Physics Beyond the Standard Model 3.1

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Beyond the Standard Model

<u>Lecture 1</u>
- Why do we need to go Beyond the SM ?
- The Hierarchy Problem: what do we need to solve it ?

<u>Lecture 2</u>
- Supersymmetry and the Hierarchy Problem

<u>Lecture 3</u>
- New Dynamics at the TeV scale: the Higgs as a (pseudo) Nambu-Goldstone Boson

Beyond the Standard Model III

- Solve the Hierarchy problem with dynamics: QCD and the σ (Technicolor, ...)

- Dynamical (composite) *light* Higgs: is a (pseudo) Goldstone boson
  The example of the pion in QCD

- Composite Higgs Models:

  Little Higgs
  Twin Higgs
  Gauge-Higgs unification in AdS_5

Where is the Scalar Sector Coming From

- But what determines m and λ ?

- Is the scalar sector resulting from some underlying dynamics ?

E.g. Superconductivity:

Cooper pairs $\Rightarrow \langle\Phi\rangle \neq 0$

$\mathcal{L}_\Phi$ is the Ginzburg-Landau theory $\Big\{$ EM broken in the SC; Meissner effect; penetration depth; ⋮

But microscopic description is BCS

Physics Beyond the Standard Model

Organize by origin of Higgs sector or solution to HP

- Supersymmetry:

  Higgs is elementary

  SUSY protects m_h

- Higgs sector is composite:

  Technicolor. No Higgs. ✗

  Higgs is a pNGB ✓

Composite Scalars: the Example of QCD

Spontaneous breaking of chiral symmetry in QCD

QCD with 2 flavors:

$$\mathcal{L}_{\rm QCD} = \bar{Q}_L\, i\, \not{D} Q_L + \bar{Q}_R\, i\, \not{D} Q_R - \bar{Q}_L\, M Q_R + \text{h.c.}$$

with

$$Q = \begin{pmatrix} u \\ d \end{pmatrix} \qquad\qquad M = \begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix}$$

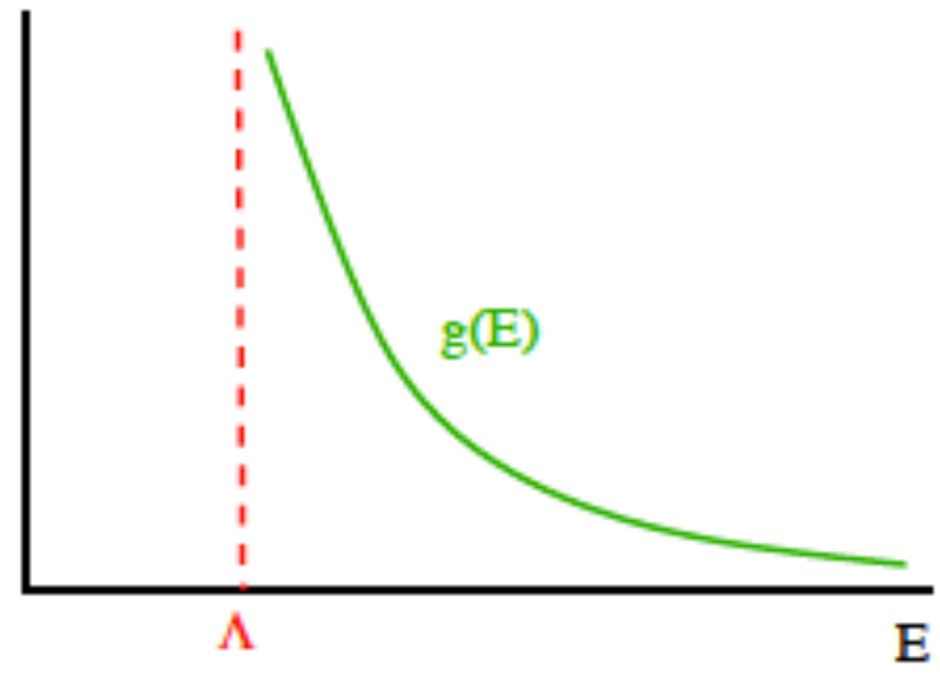
If $M = 0$, is invariant under $SU(2)_L \times SU(2)_R$

$$\begin{aligned} Q_L &\longrightarrow e^{i\ell^a t^a}\, Q_L \\ Q_R &\longrightarrow e^{i r^a t^a}\, Q_R \end{aligned}$$

with $\begin{cases} t^a = \dfrac{\sigma^a}{2}, \quad a = 1, 2, 3 \\ \ell^a,\ r^a \quad \text{free parameters} \end{cases}$

