Composite Higgs : Confronting LHC Run 2 data

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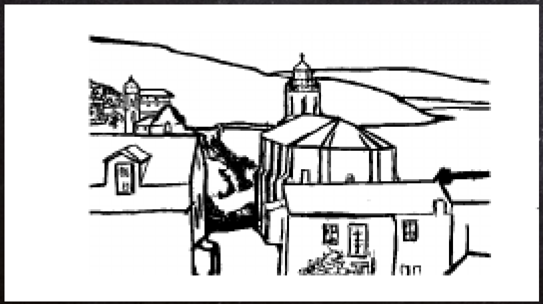


Composite Higgs : Introduction

- Higgs : composite bound state of a strongly interacting sector

  Emerges as a pNGB

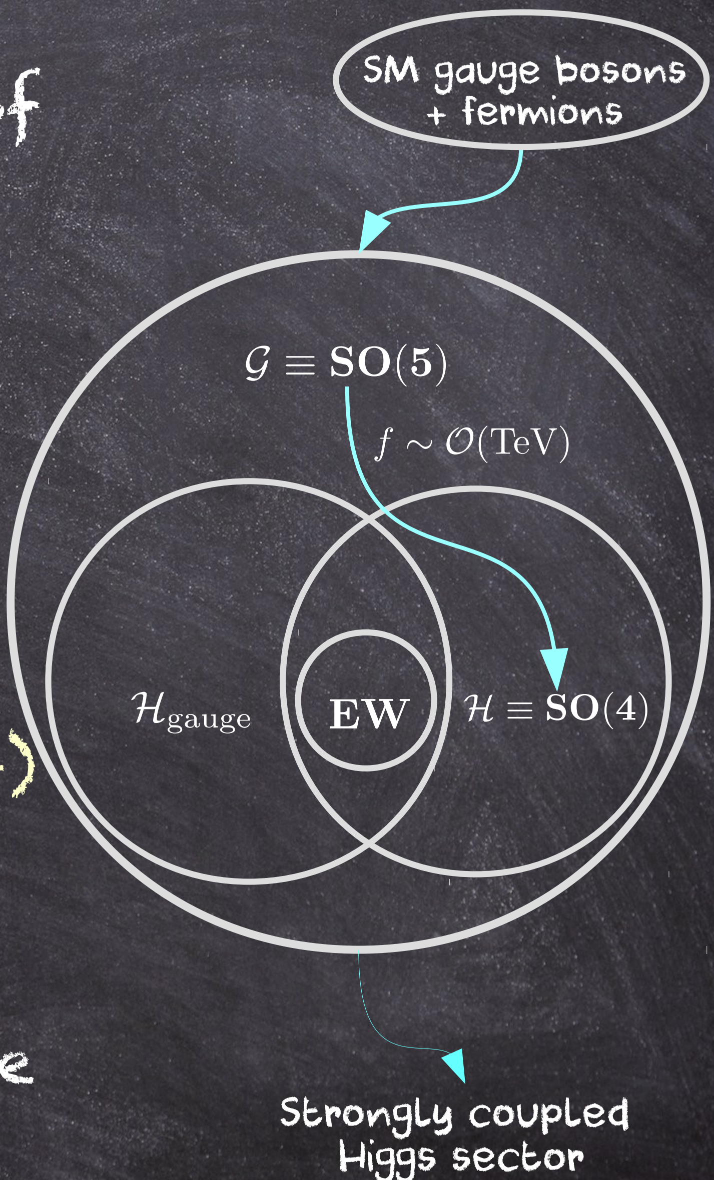
- Motivations: Hierarchy problem

  (Non-SUSY alternative)

- Minimal realization : SO(5) / SO(4)

- Partial compositeness paradigm: heavier quarks are more composite

$$|\mathrm{SM}\rangle = \cos\theta|\mathrm{elem}\rangle + \sin\theta|\mathrm{comp}\rangle$$



Higgs: too light to be composite ?

