III. Strong dynamics 1506.01961

III.1 Dimensional transmutation

- Another popular attempt to solve the hierarchy problem is to make the Higgs composite with a finite size r_H.
  - ⇒ The Higgs is now a bound state of a new strong force, with a confinement scale $m_* = 1/r_H \sim 1$ TeV.

- The hierarchy problem is solved because
  - the Higgs behaves as elementary at low energy → quadratic grows with E.
  - At $E \sim m_*$, we probe the internal structure of the Higgs and the finite size effects take over. The growing behavior with E is replaced by a peak followed by a steep fall.

  ⇒ no Higgs particle should be present in the theory for $E > m_*$.

(As for QCD when one moves from the quark to the baryon/pion picture)

- The composite sector must however not generate a new hierarchy problem when one sets m_* at the TeV scale, in particular as it emerges at a high scale $\Lambda_{UV} \gg 1$ TeV.

⇒ The composite sector should not include operators with scaling dimension well below 4 (for instance, $\mu^2 \phi^\dagger \phi$ has $d = 2$ → BAD) ≡ no unprotected scale.

i.e. no parameters with large positive dimensionality

⇒ one known example: QCD @ low-energy (no weak bosons + no heavy quarks)
The only dimensionful parameters are the quark mass ones ⇒ protected by the chiral symmetry → act like if $d \sim 4$.

Reminder: QCD with N_f massless quarks:

$$\mathcal{L}_0 = \sum_f \bar{q}_f \, i \not{D} \, q_f - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

The Lagrangian is invariant under $\underbrace{SU(N_f)_L \times SU(N_f)_R \times U(1)_L \times U(1)_R}_{\text{large global symmetry}}$

This symmetry is however broken spontaneously:

▷ $SU(N_f)_L \times SU(N_f)_R \to SU(N_f)_V$ (the axial part is broken)

$N_f = 3 \to 8$ NG bosons (massless): $\pi^\pm, \pi^0, K^\pm, K^0, \bar{K}^0, \eta$

But quark are massive ⇒ 8 PNG bosons that are much lighter than any other states.

→ $\langle \bar{q}_L q_R + \bar{q}_R q_L \rangle \propto \Lambda^3_{QCD}$

$\triangleright$ $U(1)_L \times U(1)_R = U(1)_V \times U(1)_A$ — counterterm

$U(1)_V$: baryon number

$U(1)_A$: not a symmetry (Adler-Bell-Jackiw anomaly) cannot be compensated even by a counterterm

Chiral perturbation theory: $\Delta m < \Lambda_{QCD} \rightarrow$ mass-difference effects can be treated perturbatively.

- In QCD, the confinement scale is given by

$$\log \frac{m_Z}{m^*} = \frac{1}{18} \frac{16\pi^2}{g_s^2(m_Z)} \quad (\text{RGE}) \qquad (\Lambda_{UV} = m_Z)$$

A scale m^* is generated although there is no dimensionful parameter in the Lagrangian $\equiv$ dimensional transmutation.

In the composite case, we would have $\boxed{\log \frac{\Lambda_{UV}}{m^*} = \frac{8\pi^2}{b_1 g^2(\Lambda_{UV})}}$

$\rightarrow$ we can dynamically generate the confinement scale m^* from an asymptotically free theory in which $g^2(\Lambda_{UV})$ is small.

• The theory we have contains thus 2 sectors:

1) The elementary sector with all SM particles except the Higgs
↳ weakly coupled gauge theory
↳ no Yukawa terms (as no Higgs)

