Composite Higgs from Top Condensation

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HC, B. Dobrescu, and J. Gu, arXiv:1311.5928
HC and J. Gu, arXiv:1406.6689

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Introduction

- After the discovery of the Higgs boson, one of the most important jobs is to determine its properties.
- Because of the hierarchy problem, new physics is expected near the weak scale, which can modify the Higgs sector from the Standard Model.
- A crucial question is whether the Higgs boson is elementary or composite.

Composite Higgs

- A composite Higgs boson is generically expected to be heavy. To make it light, its mass should be protected by some symmetry, i.e., Higgs as a pseudo-Nambu-Goldstone boson (pNGB) (Kaplan & Georgi '84).

- The large top quark mass is a challenge for composite Higgs models. The top quark should (at least partially) participate in the strong dynamics which forms the composite Higgs.

  - An example is top condensation (Nambu '89, Miransky et al '89): Higgs is a bound state of $\bar{t}t$.

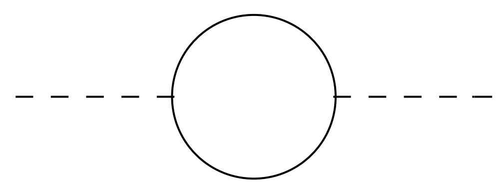
Top Condensation

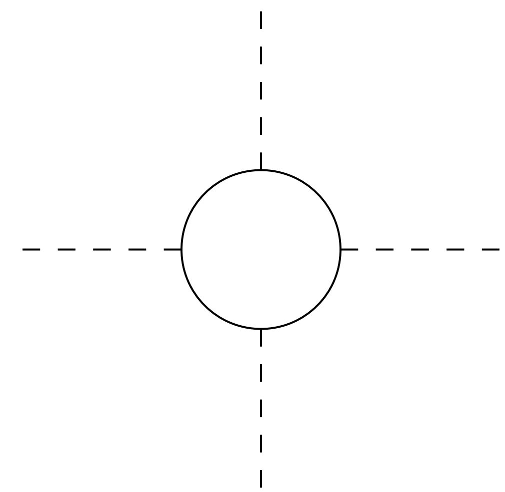
$$\frac{g^2}{\Lambda^2}(\bar{t}_R\psi_L^3)(\bar{\psi}_L^3 t_R), \qquad \psi_L^3 = (t,\, b)_L$$

- The 4-fermion interaction may arise from integrating out new physics at high scale, e.g., topcolor (Hill, '91), $SU(3)_1 \times SU(3)_2 \rightarrow SU(3)_C$.
- Similar to the Nambu-Jona-Lasinio model (1961), for $g \gg 1$, it can form $\bar{t}_R\psi_L^3$ bound state, which has the same quantum number as the Higgs field.
- The 4-fermion interaction is not confining.

Top Condensation

$$\mathcal{L}_H = Z_H \partial_\mu H^\dagger \partial^\mu H - M_H^2 H^\dagger H - (g\,\bar{\psi}_L^3 t_R H + \mathrm{H.c.}) - \frac{\lambda_H}{2}(H^\dagger H)^2$$





$$M_H^2 = \Lambda^2 \left(1 - \frac{N_c g^2}{8\pi^2}\right)$$

$$Z_H = \frac{N_c g^2}{16\pi^2} \ln \frac{\Lambda^2}{\mu^2} \qquad \lambda_H = \frac{2N_c g^2}{16\pi^2} \ln \frac{\Lambda^2}{\mu^2}$$

- For $g > g_{\rm crit} = \pi\sqrt{8/N_c} \Rightarrow$ bound state gets a VEV, breaking the chiral (EW) symmetry.

Top Condensation

- Top Yukawa coupling: $\xi \simeq \sqrt{\dfrac{8\pi^2}{N_c \ln(\Lambda/\mu)}}$

  For Λ/μ not too large, ξ ~3-4 $\Rightarrow m_t \sim 600$ GeV

- Higgs quartic coupling: in leading Nc (fermion bubble) approximation, $\lambda = 2\xi^2 \Rightarrow M_h = 2m_t$.

- M_h, m_t 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.

$$\mathcal{L} = -(\bar{t}_L \ \bar{\chi}_L) \begin{pmatrix} 0 & \frac{\xi}{\sqrt{2}} v \\ m_{\chi t} & m_{\chi\chi} \end{pmatrix} \begin{pmatrix} t_R \\ \chi_R \end{pmatrix} + \mathrm{H.c.},$$

$$v = 246 \ \mathrm{GeV}.$$

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

Top Seesaw with a Light Higgs

- What about the Higgs boson mass? If it's still heavy as one may naively expect, then it is ruled out by the discovery of a relatively 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 belongs to NGBs of U(3) $\rightarrow$ U(2)

Scalar Potential

- Assuming the underlying (non-confining) strong dynamics is approximately $U(3)_L$ X $U(2)_R$ 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: $\mathcal{L}_{\rm Yukawa} = -\xi \left(\bar{\psi}_L^3, \bar{\chi}_L\right) \Phi \begin{pmatrix} t_R \\ \chi_R \end{pmatrix} + {\rm H.c.}$

Scalar potential:

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

Symmetry Breaking

- We assume that there are large $U(2)_R$ breaking effects: $V_{\cancel{U(2)}_R} = \delta M_{tt}^2\, \Phi_t^\dagger \Phi_t + \delta M_{\chi\chi}^2\, \Phi_\chi^\dagger \Phi_\chi + (M_{\chi t}^2 \Phi_\chi^\dagger \Phi_t + \mathrm{H.c.})$ which split M_{tt}^2 and $M_{\chi\chi}^2$ such that $M_{\chi\chi}^2 < 0 < M_{tt}^2$ Nonzero $\langle \Phi_\chi \rangle$ is induced and $U(3)_L$ is spontaneously broken.

