Flavour Deconstructing the Composite Higgs

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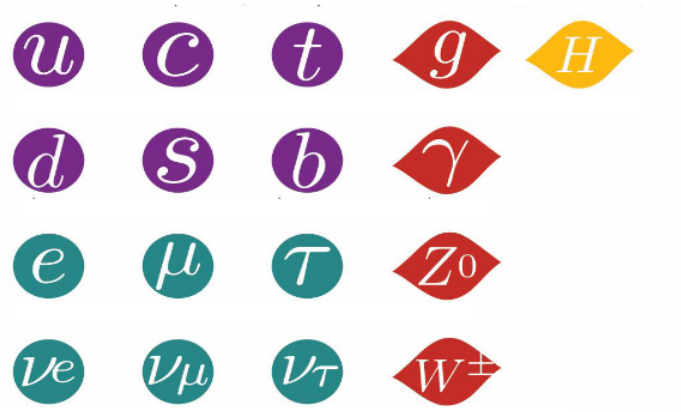
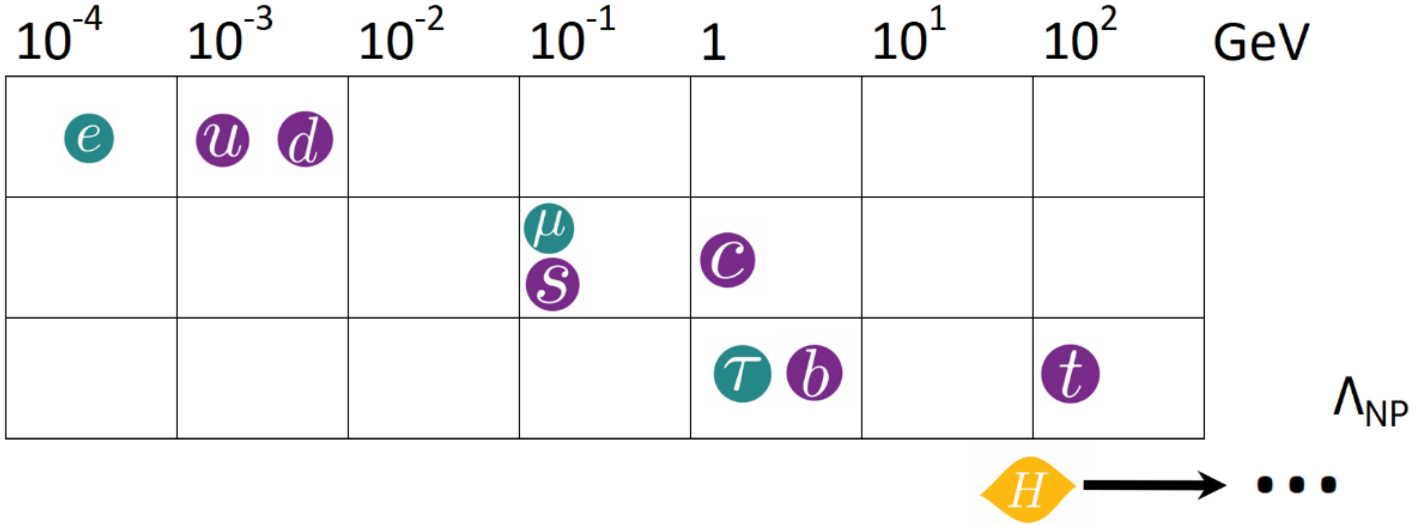
Outline

- Main Standard Model (SM) problems tackled;
- Flavour non-universal interactions and Higgs compositeness;
- Model specifics: Yukawa sector and Higgs potential;
- Phenomenological analysis of the model;
- Conclusions and outlook.

