
- Generic spurion \( Z \) to identify \( U(1) \) subgroup of \( G_R \) with \( U(1)_{B-L} \)

Consequences of constraints: \( S_{\text{natural}} \) reduced to \( SU(2)_L \times U(1)_Y \)

- Spurions \( X, Y_u, Z \) eliminated in favor of 3 constants \( \xi, \eta, \zeta \)
  - \( S_{\text{natural}} \) protects \( \xi, \eta, \zeta \) \( \Rightarrow \) use them as expansion parameters

Spurions: ignore details of mechanisms, only use symmetries
The leading-order lagrangian

Build most \textbf{general lagrangian invariant under }$S_{\text{natural}}$

- \textbf{Double expansion}: usual momentum one + spurions
  - Solve constraints on spurions, yields constants $\xi, \eta, \zeta$

\textbf{Leading order:}

- $O(p^2)$ lagrangian \textbf{without} spurions
  - GB kinetic term $\implies W^\pm$ \& $Z^0$ masses
    \[ M_{W}^2 = g^2 \frac{f^2}{4}, \quad M_{Z}^2 = \left( g^2 + g'^2 \right) \frac{f^2}{4} \]
  - Fermion interactions as in the SM (Higgs removed)

- $O(p^1)$ lagrangian with \textbf{two powers of }$X$ \textbf{or }$Y$
  - Dirac masses: \quad (\text{suggests counting } XY = O(p))
    \[ \mathcal{L}_{\text{quark masses}} = - \left( \mu_{ij}^{u} \overline{q}_{L}^{i} X^{\dagger} \sum Y_{u} q_{R}^{j} + \mu_{ij}^{d} \overline{q}_{L}^{i} X^{\dagger} \sum Y_{d} q_{L}^{j} \right) \]
What happened to the SM irrelevant operators?

Come with powers of spurions $\implies$ relegated to higher-orders

- Modification of fermion-vector couplings: $O(p^2)$ and quadratic in spurions

$$i \bar{\chi}_L \gamma^\mu X^\dagger \Sigma (D_\mu \Sigma)^\dagger X \chi_L \text{ standard gauge} = -\xi^2 \frac{e}{c_s} \left( \frac{u_L}{d_L} \right) \gamma^\mu \frac{\tau^3}{2} Z_\mu \left( \frac{u_L}{d_L} \right)$$

They are the first corrections, before the oblique ones!

- $S$, $T$ parameters do not come before loops: $O(p^2)$ and quartic in spurions

$$\left\langle G_L^{\mu\nu} X^\dagger \Sigma (Y_u - Y_d) G_{R\mu\nu} (Y_u - Y_d)^\dagger \Sigma^\dagger X \right\rangle \Rightarrow S$$

$$\Lambda^2 \left\langle \left( Y_u Y_u^\dagger - Y_d Y_d^\dagger \right) \Sigma^\dagger D_\mu \Sigma \right\rangle^2 \Rightarrow T$$

- LNV introduced by $Z \implies$ need $\zeta \ll \xi \eta \ll 1$

$$\Lambda \bar{\ell}_L X^\dagger \Sigma Y_u Z Y_d^\dagger \Sigma^\dagger X (\ell_L)^c \Rightarrow m_{\nu_L}$$

$$\Lambda \bar{\ell}_R Z (\ell_R)^c \Rightarrow m_{\nu_R}$$

- No see-saw possible: forbid $\nu$ Dirac masses by $\mathbb{Z}_2$ symmetry $\nu_R \longleftrightarrow -\nu_R$ $\implies$ Light $\nu_R$s: stable, super-weak interactions $\implies$ limits from cosmology
Conclusions

Viable effective theory of Higgs-less EWSB:

- Simultaneous expansion in $p$ and spurions
  - Corresponding loop formalism exists
  - Irrelevant operators in the SM relegated to higher orders
    - First deviations from SM are not oblique corrections, but
      - Non-standard fermion-vector interactions