A Light Higgs Boson from a Composite Higgs Theory

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Introduction

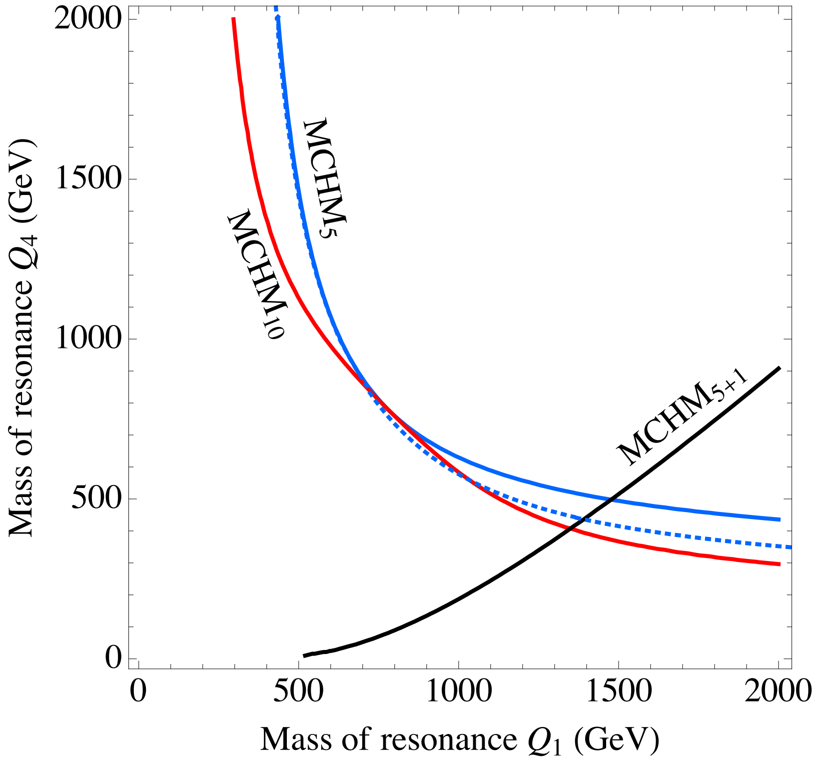
- Discovery of a Higgs boson at 126 GeV is monumental step in high energy physics. It has important implications for different possible mechanisms of electroweak symmetry breaking.
  - Technicolor w/o a light scalar is ruled out.
  - SUSY prefers a light Higgs, but 126 GeV is a bit uncomfortably heavy for MSSM.
    - Heavy stops, but more fine-tuned.
    - Extensions to enhance the quartic coupling.

Introduction

- An alternative is a composite Higgs. To make it light, there should be some symmetry to protect its mass, i.e., Higgs as a pseudo-Nambu-Goldstone boson (PNGB) (Kaplan & Georgi '84).
  - Little Higgs theories
  - Models motivated from AdS/CFT
  - Gauge-Higgs unification
- Higgs boson mass is model-dependent, e.g., whether there is a tree-level quartic coupling.

Composite Higgs

- Top quark mass is a challenge for composite Higgs models.
  - Partial compositeness (Kaplan '91): Elementary top quarks mix with composite operators, $t_L O$, ⇒ heavy top-like resonances.
  - In a class of models (MCHM) where the explicit symmetry breaking dominantly comes from such mixings, m_h=126 GeV ⇒ $m_{t'}$ < TeV



Pomarol, Riva, 1025.6434

Composite Higgs

- Top condensation (Nambu '89, Miransky et al '89): Higgs is a bound state of $\bar{t}t$.
  - $m_t \sim 600$ GeV ($y_t \sim$3-4), $m_h \sim 2m_t$ (in leading N_c approximation)
  - m_t, m_h may be reduced by raising the compositeness scale at the expenses of fine tuning, but still too heavy. (Bardeen, Hill, Linder '90)

Top Seesaw Model

- An attractive solution to the top mass problem is to invoke the seesaw mechanism (Dobrescu & Hill '98): introducing vector-like singlet quarks χ_L, χ_R to mix with top quark.

$$\mathcal{L} = -\left(\bar{t}_L \ , \ \overline{\chi}_L\right) \begin{pmatrix} m_{tt} & m_{t\chi} \\ m_{\chi t} & m_{\chi\chi} \end{pmatrix} \begin{pmatrix} t_R \\ \chi_R \end{pmatrix} + \text{h.c.}$$

$$m_{tt}^2 + m_{t\chi}^2 \sim (600\,\text{GeV})^2,$$

but a light eigenstate ~ 173 GeV can be obtained which is identified as the top quark.

