A UV description of a composite Higgs model *without* elementary scalars

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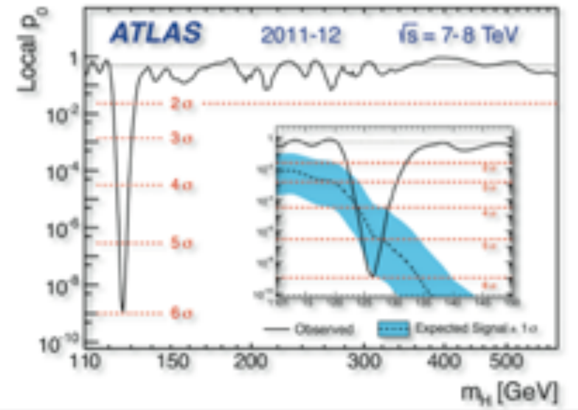
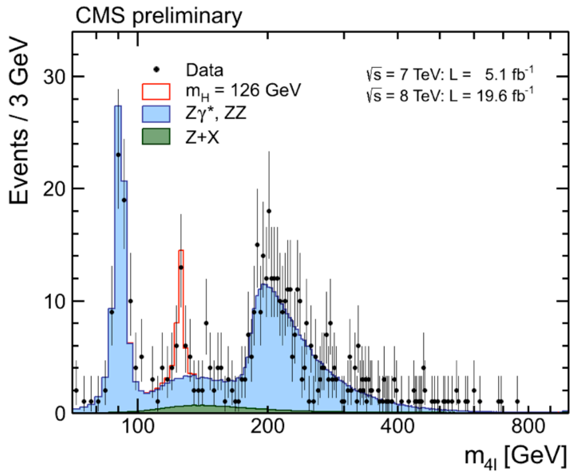
[James Barnard, TG, Tirtha Sankar Ray 1311.6562]

[James Barnard, TG, Anibal Medina, Tirtha Sankar Ray 1307.4778]

Higgs discovery - Run I





Higgs Bosons — H^0 and $H^\pm$ PDG 2013

H^0 Mass $m = 125.9 \pm 0.4$ GeV

H^0 signal strengths in different channels [n]

Combined Final States $= 1.07 \pm 0.26$ (S = 1.4)

WW^* Final State $= 0.88 \pm 0.33$ (S = 1.1)

ZZ^* Final State $= 0.89^{+0.30}_{-0.25}$

$\gamma\gamma$ Final State $= 1.65 \pm 0.33$

$b\bar{b}$ Final State $= 0.5^{+0.8}_{-0.7}$

$\tau^+\tau^-$ Final State $= 0.1 \pm 0.7$

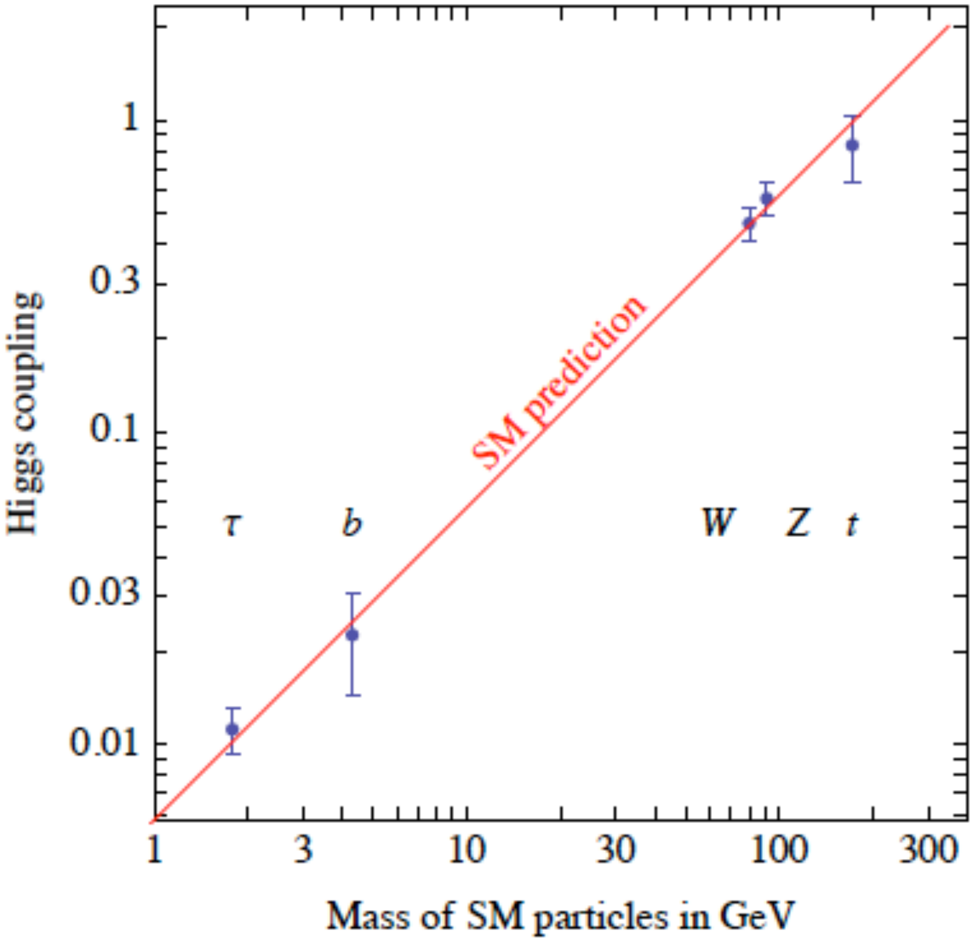
Higgs potential: $$V(h) = -\mu_h^2 |H|^2 + \lambda_h |H|^4 \qquad \langle H \rangle = \frac{1}{\sqrt{2}}(v+h)$$

