A Naturally Light Higgs without Light Top Partners

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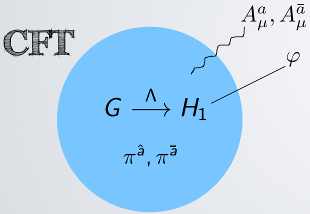
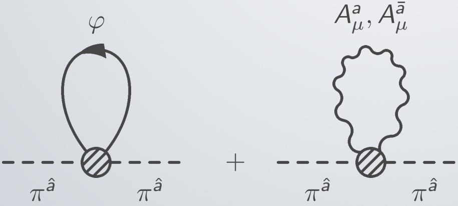
Composite Higgs

- One interesting possibility is that the Higgs is composite, the remnant of some new strong dynamics [Kaplan, Georgi '84]
- It is particularly compelling when the Higgs is the pNGB of some new strong interaction. Something like pions in QCD [Agashe, Contino, Pomarol '04]



$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_{\mathsf{SM}} + \mathcal{L}_{\mathsf{CFT}} - \frac{1}{4} F^{\alpha}_{\mu\nu} F^{\mu\nu\alpha} \\
&+ A^{\alpha}_{\mu} J^{\mu\alpha} + \varphi \cdot \mathcal{O}_{\varphi}, \quad \alpha = a, \bar a
\end{aligned}
$$



$$
m_\pi^2 = m_h^2 \sim \frac{g_{\mathrm{el}}^2}{16\pi^2} \Lambda^2
$$

Minimal Composite Higgs Models

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It is the minimal group delivering the Higgs as a pNGB with custodial protection

$$\dim\left(\mathrm{Lie}[SO(5)/SO(4)]\right) = 4 \quad \text{and} \quad SO(4) \cong SU(2)_L \otimes SU(2)_R$$

The Higgs can be parametrized by the fluctutations of the broken generators $T^{\hat{a}} \in \mathrm{Lie}[SO(5)/SO(4)]$, $\hat{a} = 1, 2, 3, 4$,

$$\Sigma = U\Sigma_0, \quad U = \exp\left(-i\sqrt{2}\frac{1}{f_\pi}\Pi_{\hat{a}}T^{\hat{a}}\right), \quad \Sigma_0 = (0, 0, 0, 0, f_\pi)^T,$$

leading, after integrating out all CFT states,

$$\begin{aligned}\mathcal{L}_{\text{eff}} &= \frac{1}{2}P^T_{\mu\nu}\left[\Pi_0^X(p)X^\mu X^\nu + \Pi_0(p)\mathrm{Tr}(A^\mu A^\nu) + \Pi_1(p)\Sigma A^\mu A^\nu \Sigma^T\right] \\ &+ \sum_k \bar{\psi}_k \not{p}\left[\Pi_0^k(p) + \Pi_1^k(p;\Sigma)\right]\psi_k + \sum_k \bar{\psi}_k\left[M_0^k(p) + M_1^k(p;\Sigma)\right]\psi_k\end{aligned}$$

that we have written in a $SO(5) \times U(1)_X$ symmetric way

Partial Compositeness

Another interesting feature of these models is that they can address the flavor puzzle through partial compositeness

$$\mathcal{L}_{\text{mix}} = \lambda_L^q \bar{\psi}_L \mathcal{O}_L^q + \lambda_R^t \bar{\psi}_R \mathcal{O}_R^t + \text{h.c.} \quad \langle 0|\mathcal{O}_L^q|\xi_n\rangle = \Delta_n \quad \langle 0|\mathcal{O}_R^t|\zeta_n\rangle = \Gamma_n$$

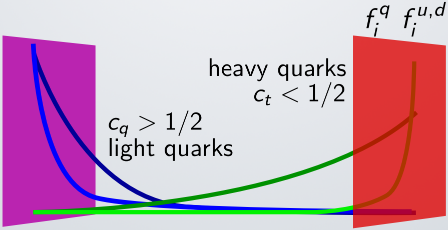
inducing at low energies

$$\mathcal{L}_{\text{mix}} = \lambda_L^q \Delta_1 \bar{\psi}_L \xi_{1R} + \lambda_R^t \Gamma_1 \bar{\psi}_R \zeta_{1R} + \text{h.c.} + \dots$$