Top Seesaw with a Light Higgs

- A light Higgs boson arises naturally if the underlying strong dynamics preserves a U(3) symmetry among (t_L, b_L, χ_L).
  - Higgs field is PNGB of U(3) → U(2)

Scalar Potential

- Assuming the underlying (non-confining) strong dynamics is approximately $U(3)_L \times U(2)_R$ symmetric for (t_L, b_L, χ_L) and (t_R, χ_R), they form composite scalars, $\Phi = \begin{pmatrix} \Phi_t & \Phi_\chi \end{pmatrix}$

$$\Phi_t = \begin{pmatrix} H_t \\ \phi_t \end{pmatrix} \sim \bar{t}_R \begin{pmatrix} \psi_L^3 \\ \chi_L \end{pmatrix}, \quad \Phi_\chi = \begin{pmatrix} -H_\chi \\ \phi_\chi \end{pmatrix} \sim \bar{\chi}_R \begin{pmatrix} \psi_L^3 \\ \chi_L \end{pmatrix}.$$

Yukawa int: $\mathcal{L}_{\text{Yukawa}} = -\xi \left(\bar{\psi}_L^3, \bar{\chi}_L\right) \Phi \begin{pmatrix} t_R \\ \chi_R \end{pmatrix} + \text{H.c.}$

Scalar potential:

$$V_\Phi = \frac{\lambda_1}{2} \text{Tr}[(\Phi^\dagger \Phi)^2] + \frac{\lambda_2}{2} \left(\text{Tr}[\Phi^\dagger \Phi]\right)^2 + M_\Phi^2 \Phi^\dagger \Phi$$

Scalar Potential

- Symmetry breaking terms

U(2) breaking: $V_{\cancel{U(2)}_R} = \delta M_{tt}^2 \, \Phi_t^\dagger \Phi_t + \delta M_{\chi\chi}^2 \, \Phi_\chi^\dagger \Phi_\chi + (M_{\chi t}^2 \Phi_\chi^\dagger \Phi_t + \mathrm{H.c.})$

U(3) breaking: singlet fermion mass terms,

$$\mathcal{L}_{\mathrm{mass}} = -\mu_{\chi t} \bar{\chi}_L t_R - \mu_{\chi\chi} \bar{\chi}_L \chi_R + \mathrm{H.c.}$$

They map into scalar tadpole terms,

$$V_{\mathrm{tadpole}} = -(0, 0, C_{\chi t}) \Phi_t - (0, 0, C_{\chi\chi}) \Phi_\chi + \mathrm{H.c.}$$

$$C_{\chi t} \approx \frac{\mu_{\chi t}}{\xi} \Lambda^2 \quad , \quad C_{\chi\chi} \approx \frac{\mu_{\chi\chi}}{\xi} \Lambda^2 \, .$$

We can use U(2) rotation to set $C_{\chi\chi} = 0$.

Scalar Potential

- Total effective scalar potential:

$$\begin{aligned} V_{\rm scalar} &= \frac{\lambda_1+\lambda_2}{2}\left[(\Phi_t^\dagger\Phi_t)^2+(\Phi_\chi^\dagger\Phi_\chi)^2\right]+\lambda_1|\Phi_t^\dagger\Phi_\chi|^2+\lambda_2(\Phi_t^\dagger\Phi_t)(\Phi_\chi^\dagger\Phi_\chi) \\ & +M_{tt}^2\Phi_t^\dagger\Phi_t+M_{\chi\chi}^2\Phi_\chi^\dagger\Phi_\chi+(M_{\chi t}^2\Phi_\chi^\dagger\Phi_t+{\rm H.c.}) \\ & -(0,0,2C_{\chi t}){\rm Re}\,\Phi_t-(0,0,2C_{\chi\chi}){\rm Re}\,\Phi_\chi \quad , \end{aligned}$$