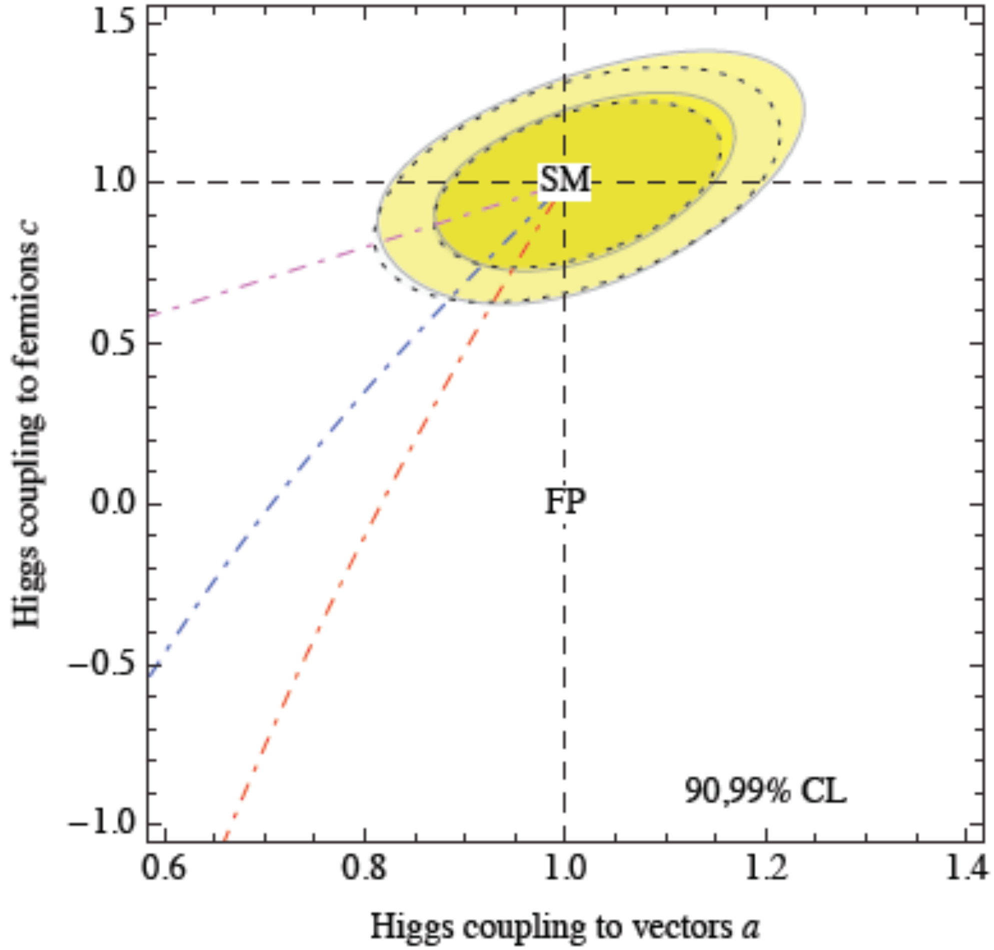
$$v^2 = \frac{\mu_h^2}{\lambda_h} \simeq (246\ \mathrm{GeV})^2 \qquad m_h^2 = 2\lambda_h v^2 \simeq (126\ \mathrm{GeV})^2$$

$$\boxed{\mu_h^2 \simeq (89\ \mathrm{GeV})^2} \qquad \boxed{\lambda_h \simeq 0.13}$$

Higgs couplings

[Giardino et al 1303.3570]





➡ Looks very much like a SM Higgs boson!

What is the nature of the Higgs boson?

HIGGS BOSON

Elementary? ⇨ Standard Model/ Supersymmetry

OR

Composite? ⇨ New strong dynamics

How to obtain a mass ~126 GeV much below the Planck scale?

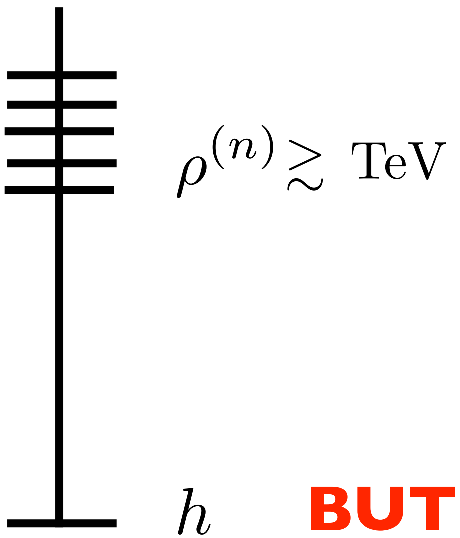
Composite Higgs

Higgs as a pseudo Nambu-Goldstone boson [Georgi, Kaplan `84]

Global symmetry G spontaneously broken to subgroup H at scale f

e.g. $SO(5)/SO(4) = \mathbf{2}$ of $SU(2)_L$

Higgs mass protected by global symmetry
-- like pions in QCD



Resonance mass: $m_\rho \sim g_\rho f \qquad 1 \lesssim g_\rho \lesssim 4\pi$

EWPT: $S \sim \dfrac{m_W^2}{m_\rho^2} \Rightarrow m_\rho \gtrsim 2.5\,\mathrm{TeV}$

BUT global symmetry must be explicitly broken
to generate $V(h) \neq 0$

Global symmetry broken by mixing with elementary sector

[Kaplan `91; Agashe, Contino, Pomarol `04]

