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Composite Higgs

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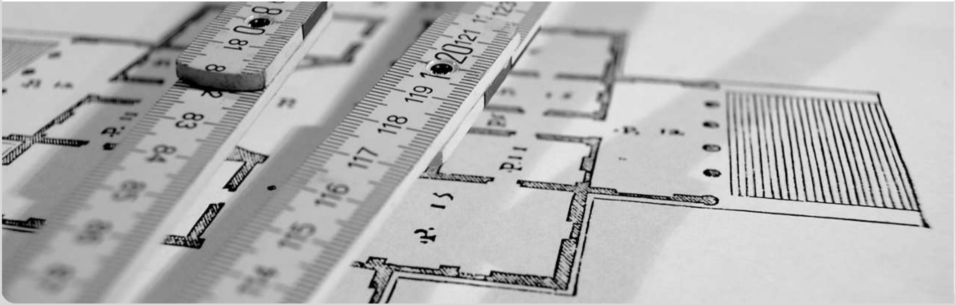

Contents

QCD

- Quantum Chromodynamics
- describes interaction between quarks
- negative β-function
- nonperturbative at low energies
- gauge group: $SU(3)$

$$\mathcal{L} = \sum_{i=1}^{nf} \overline{\Psi}_i \left(i\not{D} - m_i \right) \Psi_i - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu}$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$$

What happens at low energies?

- cannot use QCD Lagrangian for perturbation theory anymore
- quarks and gluons form a plethora of hadrons
- protons and neutrons form nuclei
- all other hadrons decay via the weak interaction
- hadrons are much more massive than quarks

Pions

- the three lightest mesons
- masses: 134,98 MeV (π^0), 139,57 MeV ($\pi^\pm$)
- much lighter than all other resonances ($m_\eta = 547{,}86$ MeV)
- pseudoscalar

Where does the proton/neutron mass come from?

- proton and neutron form an isospin doublet $\Psi = \begin{pmatrix} p \\ n \end{pmatrix}$
- in the massless case we can decompose left- and right-handed fields:

$$\mathcal{L} = i\overline{\Psi}_L \partial\!\!\!/ \Psi_L + i\overline{\Psi}_R \partial\!\!\!/ \Psi_R$$

$$\Psi_{L,R} = \frac{1}{2}(1 \mp \gamma^5)\Psi$$

- invariant under $SU(2)_L \otimes SU(2)_R$
- Gell-Mann and Levi: generate mass through spontaneous breaking of chiral symmetry

Σ-Model

$$\mathcal{L} = i\overline{\Psi}\not{\partial}\Psi - g\overline{\Psi}_L\Sigma\Psi_R - g\overline{\Psi}_R\Sigma^\dagger\Psi_L + \mathcal{L}(\Sigma)$$

- Σ transforms like $L\Sigma R^\dagger$ under $SU(2)_L \otimes SU(2)_R$
- $\mathcal{L}(\Sigma)$ invariant under $SU(2)_L \otimes SU(2)_R \Rightarrow \mathcal{L} = f\left(Tr[\Sigma\Sigma^\dagger]\right)$
- linear ansatz: $\Sigma = \sigma + i\pi^a\tau^a$ with simple symmetry breaking potential with VEV F_π and the Pauli matrices τ^a
- nonlinear ansatz: $\Sigma = \rho\exp\left(i\pi^a\tau^a/F_\pi\right)$
- both models break the chiral symmetry
- chiral current $j^a_{5,\mu} = -(\partial_\mu\pi^a)F_\pi + \mathcal{O}(\phi^2)$
  $\Rightarrow \langle 0_{\mathrm{had}}|j^a_{5,\mu}|\pi^b\rangle = iF_\pi p_\mu\delta^{ab}$

Mass sector

$$\mathcal{L}_{\text{mass}} = M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} M_Z^2 Z^\mu Z_\mu - \sum_{i,j} \left(\overline{u}_L^{(i)} M_{ij}^u u_R^{(j)} + \overline{d}_L^{(i)} M_{ij}^d d_R^{(j)} + \overline{e}_L^{(i)} M_{ij}^e e_R^{(j)} \right) + h.c.$$

- scattering of longitudinally polarized $W^\pm$ and Z bosons leads to violation of unitarity
- rewrite boson masses by introducing $\Sigma(x) = \exp(i\sigma^a \chi^a / v)$
- Goldstone bosons interact with vector bosons trough

$$D_\mu \Sigma = \partial_\mu \Sigma - ig \frac{\sigma^a}{2} W_\mu^a \Sigma + ig' \Sigma \frac{\sigma^3}{2} B_\mu$$

- under $SU(2)_L \otimes U(1)_Y$ Σ transforms as $\Sigma \to U_L(x) \Sigma U_Y^\dagger(x)$

Mass sector

$$\mathcal{L}_{\text{mass}} = \frac{v^2}{4} Tr\left[(D_\mu \Sigma)^\dagger (D^\mu \Sigma)\right] - \frac{v}{\sqrt{2}} \sum_{i,j} \left(\overline{u}_L^{(i)} \overline{d}_L^{(i)}\right) \Sigma \begin{pmatrix} \lambda_{ij}^u u_R^{(j)} \\ \lambda_{ij}^d d_R^{(j)} \end{pmatrix} + h.c.$$