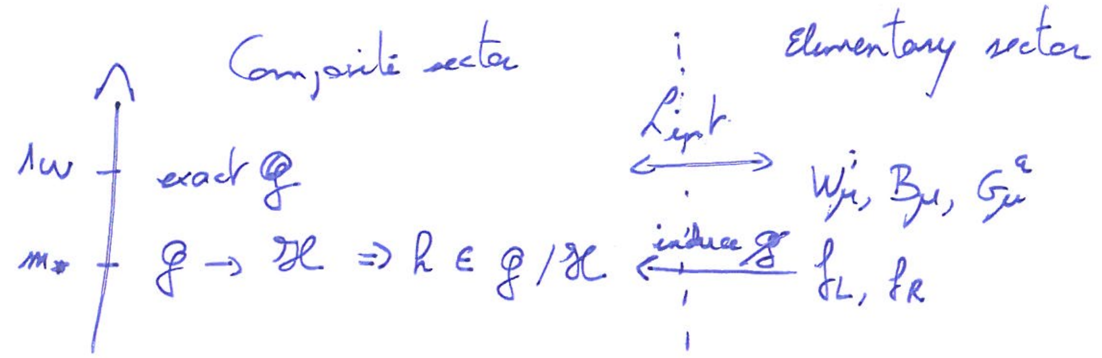
2) The composite sector
↳ need to respect the SM gauge symmetries because the SM bosons are (phenomenologically) elementary
↳ Exact symmetry group $\mathcal{G} \supset \underbrace{SU(2) \times U(1)}_{\text{gauged as usual}}$
↳ difference with QCD
(can be alleviated if needed)
↳ EW communication between the 2 sectors

Analogy with QCD: 1) leptons + photons
2) Quarks ; $\mathcal{G} = SU(3)_L \times SU(3)_R \supset U(1)_{e.m.}$
but here, $\mathcal{G}$ is broken by the quark masses
→ not the case for composite BSM.

• At a scale m^*, $\mathcal{G} \to \mathcal{H}$ ⇒ massless NG bosons in the $\mathcal{G}/\mathcal{H}$ coset.
→ the Higgs is one of them, acquires a mass + potential → breaks the EW symmetry

The symmetry group $\mathcal{G}$ is explicitly broken by the elementary sector
$\Rightarrow$ the Higgs is in fact a PNG boson.

$\Rightarrow$ This trick makes the model phenomenologically viable: the Higgs is not a bound state emerging from the composite sector $\rightarrow$ m_* can be in the TeV / multi-TeV range. $\Rightarrow$ lighter PNG bosons + heavier resonances



The breaking is small $\rightarrow$ weak perturbation (as in QCD where the weak interaction are a small perturbation of the strong dynamics) This also explains why h is light and acts as an elementary particle $\rightarrow$ tuning.

IV. 2 Vacuum misalignment

- We have a composite sector symmetry $\mathcal{G}$, and a vacuum state invariant under $\mathcal{H} \subset \mathcal{G}$.
- The spontaneous breaking $\mathcal{G} \to \mathcal{H}$ induces the appearance of NG bosons in $\mathcal{G}/\mathcal{H}$.
- $\mathcal{H}$ contains $SU(2)_L \times U(1)_Y \equiv G_{EW}$.
- $\mathcal{G}$ has to be large enough so that at least one Higgs doublet is present in the coset.

- Notations: we consider a vacuum $\vec{F}$ and a set of generators of $\mathcal{G} \equiv \{T_a, \hat{T}_{\hat{a}}\}$

  so that $T_a \vec{F} = 0$ and $\hat{T}_{\hat{a}} \vec{F} \neq 0$

  unbroken $\equiv \mathcal{H}$ $\Downarrow$ contains the G_{EW} generators

  broken $\equiv \mathcal{G}/\mathcal{H}$

  The PNG bosons $\theta_{\hat{a}}$ are: $\vec{\phi}(x) = e^{\overbrace{i\theta^{\hat{a}}(x)\hat{T}_{\hat{a}}}^{\text{local transformations in the } \hat{T}_{\hat{a}} \text{ direction}}} \vec{F}$

  $\to$ we have at least 4 of them ($\equiv$ 1 Higgs doublet)

- They develop vacuum expectation values $\langle\theta\rangle \neq 0$ that breaks G_{EW}.

example:

$\mathcal{H}$

$\mathcal{G} = SO(3)$
$\mathcal{H} = SO(2)$

$v = f \sin\langle\theta\rangle$

$\|\vec{F}\| =$ scale of the $\mathcal{G} \to \mathcal{H}$ breaking

vev breaking $SO(2)$

$\langle\theta\rangle$ is derived by minimization of the PNGB potential

- We need a small breaking:

$$\xi \equiv \frac{v^2}{f^2} = \sin^2\langle\theta\rangle \ll 1.$$

The SM limit is retrieved for $f \to \infty$ ($\xi \to 0$): the composite scale is sent to ∞. $\equiv$ decoupling of the composite sector.