Flavour puzzle

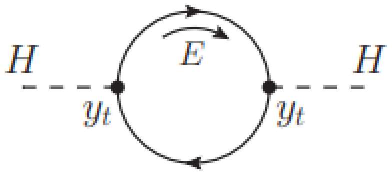




- Strongly hierarchical Yukawa sector (fermion masses and mixings) : Flavour Puzzle.
- Possible solution: introducing New Physics (NP) at high energy scales.
- Consequences on the Higgs hierarchy problem.

Higgs Hierarchy Problem

- Heavy NP (scale Λ) : corrections to Higgs mass very far from measured value;
- Precise cancellation between bare mass and corrections (in principle unrelated!)
- Fine tuning (Δ) = ratio between corrections and observed mass;
- Taking $\Lambda = M_{GUT}$,one gets $\Delta = 10^{24}$;
- Acceptable tuning (O(1%)) if Λ ~ TeV.



$$\longrightarrow \quad \delta_{\rm SM} m_H^2 = \frac{3y_t^2}{8\pi^2}\Lambda_{\rm SM}^2 \quad \longrightarrow \quad \Delta \geq \frac{\delta_{\rm SM} m_H^2}{m_H^2} = \frac{3\,y_t^2}{8\pi^2}\left(\frac{\Lambda_{\rm SM}}{m_H}\right)^2 \simeq \left(\frac{\Lambda_{\rm SM}}{450\,\mathrm{GeV}}\right)^2$$

Hints from the Standard Model

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}}$$

- Gauge sector does not distinguish fermion flavour (flavour-universal, $U(3)^5$ symmetry);
- The Higgs sector breaks this symmetry, introducing a hierarchy among families;

$$\frac{m_t}{m_u} \approx \frac{173\ \text{GeV}}{2\ \text{MeV}} \approx 10^5$$

- Approximate $U(2)^5$ symmetry for the light families;
- Third family appears to be separated from the light ones.

$$V_{\text{CKM}} \approx \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.009 & 0.04 & 1 \end{pmatrix}$$

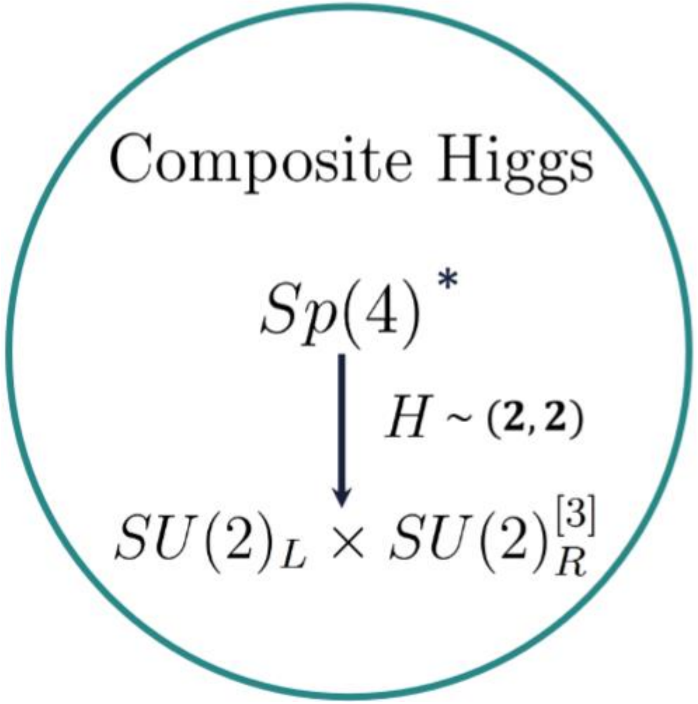
Approximate $U(2)^5$ symmetry

Small light-to-heavy FCNCs

Maybe the SM is only flavour universal at low energies!

At high E, $G = G_{12} \times G_3$?

