Composite Higgs Phenomenology

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- *The idea and model building*
- *Constraints on parameters*
- *Fine-tuning of parameters*

How different from Technicolor?

- Generation of new scale via **dimensional transmutation**

$$t = \log\left(\frac{\Lambda_{\rm UV}}{m_*}\right) \propto \frac{16\pi^2}{g^2_{\rm UV}}$$

$$m_*^2 = \Lambda^2_{\rm UV}\,\exp\left(-16\pi^2/g^2_{\rm UV}\right)$$

- **Technicolor:** Strongly coupled gauge group through slow running generates TeV scale
- Unacceptably large S parameter. $H^\dagger W_{\mu\nu} B^{\mu\nu} H \Rightarrow S \sim \frac{v^2}{f_\pi^2} \sim 1$
- **Composite Higgs:** Construct a theory for $v \ll f_\pi (\equiv f)$
- Unlike in TC, strong dynamics in composite Higgs doesn't participate directly in EWSB, only provides a set of pNGBs.

Modification of gauge and Yukawa couplings

- Nonlinear realization leads to higher dimensional operators

- Gauge scalar coupling

$$L_{\text{gauge}} = \frac{g^2}{2}\left(H^\dagger H\right)\left(W^\mu W_\mu + \frac{1}{2C_w^2} Z^\mu Z_\mu\right)$$

$$L_{\text{kin}} = \left|\partial_\mu H\right|^2 + \frac{c_H}{2f^2}\left|\partial_\mu (H^\dagger H)\right|^2 + \cdots$$

$$\Rightarrow L_{\text{kin}}^{\text{canonical}} = \frac{1}{2}\left(\partial_\mu h_{125}\right)^2$$

where $h_{125} \equiv h\sqrt{1 + c_H \frac{v^2}{f^2}}$

$$g_{hVV} \simeq g_{hVV}^{\text{SM}} \sqrt{1 - c_H \frac{v^2}{f^2}}$$

- Yukawa coupling

$$L_{\text{Yuk}} = -Y_f^{\text{SM}} \overline{Q}_L H u_R - \Delta Y_f^{\text{SM}} \frac{H^\dagger H}{f^2} \overline{Q}_L H u_R \Rightarrow -Y_f \bar{t}_L t_R h_{125}$$

$$Y_f \equiv Y_f^{\text{SM}} \left[1 + \left(\Delta - \frac{1}{2} c_H\right) \frac{v^2}{f^2}\right]$$

Minimal composite Higgs

G = SO(5), H = SO(4), G/H : 4 pNGBs ◄── 4 d.o.f for Higgs doublet

Construct $\Sigma = \exp\left(i\frac{\sqrt{2}}{f}\pi^{\hat{a}}T_{\hat{a}}\right)\Sigma_0$ where $\Sigma_0 = (0\ 0\ 0\ 0\ f+\sigma)^T$

Unitary gauge: $\pi_1 = \pi_2 = \pi_3 = 0,\ \pi_4 = h \qquad \Rightarrow \pi \equiv \sqrt{\pi_i^2} = h$

$\Rightarrow \Sigma = f\,(0\ 0\ 0\ S_h\ C_h)^T$ where $S_h \equiv \sin(h/f)\quad C_h \equiv \cos(h/f)$

$$L_{\rm kin} = \frac{1}{2}\left(\partial_\mu \Sigma\right)^2 = \frac{1}{2}\frac{1}{\left(1-\frac{h^2}{f^2}\right)}\left(\partial_\mu h\right)^2$$

Gauge and Yukawa interaction in a part of G breaks the pNGB shift symmetry. Then the Higgs develops a potential and a vev.

$$L = \frac{1}{2}\left(\partial_\mu h_{125}\right)^2 + \sqrt{1-\frac{v^2}{f^2}}\, g_{hVV}^{\rm SM}\ h_{125}\ V_\mu\ V_\mu$$

$c_H = 1$

Yukawa couplings for SO(5) / SO(4)

- Left and right-handed top quark in vector 5-plet of SO(5).
- Under SO(4) [SU(2) X SU(2)] 5 = 1 + 4 = (1 , 1) + (2 , 2)