- Higgs mass scales as:

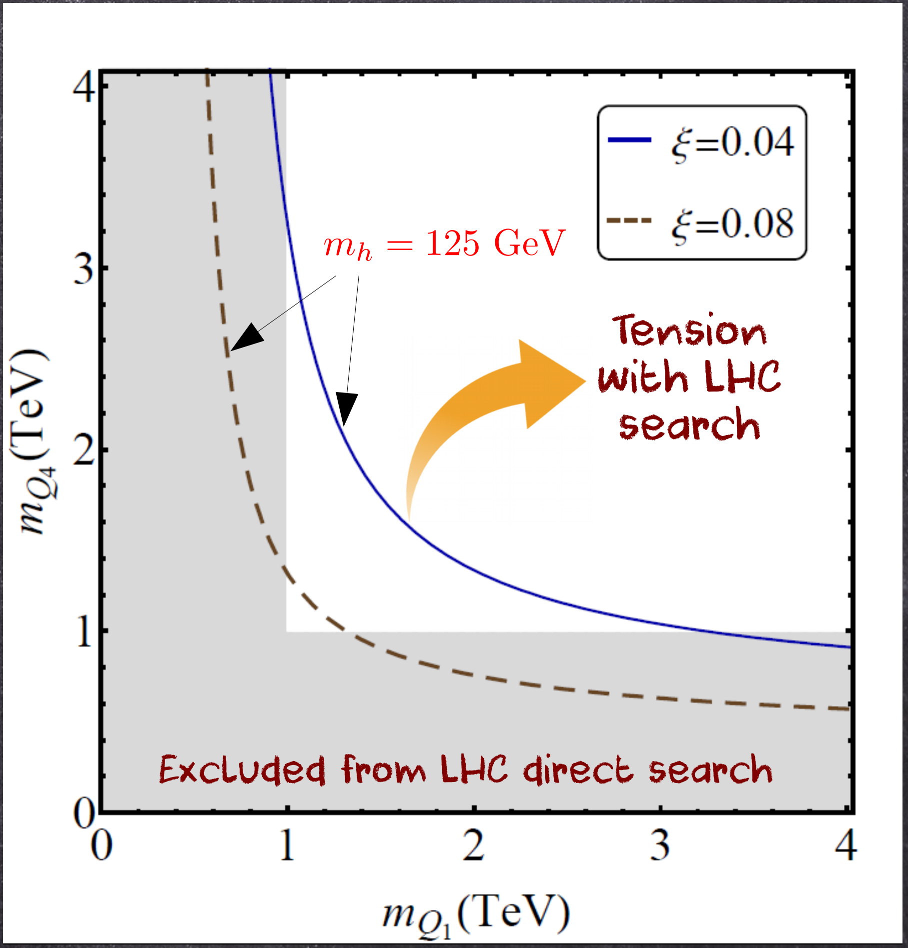
$$m_h^2 \sim \frac{N_c}{\pi^2}\frac{m_t^2 m_Q^2}{f^2}$$

$$\xi = \frac{v^2}{f^2}$$

Light top-partners

Large Fine-tuning

Light Higgs



Minimal Model: $$m_h^2 = \frac{N_c}{\pi^2}\frac{m_t^2}{f^2}\frac{m_{Q_1}^2 m_{Q_4}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)$$

Level Repulsion: improving fine-tuning

SM singlet

$m^2_{\eta\eta}$

Gauge Eigenstates

m^2_{hh}

SM doublet

$$\begin{pmatrix} m^2_{hh} & m^2_{h\eta} \\ m^2_{\eta h} & m^2_{\eta\eta} \end{pmatrix}$$

$$m_2^2 = m^2_{\eta\eta} + m^2_{h\eta} \tan\theta_{\rm mix}$$

Mass Eigenstates

$$m_1^2 = m^2_{hh} - m^2_{h\eta} \tan\theta_{\rm mix}$$

$$\sim (125\ \text{GeV})^2$$

Enlarge the coset ! → SO(6) / SO(5)