SM matter and gauge fields

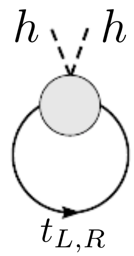
Ψ_i, A_μ

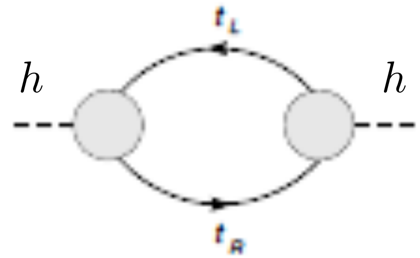
$\mathcal{L}_{mix} = \lambda_{L,R}\bar{\Psi}_{L,R}\mathcal{O}_\Psi + g_V A^\mu J_\mu$

strongly-coupled Higgs sector

$\mathcal{O}_i$

Higgs potential





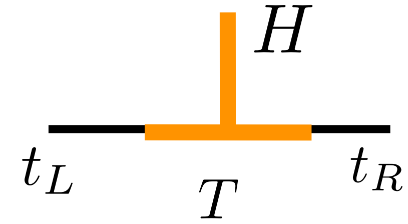
$V(h) = -\mu_h^2|H|^2 + \lambda_h|H|^4$ where $\mu_h^2 \sim \frac{g_{SM}^2}{16\pi^2} g_\rho^2 f^2$ $\quad \lambda_h \sim \frac{g_{SM}^2}{16\pi^2} g_\rho^2$

EWSB $\left(\langle H\rangle = \frac{v}{\sqrt{2}}\right)$ $\quad v^2 = \frac{\mu_h^2}{\lambda_h}$ $\Rightarrow$ **Tuning:** $\Delta^{-1} \sim \frac{v^2}{f^2} \lesssim 10\%$

$(v = 246 \text{ GeV}, f \gtrsim 750 \text{ GeV})$

Higgs mass:

$$m_h^2 \simeq \frac{N_c}{\pi^2} m_t^2 \overbrace{\frac{m_T^2}{f^2}}^{= g_T^2}$$



$m_T =$ fermion resonances (EM charges $5/3, 2/3, -1/3$)

$$m_T \sim m_\rho \gtrsim 2.5\,\text{TeV} \;\; (g_T \sim g_\rho \gtrsim 3) \quad \Rightarrow \quad m_h \gtrsim m_t$$

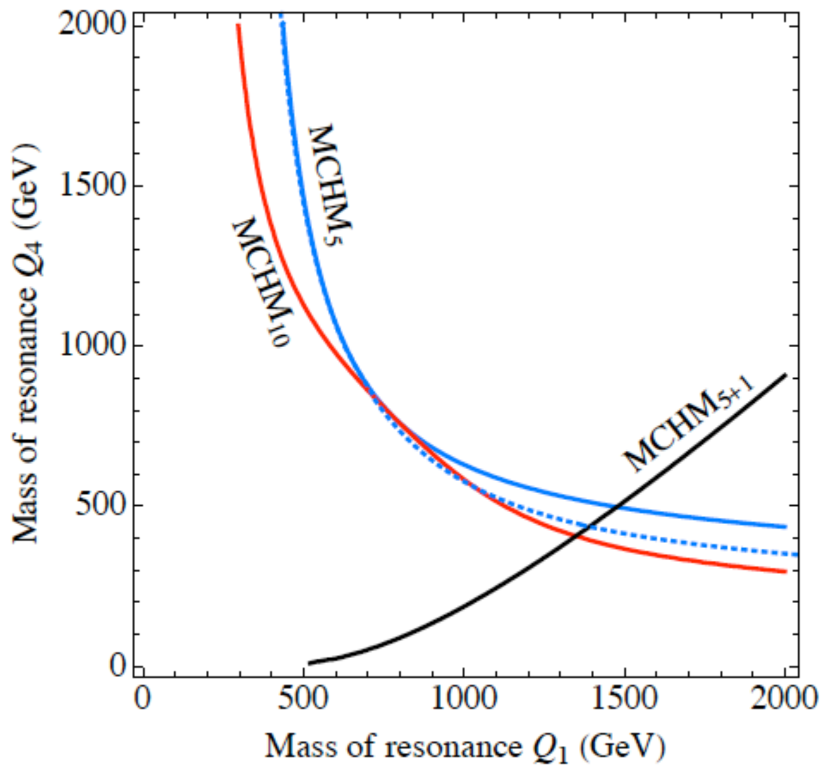
But, no need for $m_T \sim m_\rho$

$$m_h \sim 126\,\text{GeV}$$

$$\Rightarrow \quad m_T < m_\rho$$

light fermion resonances!

[Marzocca, Serone, Shu 2012; Pomarol, Riva 2012]