Non-universal dynamics and composite Higgs



Composite Higgs

$$\begin{tikzcd} Sp(4)^{*} \arrow[d, "H \sim (\mathbf{2},\mathbf{2})"] \\ SU(2)_L \times SU(2)_R^{[3]} \end{tikzcd}$$

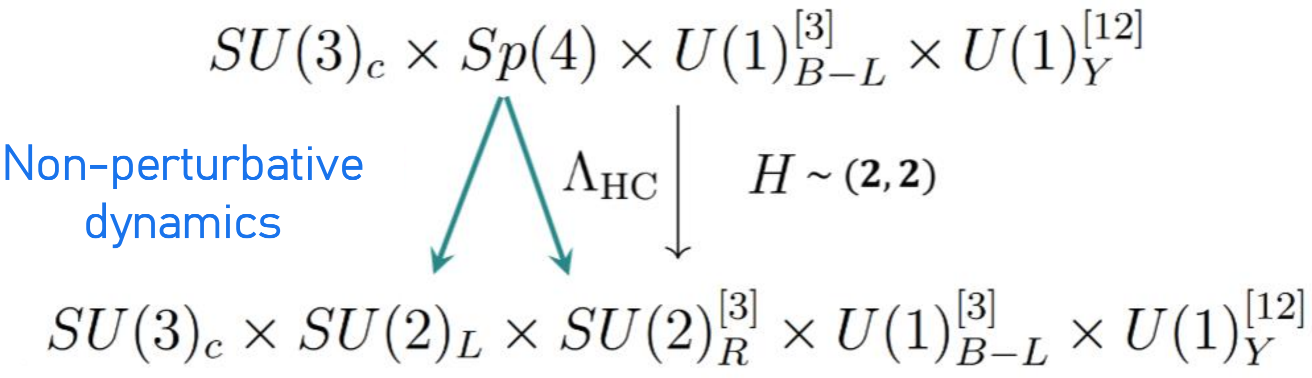
Non-universal dynamics + composite Higgs

⇓

Yukawa hierarchies + stable m_H

- Higgs : pNGB from global Sp(4) breaking .
- Shift symmetry: no Higgs mass at LO.
  Potential generated at one-loop.
- Higgs mass is shielded from high energy corrections.
  Reduced fine tuning

Breaking pattern



$$SU(3)_c \times Sp(4) \times U(1)^{[3]}_{B-L} \times U(1)^{[12]}_{Y}$$

Non-perturbative dynamics

Λ_{HC}

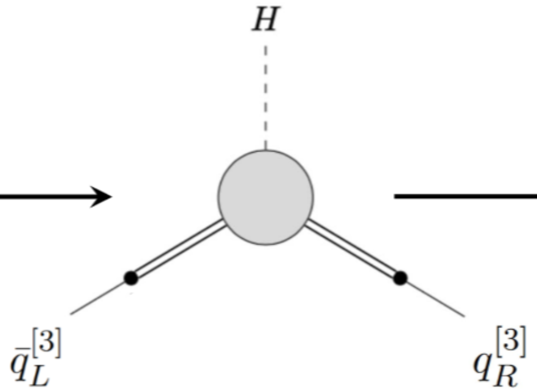
$H \sim (\mathbf{2},\mathbf{2})$

$$SU(3)_c \times SU(2)_L \times SU(2)^{[3]}_R \times U(1)^{[3]}_{B-L} \times U(1)^{[12]}_{Y}$$

Partial compositeness: 3rd family fermions mix w/ composite sector.

Top Partner

$\mathcal{L} \supset \lambda_L \bar{q}^{[3]}_L \mathcal{O}_R$ $\longrightarrow$



$\longrightarrow$ $|y_q| = \lambda^q_L \lambda^{q*}_R \kappa^q_{LR} \dfrac{F}{\sqrt{2} M_q}$