Construct $Q_{t_L}^{(5)} = \Big[(Q_{3L})_{2,2} \;,\; 0\Big]^T = \frac{1}{\sqrt{2}}(ib_L, b_L, it_L, -t_L, 0)^T$

and $T_{t_R}^{(5)} = [0,0,0,0,t_R]^T$

<u>**Yukawa invariant**</u> $\Sigma^T Q_{t_L}^{(5)} T_{t_R} \Sigma$ $(\bar{5}5\bar{5}5)$

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

$$L_{\text{Yuk}} = \Pi_{LR}(q^2) S_h C_h \bar{t}_R t_L \equiv m_t(h) \bar{t}_R t_L = \left[m_t + \frac{m_t}{v}\frac{1-2\xi}{\sqrt{1-\xi}} h_{125}\right] \bar{t}_R t_L$$

Form factor

$c_H = 1$	$\Delta = -1$
(global)	(MCHM-5)

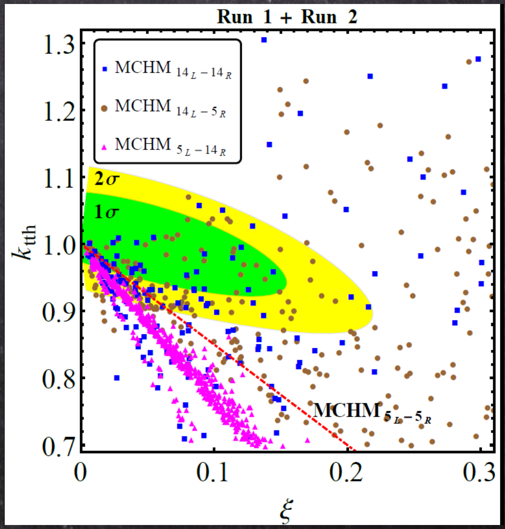
Other fermion representations

- SO(5) : 5 (fundam.) 14 (symmetric) 10 (anti-symm) 1 (singlet)
- Consider top-L : 14 , top-R : 14
- Two Yukawa invariants:

$$A\, \Sigma^T \overline{Q}^{(14)}_{t_L} T^{(14)}_{t_R} \Sigma \;+\; B \left(\Sigma^T \overline{Q}^{(14)}_{t_L} \Sigma\right) \left(\Sigma^T T^{(14)}_{t_R} \Sigma\right)$$

$$L_{\rm Yuk} = \left(\Pi^1_{LR} + \Pi^2_{LR} h^2\right) S_h C_h \bar{t}_R t_L$$

- Form factors cannot be totally absorbed in top mass. In MCHM-5 hVV and htt modifications depend on a single parameter yielding very strong constraint. With more than one Yukawa invariant it is relaxed.



$$f > 1 \text{ TeV} \quad (\text{MCHM} - 5])$$
$$f > 640 \text{ GeV} \quad (\text{extended models})$$

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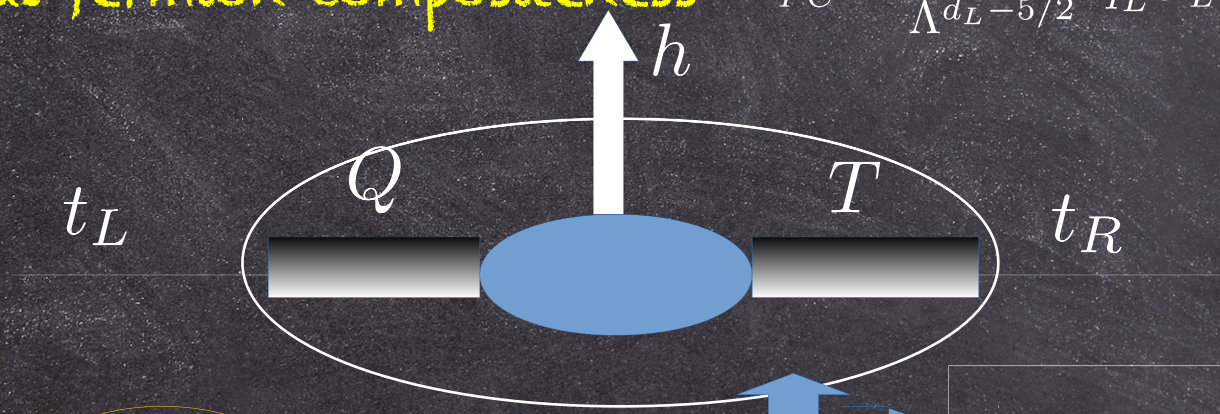
Inside the Yukawa coupling