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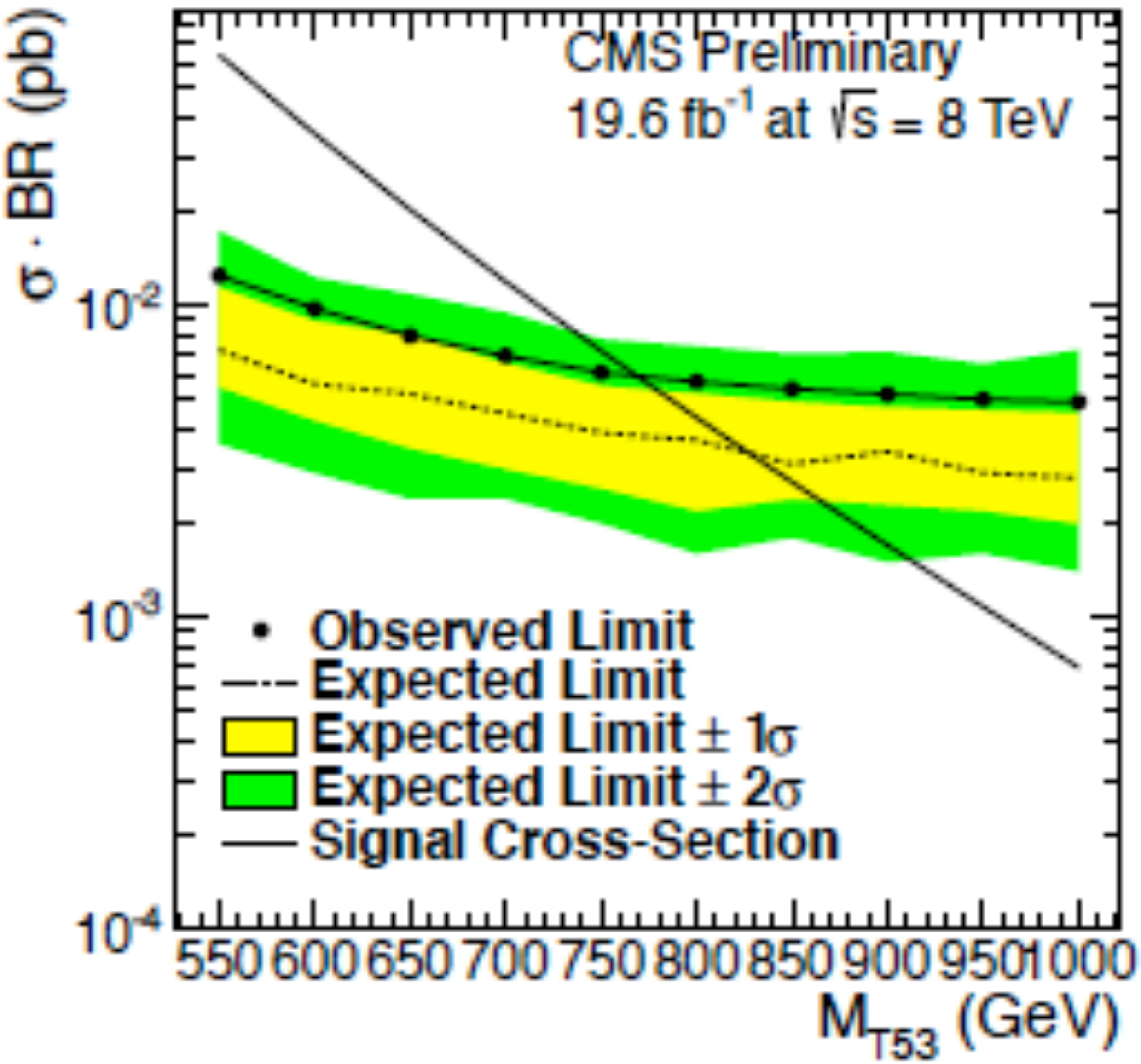
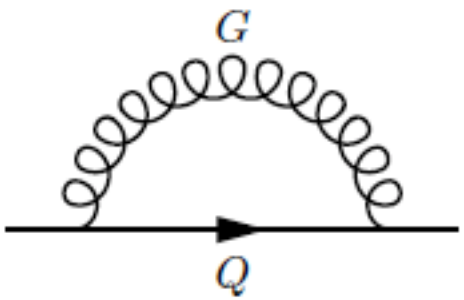


$$m_{T_{5/3}} \gtrsim 770 \text{ GeV}$$

HOWEVER, top partners ⇨ gluon partners



gluon partner coupling

$$i\Sigma(p) = \frac{16\pi}{3}\alpha_G \int \frac{\mathrm{d}^4k}{(2\pi)^4}\gamma^\mu \frac{1}{\not{k} - m_Q}\gamma^\nu \frac{\eta_{\mu\nu}}{(k-p)^2 - m_G^2}$$

gluon partner mass

where $\alpha_G \simeq \frac{g_3^2}{4\pi}\ln\left(\frac{\Lambda_{UV}}{\Lambda_{IR}}\right) \approx 3$

Contribution to Higgs mass:

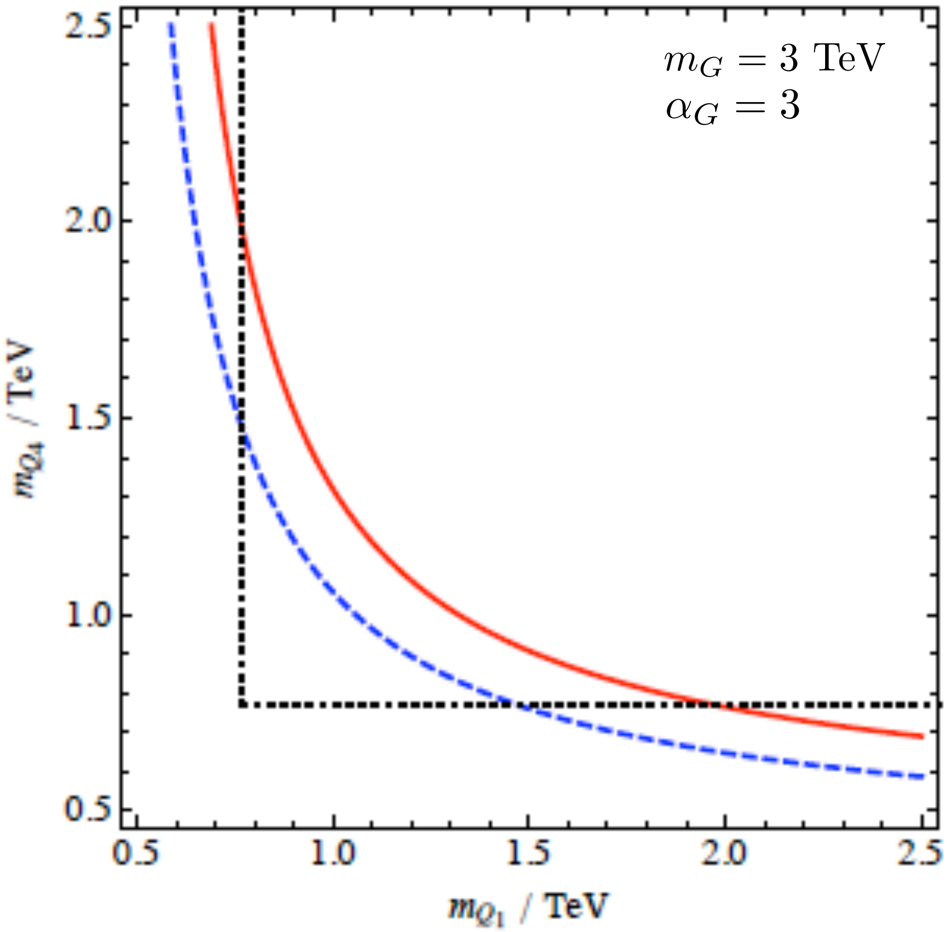
$$m_h^2 \approx \frac{8N_c v^2}{f^4}\int \frac{\mathrm{d}^4 p_E}{(2\pi)^4}\left[\frac{1}{p_E^2}\left|M(p_E^2)\right|^2 + \frac{1}{4}\Pi_L^h(p_E^2)^2 + \Pi_R^h(p_E^2)^2\right]$$