Chiral Symmetry Breaking

$SU(3)_c$ asymptotically free



At low energies, $\Lambda \simeq \Lambda_{\rm QCD}$, quark condensation

$$\langle \bar{Q}_L Q_R \rangle \neq 0 \quad \Rightarrow SU(2)_{\times} SU(2)_R \longrightarrow \quad SU(2)_V$$

- Quarks acquire a dynamical mass

$$m_Q \sim \Lambda_{\rm QCD}$$

Chiral Symmetry Breaking

- 3 broken generators $\Longrightarrow$ 3 NGBs (π^+, π^-, π^0)

Since $SU(2)_L \times SU(2)_R = SU(2)_V \times SU(2)_A \longrightarrow SU(2)_V$

Axial current $j_\mu^{a5} = \bar{Q}\gamma_\mu\gamma^5 Q$

does not annihilate the vacuum

$$\langle 0 | j_\mu^{a5} | \pi^b(p_\mu) \rangle = i f_\pi \, p_\mu \, \delta^{ab}$$

But still conserved if $m_\pi = 0$

$$\partial^\mu \, j_\mu^{a5} = f_\pi m_\pi^2$$

Spontaneous Breaking of Chiral Symmetry

Linear σ model

$$\mathcal{L} = \frac{1}{4}\mathrm{Tr}\left[\partial_\mu \Sigma^\dagger \partial^\mu \Sigma\right] + \frac{\mu^2}{4}\mathrm{Tr}\left[\Sigma^\dagger \Sigma\right] - \frac{\lambda}{16}\left(\mathrm{Tr}\left[\Sigma^\dagger \Sigma\right]\right)^2$$

with

$$\Sigma = \sigma + i\, t^a \pi^a$$

If $\mu^2 > 0 \quad \Rightarrow \langle \Sigma \rangle = v \neq 0$

$$v = \sqrt{\frac{\mu^2}{\lambda}}$$

$\Rightarrow$ Spontaneous breaking of chiral symmetry

$$m_\sigma = \sqrt{2\lambda}\, v$$

$$m_\pi = 0$$

Spontaneous Breaking of Chiral Symmetry

<u>In real QCD:</u>

- $\begin{cases} m_\sigma \sim \Gamma_\sigma \sim \; O(1)\ \text{GeV} & \text{Cutoff of the effective theory} \\ \sigma \; \text{is not a low energy state (too broad to be observable)} \end{cases}$

- $m_u,\ m_d \neq 0 \quad \Longrightarrow$ Explicit symmetry breaking

$m_\pi \neq 0$ $\qquad$ $\pi' s$ are pseudo NGBs

But still light

$$m_\pi \simeq 0.14\text{GeV} \ll O(1)\ \text{GeV}$$

GeV vs. TeV Scales

Build a TeV-scale model of *EWSB* in analogy with QCD

Two avenues:

- Fermionic sector breaks *EWS* just as in QCD

  Higgs (σ) is not is the light spectrum

- Strong sector breaks global symmetry

  Higgs is a (pseudo) NGB remnant

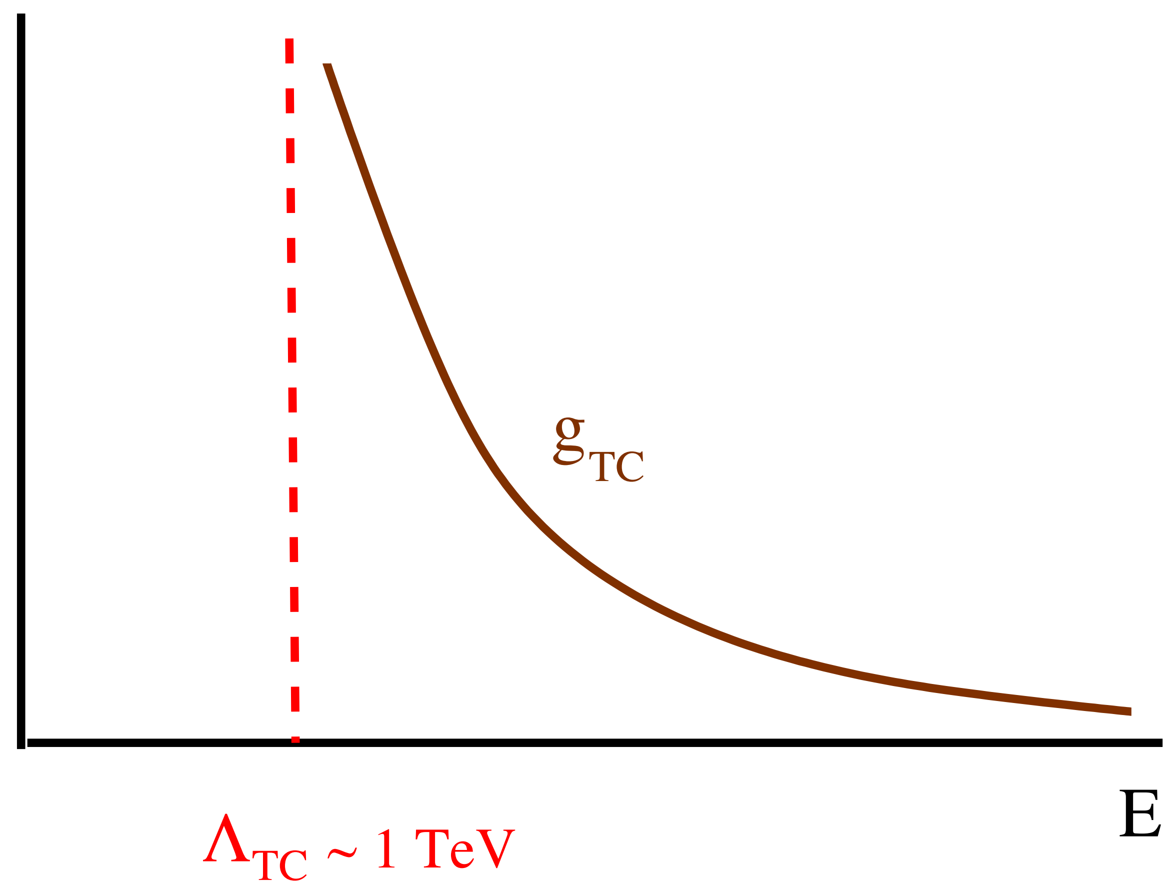
  just like the $\pi's$

Strong Dynamics at the TeV Scale

Scaled up QCD

- New gauge interaction
- Strong at the TeV scale
- Breaks EWS by

$$\langle \bar{F} F \rangle \neq 0$$



Basic Technicolor Model

- Asymptotically-free interaction $SU(N_T)$
- New fermions: $SU(2)_L$ doublet

$$Q_L = \begin{pmatrix} T \\ B \end{pmatrix}_L \qquad (N_T, 1, 2, Y_Q)$$

$$T_R \qquad (N_T, 1, 1, Y_T)$$

$$B_R \qquad (N_T, 1, 1, Y_B)$$

- At Λ_{TC} we have $\langle \bar{Q}_L Q_R \rangle \neq 0$

$\Rightarrow$ { Spontaneous breaking of global $SU(2)_L \times SU(2)_R$

Also SB of the gauge $SU(2)_L \times U(1)_Y \to U(1)_{\rm EM}$

Higgs Mechanism without a Higgs

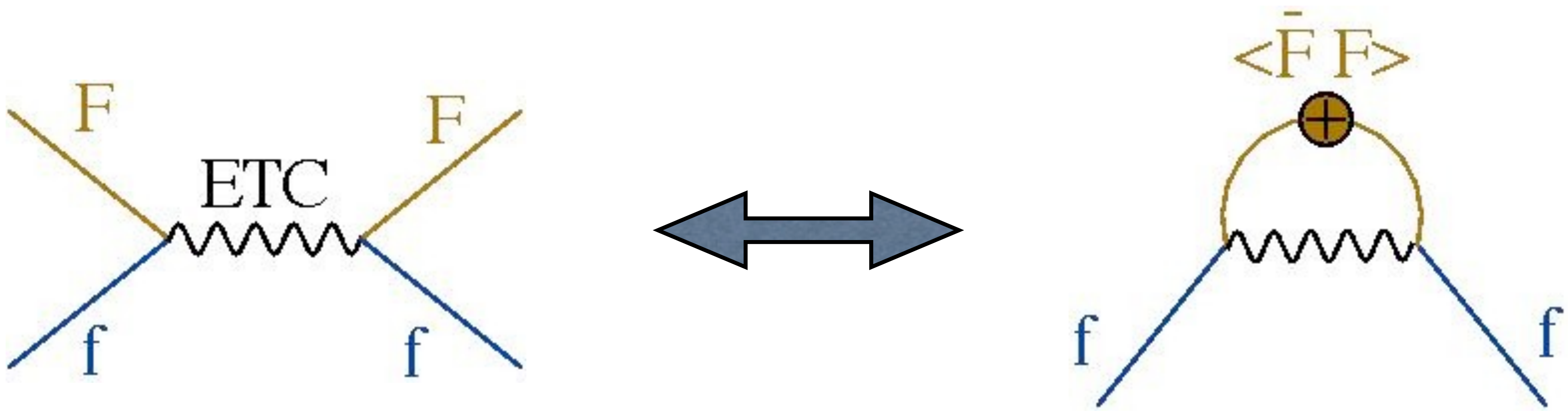