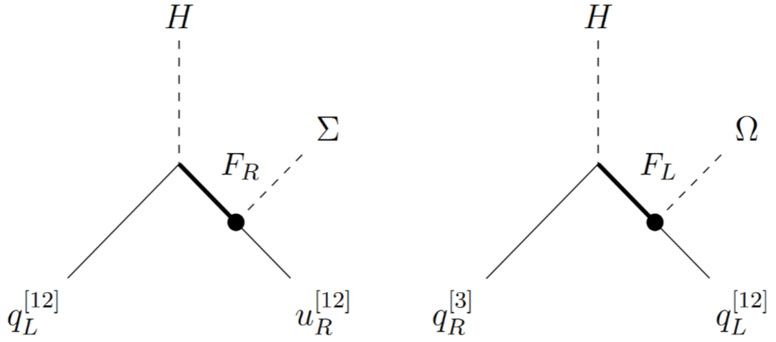
Breaking pattern

$$\begin{tikzcd}
SU(3)_c \times SU(2)_L \times SU(2)_R^{[3]} \times U(1)_{B-L}^{[3]} \times U(1)_Y^{[12]} \arrow[d, "\langle \Omega \rangle", "\langle \Sigma_R \rangle"'] \\
SU(3)_c \times SU(2)_L \times U(1)_Y
\end{tikzcd}$$

Horizontal breaking

$$\boxed{\begin{array}{l} SU(2)_R^{[3]} \times U(1)_{T_R^3}^{[12]} \xrightarrow{\langle \Sigma \rangle} U(1)_{T_R^{[3]}} \\ U(1)_{B-L}^{[3]} \times U(1)_{B-L}^{[12]} \xrightarrow{\langle \Omega \rangle} U(1)_{B-L} \end{array}} \xrightarrow[\epsilon_\Omega = \frac{\langle \Omega \rangle}{M_F}]{\epsilon_R = \frac{\langle \Sigma \rangle}{M_F}} Y_{u,d,e} \sim \begin{pmatrix} \overset{U(2)^5}{\boxed{\epsilon_R}} & \epsilon_\Omega \\ \epsilon_R \epsilon_\Omega & 1 \end{pmatrix}$$

- VEV of elementary scalars generate breaking to G_{SM} at low energy ;
- Yukawa coupling effectively generated through insertion of heavy vector-like fermions (100 TeV).



Yukawa sector

- Observed Yukawa matrices are obtained by tuning the ratio of the scalar VEV and the VLF mass

$$\epsilon_R = \frac{\langle \Sigma \rangle}{M_F} \qquad \epsilon_\Omega = \frac{\langle \Omega \rangle}{M_F}$$

- Tuning requirements on the Higgs potential do not uniquely fix the scale of flavour non universality !

