Partial compositeness

Monika Blanke

Quick recap: composite models

Basics:

- Higgs boson is a composite pNGB, similar to the pion
  ➢ avoid naturalness problem
- gauged EW symmetry as subgroup of global symmetry of composite sector
- EW symmetry breaking realised dynamically
  ➢ two-step symmetry breaking to ensure sufficient separation of strong scale
- Little Higgs: top quark embedded in incomplete representation of global symmetry

Challenge: UV-complete model for Yukawa couplings & fermion masses

Partial compositeness in a nutshell

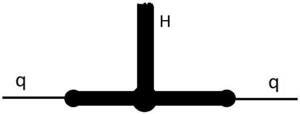
composite sector
operators describing composite states in complete multiplets

$\longleftrightarrow$

elementary sector
known SM fermion fields

linear mixing

- observed Yukawa couplings are a combination of strong sector coupling Y to the Higgs and elementary-composite mixings $f_{L,R}$:



- elementary-composite mixing controls hierarchies of effective Yukawas

Separating elementary and composite sector

Main idea:

separate spontaneous $G \to H$ breaking from explicit breaking of G (incomplete gauge & fermion rep.)

composite sector

- strongly coupled sector with global symmetry G
- spontaneous $G \to H$ breaking by condensate
- resonances in complete G multiplets

elementary sector

- does not respect full G symmetry
- gauged $SU(2)_L \times U(1)_Y$ symmetry
- contains SM fermion fields $\Psi_L = \mathbf{2}_{1/6}, \Psi_{uR} = \mathbf{1}_{2/3}$ etc.

The two-sector Lagrangian

$$\mathcal{L}_{\text{CH}} = \mathcal{L}_{\text{composite}} + \mathcal{L}_{\text{elementary}} + \mathcal{L}_{\text{mix}}$$

$\mathcal{L}_{\text{composite}}$
non-linear sigma model Lagrangian involving complete G multiplets $\mathcal{O}_L, \mathcal{O}_R$ and the nlσm field Σ

$\mathcal{L}_{\text{elementary}}$
Lagrangian containing elementary fermion fields Ψ_L, Ψ_R with $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge symmetry

$\mathcal{L}_{\text{mix}}$
linear mixing term connecting the two sectors

Linear mixing

$$\mathcal{L}_{\text{mix}} = f\bar{\Psi}_L\lambda_L\mathcal{O}_L + f\bar{\Psi}_R\lambda_R\mathcal{O}_R$$

$\boldsymbol{\lambda_{L,R}}$ spurions

- break $G \times [SU(2) \times U(1)]$ to diagonal $SU(2) \times U(1)$
- source of explicit breaking of global symmetry
- linear mixing between elementary fiels $\Psi_{L,R}$ and composite states in $\mathcal{O}_{L,R}$ with the same $SU(2) \times U(1)$ quantum numbers

➢ **fermion mass eigenstates are admixtures of elementary and composite states**

Fermion mass eigenstates

including composite sector masses for $\mathcal{O}_{L,R}$

$$\underbrace{f\bar{\Psi}_L\lambda_L\mathcal{O}_L + f\bar{\Psi}_R\lambda_R\mathcal{O}_R}_{\text{mixing}} + \underbrace{M_L\bar{\mathcal{O}}_L\mathcal{O}_L + M_R\bar{\mathcal{O}}_R\mathcal{O}_R}_{\text{composite masses}}$$

rotating to mass eigenbasis

$$\begin{pmatrix} \bar{\Psi}_L^{\mathrm{SM}} \\ \bar{\Psi}_L^{\mathrm{H}} \end{pmatrix} = \begin{pmatrix} 1 & -f_L \\ f_L & 1 \end{pmatrix} \begin{pmatrix} \bar{\Psi}_L \\ \bar{\mathcal{O}}_L \end{pmatrix} \qquad \begin{pmatrix} \Psi_R^{\mathrm{SM}} \\ \Psi_R^{\mathrm{H}} \end{pmatrix} = \begin{pmatrix} 1 & -f_R \\ f_R & 1 \end{pmatrix} \begin{pmatrix} \Psi_R \\ \mathcal{O}_R \end{pmatrix}$$

with $f_L \sim \lambda_L f/M_L$, $f_R \sim \lambda_R f/M_R$ and assuming $M_{L,R} \gg \Lambda_{L,R} f$