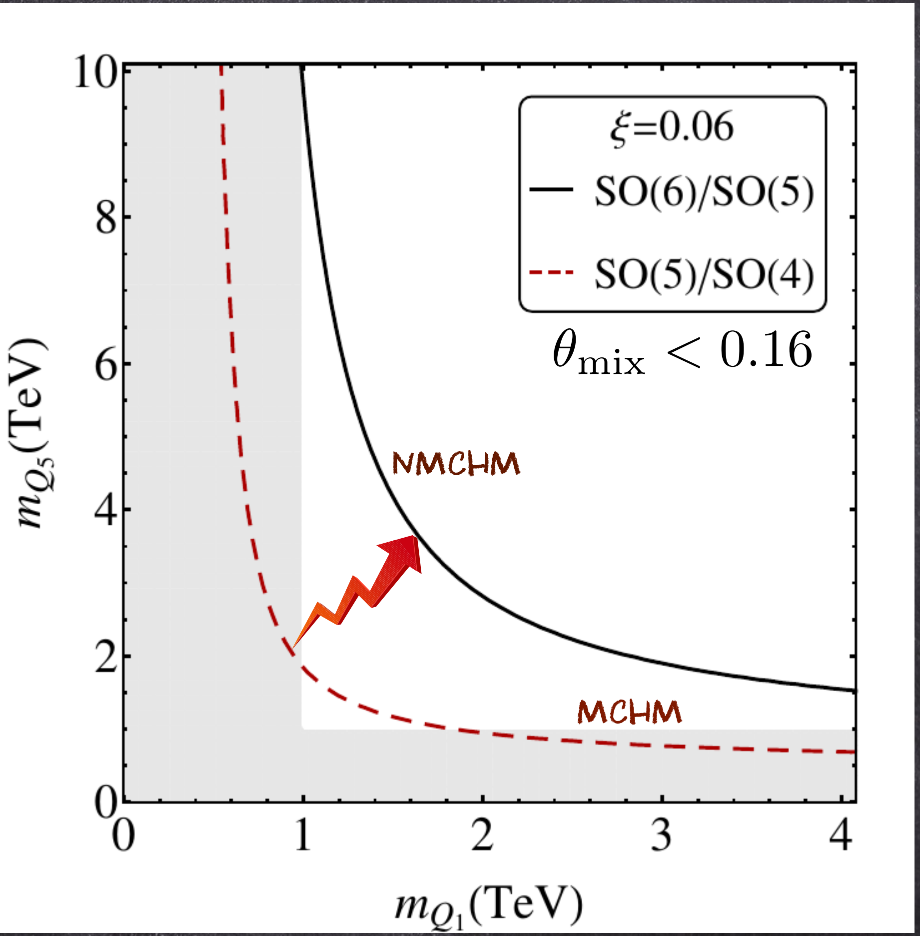
$$V_{\rm eff}(h,\eta) = -\frac{\mu_1^2}{2}h^2 + \frac{\lambda_1}{4}h^4 - \frac{\mu_2^2}{2}\eta^2 + \frac{\lambda_2}{4}\eta^4 - \frac{\lambda_m}{2}h^2\eta^2$$

Mixing

AB, G Bhattacharyya, T S Ray; 1703.08011

Level Repulsion: improving fine-tuning

More breathing space for top-partners



Modified Higgs Couplings

$$\Delta\mathcal{L} \sim \frac{1}{2f^2}\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H) - \sum_{i=u,d}\Delta'_i y_i \frac{H^\dagger H}{f^2}\bar{q}_{L_i} H\psi_{R_i}$$