Partial fermion compositeness $L_{PC} = \frac{\lambda_L}{\Lambda^{d_L - 5/2}}\, \bar{q}_L \mathcal{O}_L \;+\; \frac{\lambda_R}{\Lambda^{d_R - 5/2}}\, \bar{q}_R \mathcal{O}_R$



Strong dynamics

$$L_{\text{Yuk}} = \Pi_{LR}(q^2)\, S_h C_h\, \bar{t}_R t_L \;+\; \text{h.c.}$$

$$\Pi_{LR}(q^2) \sim \sum_n \frac{F_L F_R^*\, m_{Q(n)}}{q^2 + m_{Q(n)}^2}$$

$$|\text{phys}\rangle \;=\; \cos\theta\; |\text{elem}\rangle \;+\; \sin\theta\; |\text{comp}\rangle$$

$$\Pi_{LR}(q^2) = \sum_n \epsilon_L^{(n)}(q^2)\, \epsilon_R^{(n)}(q^2)\, m_{Q_{(n)}}$$

$$m_t \sim \epsilon_L \epsilon_R^*\, m_Q\, \sqrt{\xi\,(1-\xi)}$$

Fine-tuning of VEV and Higgs mass

- Effective Coleman-Weinberg potential (only fermionic, simplified)

$$V_{\text{eff}} = -2N_c \int \frac{d^4q}{(2\pi)^4} \ln\left[1 + \frac{\Pi_{LR}^2(q^2)\ S_h^2\ C_h^2}{q^2}\right] = -\frac{\mu^2}{2}h^2 + \frac{\lambda}{4}h^4$$

$$\left.\begin{aligned}\mu^2 &\equiv \mu^2\left(F_L, F_R, m_Q\right)\\ \lambda &\equiv \lambda\left(F_L, F_R, m_Q\right)\end{aligned}\right\} \quad v \equiv \frac{\mu^2}{\lambda} = 246\ \text{GeV} \qquad v \ll f$$

F.T. between fermion and gauge contribution

$$m_h^2 \sim \frac{N_c}{8\pi^2}\ \frac{1}{f^2}\ m_t^2\ m_Q^2 \sim \frac{N_c}{8\pi^2}\ g_*^2\ m_t^2\ \ (1 < g_* < 4\pi)$$

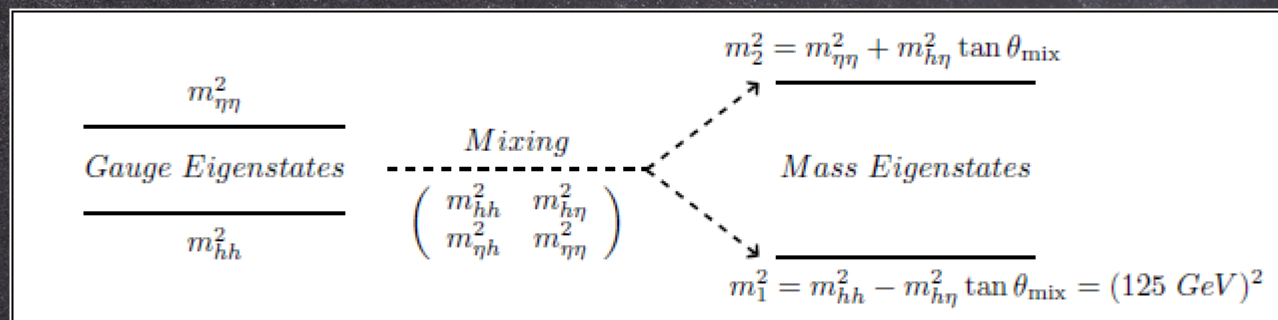
(loop) (GB) (2 vertices In PC) (cutoff)