The SM states will be a mixture of elementary and composite states, with masses after EWSB

$$m_t \sim \lambda_L^q \lambda_R^t f_\pi v / \min(m_{\xi_1}, m_{\zeta_1})$$

In the holographic language of AdS_5 models



The Higgs Effective Potential

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The couplings of the elementary fermions and gauge bosons break the global symmetry of the strong sector, generating at the loop level a Higgs potential

- The gauge contribution is aligned with zero vev

$$V_g(h) = \frac{3}{2}\int \frac{d^4p}{(2\pi)^4}\left[2\log\left(1+\frac{s_h^2}{4}\frac{\Pi_1}{\Pi_0}\right)+\log\left(1+\frac{s_h^2}{4}\frac{\Pi_1}{\Pi_0}\frac{2\Pi_0+\Pi_0^X}{\Pi_0+\Pi_0^X}\right)\right]$$

- The fermion contribution is responsible for EWSB but model-dependent, relaying on the $SO(5)$ representations assumed for the composite sector

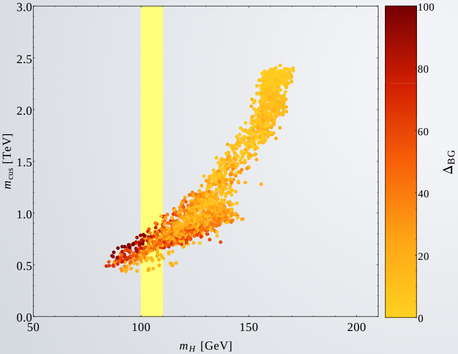
$$\begin{aligned} V_t(h) &= -2N_c\int \frac{d^4p}{(2\pi)^4}\log\left(p^2\Pi_{t_L}(p;h)\Pi_{t_R}(p;h)-\Pi^2_{t_L t_R}(p;h)\right) \\ &\approx \alpha\sin^2(h/f_\pi)^2-\beta\sin^2(h/f_\pi)\cos^2(h/f_\pi)=\alpha s_h^2-\beta s_h^2c_h^2 \end{aligned}$$

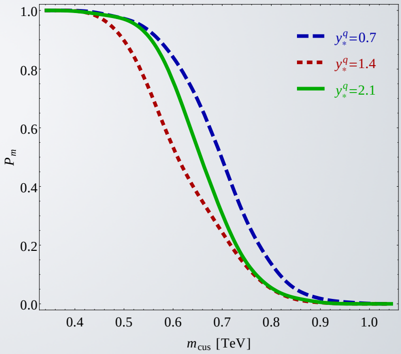
Up to a possible prefactor, for the simplest cases

$$m_h \approx \sqrt{\frac{N_c}{\pi^2}}\, m_t\frac{m_q^*}{f_\pi} \Rightarrow \text{Light resonances!}$$

Light Resonances

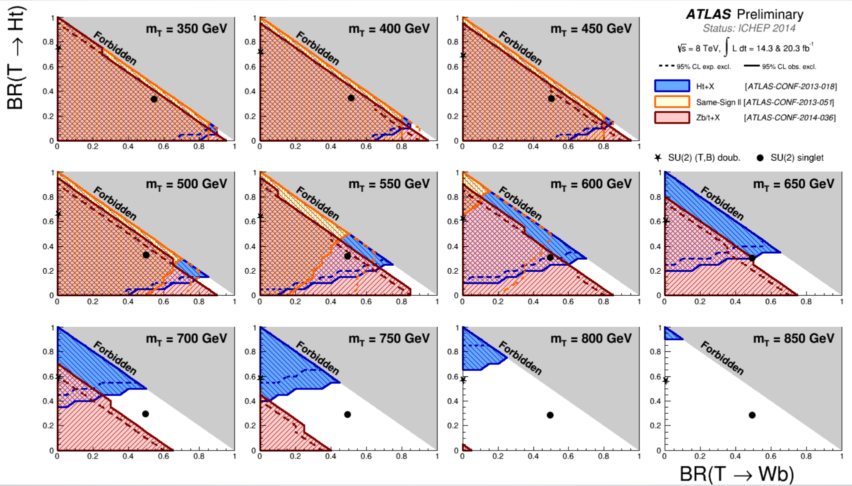
In the $MCHM_5$ e.g. with $f_\pi = 0.8$ TeV, all top partners are below 1 TeV





In the $MCHM_{10}$ this is typically even worse!