- hVV: uniquely determined by composite scale

$$k_V = \frac{g_{hVV}}{g^{SM}_{hVV}} = \sqrt{1-\xi}$$

- Yukawa : model dependent

$$k_t = 1 + \Delta_t \xi$$

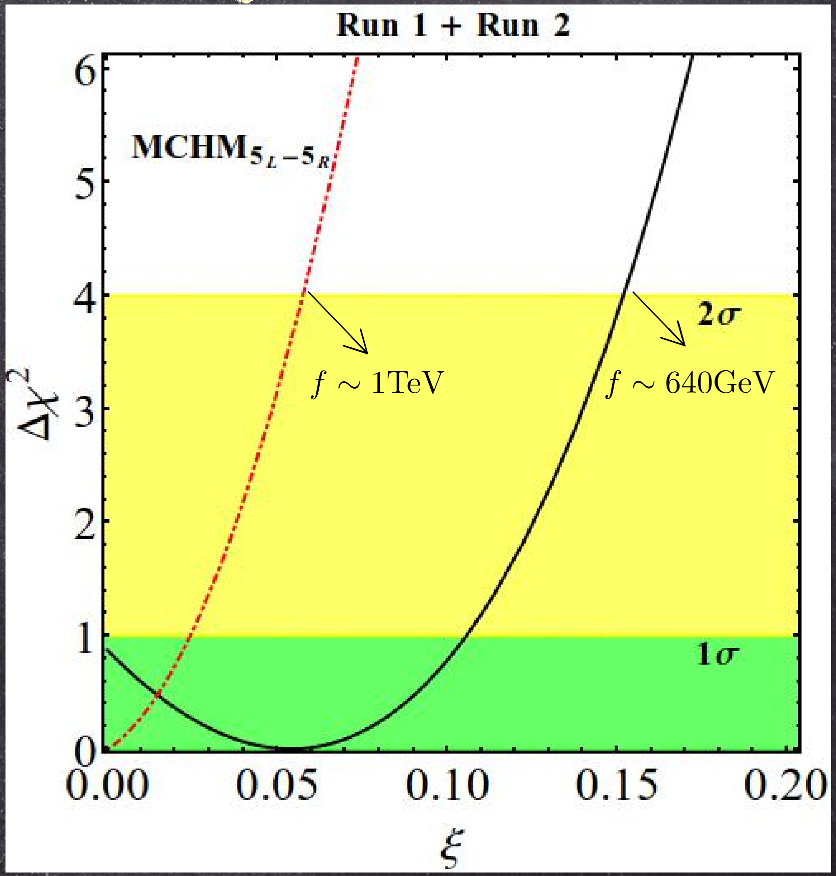
$MCHM_{5L-5R}$

$$\Delta_t = -\frac{3}{2}$$

$MCHM_{14L-14R, 14L-5R, 5L-14R}$

$$\Delta_t = \Delta_t(F_Q, m_Q)$$

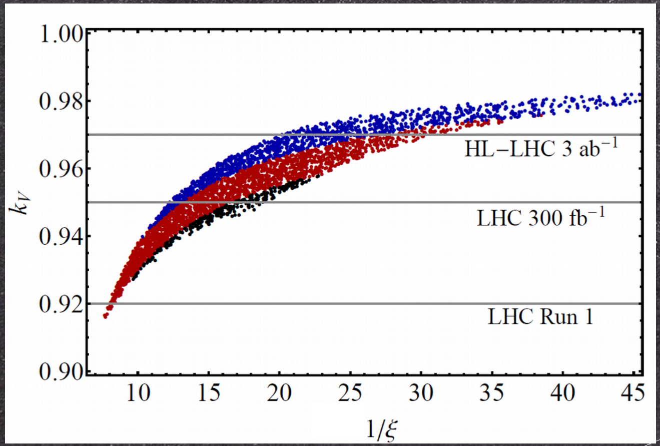
Confronting LHC data (7-8 TeV + 13TeV)