- The $U(3)_L$ is also explicitly broken by the quark 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 in low energy EFT, $V_{\mathrm{tadpole}} = -(0, 0, C_{\chi t}) \Phi_t - (0, 0, C_{\chi\chi}) \Phi_\chi + \mathrm{H.c.}$

$$C_{\chi t} \approx \mu_{\chi t} \Lambda^2/\xi\,,\; C_{\chi\chi} \approx \mu_{\chi\chi} \Lambda^2/\xi\,.$$

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

Minimizing the Scalar Potential

- The tadpole $C_{\chi t}$ induces a nonzero $\langle \phi_t \rangle$,
  $\langle H_\chi \rangle$ is then induced by $M^2_{\chi t}$, $M^2_{\chi\chi}$, breaking EW sym.

  Minimizing the potential, we obtain:

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

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

$$f \equiv \sqrt{u^2 + v^2} \, (\approx u \gg v),$$

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

$$\sqrt{2} C_{\chi t} = u \, s_\gamma \, M^2_{H^\pm} \qquad M^2_{\chi t} = -\frac{\lambda_1}{2} u^2 s_\gamma c_\gamma \,,$$

$$C_{\chi\chi} = 0 \qquad M^2_{\chi\chi} = -\frac{\lambda_1}{2} \left(u^2 c^2_\gamma + v^2 \right) - \frac{\lambda_2}{2} \left(u^2 + v^2 \right)$$

Top Quark Mass

- Charge-2/3 fermion mass matrix:

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

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: $m_{t'} \approx \frac{\xi}{\sqrt{2}} u \;\; (\sim 2.5 f)$

Light Higgs Mass

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

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

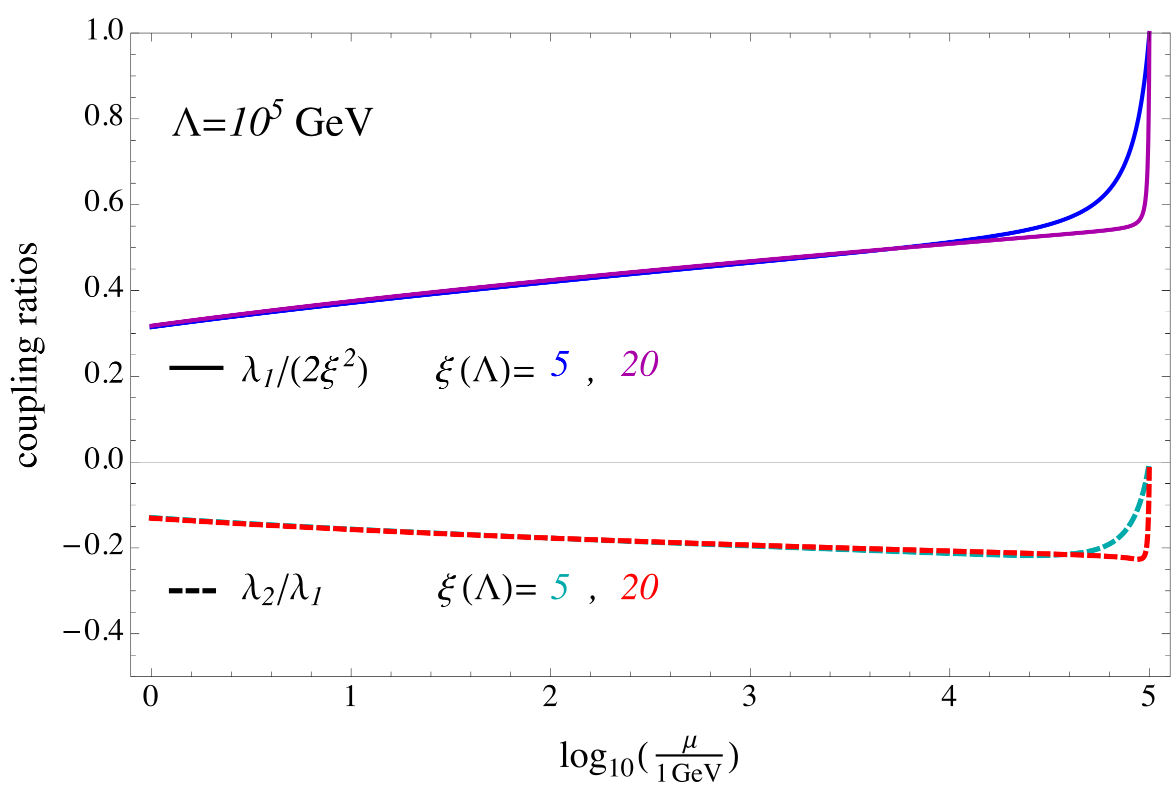
Lightest eigenvalue: $M_h^2 \simeq \left(\frac{\lambda_1}{2\xi^2}\right)\left(\frac{M_{H^\pm}^2}{M_{H^\pm}^2+\lambda_1 u^2/2}\right) y_t^2 v^2$

In the limit $\xi \to \infty$ or $m_t \to 0$, $\sin\gamma \to 0$ and $C_{\chi t} \to 0$, there is no explicit U(3) breaking, Higgs becomes an exact NGB.