$SU(2)_L \times SU(2)_R \to SU(2)_V \quad \Longrightarrow$ 3 Nambu-Goldstone bosons

NGBs eaten as gauge boson longitudinal polarizations

$$i\frac{g^2\,F_T^2}{4}\left(g_{\mu\nu}-\frac{q_\mu q_\nu}{q^2}\right)$$

Fermion Masses without a Higgs

Need extended interaction mixing SM fermions with tfermions



$$-\frac{g^2_{\rm ETC}}{M^2_{\rm ETC}}\,\bar{f} f\,\bar{F} F \qquad \Rightarrow \qquad m_f \sim \frac{g^2_{\rm ETC}}{M^2_{\rm ETC}}\,\Lambda^3_{\rm TC}$$

Extended Technicolor

ETC requires more techni-fermions

$\begin{pmatrix} T \\ B \end{pmatrix}_L^i$ $\quad T_R^i,\ B_R^i$ techni-quarks

$\begin{pmatrix} N \\ E \end{pmatrix}_L$ $\quad N_R,\ E_R$ techni-leptons

- Number of doublets higher $N_D = 4$

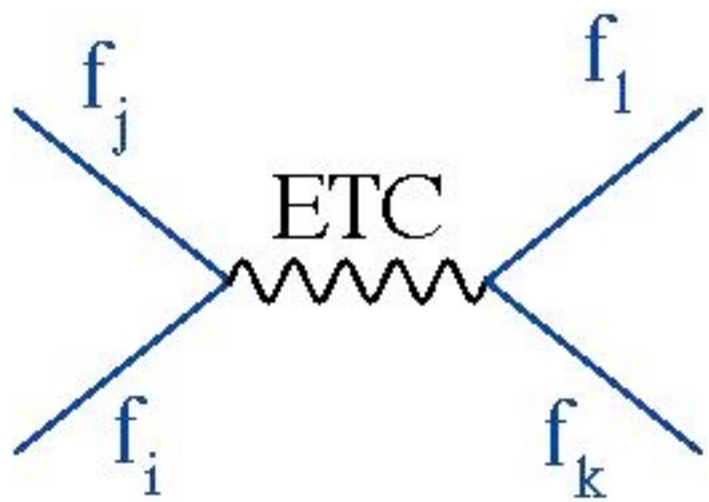
  Problems with EWPC

- Larger chiral symmetry broken $SU(8)_L \times SU(8)_R \longrightarrow SU(8)_V$

  63 -3 = 60 NGBs left in the spectrum!