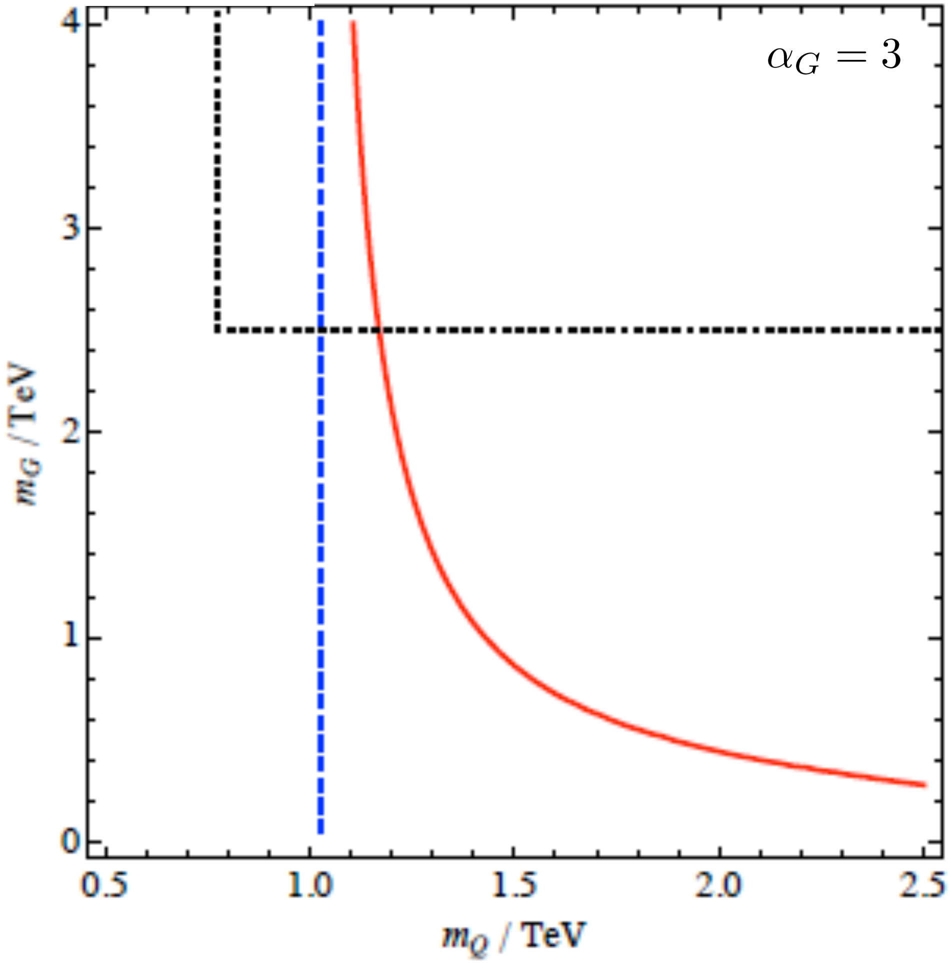
where $M(p^2) = \sum_{n=1}^{\infty}\frac{b_n F_n^L F_n^{R*}(m_{Q_n} + \Delta m_{Q_n}(p^2))}{p^2 - (m_{Q_n} + \Delta m_{Q_n}(p^2))^2}$ $\quad \Pi(p^2)_{L/R} = \sum_{n=1}^{\infty}\frac{a_n |F_n^{L/R}|^2}{p^2 - (m_{Q_n} + \Delta m_{Q_n}(p^2))^2}$

and $\Delta m_Q(p^2) = \frac{2\alpha_G}{3\pi} m_Q \int_0^1 \mathrm{d}x\,(x-2)\ln\left[\frac{(1-x)m_Q^2 + x m_G^2 - x(1-x)p^2}{(1-x)^2 m_Q^2 + x m_G^2}\right]$

⇨ ***Gluon partner correction to Higgs mass is negative***

Contours of $m_h = 126$ GeV [Barnard, TG, Medina, Sankar Ray 1307.4778]





For $\alpha_G = 3$ and $m_G = 3$ TeV obtain $\approx 10\%$ correction

➡ *Eases tension of having light top partners!*

Features of Composite Higgs models:

- Higgs is pseudo Nambu-Goldstone boson

$G \to H$ at scale f where $H \supset SO(4) \sim SU(2)_L \times SU(2)_R$

- Partially composite top $\mathcal{L} = \lambda_L t_L \mathcal{O}_R + \lambda_R t_R \mathcal{O}_L$

$m_t \sim \lambda_L \lambda_R v$ where $\lambda_{L,R} \sim \left(\frac{\Lambda}{\Lambda_{UV}}\right)^{\dim\, \mathcal{O}_{L,R} - \frac{5}{2}}$ $\Rightarrow$ $\dim\, \mathcal{O}_{L,R} \sim \frac{5}{2}$

What is the UV description responsible for these features?

- AdS/CFT -- D-brane engineering
- Supersymmetric (e.g. Seiberg duality)

} Involves scalars

[Caracciolo, Parolini, Serone 1211.7290]

Look for one without elementary scalars...