But the LHC constraints on them are getting stronger!

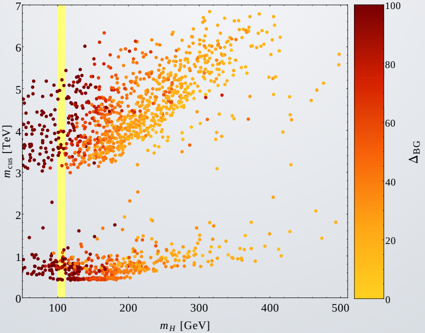


Non-Minimal Representations

This can be avoided for instance going to larger fermionic representations, e.g. [Panico, Redi, Tesi, Wulzer, '13] [Pappadopulo, Thamm, Torre, '13]

$$\mathcal{O}_L^q \sim \mathbf{14} \qquad \mathcal{O}_R^t \sim \mathbf{1}$$

- In this case $\alpha_t \sim \beta_t$, so we do not need to tune α to have EWSB $\Rightarrow$ Minimally tuned models
- However, the Higgs is typically too heavy so we need to make both terms small to get a light Higgs $\Rightarrow$ Ad-hoc tuning



What about leptons?

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Looking at their masses we would naively say that they should be always elementary. However ...

1. Contrary to the quark case, the PMNS lepton mixing matrix is non-hierarchical
2. We still do not know if neutrinos are Dirac or Majorana

- The first comment may suggest some flavor symmetry acting on the lepton sector. We could have some additional Yukawa suppresion leading to a τ_R more composite than expected [del Aguila,AC,Santiago '10]
- If neutrino masses are generated by a see-saw mechanism, the requirement of minimality can in some cases intertwine flavor and EWSB [AC,Goertz '14, in preparation]

A Very Minimal MCHM

We know that $\mathbf{14} = (\mathbf{1}, \mathbf{1}) \oplus (\mathbf{2}, \mathbf{2}) \oplus (\mathbf{3}, \mathbf{3})$ can solve some problems of EWSB and lift the masses of the top partners but

Why should we consider such a large representation?

- For quarks, there is no such reason besides being open-minded and trying to exhaust all possibilites
- However, for leptons it is the minimal rep where one can accommodate at the same time a $\mathbf{3}_0$ of $SU(2)_L \times U(1)$ as well as a P_{LR} protected RH charged lepton $\Rightarrow$ You can build the most minimal type-III see-saw CHM

If one builts such a model,

$$\mathcal{O}_L^{l_k} \sim \mathbf{5}, \quad \mathcal{O}_R^{e_k} \sim \mathbf{14}, \quad k = 1, 2, 3,$$

with additional elementary triplets of the EW group $\rho_R^k \sim \mathbf{3}_0$, talking to the $\mathbf{14}$s and with Majorana masses $\mathcal{O}(M_{\mathrm{Pl}})$, the size of neutrino mass splittings wants the mixing with the $\mathbf{14}$s to be large!

A Very Minimal MCHM

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Being more concrete, we consider 5D multiplets of $SO(5) \times U(1)_X$

$$\zeta_{1\tau} \sim \mathbf{5_{-1}} = \tau_1'[-,+] \oplus \begin{pmatrix} \nu_1^\tau[+,+] & \tilde{\tau}_1[-,+] \\ \tau_1[+,+] & \tilde{Y}_1^\tau[-,+] \end{pmatrix}$$

$$\zeta_{2\tau} \sim \mathbf{14_{-1}} = \tau_2'[-,-] \oplus \begin{pmatrix} \nu_2^\tau[+,-] & \tilde{\tau}_2[+,-] \\ \tau_2[+,-] & \tilde{Y}_2^\tau[+,-] \end{pmatrix}$$