- $\xi \ll 1$ may sound unnatural (ξ should be $\mathcal{O}(1)$)
  - ▷ $\xi \sim 0.1 \to$ reasonable fine-tuning
  - ▷ Built-in mechanism (e.g. little-Higgs program where quartic couplings are enlarged $\to$ hard to get $m_H \sim 125\,\text{GeV}$)

III.3 A minimal example

- The simplest option:

$$\left.\begin{array}{l} \mathcal{G} = SO(5) \\ \mathcal{H} = SO(4) \end{array}\right\} \mathcal{G}/\mathcal{H} \to 4 \text{ PNG bosons}$$

- Fundamental representation of $SO(5)$: 10 antisymmetric real 5×5 matrices
  $SO(4)$: 6 " " 4×4 matrices
  (↳ $SO(4) \sim SU(2)_L \times SU(2)_R$ and we identify $t^3_R \sim Y$) $\to \mathcal{G}_{EW}$ is included
- We now consider the Lagrangian

$$\mathcal{L} = \frac{1}{2}\partial_\mu \vec{\phi}^T \cdot \partial^\mu \vec{\phi} - \frac{g_*^2}{8}\left(\vec{\phi}^T \cdot \phi - f^2\right)^2$$

$\vec{\phi}$ is here an $SO(5)$ fiveplet and the theory is invariant under global $SO(5)$ transformations:

$$\vec{\phi} \to e^{i\alpha_A T^A}\vec{\phi} \qquad \text{with } A = 1, 2, \dots, 5$$

Here, the $SO(5)$ generators in the fundamental are:

$$T^a = \begin{bmatrix} t_L^\alpha & 0 \\ 0 & 0 \end{bmatrix}, \quad \begin{bmatrix} t_R^\alpha & 0 \\ 0 & 0 \end{bmatrix} \quad \text{with } (t_L^\alpha)_{ij} = \frac{1}{4}\mathrm{Tr}\left[\bar{\sigma}_i^\dagger \sigma^\alpha \bar{\sigma}_j\right], \quad \alpha = 1,2,3$$

$$(t_R^\alpha)_{ij} = \frac{1}{4}\mathrm{Tr}\left[\bar{\sigma}_i \sigma^\alpha \bar{\sigma}_j^\dagger\right]$$

$$\underbrace{\text{where } \bar{\sigma}_i = \{i\sigma_\alpha, 1\}}_{6\ SO(4)\text{ generators}}$$

$$(\hat{T}^{\hat{a}})_{ij} = -\frac{i}{\sqrt{2}}\left(\delta_i^{\hat{a}}\delta_j^5 - \delta_j^{\hat{a}}\delta_i^5\right) \qquad 4 \text{ broken generators}$$

$\vec{\phi}$ acquires a vev $\langle\vec{\phi}\rangle$: $SO(5) \to SO(4)$

vacuum configuration : $\vec{F} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ f \end{pmatrix}$

We will parametrize $\vec{\phi}$ around the vacuum: $\hat{\phi}(x) = e^{i\frac{\sqrt{2}}{f}\Pi_{\hat{a}}(x)\hat{T}^{\hat{a}}} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ f+\sigma(x) \end{pmatrix}$

normalization to get canonical kin. term

4 NG bosons

(resonance field)

we in fact have : one "radial" coordinate $\sigma(x)$
four "angular" coordinates $\vec{\Pi}(x)$ } describe fluctuations around the broken generators

$$\Rightarrow \hat{\phi}(x) = \underbrace{\begin{pmatrix} \mathbb{1}_{4\times 4} - \left(1-\cos\frac{\pi}{f}\right)\dfrac{\overset{\substack{4\times 1 \text{ vector} \\ \downarrow}}{\vec{\pi}}\cdot\vec{\pi}^{T}}{\pi^2} & \sin\frac{\pi}{f}\,\frac{\vec{\pi}}{\pi} \\ -\sin\frac{\pi}{f}\,\frac{\vec{\pi}^{T}}{\pi} & \cos\frac{\pi}{f} \end{pmatrix}}_{\left(= \exp\left(i\frac{\sqrt{2}}{f}\pi_{\hat{a}}\hat{T}^{\hat{a}}\right)\right)} \begin{pmatrix} \vec{0}_{4\times 1} \\ f+\sigma(x) \end{pmatrix}$$

with $\pi^2 = \sqrt{\vec{\pi}^{T}\cdot\pi}$

$$\Rightarrow \hat{\phi}(x) = (f+\sigma(x)) \begin{pmatrix} \sin\frac{\pi(x)}{f}\,\frac{\vec{\pi}(x)}{\pi} \\ \cos\frac{\pi(x)}{f} \end{pmatrix}$$