Light Higgs Mass

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

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



$$\left(\frac{M_{H^\pm}^2}{M_{H^\pm}^2+\lambda_1 u^2/2}\right) < 1$$

$y_t^2 \sim 0.6$ @ 10 TeV

$$\Rightarrow M_h < 185\ \mathrm{GeV}$$

Electroweak Interactions

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

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

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

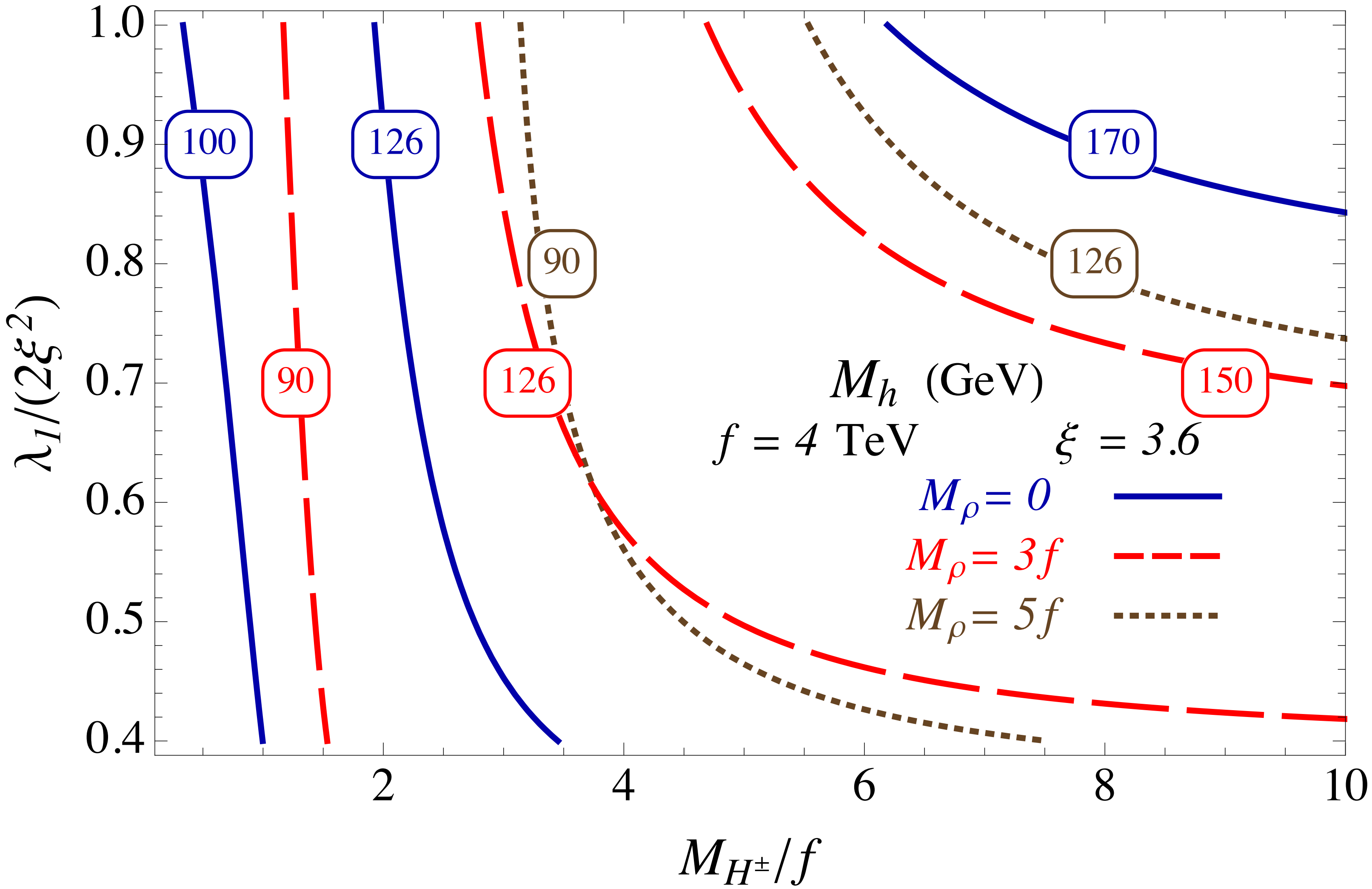
(quartic splitting)

where M_ρ is the cutoff the EW gauge loop.

- M_h =125 GeV corresponds to λ_h = 0.14 @ 10 TeV.

Numerical Results

- Higgs mass depends on $\lambda_1/(2\xi^2), M_{H^\pm}/f, M_\rho/f$, but is insensitive to ξ, λ_2, f.



Expected range:

$$\xi \sim 3 - 4$$

$$0.4 \lesssim \frac{\lambda_1}{2\xi^2} \lesssim 1$$

$$-0.2 \lesssim \lambda_2/\lambda_1 \lesssim 0$$

$$M_{H^\pm}/f,\ M_\rho/f \lesssim 4\pi$$

$$f \gtrsim 3.5\,\text{TeV}$$

(T-parameter)

Requiring $\lambda_h > 0$ at $m_{t'}$ puts a lower bound ~ 80 GeV

$$80\,\text{GeV} \lesssim M_h \lesssim 175\,\text{GeV}$$

Weak-isospin violation

- The main constraint comes from weak isospin violating *T* parameter from the *t'* loop contribution. [U(3)$_L$ doesn't contain a custodial SU(2) symmetry.]

$$T = \frac{3s_L^2}{16\pi^2\alpha v^2}\left[s_L^2 m_{t'}^2 + 4(1-s_L^2)\frac{m_{t'}^2 m_t^2}{m_{t'}^2 - m_t^2}\ln\left(\frac{m_{t'}}{m_t}\right) - (2-s_L^2)m_t^2\right]$$