AB, G Bhattacharyya, N Kumar, T S Ray; 1712.07494

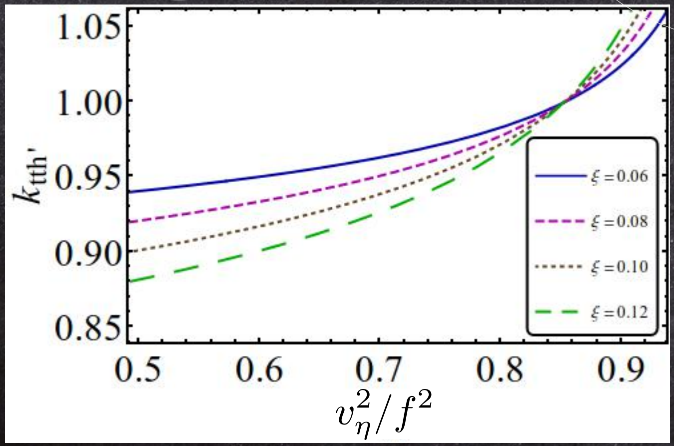
SO(6)/SO(5) Case

$$k_V = \cos\theta_{\rm mix}\sqrt{1-\xi}$$

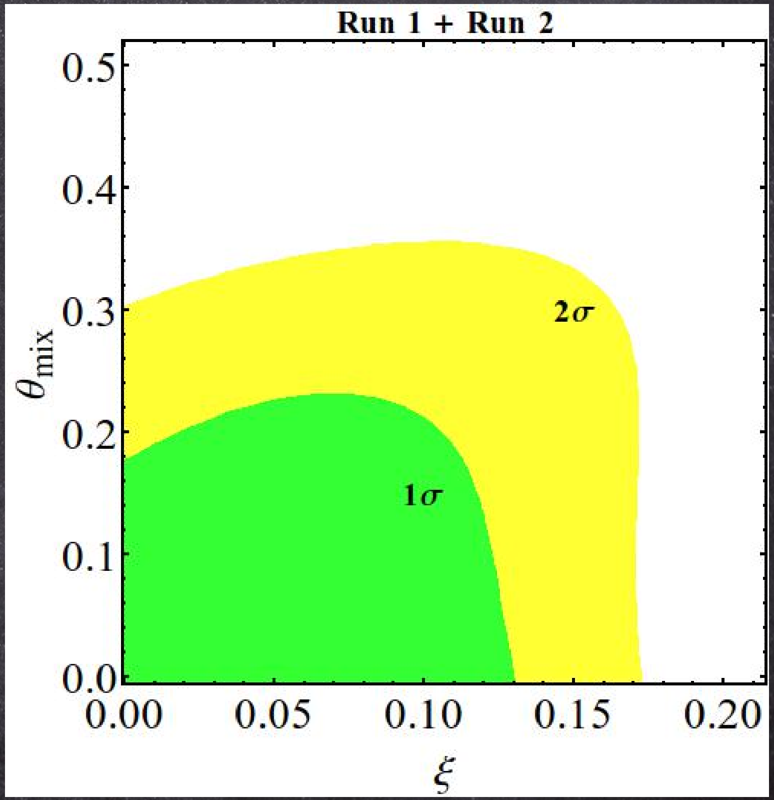


$$\Delta\mathcal{L}_\eta \sim -\sum_{i=u,d} y_i(\Delta_i^\eta)'\frac{\eta^2}{f^2}\bar{q}_{L_i}H\psi_{R_i}$$

$$k_t = \cos\theta_{\rm mix}\,(1+\Delta_t\xi) + \Delta_t^\eta\sin\theta_{\rm mix}\sqrt{\frac{\xi v_\eta^2}{f^2-v_\eta^2}}$$



- LHC bounds on doublet-singlet mixing :



Summary

- Minimal composite model : requires either large fine-tuning or light top-partners
- Next-to-minimal case extends the coset to SO(6)/SO(5) : Higgs doublet + SM singlet scalar
- Doublet-singlet mixing can give a handle to tame fine-tuning and accommodate heavier top-partners
- Phenomenological consequences : modified Higgs couplings constrained by LHC data

THANK YOU!