Assuming $M_{\chi\chi}^2 < 0 < M_{tt}^2,$ minimize the potential:

$$\langle H_t\rangle = 0, \quad \langle\phi_t\rangle = u_t \equiv u\sin\gamma = u\,s_\gamma,$$

$$\langle H_\chi\rangle = v, \quad \langle\phi_\chi\rangle = u_\chi \equiv u\cos\gamma = u\,c_\gamma,$$

$$M_{H^\pm}^2 = M_{tt}^2+\frac{\lambda_1}{2}u^2 s_\gamma^2+\frac{\lambda_2}{2}\left(u^2+v^2\right)$$

$$\sqrt{2}C_{\chi t} = u\,s_\gamma\,M_{H^\pm}^2$$

$$C_{\chi\chi} = 0$$

$$\begin{aligned} M_{\chi t}^2 &= -\frac{\lambda_1}{2}u^2 s_\gamma c_\gamma\,, \\ M_{\chi\chi}^2 &= -\frac{\lambda_1}{2}\left(u^2c_\gamma^2+v^2\right)-\frac{\lambda_2}{2}\left(u^2+v^2\right) \end{aligned}$$

Top Quark Mass

- Charge-2/3 fermion mass matrix:

$$-\frac{\xi}{\sqrt{2}}\,(t_L,\chi_L)\begin{pmatrix}0 & v\\ us_\gamma & uc_\gamma\end{pmatrix}\begin{pmatrix}t_R\\ \chi_R\end{pmatrix}+\mathrm{H.c.}$$

Light eigenvalue: $m_t \approx \frac{\xi}{\sqrt{2}} v\, s_\gamma \;\Rightarrow\; s_\gamma \approx \frac{y_t}{\xi} \approx \frac{1}{4} \sim \frac{1}{5}.$

Heavy *t'* fermion: $m_{t'} \approx \frac{\xi}{\sqrt{2}} u$

Light Higgs Mass

- CP-even scalar mass matrix: $(h_t, h_\chi, \phi_t, \phi_\chi)$

$$\begin{pmatrix} M_{H^\pm}^2 + \frac{\lambda_1}{2}v^2 & 0 & -\frac{\lambda_1}{2}uvc_\gamma & -\frac{\lambda_1}{2}uvs_\gamma \\ 0 & (\lambda_1+\lambda_2)v^2 & \lambda_2 uvs_\gamma & (\lambda_1+\lambda_2)uvc_\gamma \\ -\frac{\lambda_1}{2}uvc_\gamma & \lambda_2 uvs_\gamma & M_{H^\pm}^2+\left[\lambda_1\left(1-\frac{c_\gamma^2}{2}\right)+\lambda_2\right]u^2 & \left(\frac{\lambda_1}{2}+\lambda_2\right)u^2 s_\gamma c_\gamma \\ -\frac{\lambda_1}{2}uvs_\gamma & (\lambda_1+\lambda_2)uvc_\gamma & \left(\frac{\lambda_1}{2}+\lambda_2\right)u^2 s_\gamma c_\gamma & \left[\lambda_1\left(1-\frac{s_\gamma^2}{2}\right)+\lambda_2 c_\gamma^2\right]u^2 \end{pmatrix}$$

Lightest eigenvalue:

$$m_h^2 = \left(\frac{\lambda_1\, s_\gamma^2}{2}\right)\left(\frac{M_{H^\pm}^2}{M_{H^\pm}^2+\lambda_1 u^2/2}\right)v^2 + \mathcal{O}(s_\gamma^4)$$

$$\approx \left(\frac{\lambda_1}{2\xi^2}\right)\left(\frac{M_{H^\pm}^2}{M_{H^\pm}^2+\lambda_1 u^2/2}\right)y_t^2 v^2$$

Light Higgs Mass

Effective Higgs quartic coupling:

$$\lambda_h \approx \left(\frac{\lambda_1}{2\xi^2}\right)\left(\frac{M_{H^\pm}^2}{M_{H^\pm}^2+\lambda_1 u^2/2}\right) y_t^2$$

In the limit ξ→∞ or m_t→0, sinγ→0 and $C_{\chi t}$→0, there is no explicit U(3) breaking, Higgs becomes an exact NGB.

(IR fixed point) $0.4 < \frac{\lambda_1}{2\xi^2} < 1$ (fermion loop approx.)