(actually a general expression for any $SO(N)/SO(N-1)$ ~~coset~~ coset)

We can now work out the Lagrangian.

$$\mathcal{L} = \frac{1}{2}(\partial_\mu\vec{\phi})^{T}\cdot\partial^\mu\vec{\phi} - \frac{g_*^2}{8}\left(\vec{\phi}^{T}\cdot\phi - f^2\right)^2$$

with $\partial_\mu\vec{\phi} = \partial_\mu\sigma \begin{pmatrix} \sin\frac{\pi}{f}\,\frac{\vec{\pi}}{\pi} \\ \cos\frac{\pi}{f} \end{pmatrix} + (f+\sigma)\begin{pmatrix} -\frac{\partial_\mu\pi}{f}\cos\frac{\pi}{f}\,\frac{\vec{\pi}}{\pi} + \sin\frac{\pi}{f}\,\frac{\partial_\mu\vec{\pi}\,\pi - \vec{\pi}\,\partial_\mu\pi}{\pi^2} \\ \frac{\partial_\mu\pi}{f}\sin\frac{\pi}{f} \end{pmatrix}$

LIO UNIVERSITE DE LYON

$$\Rightarrow \mathcal{L}_\phi = \frac{1}{2}\partial_\mu\sigma\,\partial^\mu\sigma + \frac{1}{2}\left(1+\frac{\sigma}{f}\right)^2\left(\frac{f^2}{\pi^2}\sin^2\frac{\pi}{f}\,\partial_\mu\vec{\pi}^T\cdot\partial^\mu\vec{\pi} + \frac{f^2}{4\pi^4}\left(\frac{\pi^2}{f^2}-\sin^2\frac{\pi}{f}\right)\partial_\mu\vec{\pi}^2\,\partial^\mu\vec{\pi}^2\right)$$
$$-\frac{g_*^2}{8}\sigma^4 - \frac{g_*^2}{2}f\sigma^3 - \frac{g_*^2}{2}f^2\sigma^2$$

▷ We can Taylor-expand this Lagrangian around $\pi = 0$ (regular point)

→ many multi-NG-boson interactions ($\propto \frac{1}{f^n}$ as we always have $\frac{\pi}{f}$ in the Lagrangian) with up to 2 derivatives

▷ f plays the role of the "Higgs decay constant" (as for the pion decay constant in QCD)

▷ $\vec{\pi}$ describes the dynamics of 4 massless bosons (as 4 broken generators $\hat{T}^{\hat{a}}$)

▷ σ is massive: $m_\sigma = \underbrace{m_*}_{g_* \in [1,4\pi[\ \Rightarrow \text{ separation of the } f \text{ and } m_* \text{ scales}} = g_* f$ (see last term) (↳ connected to the vev via ξ)

→ σ-resonance in analogy with the QCD resonances (but multi-TeV cf. data)

$m_* \rightsquigarrow \Lambda_{QCD}$ in QCD = confinement scale of the composite sector

$g_* \rightsquigarrow$ low-energy coupling of the strong sector

↳ could be perturbative or even $\approx 4\pi$ (depends on the # colours)

. We now need to identify the SM Higgs doublet. → what are the lagrangian symmetries?

⇒ $SO(4)$ group under which $\vec{\pi}$ (→ global) is a four-plet:

$$\vec{\pi} \to e^{i\alpha_a t^a} \vec{\pi}$$

or in the $\vec{\phi}$ language: $\hat{\phi} \to e^{i\alpha_a T^a} \hat{\phi}$, $\approx \begin{bmatrix} X_{4\times 4} & 0 \\ 0 & 0 \end{bmatrix}$

the 4x4 sub-block of the unbroken generators

≡ linearly realized symmetry (linear and homogeneous on the field)