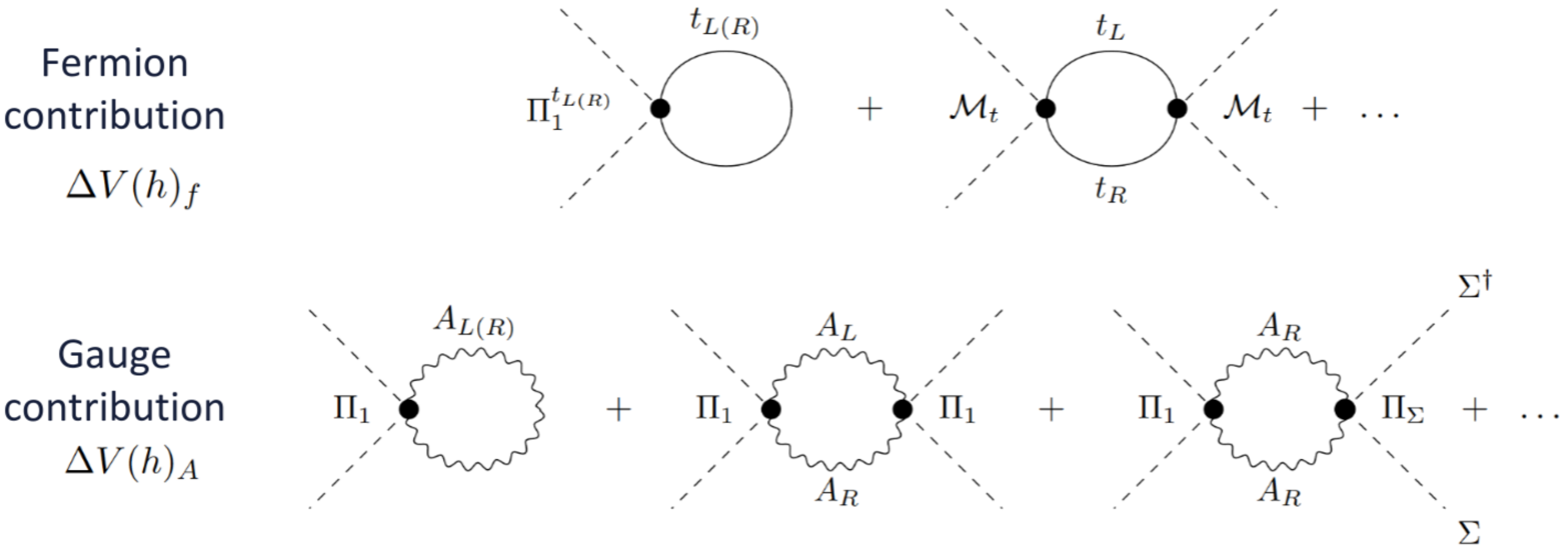
$$Y_{u,d,e} \sim \begin{pmatrix} \overset{U(2)^5}{\boxed{\epsilon_R}} & \epsilon_\Omega \\ \epsilon_R \epsilon_\Omega & 1 \end{pmatrix}$$

$$\epsilon_\Omega = O\left(|V_{cb}|\right) = O\left(10^{-1}\right)$$

$$\epsilon_R = O\left(m_c/m_t\right) = O\left(10^{-2}\right)$$

Higgs potential

- Sp(4) explicitly broken by Gauge interactions and mixing w/ composite sector;
- Radiatively generated potential (Coleman – Weinberg);
- VEV of Σ induces changes on tuning.



Higgs potential

- Potential is periodic in h, comprising 2 independent trig. functions.

$$V(h) = \Delta V_f(h) + \Delta V_A(h) \approx c_0 - c_1 \sin^2\left(\frac{h}{2F}\right) + c_2 \sin^4\left(\frac{h}{2F}\right)$$

- Tuning requirements from matching to SM.

$$\left.\frac{c_1}{F^4}\right|_{\mathrm{phys.}} = \frac{m_h^2}{F^2} \longrightarrow \text{Tuning (} m_h^2/F^2 \lesssim 0.03 \text{)} \qquad \left.\frac{c_2}{F^4}\right|_{\mathrm{phys.}} = \frac{2m_h^2}{v^2} \approx \frac{1}{2}$$

- Flavour non-universality: freedom to choose suitable SU(2)R coupling.

Higgs potential: quadratic term

- Tuning only stems from c_1
- To stabilize Higgs potential, we need:
  - Introduction of L-R symmetry.
  - Suitable choice of gR to suppress top-partner contribution

$$\left.\frac{c_1}{F^4}\right|_{\text{phys.}} = \frac{m_h^2}{F^2} \longrightarrow \text{Tuning} \left(m_h^2/F^2 \lesssim 0.03 \right)$$

$$\frac{c_1}{F^4} = \frac{N_c}{8\pi^2}\underbrace{\left[\left(\lambda_R^t\right)^2\kappa_R^t - \left(\lambda_L^t\right)^2\kappa_L^t\right]}_{\text{L-R symmetry}}\frac{M_f^2}{F^2} + \overset{\text{Top partner}}{\boxed{\frac{N_c y_t^2}{4\pi^2}\frac{M_T^2}{F^2}}} \overset{\downarrow}{-} \overbrace{\frac{9g_R^2}{32\pi^2}\left(1-\frac{g_R^2 v_\Sigma^2}{2M_\rho^2}\right)\frac{M_\rho^2}{F^2}}^{\text{Gauge contribution}} + \mathcal{O}\left(g_L g_R, g_L^2\right)$$