$y_t^2 \sim 0.6$ @ 10 TeV

$$\Rightarrow m_h < 185 \text{ GeV}$$

Electroweak Interactions

- Explicit U(3) breaking electroweak interaction can further decreases the Higgs boson mass.

$$\Delta m^2_{h\,(\mathrm{mass})} = \frac{9g_2^2+3g_1^2}{64\pi^2}\frac{M_\rho^2}{u^2}v^2 \approx -0.16v^2\frac{M_\rho^2}{(5u)^2}$$ (mass splitting)

$$\Delta m^2_{h\,(\mathrm{quartic})} = -\frac{9g_2^2+3g_1^2}{64\pi^2}\lambda_1 v^2 \ln\frac{M_\rho}{\mu} \approx -0.16v^2\left(\frac{\lambda_1}{2\xi^2}\right)\left(\frac{\xi}{3.6}\right)^2 \ln\frac{M_\rho}{\mu}$$

(quartic splitting)

where M_ρ is the cutoff the EW gauge loop.

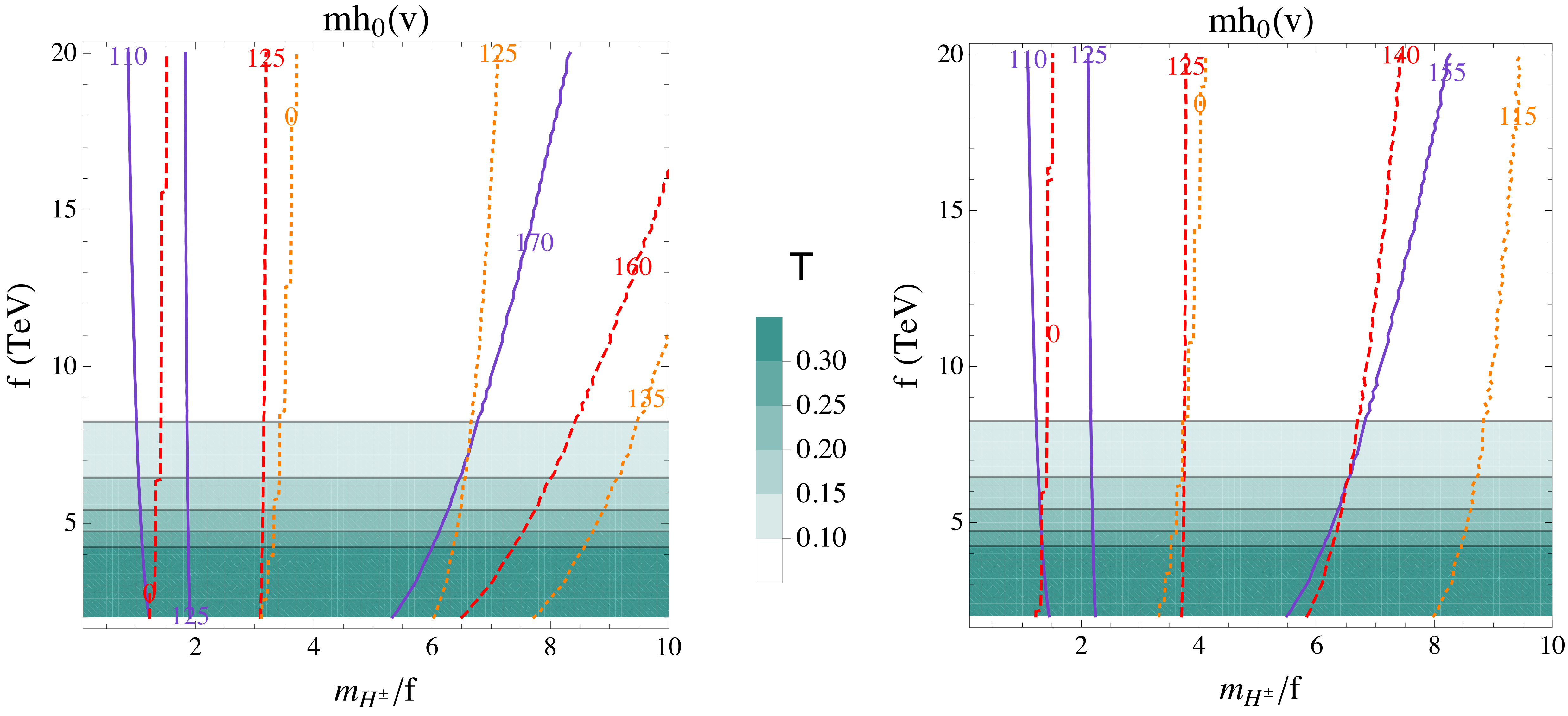
- m_h=126 GeV corresponds to λ_h=0.14 @ 10 TeV.