Candidate: SO(6)/SO(5) model

[Gripaios, Riva, Pomarol, Serra `09]

[Other possibilities classified by Ferretti, Karateev 1312.5330]

$$SO(6)/SO(5) \sim SU(4)/Sp(4)$$
$$= \underbrace{\mathbf{2}}_{\text{Higgs doublet}} \text{ of } SU(2)_L + \mathbf{1} \text{ singlet}$$

Symmetry breaking-pattern $SU(4) \xrightarrow{f} Sp(4)$

What is the dynamics that realizes this?

Introduce new strong gauge group $Sp(2N_c)$
with 4 Weyl fermion flavors ψ^a $(a = 1, \ldots, 4)$

⇨ $SU(4)$ global symmetry

Gauge-invariant fermion bilinear: $\Omega_{ij}\psi_i^a\psi_j^b = \mathbf{6}$ of $\mathrm{SU}(4)$

$Sp(2N_c)$ is asymptotically free $b = \frac{11}{3}(2N_c + 2) - \frac{2}{3} \times 4 = \frac{2}{3}(11N_c + 7) > 0$

and confines ⇨ $SU(4) \to Sp(4)$

Under what conditions does this happen?

SU(4) gauged NJL model

$$\mathcal{L}_{\text{int}} = \frac{\kappa_A}{2N_c}(\psi^a\psi^b)(\bar{\psi}_a\bar{\psi}_b) + \frac{\kappa_B}{8N_c}\left[\epsilon_{abcd}(\psi^a\psi^b)(\psi^c\psi^d) + \text{h.c.}\right]$$

	$\text{Sp}(2N_c)$	$\text{SU}(4)$
ψ	$\square$	$\mathbf{4}$
M	$\mathbf{1}$	$\mathbf{6}$

Can be rewritten as

$$\mathcal{L}_{\text{int}} = -\frac{1}{\kappa_A + \kappa_B}\left[\left(\kappa_A M^*_{ab} + \frac{1}{2}\kappa_B \epsilon_{abcd} M^{cd}\right)(\psi^a\psi^b) + \text{h.c.}\right] - \frac{2N_c\kappa_A}{(\kappa_A+\kappa_B)^2} M^{ab} M^*_{ab} - \frac{N_c\kappa_B}{2(\kappa_A+\kappa_B)^2}\left(\epsilon_{abcd} M^{ab} M^{cd} + \text{h.c.}\right)$$

Like "massive Yukawa theory"

where $\quad M^{ab} = -\frac{\kappa_A + \kappa_B}{2N_c}(\psi^a\psi^b)$ "auxiliary scalar field"

One-loop effective potential

$$V(m) = \frac{N_c \kappa_A}{\kappa_A^2 - \kappa_B^2}(\bar{m}_1^2 + \bar{m}_2^2) - \left|\frac{2N_c\kappa_B}{\kappa_A^2 - \kappa_B^2}\right| \bar{m}_1 \bar{m}_2$$
$$- \frac{N_c}{8\pi^2}\sum_{i=1}^{2}\left[\Lambda^2 \bar{m}_i^2 + \bar{m}_i^4 \ln\left(\frac{\bar{m}_i^2}{\Lambda^2 + \bar{m}_i^2}\right) + \Lambda^4 \ln\left(\frac{\Lambda^2 + \bar{m}_i^2}{\Lambda^2}\right)\right]$$

Λ = UV cutoff scale

where

$$M = \begin{pmatrix} 0 & m_1 & 0 & 0 \\ -m_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & m_2 \\ 0 & 0 & -m_2 & 0 \end{pmatrix} \qquad |\bar{m}_1|^2 = \frac{4|\kappa_A m_1^* + \kappa_B m_2|^2}{(\kappa_A + \kappa_B)^2} \qquad |\bar{m}_2|^2 = \frac{4|\kappa_A m_2^* + \kappa_B m_1|^2}{(\kappa_A + \kappa_B)^2}$$

Minimum condition

$$\boxed{1 - \frac{\bar{m}^2}{\Lambda^2}\ln\left(\frac{\Lambda^2 + \bar{m}^2}{\bar{m}^2}\right) = \frac{4\pi^2}{\Lambda^2}\left(\frac{\kappa_A}{\kappa_A^2 - \kappa_B^2} - \left|\frac{\kappa_B}{\kappa_A^2 - \kappa_B^2}\right|\right) \equiv \frac{1}{\xi}}$$

Solutions

$$\begin{cases} m_1 = m_2 = 0 & 0 < \xi < 1 & SU(4) \text{ unbroken} \\ m_1 = m_2 = \dfrac{\bar{m}}{2} & \xi > 1 & SU(4) \to Sp(4) \end{cases}$$

⇨ $\xi = 1$ is a critical point

Treat Λ as a renormalization scale: $\beta(\xi) = \Lambda \dfrac{\partial \xi}{\partial \Lambda} \approx 2\xi(1-\xi)$

⇨ UV fixed point at $\xi = 1$ $(\Lambda \to \infty \text{ with } \bar{m} \text{ finite})$

Dynamically generated fermion mass $\bar{m} = -\dfrac{4\pi^2 \xi}{N_c \Lambda^2} \langle \psi \psi \rangle$

Near $\xi \approx 1$ $\bar{m}(\Lambda) = \left(\dfrac{\mu_0}{\Lambda}\right)^2 \bar{m}(\mu_0) \equiv Z_m \bar{m}(\mu_0)$ $\mu_0 =$ reference scale