Higgs potential: quadratic term

$$\frac{c_1}{F^4} \supset \frac{N_c y_t^2}{4\pi^2}\frac{M_T^2}{F^2} - \frac{9g_R^2}{32\pi^2}\left(1 - \frac{g_R^2 v_\Sigma^2}{2M_\rho^2}\right)\frac{M_\rho^2}{F^2}$$

- Potential stabilized by appropriate g_R choice (allowed by non-universality)

$$g_{R,3} = O(1) \gg g_{R,12} \approx g_Y^{\mathrm{SM}}$$

- Large enough to be of the same order of y_t contribution

- Small enough not to generate a sign inversion in the Gauge contribution

$$M_{W_R}^2 = \frac{1}{4}g_R^2 v_\Sigma^2 < \frac{1}{2}M_\rho^2$$

Experimental constraints: super-strong sector

- Effects on VVh and VVhh couplings → $\Lambda_{\mathrm{HC}} \gtrsim 12\ \mathrm{TeV}\ (95\%\ \mathrm{CL})$
- Top partners, TeV scale resonances → $M_T \gtrsim 1.5\ \mathrm{TeV} \longrightarrow \Lambda_{\mathrm{HC}} \gtrsim 15\ \mathrm{TeV}$

  $M_\rho \gtrsim 5\ \mathrm{TeV}$
- EWPO, S parameter → $g^2_{L,R}\dfrac{v^2}{M^2_\rho} \lesssim 10^{-3}$

Experimental constraints: Gauge bosons

- Flavour (e.g. B → X_s + γ) and Z-pole $v_\Sigma \gtrsim 3\,\mathrm{TeV}$
- Drell-Yan from LHC $v_\Sigma \gtrsim 2.7\,\mathrm{TeV}$
- B_s mixing $v_\Sigma \gtrsim 2\,\mathrm{TeV}$

Summary of model

- O(1) $SU(2)_R$ gauge coupling from third family → 3% fine tuning

- Light top-partner (2 TeV) and 10 TeV resonances → O(1%) modifications to Higgs couplings

- Compositeness scale $\Lambda \sim 20$ TeV and $v_\Sigma \sim 3$ TeV → $O(10^{-3})$ modifications to EW sector