<u>Reminder</u>: $SO(4) \sim SU(2)_L \times SU(2)_R$

⇒ The $SO(4)$ fourplet can be expressed as a (2, 2) bidoublet (pseudo real matrix)

$$\hookrightarrow \Sigma = \frac{1}{\sqrt{2}} \left(i\sigma_\alpha \pi^\alpha + \pi^4 \right) \qquad (\alpha = 1, 2, 3)$$

$$= \begin{pmatrix} \frac{\pi^4 + i\pi^3}{\sqrt{2}} & \frac{\pi^2 + i\pi^1}{\sqrt{2}} \\ \frac{\pi^2 - i\pi^1}{\sqrt{2}} & \frac{\pi^4 - i\pi^3}{\sqrt{2}} \end{pmatrix} \equiv (H^c, H)$$

$(\hookrightarrow i\sigma_2 H^*)$

LIO
UNIVERSITE DE LYON

$$\Rightarrow H = \begin{pmatrix} H_u \\ H_d \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \pi^2 + i\pi^1 \\ \pi^4 - i\pi^3 \end{pmatrix} \Rightarrow \vec{\pi} = \frac{1}{\sqrt{2}} \begin{pmatrix} -i(H_u - H_u^+) \\ H_u + H_u^+ \\ i(H_d - H_d^+) \\ H_d + H_d^+ \end{pmatrix}$$

Under an $SU(2)_L \times SU(2)_R$ transformation: $\Sigma \to g_L \Sigma g_R^+$

$\Rightarrow \delta_L \Sigma = i \delta_\alpha^L \frac{\sigma^\alpha}{2} \Sigma \rightarrow SU(2)_L$ doublet

$\delta_R^3 \Sigma = -i \delta_3^R \Sigma \begin{pmatrix} 1/2 & 0 \\ 0 & -1/2 \end{pmatrix} \rightarrow U(1)_Y$ quantum number is $1/2$

(H_c is $-1/2$)

$4 = (2,2) \rightarrow 2_{1/2}$

- We can show that the Lagrangian is also invariant under

$$\vec{\pi} \rightarrow \vec{\pi} + \pi \cot\frac{\pi}{f} \vec{\alpha} + \left(\frac{f}{\pi} - \cot\frac{\pi}{f}\right)\left(\vec{\alpha}^T \cdot \vec{\pi}\right)\frac{\vec{\pi}}{\pi}$$

$$\approx \vec{\phi} \rightarrow \vec{\phi} + i\alpha_{\hat{a}} T^{\hat{a}} \vec{\phi}$$

= symmetry in the broken generator direction, but non-linear and non-homogeneous ($\vec{0} \rightarrow f\vec{\alpha} \neq 0$)

$\Rightarrow$ conversely, any non-zero vev can be brought back to $\vec{0}$

$\rightarrow$ no effect

The EW interactions are finally introduced by gauging the $SU(2)_L \times U(1)_Y$ subgroup of $SO(4)$:

- $\partial_\mu \vec{\phi} \to D_\mu \vec{\phi} = \left(\partial_\mu - i g W_{\mu i} T_L^i - i g' B_\mu T_R^3 \right) \vec{\phi}$

- We add $\mathcal{L}_{gauge} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} W_{\mu\nu}^i W_i^{\mu\nu}$ to the lagrangian

- In terms of the Higgs, $\mathcal{L}_\phi$ becomes: (ignoring the σ-pieces)

$$\mathcal{L}_\phi = \dots + \frac{f^2}{2|H|^2} \sin^2 \frac{\sqrt{2} H}{f} D_\mu H^\dagger D^\mu H + \frac{f^2}{8|H|^4} \left(2\frac{|H|^2}{f^2} - \sin^2 \frac{\sqrt{2}|H|}{f} \right) D_\mu |H|^2 D^\mu |H|^2$$

$\Rightarrow$ Adopting the unitarity gauge: $H = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(V+h) \end{pmatrix}$

$$\mathcal{L}_\phi \simeq \frac{1}{2} \partial_\mu h \, \partial^\mu h + \frac{g^2}{4} f^2 \sin^2 \frac{V+h}{f} \left(W_\mu^+ W^{\mu -} + \frac{1}{2 c_W^2} Z_\mu Z^\mu \right) + \dots$$

$$\Rightarrow m_W = c_W m_Z = \frac{g f}{2} \sin \frac{V}{f} \equiv \frac{1}{2} g v^{\,246\,\text{GeV}}$$

$$\Rightarrow \xi = \frac{v^2}{f^2} = \sin^2 \frac{V}{f}$$ $\Rightarrow v$ is connected to the Higgs decay constant