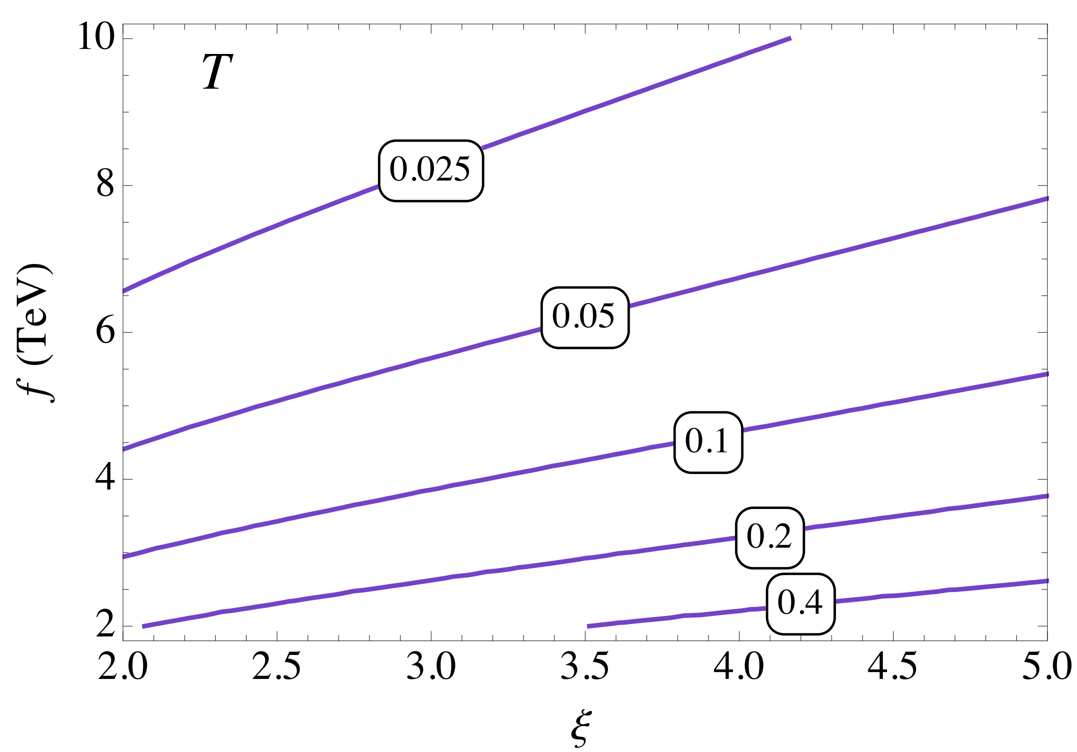
$$s_L = \sin\theta_L \simeq v/f$$

$T < 0.1\,(0.15)$ [68% (95%) CL]

$\Rightarrow f \gtrsim 4.3\,(3.5)$ TeV for $\xi = 3.6$

if there is no cancellation

with other contributions.



Phenomenology

- Large f implies fine tuning ($\sim v^2/f^2$) of the EW scale, also makes all other states very heavy [except the 5th PNGB, A_1, with a mass ~ $(f/v)\ M_h$]. They are beyond of reach of the LHC.

- It also means the model is near the decoupling limit. Corrections to the Higgs coupling to SM fields is ~ $v^2/(2f^2) \lesssim 0.2\%$, difficult even for a future lepton collider. However, T-parameter can be precisely measured at a future Z factory

- t' of mass up to ~10 TeV may be reachable at a 100 TeV collider, through $t' \to Wb,\ tZ,\ th,\ tA_1$.

Custodial SU(2) Extensions

(HC and J. Gu, arXiv:1406.6689)

- The *T* constraint could be alleviated if the model can be extended to include a custodial SU(2).

- Extension to bottom seesaw is strongly constrained by $Z \to b\bar{b}$.

- To avoid the constraint from $Z \to b\bar{b}$, we need to assign $(t, b)_L$ as (2, 2) under $SU(2)_L \times SU(2)_R$ with a P_{LR} symmetry. (Agashe et al, hep-ph/0605341)

  - Introduce a vector-like hypercharge +7/6 doublet quark (X, T) in addition to the singlet χ. The weak isospin can be protected by the $O(5)_L \subset U(5)_L$ among $\Psi_L = (t_L, b_L, X_L, T_L, \chi_L)$.

Weak-isospin T Parameter

Explicit $O(5)_L$ breaking masses:

$$\mathcal{L}_{\text{fermion masses}} = -\mu_t \overline{\chi}_L t_R - \mu_{\chi\chi} \overline{\chi}_L \chi_R - \mu_Q \begin{pmatrix} \overline{X}_L & \overline{T}_L \end{pmatrix} \begin{pmatrix} X_R \\ T_R \end{pmatrix} + \text{H.c.}$$