- v is the Higgs VEV
- in unitary gauge $\langle \Sigma \rangle = 1$ this reproduces the former mass Lagrangian
- $\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} = 1$

Custodial Symmetry

- $\mathcal{L}_{\text{mass}}$ invariant under $SU(2)_L \otimes SU(2)_R$ for $g' = 0$ and $\lambda_{ij}^{u,d} = 0$
- $SU(2)_C$ remains after EWSB
- χ^a triplett under $SU(2)_C \Rightarrow M_W = M_Z$
- $g' \neq 0 \Rightarrow M_W = M_Z \cos^2\theta_W$
- Yukawa couplings lead to small corrections to ρ
- Extensions of the SM should respect $SU(2)_C$

SM Higgs Boson

- introduce $h(x)$ as a singlet under $SU(2)_L \otimes SU(2)_R$

$$\mathcal{L}_{\mathrm{H}} = \frac{1}{2}(\partial_\mu h)^2 + V(h)$$
$$+ \frac{v^2}{4} Tr\left[(D_\mu \Sigma)^\dagger (D^\mu \Sigma)\right]\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \mathcal{O}(h^3)\right)$$
$$- \frac{v}{\sqrt{2}} \sum_{i,j} \left(\overline{u}_L^{(i)} \overline{d}_L^{(i)}\right) \Sigma \left(1 + c\frac{h}{v} + \mathcal{O}(h^2)\right) \begin{pmatrix} \lambda_{ij}^u u_R^{(j)} \\ \lambda_{ij}^d d_R^{(j)} \end{pmatrix}$$
$$+ h.c.$$

- unitarizes scattering of Goldstone bosons for $a = b = c = 1$
- takes the standard form with:

$$H(x) = \frac{1}{\sqrt{2}} \exp(i\sigma^a \chi^a / v) \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

Why would one want another strong sector?

- no mass corrections from above the compositness scale
  $\Rightarrow$ solves hierachy problem
- new resonances unitarize theory
- possible connection to higher dimensional models
  $\Rightarrow$ new physics to explore

Ingredients

- global symmetry G, broken down to H_1 at a scale f
  $\Rightarrow n = \dim(G) - \dim(H_1)$ Goldstone bosons
- $H_0 \subset G$ gauged by external vector bosons
- $H = H_1 \cap H_0$ unbroken gauge group
  $\Rightarrow n_0 = \dim(H_0) - \dim(H)$ eaten up $\Rightarrow n - n_0$ survive

A minimal example

- For the SM $H_0 = SU(2)_L \otimes U(1)_Y$
- $G = SO(5) \otimes U(1)_X$ broken down to $SO(4) \otimes U(1)_X$
  $\Rightarrow n = 4$
- $H_0 \subset SO(4) \simeq SU(2)_L \otimes SU(2)_R$
  $\Rightarrow n_0 = 0$
- hypercharge generator $Y = T^{3R} + X$
- (H, H^c) transforms as $(2, 2)$ under $SU(2)_L \otimes SU(2)_R$
- $SU(2)_L \otimes U(1)_Y$ unbroken at tree level
- G explicitly broken by couplings of SM particles to the strong sector
  $\Rightarrow$ fermions and gauge bosons generate Higgs potential
- $m_h \sim g_{SM} v$, $m_\rho \sim g_\rho f$

Back to the Σ-model

- $\Sigma = \Sigma_0 \exp\left(-i\sqrt{2}T^{\hat{a}}h^{\hat{a}}(x)/f\right)$
- Σ_0 preserves $SO(4)$ symmetry: $\Sigma_0 = (0,0,0,0,1)$
  $\Rightarrow \Sigma = \frac{\sin(h/f)}{f}\left(h^1, h^2, h^3, h^4, h\cot(h/f)\right)$
- consider the whole $SO(5) \otimes U(1)_X$ is gauged, so we can write $\mathcal{L}$ in momentum space:
  $\mathcal{L} = \frac{1}{2}P_T^{\mu\nu}\left[\Pi_0^X(q^2)X_\mu X_\nu + \Pi_0(q^2)Tr(A_\mu A_\nu) + \Pi_1(q^2)\Sigma A_\mu A_\nu \Sigma^T\right]$
- Σ classical background, derivative interactions not included
- expanding around Σ_0 one obtains
  $\mathcal{L} = \frac{1}{2}P_T^{\mu\nu}\left[\Pi_0^X(q^2)X_\mu X_\nu + \Pi_a(q^2)Tr(A^a_\mu A^a_\nu) + \Pi_{\hat{a}}(q^2)A^{\hat{a}}_\mu A^{\hat{a}}_\nu\right],$
  $\Pi_a = \Pi_0, \Pi_{\hat{a}} = \Pi_0 + \frac{\Pi_1}{2}$