Large anomalous dimension $\gamma_m \equiv -\dfrac{\Lambda}{Z_m} \dfrac{\partial Z_m}{\partial \Lambda} = 2$ [Kondo, Tanabashi, Yamawaki \`92 Yamawaki \`96]

$$\dim \psi\psi = 3 - \gamma_m = 1$$

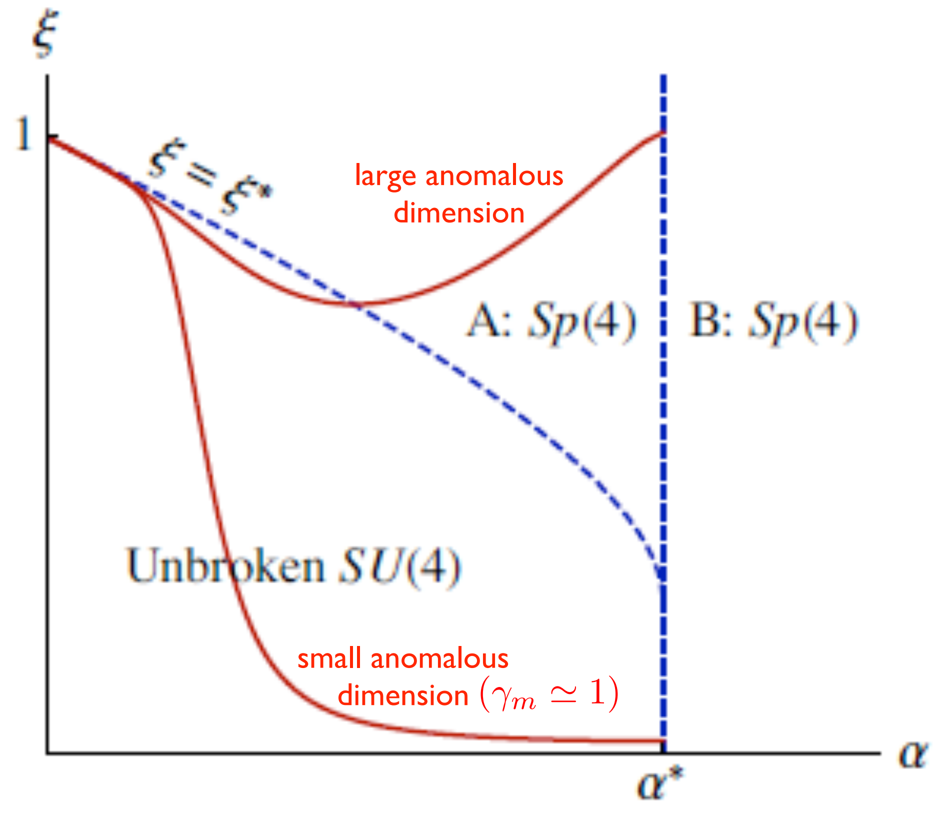
⇨ Four-fermion operator has dimension 2

-- model appears to be renormalisable in the UV!

Need to include gauge interaction and solve Schwinger-Dyson equation

[Bardeen, Leung, Love `86; Kondo, Mino, Yamawaki `89]

For Sp(2Nc) gauge group obtain [Barnard, TG, Sankar Ray 1311.6562]



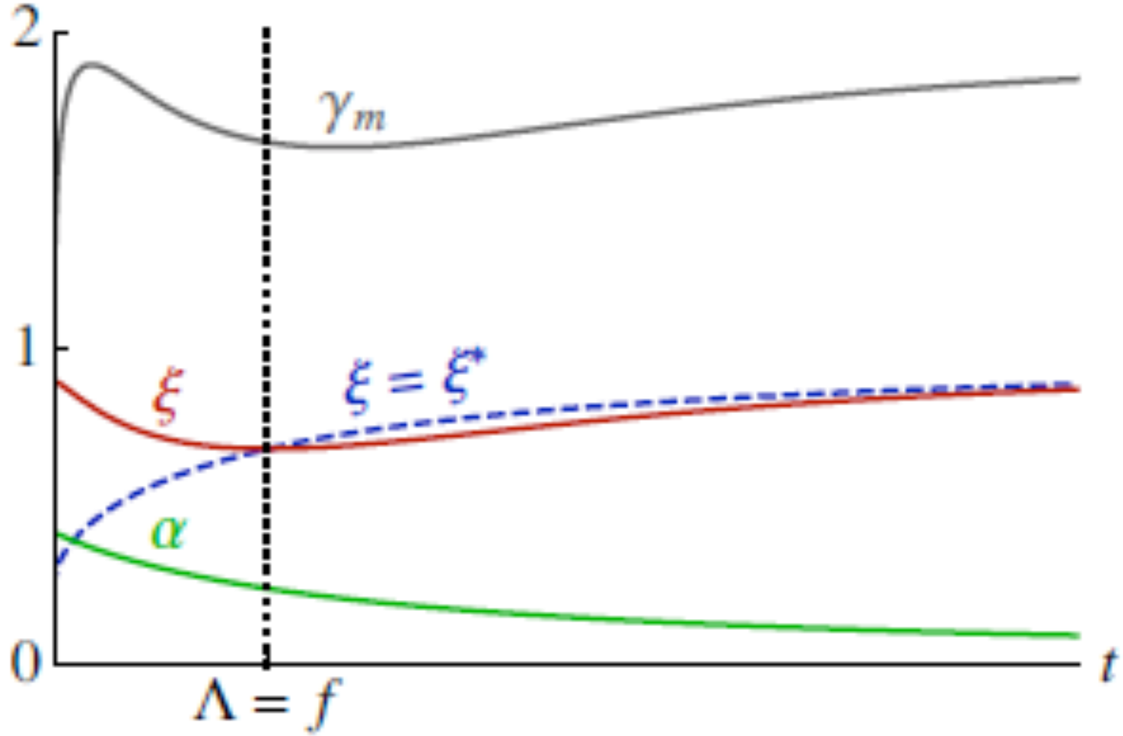
Large anomalous dimension for

$\xi \approx \xi^*$ and $\alpha \ll \alpha^*$

$$\boxed{\gamma_m \simeq 2 - \frac{\alpha}{2\alpha^*}}$$

Evolution of couplings: (for upper trajectory)