➢ SM fermions are elementary with a (small) composite admixture parametrised by $f_{L,R}$

Yukawa coupling

- Yukawa coupling within composite sector – expect $Y \sim \mathcal{O}(1)$

$$Y \bar{\mathcal{O}}_L H \mathcal{O}_R$$

- elementary-composite mixing translates this into SM Yukawa coupling

$$y \bar{\Psi}_L^{\text{SM}} H \Psi_R^{\text{SM}} \qquad \text{with} \qquad y = f_L Y f_R$$

- including down-type quarks and three generations

$$y_{ij}^u = f_i^q Y_{ij}^u f_j^u \qquad y_{ij}^d = f_i^q Y_{ij}^d f_j^d$$

note: $f^{q,u,d}$ chosen diagonal w.l.o.g.

From anarchic flavour to hierarchical Yukawas

- assume structureless ("anarchic") Yukawa couplingd $Y^{u,d}$ in composite sector
- observed hierarchies in $y^{u,d}$ then require hierarchical elementary-composite mixings $f^{q,u,d}$

$$f_1^q \ll f_2^q \ll f_3^q \qquad f_1^u \ll f_2^u \ll f_3^u \qquad f_1^d \ll f_2^d \ll f_3^d$$

- possible origin: large anomalous dimensions $d_i^{q,u,d}$

$$f_i^{q,u,d}(\Lambda_C) \sim f_i^{q,u,d}(\Lambda_F) \left(\frac{\Lambda_C}{\Lambda_F}\right)^{d_i^{q,u,d}-5/3}$$

Λ_C – compositeness scale
Λ_F – fundamental high-energy cutoff scale

➢ **hierarchy $\Lambda_C \ll \Lambda_F$ translates into hierarchical SM flavour sector**

CKM hierarchy from partial compositeness

hierachical structure of effective SM Yukawa couplings

$$y^u \sim \begin{pmatrix} f_1^q f_1^u & f_1^q f_2^u & f_1^q f_3^u \\ f_2^q f_1^u & f_2^q f_2^u & f_2^q f_3^u \\ f_3^q f_1^u & f_3^q f_2^u & f_3^q f_3^u \end{pmatrix} \qquad y^d \sim \begin{pmatrix} f_1^q f_1^d & f_1^q f_2^d & f_1^q f_3^d \\ f_2^q f_1^d & f_2^q f_2^d & f_2^q f_3^d \\ f_3^q f_1^d & f_3^q f_2^d & f_3^q f_3^d \end{pmatrix}$$

also generates small off-diagonal CKM elements:

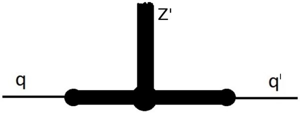
$$|V_{us}| \sim \frac{f_1^q}{f_2^q} \qquad |V_{ub}| \sim \frac{f_1^q}{f_3^q} \qquad |V_{cb}| \sim \frac{f_2^q}{f_3^q}$$

➢ **prediction:** $|V_{us}| \cdot |V_{cb}| \sim |V_{ub}|$

check: $|V_{us}| \sim 0.2$, $|V_{cb}| \sim 4 \cdot 10^{-2}$ ➢ $|V_{us}| \cdot |V_{cb}| \sim 8 \cdot 10^{-3} \sim 2|V_{ub}|$

Suppression of FCNCs – the RS-GIM mechanism

- composite sector generally introduces large tree level FCNCs
- mediated to the SM fermions by elementary-composite mixing



➢ suppressed by the same hierarchical pattern that generates the hierarchic quark masses and CKM mixing

Is this suppression sufficient?