Flavor Violation from ETC Interactions

ETC leads to tree-level flavor violation



$\Rightarrow$ effects in $(K^0 - \bar{K}^0),\ (B^0 - \bar{B}^0),$ mixing, ...

$$\Rightarrow\ M_{\rm ETC} > 1000\ {\rm TeV}$$

But $M_{\rm ETC}$ cannot be too large or it would suppress m_t, m_b, m_c too much

Walking Technicolor and Separation of Scales

To get heavier masses need to enhance TC condensate

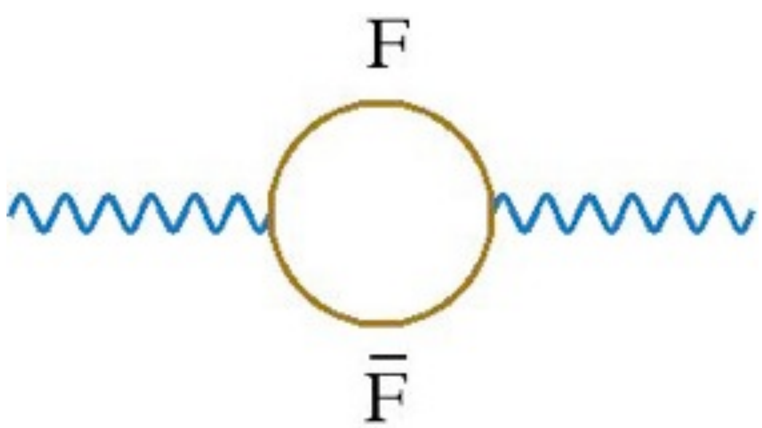
$$\Rightarrow \begin{cases} \text{Near-conformal behavior of TC interaction} \\ \text{Coupling walks} \end{cases}$$

But walking takes long time for coupling to become super-critical

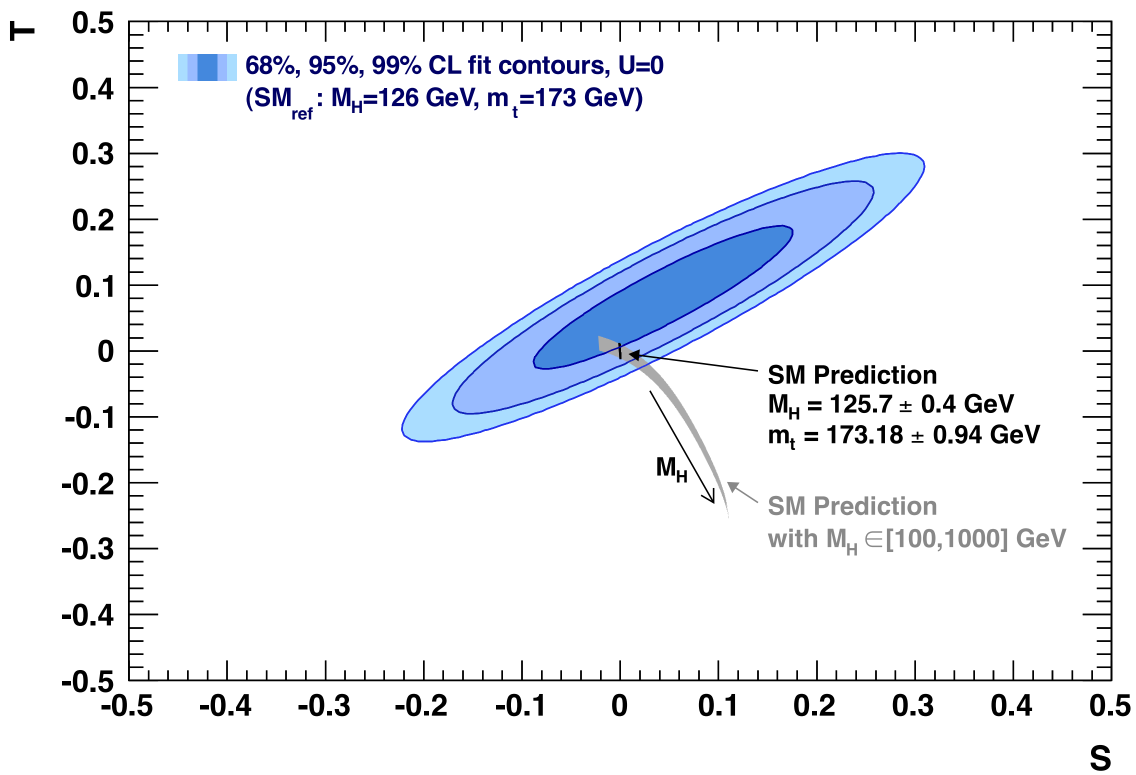
$\Longrightarrow$ Walking generates large separation of scale