The lagrangian also contains VVh^n interactions:

$$\mathcal{L}_\phi \simeq \frac{g^2 v^2}{4} \left(W_\mu^+ W^{\mu -} + \frac{1}{2 c_W^2} Z_\mu Z^\mu \right) \left(\overbrace{2\sqrt{1-\xi}}^{\text{constrained experimentally}} \frac{h}{v} + (1-2\xi) \frac{h^2}{v^2} - \frac{4}{3} \xi \sqrt{1-\xi} \frac{h^3}{v^3} + \dots \right)$$

Another interesting point is that $\rho = 1$ at all orders in $1/f$ as the model embeds the custodial symmetry. ($SO(4) \to SO(3)$ = fix the W/Z mass ratio)

$\Rightarrow$ all viable model must actually include the custodial symmetry, or ξ will be unacceptably small (fine-tuning).

III. 4. Partial compositeness

III. 4. 1) Generalities

= tool to introduce the fermion masses (the Higgs does not couple to fermions)

The SM fermions are elementary and coupled to the composite sector via linear q.

$$\mathcal{L}_{int} = \frac{\lambda_q^L}{\Lambda_{UV}^{d-5/2}} \bar{Q}_L \cdot \mathcal{O}_F^L + \frac{\lambda_u^R}{\Lambda_{UV}^{d_u-5/2}} \bar{u}_R\, \mathcal{O}_{u,F}^R + \frac{\lambda_d^R}{\Lambda_{UV}^{d_d-5/2}} \bar{d}_R \cdot \mathcal{O}_{d,F}^R + \dots$$

$\Rightarrow$ give rise of the mixing of elementary fields with composite ones. The λ parameters control the composite fractions, after evolution to m_*:

$$\lambda_i(m_*) = \lambda_i \left(\frac{m_*}{\Lambda_{UV}}\right)^{d_i - 5/2}$$

Large Yukawas can be generated for large scale separation if $d \sim 5/2$

$\Rightarrow$ 3rd generation $\Rightarrow$ $d \sim 5/2$; large ok for other generations ($\to$ smaller masses) searched for @LHC

- In details, let's assume 3 resonances Q, U and D that are generated at the scale m_*. ≡ partners.
- These resonances must have the same quantum numbers as the SM counterparts (but are in fact embedded in larger rep. like SO(4) in the minimal model).
- The resonance mass are generated by the strong dynamics (not the EWSB)
  $\Rightarrow$ Dirac mass terms $\Rightarrow$ vector-like fermions
- Each operator related to the SM masses is expected to be capable to excite from the vacuum a single-particle state:

$$\left.\begin{array}{l} \langle 0 | O_F^L | Q \rangle \neq 0 \\ \langle 0 | O_{uF}^R | U \rangle \neq 0 \\ \langle 0 | O_{dF}^R | D \rangle \neq 0 \end{array}\right\} \rightarrow \text{generates mixing with the quarks}$$

III.4.2 The SO(5)/SO(4) example

- At the high scale, operators are written as SO(5) invariants
  → choice of the representation ⇝ model building task
  → Only operators with the lowest dimension matter (otherwise, running effects tame them down).
- We need operators including the $2_{1/6}$, $1_{2/3}$ and $1_{-1/3}$ of G_{EW} → they don't exist in SO(5). $\Rightarrow$ we need to extend the composite global symmetry

- The simplest option is $SO(5)\times U(1)_X \longrightarrow SO(4)\times U(1)_X \quad (\times SU(3)_c)$

The hypercharge now arises from both T_R^3 (of $SU(2)_R$) and $U(1)_X$:

$$Y = T_R^3 + X$$

(Higgs + gauge bosons are neutral $\rightarrow$ pheno is unchanged)

- The simplest representation is the fundamental one (the 5). If $X = 2/3$:

$$5_{2/3} \rightarrow \underbrace{4_{2/3}\oplus 1_{2/3}}_{(SO(4))} \rightarrow \underbrace{2_{7/6}\oplus 2_{1/6}\oplus 1_{2/3}}_{(G_{EW})}$$