Higgs mass too large unless tuned

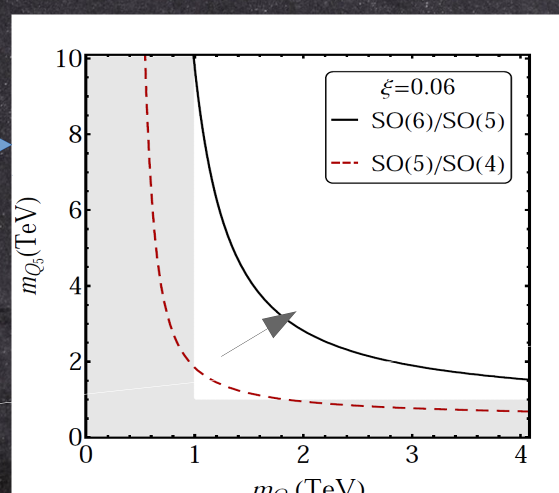
Improving the tuning

- Next-to-minimal SO(6) / SO(5) gives 5 pNGBs.
- 4 d.o.f. constitute H, the new one is a singlet scalar.

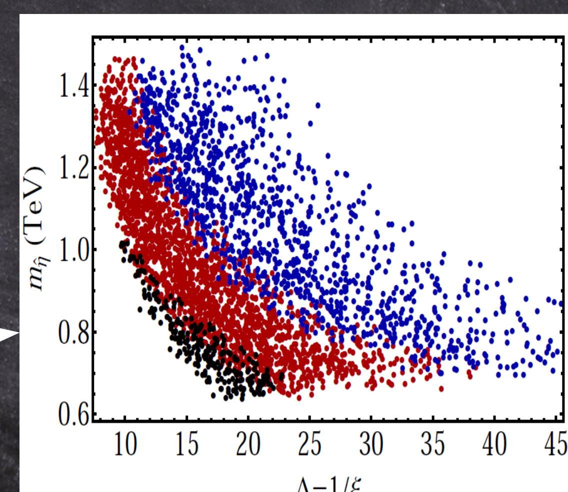
Level repulsion 1703.08011



Improved FT due to mixing



Lighter singlet at the expense of increased FT

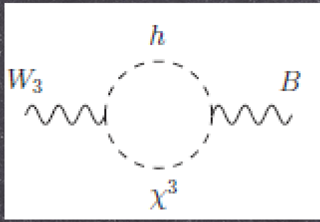


Electroweak precision tests

- Contributions to S and T significant, but model dependent

$$S \propto \Pi'_{3B} \qquad T \propto (\Pi_{11} - \Pi_{33})$$

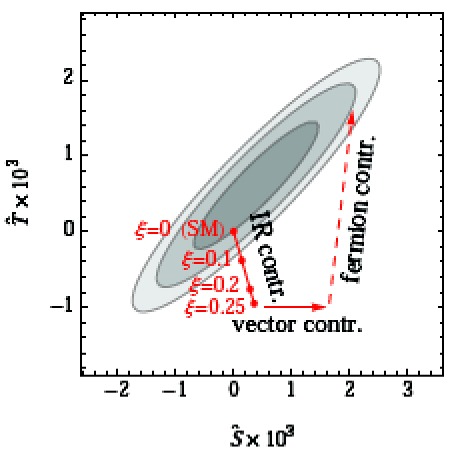
- hVV distortion --> incomplete divergence cancellation



- Vector resonance contribution

$$\Delta S = \frac{g^2}{192\pi^2}\,\xi\,\log\left(\frac{m_\rho^2}{m_h^2}\right)$$

$$\Delta T = \frac{-3g'^2}{64\pi^2}\,\xi\,\log\left(\frac{m_\rho^2}{m_h^2}\right)$$



$$f > 1.1 \text{ TeV} \ (2\sigma)$$

Grojean, Matsedonskyi, Panico
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Conclusions

- Big hierarchy is solved as beyond the cutoff the Higgs dissolves.
- Interpolation between SM and Technicolor (Higgsless).
- Non-linearity of pNGB dynamics modifies Higgs couplings.
- hVV modifications universal, hff modifications depend on reps.
- In MCHM-5, $f > 1$ TeV; relaxed in extended models $f > 640$ GeV.
- EWPT constraints (primarily S): $f > 1$ TeV (assumptions).
- Higgs mass tuning can be relaxed in next-to-minimal model.