Numerical Results

- Light Higgs boson mass:

For $\xi = 3.6, \quad \lambda_2/\lambda_1 = 0,$

Purple: no gauge contribution
red: Mρ/f=3
orange: Mρ/f=5

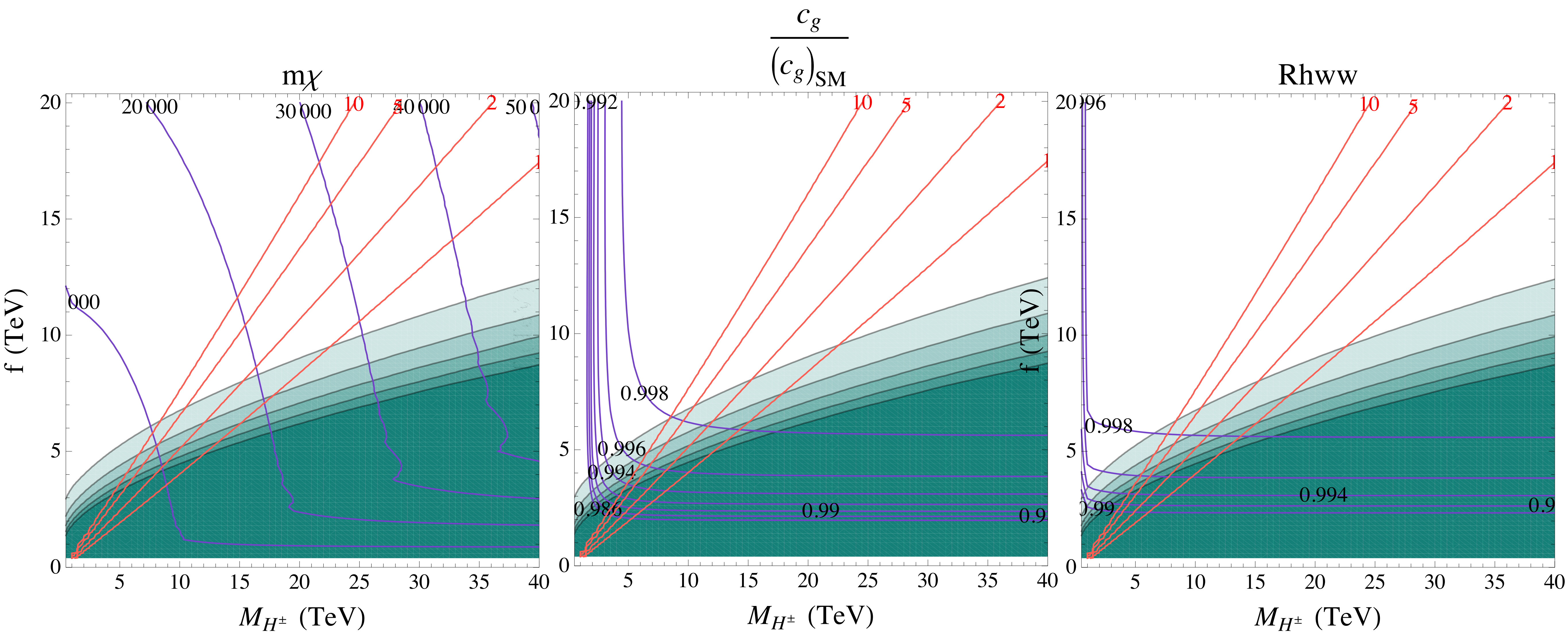


$\lambda_1/(2\xi^2) = 1$

$\lambda_1/(2\xi^2) = 0.7$

Numerical Results

- Constraint on T-parameter (assuming no cancellation) requires f ($\approx u$)$\gtrsim$ 6 TeV → some fine tuning is needed to get $v \ll f$. It also implies other scalars and fermions are heavy, close to the decoupling limit.



Conclusions

- A light Higgs boson arises naturally in a composite Higgs model where the top and a new vector-like quarks participate in the strong dynamics which preserve a U(3) global symmetry. It is compatible with the 126 GeV Higgs boson discovered.
- The strongest constraint comes from the T parameter due to lack of the custodial SU(2) symmetry. The U(3) breaking $\gtrsim$ 6 TeV pushes the model to the decoupling limit.
- Probing heavy scalar and fermion states probably needs future generation colliders.