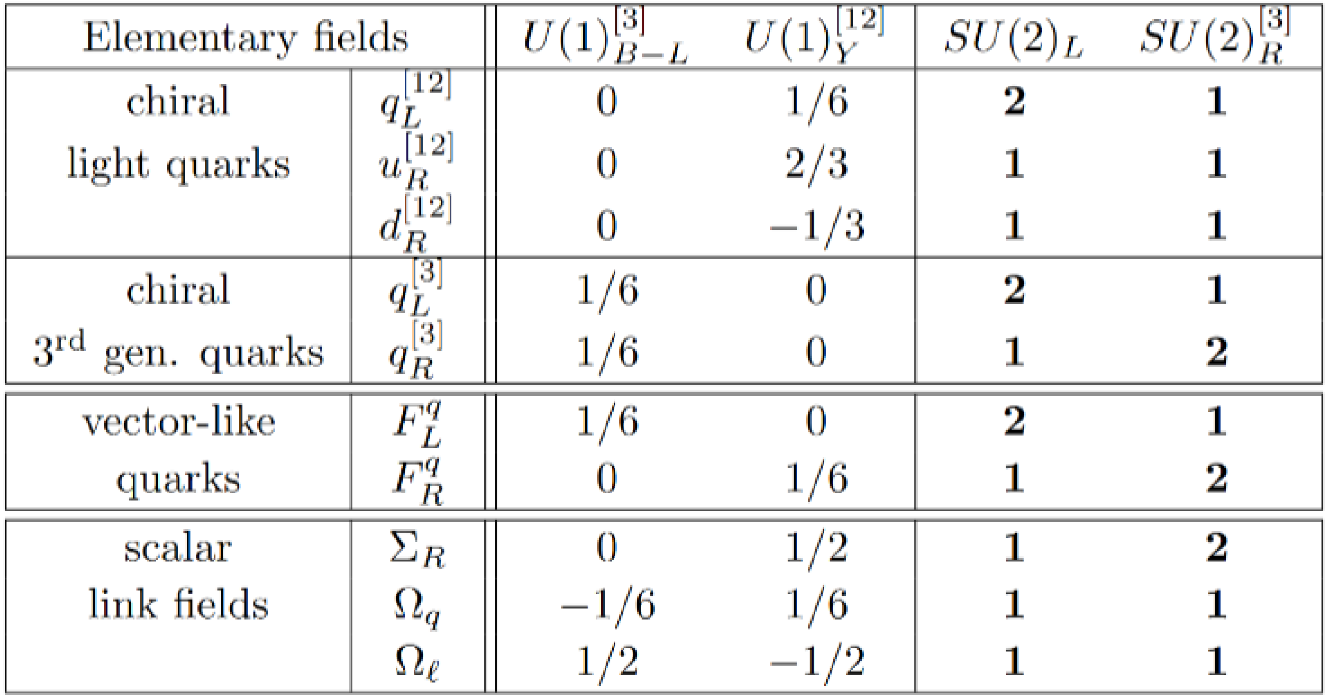
Conclusions and outlook

- TeV scale NP coupled to 3rd generation is compatible with current exp. bounds.
- Higgs compositeness + non-universality → Predictive BSM model
- Future direction: composite link fields

$$Sp(6)_{\text{global}} \longrightarrow SU(2)_L \times SU(2)_R^{[3]} \times SU(2)_R^{[12]}$$

Thank you for your attention!