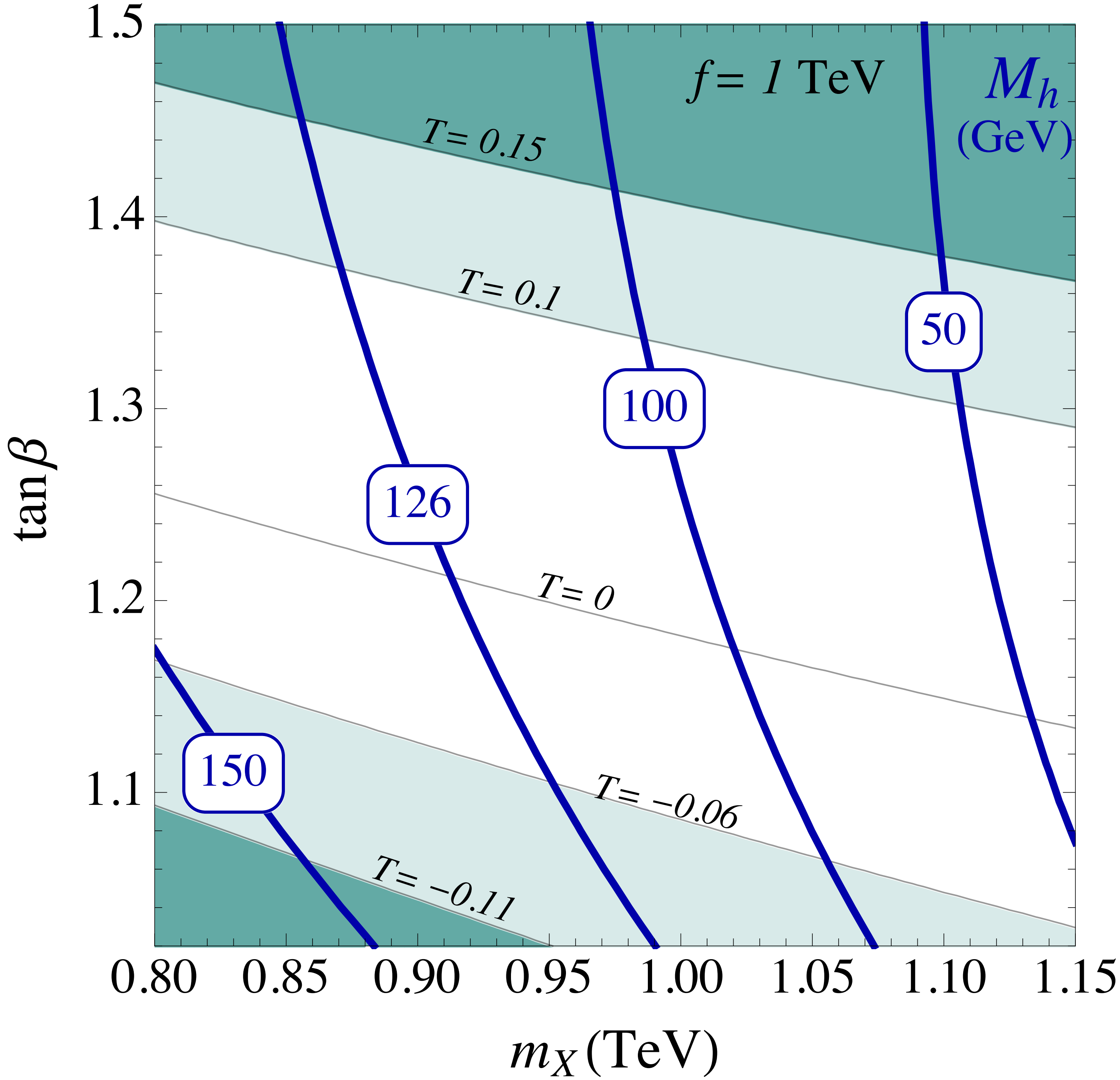
- In the limit $\mu_Q \to 0$ ($M_X \to 0$), adding $(X, T)_L$ cancels the SM $(t, b)_L$ contribution to T, resulting in a negative T.

- In the limit $\mu_Q \to \infty$ ($M_X \to \infty$), (X, T) decouples and we recover the minimal model. There is a large positive contribution to T if f is low.

- For a suitable range of μ_Q ($M_X \lesssim f$) we expect to get a T value compatible with the EW precision measurement.

Higgs Boson Mass

Current bound M_X >800 GeV (CMS). Small T and correct Higgs mass can be obtained for $M_X \lesssim f$.