↳ coupling to Q_L, U_R

only the 5^{th} component couples to u_R

$$\Rightarrow \mathcal{L}^{(1)}_{int} = \tilde{\lambda}_U^R\, \bar{u}_R \left(O^R_{M,F}\right)_5 \subset \tilde{\lambda}_U^R\, \bar{U}_R^I \left(O^R_{M,F}\right)_I$$

with $I = 1,2,\ldots,5$

$$= (\underbrace{\ldots}_{4_{2/3}}, \underbrace{u_R}_{1_{2/3}})^t$$

$$\mathcal{L}^{(2)}_{int} = \tilde{\lambda}_Q^L\, \bar{q}_L \left(O^L_F\right)_5 \subset \tilde{\lambda}_Q^L\, \bar{Q}_L^I \left(O^L_F\right)_I$$

$$(\underbrace{-ib_L, -b_L, -it_L, t_L}_{4_{2/3}}, \underbrace{\ldots}_{1_{2/3}})^t$$

LIO UNIVERSITE DE LYON

• In general, one dresses the source with the Goldstone matrix (CCWZ formalism)

$$\left(U_R^4, U_R^1\right)^T = U[\Pi]^{-1} U_R \qquad \left(U[\Pi] = e^{i\frac{\sqrt{2}}{f}\Pi_{\hat{a}}(x)\hat{T}^{\hat{a}}} \right)$$

$$\left(Q_L^4, Q_L^1\right)^T = U[\Pi]^{-1} Q_L$$

(this allows to turn a $\mathcal{G}$ index into an $\mathcal{H}$ index)

$$\Rightarrow \overline{Q}_L^4 \cdot U_R^4 + \overline{Q}_L^1 U_R^1 = \overline{Q}_L U_R = 0 \Rightarrow \text{only } \overline{Q}_L^4 \cdot U_R^4 \text{ or } \overline{Q}_L^1 \cdot U_R^1 \text{ should be used.}$$

$$\Rightarrow \mathcal{L}_{yuk} = -c \frac{\lambda_Q^L \lambda_U^R}{g_*^2} m_* \overline{Q}_L^1 U_R^1$$

$$= -c \frac{\lambda_Q^L \lambda_U^R}{g_*^2} m_* \frac{1}{2\sqrt{2}|H|} \sin \frac{2\sqrt{2}|H|}{f} \overline{q}_L H^c u_R + h.c.$$

$$\Rightarrow m_Q = \frac{c \lambda_Q^L \lambda_U^R}{g_*^2} m_* \frac{\sqrt{\xi(1-\xi)}}{\sqrt{2}} \text{ and } y_Q = \frac{1-2\xi}{\sqrt{1-\xi}} y_Q^{SM}$$

The bottom sector is built similarly, from $5_{-1/3} \to 2_{1/6} \oplus 2_{5/6} \oplus 1_{-1/3}$

$Q = \frac{1}{\sqrt{2}}(-ib_L, b_L, ib_L, b_L, 0)^t$

$D = (0,0,0,0, b_R)^t$

• Other option: take the spinorial rep of $SO(5)$: $4_{1/6} \to (2,1)_{1/6} \oplus (1,2)_{1/6}$

$$\to \underbrace{2_{1/6} \oplus 1_{2/3} \oplus 1_{-1/3}}_{1 \text{ family (of quarks)}}$$

$Q_L = (t_L, b_L, 0, 0)^t$
$U_R = (0, 0, t_R, 0)^t$
$D_R = (0,0,0, b_R)^t$

VI.5 Higgs potential

The generation of the Higgs potential (that generates EWSB) is quite complex. It comes from the explicit breaking of the goldstone symmetry by the elementary sector
← H = goldstone → no potential

LIO
UNIVERSITE DE LYON

→ loop - induced

→ $V \doteq -\alpha f^2 \sin^2 \frac{H}{f} + \beta f^2 \sin^4 \frac{H}{f}$

↑ EW gauge + fermions

↑ fermions only

→ generation of the Higgs mass.

Laboratoire d'Excellence LIO - *Institut des Origines de Lyon*

Contact - Bruno Guiderdoni, responsable scientifique et technique
9 avenue Charles André, 69230 Saint Genis Laval / bruno.guiderdoni@univ-lyon1.fr