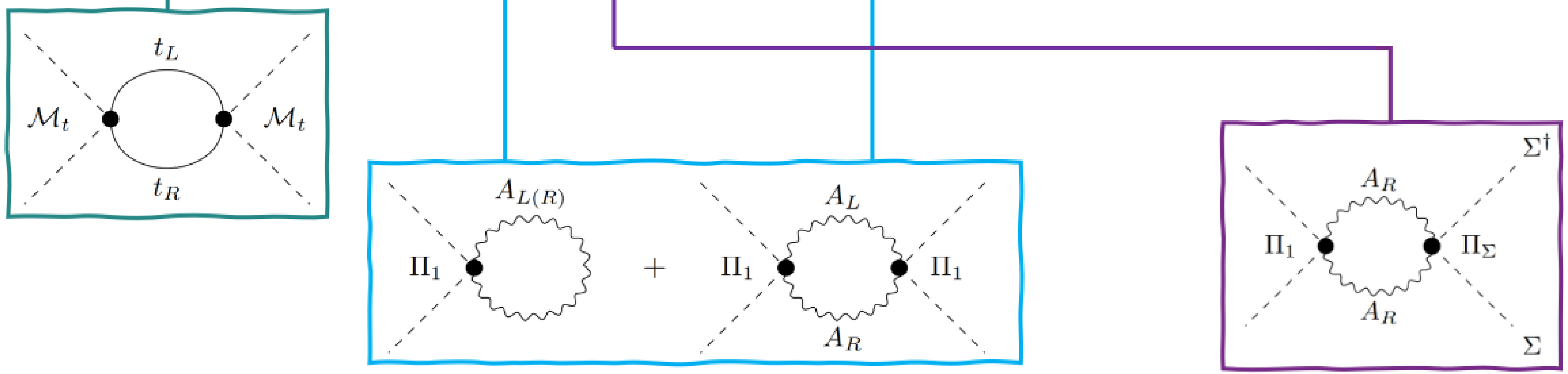
Backup slides



Elementary fields		$U(1)^{[3]}_{B-L}$	$U(1)^{[12]}_{Y}$	$SU(2)_L$	$SU(2)^{[3]}_R$
chiral light quarks	$q_L^{[12]}$	0	$1/6$	$\mathbf{2}$	$\mathbf{1}$
	$u_R^{[12]}$	0	$2/3$	$\mathbf{1}$	$\mathbf{1}$
	$d_R^{[12]}$	0	$-1/3$	$\mathbf{1}$	$\mathbf{1}$
chiral 3rd gen. quarks	$q_L^{[3]}$	$1/6$	0	$\mathbf{2}$	$\mathbf{1}$
	$q_R^{[3]}$	$1/6$	0	$\mathbf{1}$	$\mathbf{2}$
vector-like quarks	F_L^q	$1/6$	0	$\mathbf{2}$	$\mathbf{1}$
	F_R^q	0	$1/6$	$\mathbf{1}$	$\mathbf{2}$
scalar link fields	Σ_R	0	$1/2$	$\mathbf{1}$	$\mathbf{2}$
	Ω_q	$-1/6$	$1/6$	$\mathbf{1}$	$\mathbf{1}$
	Ω_ℓ	$1/2$	$-1/2$	$\mathbf{1}$	$\mathbf{1}$

$$V(h) = \Delta V_f(h) + \Delta V_A(h) \approx c_0 - c_1 \sin^2\left(\frac{h}{2F}\right) + c_2 \sin^4\left(\frac{h}{2F}\right)$$

$$\frac{c_2}{F^4} = \frac{N_c y_t^2}{4\pi^2}\frac{M_T^2}{F^2} + \overbrace{\frac{9g_R^2}{32\pi^2}\delta_\pi\left(1-\frac{g_R^2 v_\Sigma^2}{2M_\rho^2}\right)\frac{M_\rho^2}{F^2} - \frac{9g_R^4}{64\pi^2}\log\left(\frac{M_\rho^2}{M_{W_R}^2}\right)}^{\text{Gauge contributions}} + \mathcal{O}(g_L g_R, g_L^2)$$



$$V(h) = \Delta V_f(h) + \Delta V_A(h) \approx c_0 - c_1 \sin^2\left(\frac{h}{2F}\right) + c_2 \sin^4\left(\frac{h}{2F}\right)$$

$$\frac{c_2}{F^4} = \underbrace{\boxed{\frac{N_c y_t^2}{4\pi^2}\frac{M_T^2}{F^2}}}_{\text{Light Top partner}} + \overbrace{\frac{9g_R^2}{32\pi^2}\delta_\pi\left(1-\frac{g_R^2 v_\Sigma^2}{2M_\rho^2}\right)\frac{M_\rho^2}{F^2} - \underbrace{\frac{9g_R^4}{64\pi^2}\log\left(\frac{M_\rho^2}{M_{W_R}^2}\right)}_{\text{Negligible for } g_R \lesssim 2}}^{\text{Gauge contributions}} + \mathcal{O}(g_L g_R, g_L^2)$$

$\delta_\pi \ll 1$ from spurion analysis ⟶ $M_T \approx 2.5F$

Potenziale di Higgs: termine quartico

c_2 naturale (O(1)) dal matching con il MS

$$\frac{c_2}{F^4}\bigg|_{\text{phys.}} = \frac{2m_h^2}{v^2} \approx \frac{1}{2}$$

Constraint sul rapporto M_T/F

$$\frac{c_2}{F^4} = \frac{N_c y_t^2}{4\pi^2}\frac{M_T^2}{F^2} + \text{Gauge contributions (suppressed)}$$

↑

Top partner $\longrightarrow$ $\boxed{M_T \approx 2.5F}$