Electroweak Precision Constraints

<u>For the simple scaled up QCD scenario</u>



$$\Rightarrow \qquad S \sim \frac{N_T N_D}{6\pi}$$



S is very large in QCD-like models

New Ideas in Techni-Color Models

- Minimal Walking Technicolor (F. Saninno *et al.*)

  $$N_T = 2, N_D = 1$$

  No flavor theory

  Not clear how to get a light Higgs

  Can be modeled in AdS_5

- Conformal Technicolor (M. Luty *et al.*)

  Strong sector is near a conformal fixed point in the UV

  Explicit conformal breaking $\rightarrow$ EWSB

  First basic models accommodate light Higgs as pNGB

Higgs is a pseudo Nambu-Goldstone Boson

Back to the analogy of QCD at low energies

- Build models where the Higgs is like π instead of σ

  Need to break global symmetry spontaneously

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

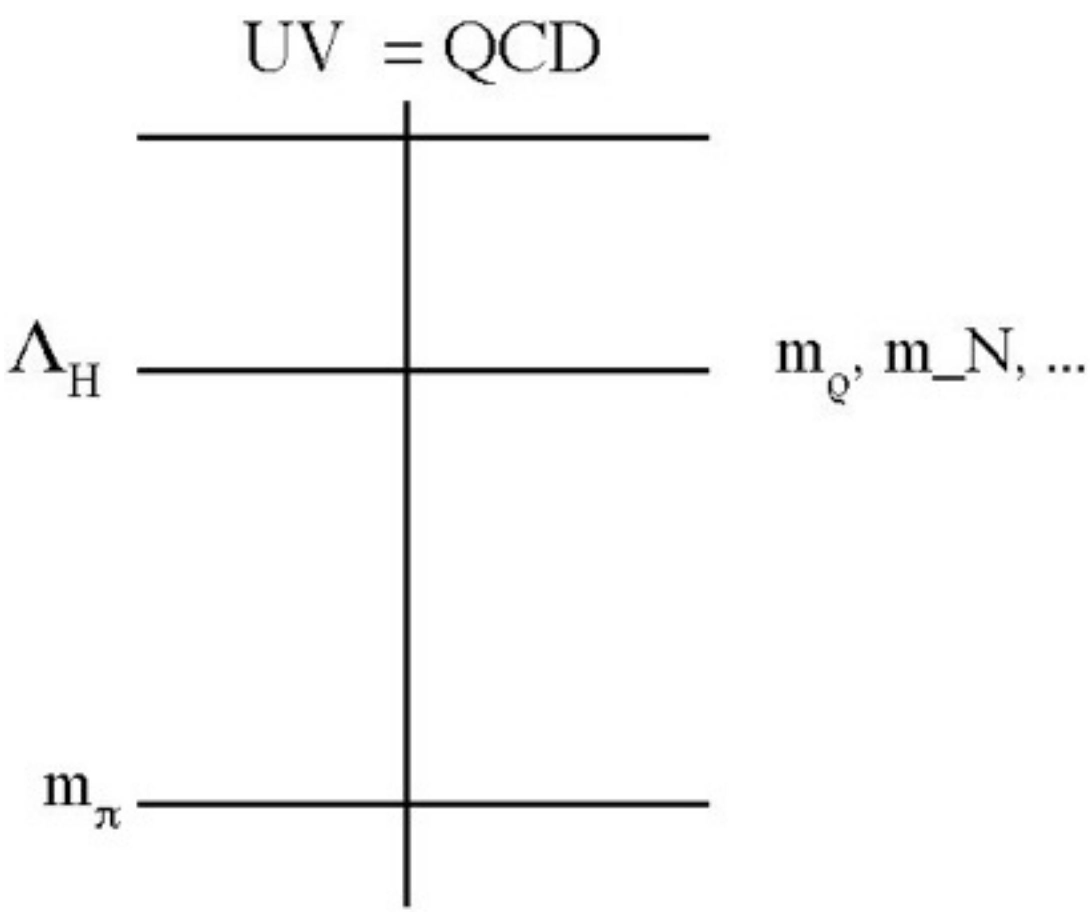
Number of NGBs: $3+3-3=3 \qquad (\pi^+, \pi^-, \pi^0)$