$$\oplus \begin{pmatrix} \hat{\lambda}_2^\tau[-,-] & \nu_2^{\tau\prime\prime}[+,-] & \tau_2^{\prime\prime\prime}[+,-] \\ \hat{\nu}_2^\tau[-,-] & \tau_2^{\prime\prime}[+,-] & Y_2^{\tau\prime\prime\prime}[+,-] \\ \hat{\tau}_2[-,-] & Y_2^{\tau\prime\prime}[+,-] & \Theta_2^{\tau\prime\prime\prime}[+,-] \end{pmatrix}$$

with UV and IR brane terms

$$\mathcal{S}_{\mathrm{UV}} = -\frac{1}{2} \sum_{j=e,\mu,\tau} \int \mathrm{d}^4x \left\{ a^4(z) M_\Sigma^j \, \mathrm{Tr}\left(\bar{\Sigma}_{jR} \Sigma_{jR}^c\right) \right\}_{z=R} + \mathrm{h.c.},$$

$$\mathcal{S}_{\mathrm{IR}} = \sum_{j=e,\mu,\tau} \int \mathrm{d}^4x \left\{ a^4(z) \left[M_S^j \left(\bar{\zeta}_{1jL}^{(1,1)} \zeta_{2jR}^{(1,1)} \right)_{55} + M_B^j \left(\bar{\zeta}_{1jL}^{(2,2)} \zeta_{2jR}^{(2,2)} \right)_{55} \right] \right\}_{z=R'}$$

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A Very Minimal MCHM

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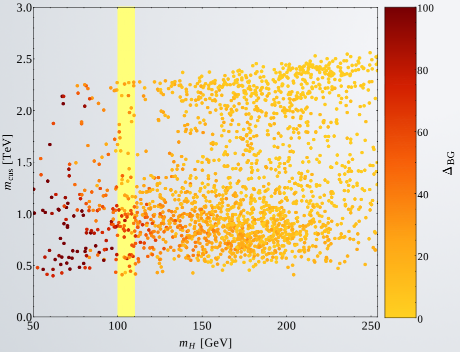
- As all the RH charged leptons have to be partially composite they can partially overcome the relative color suppression in the Higgs potential
- We consider quarks in *small* reps, e.g. $MCHM_5$ or $MCHM_{10}$



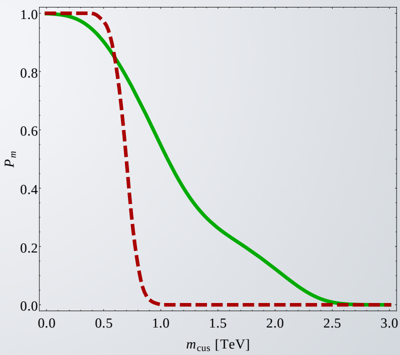


Figure: $y_*^l = 0.35,\ y_*^q = 0.7,\ f_\pi = 0.8$ TeV, $g_* \sim 4$

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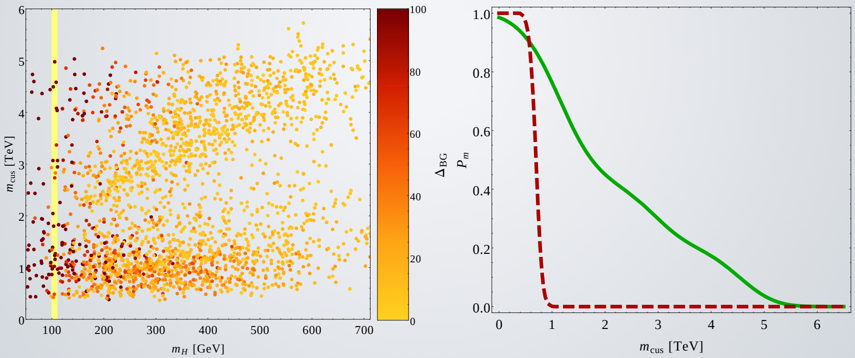

Figure: $y_*^l = 0.35, \quad y_*^q = 0.7, \; f_\pi = 0.8 \text{ TeV}, \; g_* \in [4, 6.3]$

Conclusions

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- Models of composite Higgs offer a nice solution of the hierarchy problem as well as a rationale behind EWSB
- A 125 GeV Higgs puts the simplest models in the quark sector under constraint
- Leptons may play a non-negligible role in EWSB in these models
- We can build very minimal models in the lepton sector having a large impact on the Higgs potential