Back to the Σ-model

- from our discussion of pions we can deduce that $P_T^{\mu\nu}\Pi_{\hat{a}}(0) = \left\langle J_{\hat{a}}^{\mu}(0) J_{\hat{a}}^{\nu}(0) \right\rangle = \eta^{\mu\nu}\frac{f^2}{2}$
- a similar discussion leads to $\Pi_a(0) = 0$ $\Rightarrow \Pi_0(0) = \Pi_0^X(0) = 0, \Pi_1(0) = f^2$
- switching off the unphysical gauge fields and using our ansatz for Σ we obtain

$$\mathcal{L} = \frac{1}{2}P_T^{\mu\nu}\Bigg[\left(\Pi_0^X(q^2) + \Pi_0(q^2) + \frac{\sin^2(h/f)}{4}\Pi_1(q^2)\right)B_\mu B_\nu + \left(\Pi_0(q^2) + \frac{\sin^2(h/f)}{4}\Pi_1(q^2)\right)W_\mu^a W_\nu^a + 2\sin^2(h/f)\Pi_1(q^2)\hat{H}^\dagger T^{aL} Y \hat{H} A_\mu^{aL} B_\nu\Bigg]$$

Let's compare this to the SM

- for $q^2 \ll m_\rho^2$ and aligning the Higgs VEV along the h^3 direction we obtain

$$\mathcal{L} = P_T^{\mu\nu}\Bigg[\frac{1}{2}\left(\frac{f^2\sin^2(\langle h\rangle/f)}{4}\right)\left(B_\mu B_\nu + W_\mu^3 W_\nu^3 - 2W_\mu^3 B_\nu\right) + \left(\frac{f^2\sin^2(\langle h\rangle/f)}{4}\right) W_\mu^+ W_\nu^- + \frac{q^2}{2}\left[\Pi_0'(0) W_\mu^a W_\nu^a + (\Pi_0'(0) + \Pi_0^{X\prime}(0)) B_\mu B_\nu\right] + \dots\Bigg]$$

- for the gauge couplings we obtain $\frac{1}{g^2} = -\Pi_0'(0)$ and $\frac{1}{g'^2} = -(\Pi_0'(0) + \Pi_0^{X\prime}(0))$
- the Higgs VEV is given by $v = f\sin\frac{\langle h\rangle}{f}$, define $\xi \equiv \frac{v^2}{f^2}$

Let's compare this to the SM

- expanding $f^2 \sin^2 \frac{h}{f}$ leads to $v^2 + 2v\sqrt{1-\xi}h + (1-2\xi)h^2$ where h is now the physical Higgs field
- w.r.t the SM the VVh and VVhh couplings are modified: $g_{VVh} = g_{VVh}^{SM}\sqrt{1-\xi}, g_{VVhh} = g_{VVhh}^{SM}(1-2\xi)$
- this means $a = \sqrt{1-\xi}$ and $b = (1-2\xi)$
- for nonvanishing ξ the Higgs only partly unitarizes the scattering of vector bosons
- for $\xi = 1$ $f = v$ and we obtain a minimal Technicolor theory with a light scalar

What changes w.r.t Fermions?

- things work different than in the boson sector
- have to choose a representation of $SO(5)$ in which the fermions live
- spinorial representation (MCHM4): $c = \sqrt{1 - \xi}$
- fundamental representation (MCHM5): $c = \frac{1-2\xi}{\sqrt{1-\xi}}$

How do observables change in the MCHM4?

- fermionic and bosonic couplings scale by a factor of $\sqrt{1-\xi}$
- branching ratios remain the same
- total width reduced by a factor $1-\xi$
- the same for production cross-sections
- in principle loop induced decays could be modified by new particles (e.g. top-partners)

How do observables change in the MCHM5?

- fermionic and bosonic couplings scale differently
- partial decay width for fermions and gluons reduced by $\frac{(1-2\xi)^2}{1-\xi}$
- partial decay width for vector bosons reduced by $(1-\xi)$
- Higgs coupling to photons more complicated, since there are fermion- and W-loops
- gluon fusion and $t\bar{t}H$ cross-sections reduced by $\frac{(1-2\xi)^2}{1-\xi}$

How do branching ratios change in the MCHM5?

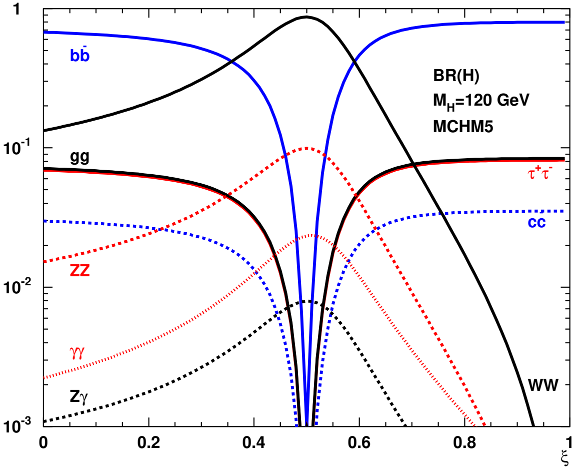

Figure: Espinosa, Grojean and Mühlleitner [arXiv:1003.3251]