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Singlet Phenomenology

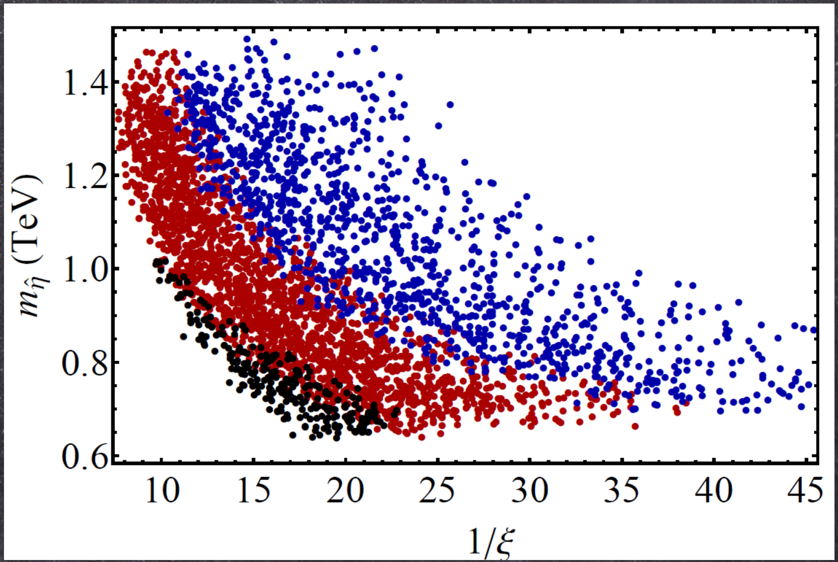
- Non trivial couplings with gauge bosons and 3rd generation quarks

$$c_{\eta VV} \propto \sin\theta_{\rm mix}\sqrt{1-\xi}$$

$$c_{\eta\bar{t}t} \propto -\cos\theta_{\rm mix}\Delta_t^{\eta}\sqrt{\frac{\xi v_\eta^2}{f^2-v_\eta^2}}+\sin\theta_{\rm mix}(1+\Delta_t\xi)$$

- Large mass of η ⟹

  Production modes and decay channels similar to Higgs, modulo suppressions due to large mass, small couplings



- New search topologies: $\eta \to hh\,,\ \eta \to t\bar{t}$ provided ($m_\eta > 2m_h, 2m_t$)

Niehoff et.al. 16

Partial Compositeness Paradigm

Elementary-composite
Linear mixing
(breaks strong-sector
symmetry explicitly)

Composite sector

Higgs ,
Composite-
resonances

$$\mathcal{O}, J_\mu$$

Elementary sector

ALL SM fields except Higgs

$$\psi_{L,R}, A_\mu$$

$$\mathcal{L}_{\rm mix} \sim \lambda_L \overline{\psi}_L \mathcal{O}_R + L \to R + g A_\mu J^\mu$$

$$\mathcal{L}_{\rm comp} \sim \frac{f^2}{2}(\partial_\mu \Sigma^T)(\partial^\mu \Sigma)$$

$$\mathcal{L}_{\rm elem} \sim \overline{\psi} i D \psi - \frac{1}{4} F^{\mu\nu} F_{\mu\nu}$$