- Explicit symmetry breaking:

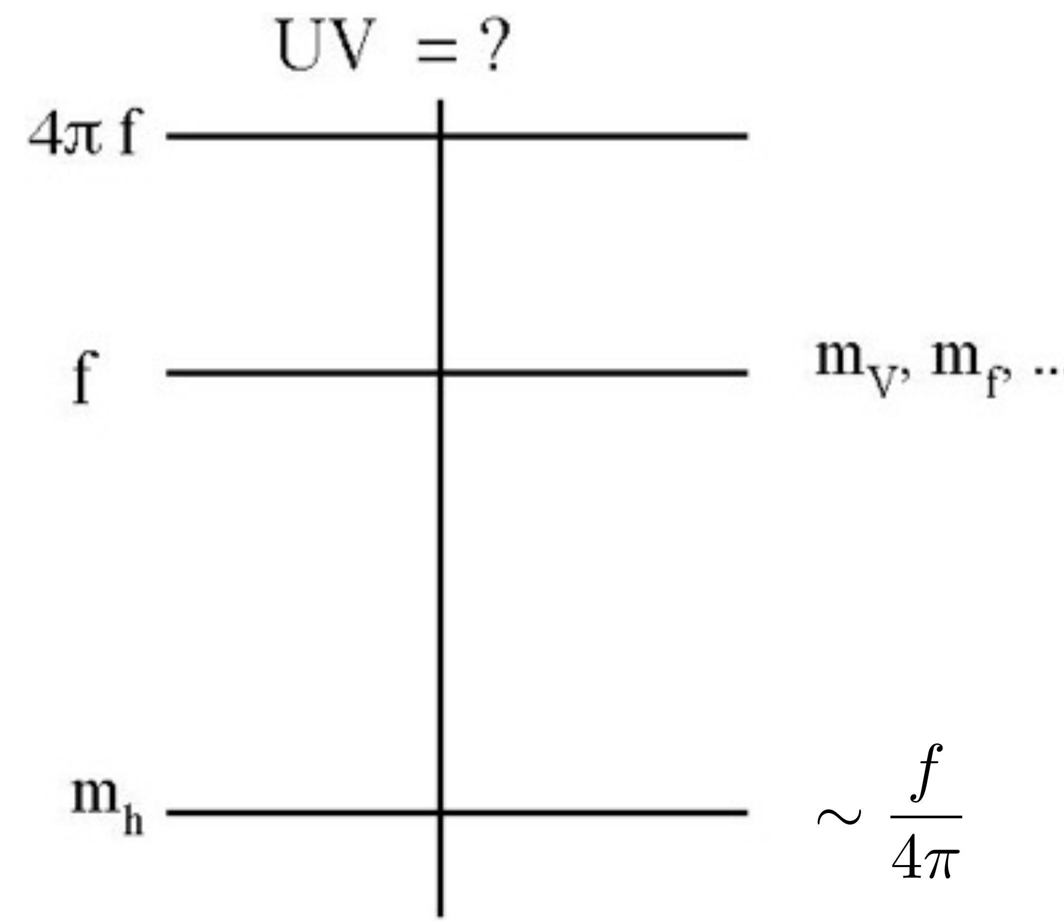
$$m_\pi^2 = B_0\, m_q$$

gives mass to the NGB

Higgs is a pNGB



QCD



Electroweak