[Barnard, TG, Sankar Ray 1311.6562]



*Spontaneous breaking of global symmetry driven **mainly** by 4-fermion interaction!*

Top partners

Introduce a pair of colored vector-like fermions $\chi, \tilde{\chi}$

transform as two-index antisymmetric representation of Sp(2Nc)

	$\mathrm{Sp}(2N_c)$	$\mathrm{SU}(4)$	$\mathrm{SU}(3)_c \times \mathrm{U}(1)$
ψ	$\square$	$\mathbf{4}$	$\mathbf{1}_0$
χ	$\begin{array}{c}\square\\[-3pt]\square\end{array}$	$\mathbf{1}$	$\mathbf{3}_{+2/3}$
$\tilde{\chi}$	$\begin{array}{c}\square\\[-3pt]\square\end{array}$	$\mathbf{1}$	$\bar{\mathbf{3}}_{-2/3}$

Gauge-invariant combinations: $(\psi^a \chi^f \psi^b) = \psi^a_i \Omega_{ij} \chi^f_{jk} \Omega_{kl} \psi^b_l$ etc.

$$\Psi_1{}^{abf} = (\psi^a \chi^f \psi^b) \qquad \Psi_2{}^{f}_{ab} = (\bar{\psi}_a \chi^f \bar{\psi}_b) \qquad \Phi^b_{af} = (\bar{\psi}_a \tilde{\chi}_f \psi^b)$$

$$\tilde{\Psi}_1{}^{abf} = (\psi^a \tilde{\chi}_f \psi^b) \qquad \tilde{\Psi}_2{}^{f}_{ab} = (\bar{\psi}_a \tilde{\chi}_f \bar{\psi}_b) \qquad \tilde{\Phi}^b_{af} = (\bar{\psi}_a \bar{\tilde{\chi}}^f \psi^b)$$

transform as

	$\mathrm{Sp}(2N_c)$	$\mathrm{SU}(4)$	$\mathrm{SU}(3)_c \times \mathrm{U}(1)$
$\Psi_{1,2}$	$\mathbf{1}$	$\mathbf{6}$	$\mathbf{3}_{+2/3}$
Φ	$\mathbf{1}$	$\mathbf{15} \oplus \mathbf{1}$	$\bar{\mathbf{3}}_{-2/3}$
$\tilde{\Psi}_{1,2}$	$\mathbf{1}$	$\mathbf{6}$	$\bar{\mathbf{3}}_{-2/3}$
$\tilde{\Phi}$	$\mathbf{1}$	$\mathbf{15} \oplus \mathbf{1}$	$\mathbf{3}_{+2/3}$

top partner candidates

Recall: $\mathcal{L} = \lambda_L t_L \mathcal{O}_R + \lambda_R t_R \mathcal{O}_L$

UV description: $\mathcal{O}_{L,R} \leftrightarrow \underbrace{\psi\chi\psi}$ (Diquark approximation to baryons [Ball `90])

= tightly bound $\psi\psi$ by 4-fermion interaction, bound to χ by Sp(2Nc) gauge interaction $(\xi \gg \sqrt{\alpha})$

$$\dim \mathcal{O}_{L,R} = \dim \psi\chi\psi \approx \underbrace{\dim \psi\psi}_{3-\gamma_m} + \frac{3}{2} = \frac{5}{2} + \frac{\alpha}{2\alpha^*}$$

Marginally irrelevant!

⇨ Allows for order-one top Yukawa coupling!

$\xi \gg \sqrt{\alpha}$

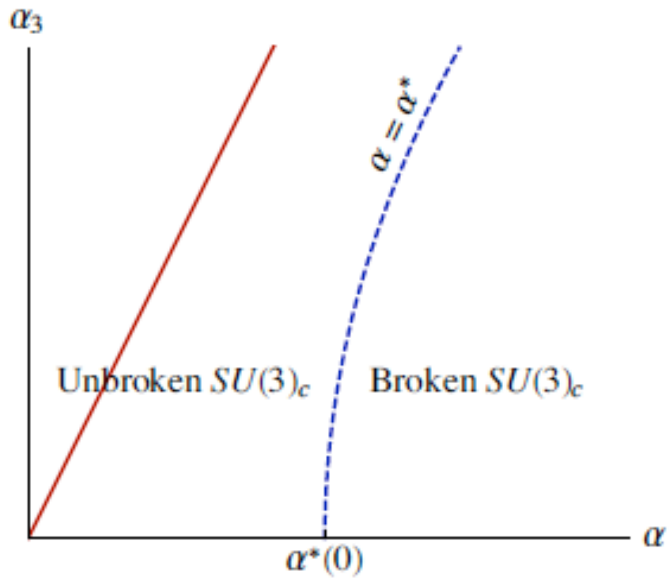
⇨ Top partners are naturally lighter than uncolored partners!

In addition there are ***scalar*** bound states:

	$\mathrm{Sp}(2N_c)$	$\mathrm{SU}(4)$	$\mathrm{SU}(3)_c \times \mathrm{U}(1)$
M	$\mathbf{1}$	$\mathbf{6}$	$\mathbf{1}_0$
S	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}_0$
R	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{8}_0$
P	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{6}_{+4/3}$
$\tilde{P}$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\mathbf{6}}_{-4/3}$

Coloured bound states cannot get a VEV

Coloured scalars must be stabilised by the SU(3) gauge interactions.



Require: $$\frac{\alpha}{\alpha_3} < \frac{d\alpha^*}{d\alpha_3}$$

Conclusion

- The Higgs boson could be composite

  --- Higgs is a pseudo Nambu-Goldstone boson

  --- Partially composite top sector

- SO(6)/SO(5) model has a simple UV description

  --- Only fermions and gauge bosons, *no elementary scalars!*

  --- Large anomalous dimension implies four-fermion interaction is renormalisable

- This simple framework can be applied to other coset groups