- mostly yes
- however some tension with CP violation in the kaon system (ε, ε'/ε)
  - ➢ strong resonance masses $\gtrsim 10$ TeV required – or some extended model (or a bit of tuning of parameters)

Top partners

large top quark mass requires $y_t^{\mathsf{SM}} \sim \mathcal{O}(1)$

$$f_3^{q,u} = \frac{\lambda_3^{q,u} f}{\sqrt{(\lambda_3^{q,u})^2 + M_T^2}} \sim \mathcal{O}(1)$$

Implications:

- large symmetry breaking spurions $\lambda_3^{q,u} \sim \mathcal{O}(1)$
- top partner mass

$$M_T = g_* f \ll \Lambda = 4\pi f$$

➢ TeV-scale top partners observable at the LHC

P_{LR} symmetry and $Zb\bar{b}$

t_L and b_L share $SU(2)_L$ doublet

- ➢ large top Yukawa implies large composite admixture also for b_L
- ➢ large contribution to anomalous $Zb_L\bar{b}_L$ coupling, at odds with data

Discrete parity P_{LR} : $SU(2)_L \leftrightarrow SU(2)_R$

- generic $Z\psi\bar{\psi}$ coupling: $\frac{g}{\cos\theta_W}(Q_L^3 - Q\sin^2\theta_W)$
- anomalous contribution $Q_L^3 \neq T_L^3$ possible after EWSB
- however $SU(2)_V$ left unbroken (custodial symmetry!)
  ➢ $\delta Q_V^3 = \delta Q_L^3 + \delta Q_R^3 = 0$
- for P_{LR} eigenstates: $\delta Q_L^3 = 0$

➢ **embed (t_L, b_L) in $SU(2)_L \times SU(2)_R$ bidoublet**

Fermions in the MCHM

- symmetry breaking pattern $SO(5) \times U(1)_X \to SO(4) \times U(1)_X$
- Higgs transforms as bidoublet $H \sim \mathbf{4}_0 \cong (\mathbf{2}, \mathbf{2})_0$
- composite top sector with P_{LR} symmetry

$$\mathcal{L}_{\text{top}} = f\lambda_q \bar{q}_L \mathcal{O}_q + f\lambda_u \bar{u}_R \mathcal{O}_u + f\lambda_d \bar{d}_R \mathcal{O}_d$$

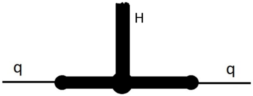
$$\mathcal{O}_q \sim \mathbf{5}_{2/3} \to (\mathbf{2}, \mathbf{2})_{2/3} + (\mathbf{1}, \mathbf{1})_{2/3}$$
$$\mathcal{O}_u \sim \mathbf{5}_{2/3} \to (\mathbf{2}, \mathbf{2})_{2/3} + (\mathbf{1}, \mathbf{1})_{2/3}$$
$$\mathcal{O}_d \sim \mathbf{10}_{2/3} \to (\mathbf{2}, \mathbf{2})_{2/3} + (\mathbf{1}, \mathbf{3})_{2/3} + (\mathbf{3}, \mathbf{1})_{2/3}$$

➢ prediction of top partners with electric charge $+5/3$

Summary

Study goal: partial compositeness

- ➢ elementary-composite mixing
- ➢ flavour hierarchies from anarchy
- ➢ RS-GIM mechanism
- ➢ top partners



Reading assignment

- chapter 3.4–3.7 of C. Csaki, S. Lombardo, O. Telem, *TASI Lectures on Non-Supersymmetric BSM Models*, `arXiv:1811.04279`
- P_{LR} symmetry: K. Agashe, R. Contino, L. Da Rold, A. Pomarol, *A custodial symmetry for Zbb*, `hep-ph/0605341`