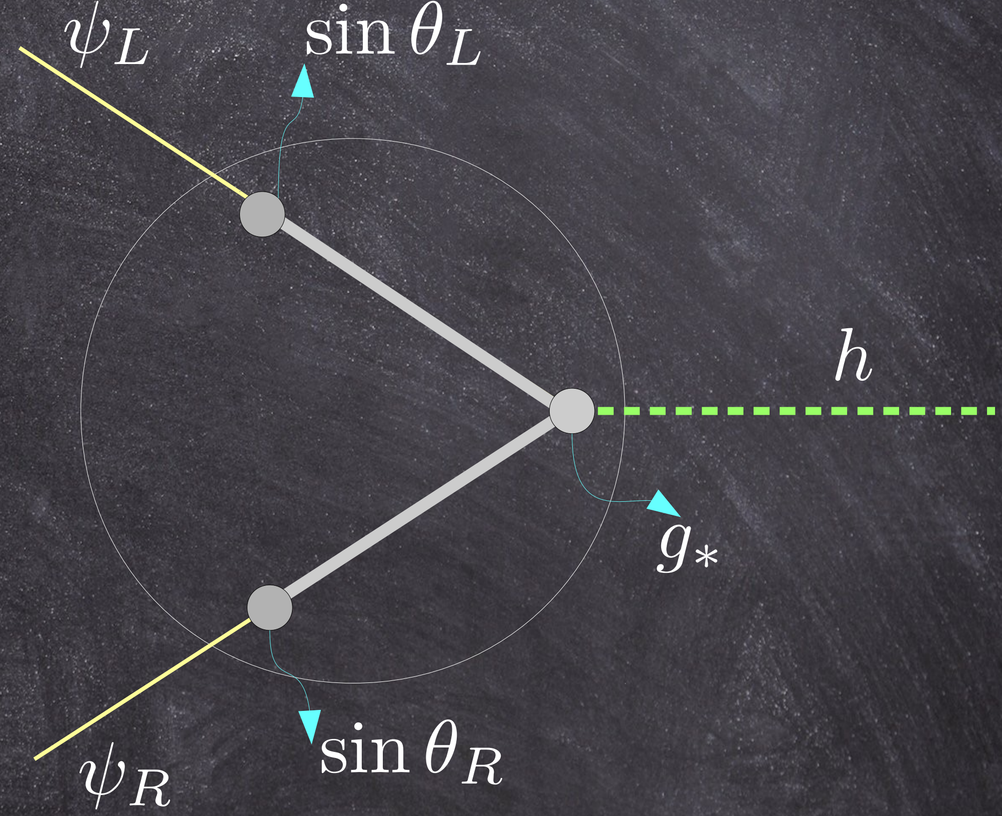
Yukawa Coupling

- SM fermions : massive after EWSB

- Interaction with Higgs

  ➡ via composite resonances

- Top can be substantially composite, while other light quarks are mostly elementary



Yukawa coupling :

$y_\psi \simeq g_* \sin\theta_L \sin\theta_R$

Lagrangian and EWSB Potential

- Gauge Contribution : similar to minimal model

$$\mathcal{L} = \frac{1}{2} P_T^{\mu\nu} \left[\left(\Pi_0(q^2) + \frac{\Pi_1(q^2)}{4} \frac{h^2}{f^2} \right) (B_\mu B_\nu + W_\mu^a W_\nu^a) + \ldots \right]$$

- Fermion contribution (top-quark) :

$$\mathcal{L} = \bar{t}_L p \left[\Pi_0^{t_L} + \frac{\Pi_1^{t_L}}{2} \frac{h^2}{f^2} \right] t_L + \bar{t}_R p \left[\Pi_0^{t_R} + \Pi_1^{t_R} \left(1 - \frac{h^2}{f^2} - \frac{\eta^2}{f^2} \right) \right] t_R \\ + \bar{t}_L \left[\frac{\Pi^{t_L t_R}}{\sqrt{2}} \frac{h}{f} \sqrt{1 - \frac{h^2}{f^2} - \frac{\eta^2}{f^2}} \right] t_R + \text{h.c.}$$

- C-W Potential for h and η :

$$V_{\text{eff}} = \int \frac{d^4 q}{2\pi^4} \left[\frac{9}{2} \log \Pi_W(h) - 2N_c \log \left(q^2 \Pi_{t_L}(h,\eta) \Pi_{t_R}(h,\eta) + |\Pi_{t_L t_R}(h,\eta)|^2 \right) \right]$$