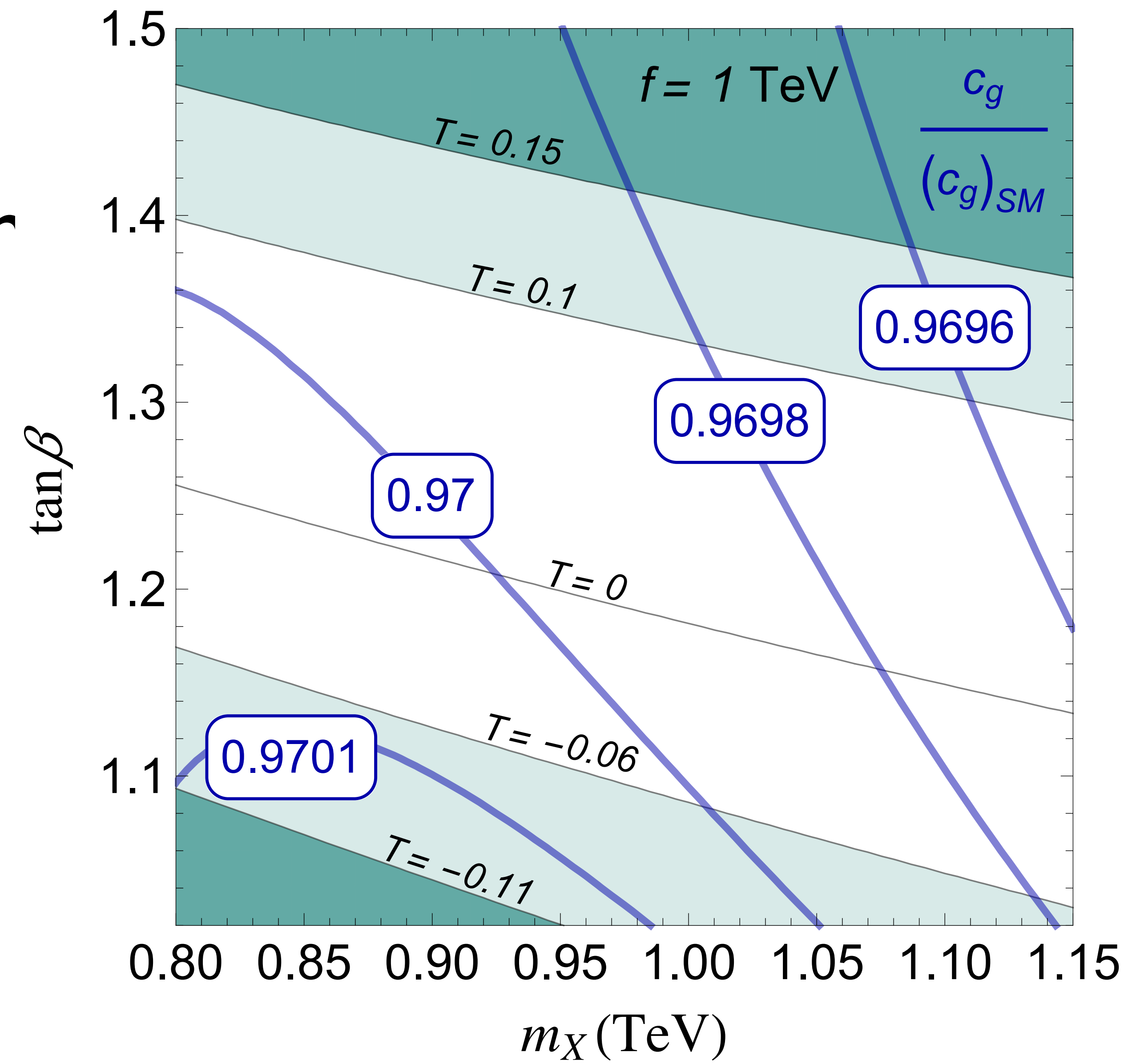


$$f = 1\,\text{TeV},$$
$$\xi = 3.6,$$
$$\lambda_1/(2\xi^2) = 0.7,$$
$$\lambda_1/\lambda_2 = 0,$$
$$M_\rho = 3f,$$
$$M_{\Sigma_{X,T,t}} = 10f$$

Higgs Couplings

- Most tree-level Higgs couplings are suppressed by *$1-v^2/(2f^2)$*. Corrections are ~3% for f=1 TeV.

- *hgg* coupling receives loop contributions from top partners. However, they are small within the allowed parameter space.



Compared with other models

- Holographic composite Higgs: (Agashe, Contino, Pomarol, ...)
  - The global symmetry is preserved by the strong sector exactly. Explicit breaking comes from coupling to SM fermions, which are not complete multiplets.
  - Higgs boson mass related to the top partner masses which cut off the radiative contributions.
- Top seesaw model:
  - Top and new quarks form a complete multiplet of the global symmetry. Explicit breaking comes from fermion mass terms, similar to QCD.
  - Higgs boson mass related to the top quark mass through the top seesaw mechanism.

Conclusions

- A light Higgs boson of 125 GeV can arise naturally in a composite Higgs model from top condensation with the top seesaw mechanism.
- The simplest model based on U(3) symmetry requires a large $f \Rightarrow$ fine-tuned and probably out of the reach of LHC.
- Extension to O(5) can reduce fine-tuning. It requires relatively light exotic top partners $(X^{\frac{5}{3}}, T^{\frac{2}{3}})$. The 14 TeV LHC can significantly extend their reach.
- Most heavy states (scalars and singlet top partner) require a higher energy machine beyond LHC.

Backup Slides

Light Fermion Masses and FCNC

- The light SM fermion masses come from 4-fermion interactions at the compositeness scale.
- There are 2 Higgs doublets. Large tree-level FCNCs can be induced if they have general couplings (not type I or II) to fermions.
- However, fermion masses and mixings are hierarchical. It's likely there is some approximate flavor symmetry which controls the 4-fermion interactions. In that case FCNC constraints can be satisfied if the other Higgses are heavier than ~ 1 TeV. (Cheng, Sher, '84, , Antaramian, Hall, Rasin, '92, ...)

Custodial SU(2) Extensions

- We introduce a vector-like hypercharge +7/6 doublet quark (X, T) in addition to the singlet χ.

The strong dynamics has approximate $U(5)_L \times U(4)_R$ symmetry among $\Psi_L=(t_L, b_L, X_L, T_L, \chi_L)$ and $\Psi_R=(X_R, T_R, t_R, \chi_R)$.

$$\mathcal{L} = \mathcal{L}_{\text{kinetic}} + G(\overline{\mathbf{\Psi}}_{L_i} \mathbf{\Psi}_{R_j})(\overline{\mathbf{\Psi}}_{R_j} \mathbf{\Psi}_{L_i})$$

They form scalar bound states:

$$\Phi = \begin{pmatrix} \sigma^{-}_{tX} & \sigma^{0}_{tT} & \sigma^{0}_{tt} & \phi^{0}_{t\chi} \\ \sigma^{--}_{bX} & \sigma^{-}_{bT} & \sigma^{-}_{bt} & \phi^{-}_{b\chi} \\ \sigma^{0}_{XX} & \sigma^{+}_{XT} & \sigma^{+}_{Xt} & \phi^{+}_{X\chi} \\ \sigma^{-}_{TX} & \sigma^{0}_{TT} & \sigma^{0}_{Tt} & \phi^{0}_{T\chi} \\ \sigma^{-}_{\chi X} & \sigma^{0}_{\chi T} & \sigma^{0}_{\chi t} & \phi^{0}_{\chi\chi} \end{pmatrix} \equiv \begin{pmatrix} \Sigma_X & \Sigma_T & \Sigma_t & \Phi_\chi \end{pmatrix}.$$

with Yukawa interaction $\mathcal{L}_{\text{Yukawa}} = -\xi \overline{\mathbf{\Psi}}_L \Phi \mathbf{\Psi}_R + \text{ H.c.}$

Custodial SU(2) Extensions

The vector-like fermion can have gauge invariant masses,

$$\mathcal{L}_{\text{fermion masses}} = -\mu_t \overline{\chi}_L t_R - \mu_{\chi\chi} \overline{\chi}_L \chi_R - \mu_Q \left(\overline{X}_L \quad \overline{T}_L \right) \begin{pmatrix} X_R \\ T_R \end{pmatrix} + \text{H.c.}$$

They turn into scalar tadpole terms in low energy EFT. We also assume that $U(4)_R$ is strongly broken so that only Φ_χ have negative mass-squared, while Σ_X, Σ_T, Σ_t remain heavy. The scalar potential at low energy is given by

$$\begin{aligned} V = &\frac{\lambda_1}{2} \text{Tr}[(\Phi^\dagger \Phi)^2] + \frac{\lambda_2}{2} (\text{Tr}[\Phi^\dagger \Phi])^2 \\ &+ M^2_{\Sigma_{X,T}} \Sigma_X^\dagger \Sigma_X + M^2_{\Sigma_{X,T}} \Sigma_T^\dagger \Sigma_T + M^2_{\Sigma_t} \Sigma_t^\dagger \Sigma_t + M^2_{\Phi_\chi} \Phi_\chi^\dagger \Phi_\chi \\ &- C_Q \sigma^0_{XX} - C_Q \sigma^0_{TT} - C_{\chi t} \sigma^0_{\chi t} - C_{\chi\chi} \phi^0_{\chi\chi} + \text{H.c.} \end{aligned}$$

Custodial SU(2) Extensions

For heavy $\Sigma_X, \Sigma_T, \Sigma_t$, they can be integrated out and we focus on Φ_χ. The leading effects of $\Sigma_X, \Sigma_T, \Sigma_t$ are their VEVs induced by the tadpole terms.

$$V = \frac{\lambda_1}{2}\,\mathrm{Tr}[(\Phi^\dagger\Phi)^2] + \frac{\lambda_2}{2}(\mathrm{Tr}[\Phi^\dagger\Phi])^2 + M^2_{\Phi_\chi}\Phi^\dagger_\chi\Phi_\chi - C_{\chi\chi}(\phi_\chi + \phi^\dagger_\chi),$$

$$\Phi = \begin{pmatrix} 0 & 0 & 0 & \phi_t^0 \\ 0 & 0 & 0 & \phi_b^- \\ \frac{w}{\sqrt{2}} & 0 & 0 & \phi_X^+ \\ 0 & \frac{w}{\sqrt{2}} & 0 & \phi_T^0 \\ 0 & 0 & \frac{u_t}{\sqrt{2}} & \phi_\chi^0 \end{pmatrix}, \quad \Phi_\chi = \begin{pmatrix} \phi_t^0 \\ \phi_b^- \\ \phi_X^+ \\ \phi_T^0 \\ \phi_\chi^0 \end{pmatrix},$$

$$\langle\sigma_{XX}\rangle = \langle\sigma_{TT}\rangle \equiv \frac{w}{\sqrt{2}}\,, \qquad \langle\sigma_{\chi t}\rangle \equiv \frac{u_t}{\sqrt{2}}\,.$$

Custodial SU(2) Extensions

To avoid 2 light Higgs doublets and to protect the custodial symmetry, we include a scalar mass term which breaks $U(5)_L$ down to $O(5)_L$,

$$V_{\cancel{U(5)}} = \frac{1}{2} K^2 \left(\mathrm{Tr}[\Sigma'^\dagger \Sigma'] + A_\chi^2 \right) ,$$

$$\Sigma \equiv \begin{pmatrix} \phi_t^{0*} & \phi_X^+ \\ \phi_b^- & \phi_T^0 \end{pmatrix} , \quad \Sigma' \equiv \frac{1}{\sqrt{2}} (\Sigma - \epsilon \Sigma^* \epsilon^T) = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_t^{0*} - \phi_T^{0*} & \phi_X^+ + \phi_b^+ \\ \phi_X^- + \phi_b^- & -\phi_t^0 + \phi_T^0 \end{pmatrix}$$

$$A_\chi = \sqrt{2}\, \mathrm{Im}\, \phi_\chi$$

$O(5)_L$ is then spontaneously broken by negative $M^2_{\Phi_\chi}$, generating light Goldstone bosons as the Higgs.

Custodial SU(2) Extensions

Due to the tadpoles, ϕ_t^0, ϕ_T^0 also obtain VEVs in addition to ϕ_χ^0, breaking EW symmetry.

$$\phi_t^0 = \frac{v_t + h_t + iA_t}{\sqrt{2}} , \qquad \phi_T^0 = \frac{v_T + h_T + iA_T}{\sqrt{2}} , \qquad \phi_\chi^0 = \frac{u_\chi + h_\chi + iA_\chi}{\sqrt{2}} .$$

$$v = \sqrt{v_t^2 + v_T^2} = 246\,\mathrm{GeV}, \qquad \tan\beta \equiv \frac{v_t}{v_T} > 1$$

$$(\tan\beta \to 1 \text{ as } K^2 \to \infty)$$

Chiral symmetry breaking scale: $f = \sqrt{v_t^2 + v_T^2 + u_\chi^2}$

Generalized Top Seesaw

$$\mathcal{L} \supset -\frac{\xi}{\sqrt{2}} \left(\overline{t_L} \quad \overline{T_L} \quad \overline{\chi_L} \right) \begin{pmatrix} 0 & 0 & v_t \\ 0 & w & v_T \\ u_t & 0 & u_\chi \end{pmatrix} \begin{pmatrix} t_R \\ T_R \\ \chi_R \end{pmatrix} - \frac{\xi w}{\sqrt{2}} \overline{X_L} X_R \; .$$

$$m_{\rm top}^2 \approx \frac{\xi^2 v_t^2}{2} \frac{u_t^2}{f^2} \qquad \Rightarrow \qquad \frac{u_t}{f} \approx \frac{y_t}{\xi \sin\beta}$$

The heavy top partners:

$$m_{t_2} \approx m_X = \frac{\xi w}{\sqrt{2}} \quad (< f \text{ to minimize } T)$$

$$m_{t_3} \approx \frac{\xi f}{\sqrt{2}} \sim (2-3) f$$

Current experimental bound: m_X > 800 GeV (CMS).

Higgs Boson Mass

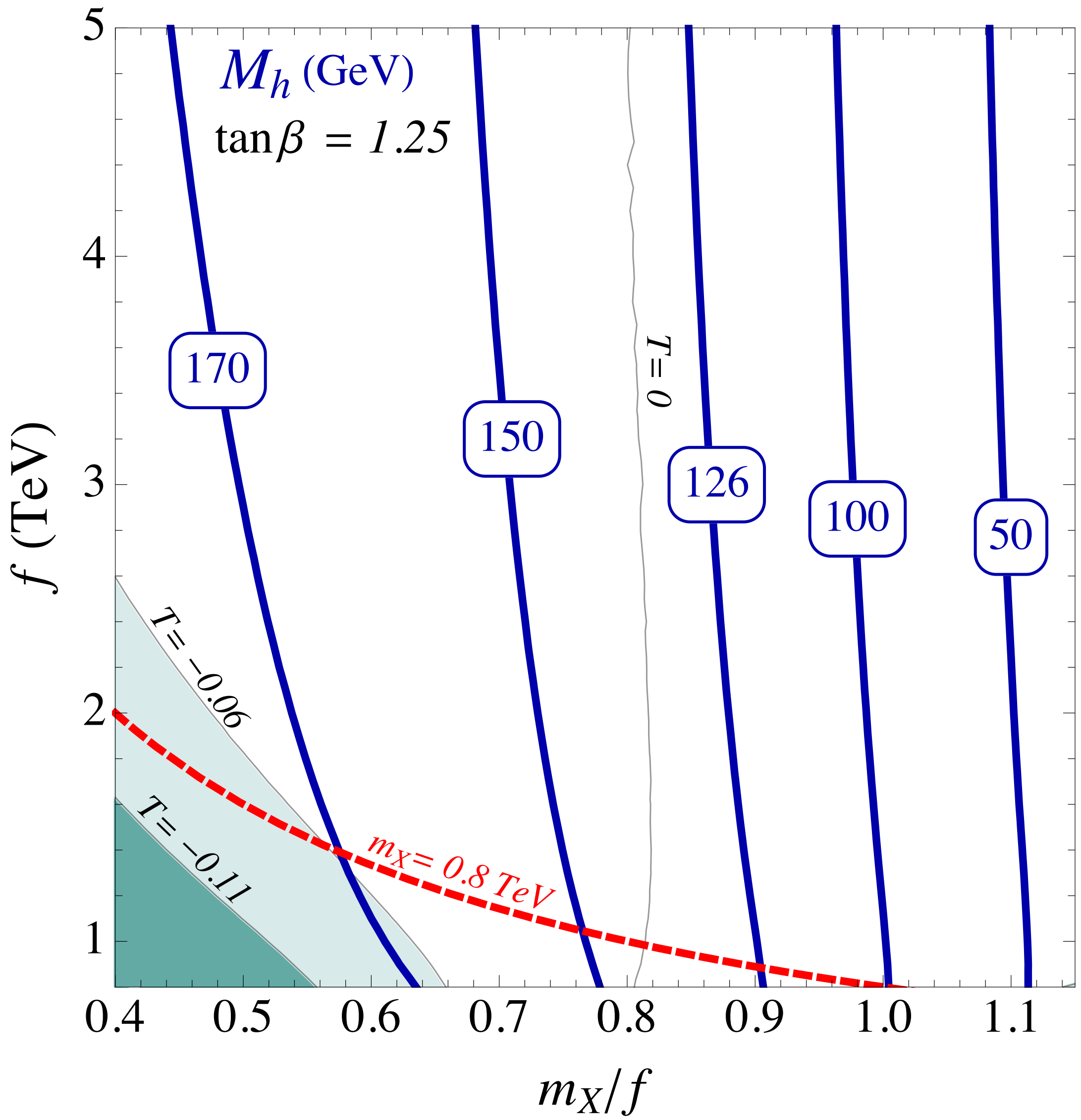
CP-even scalars: $$\begin{pmatrix} h_1 \\ h_2 \\ h_\chi \end{pmatrix} = \begin{pmatrix} \frac{v_t}{v} & \frac{v_T}{v} & 0 \\ -\frac{v_T}{v} & \frac{v_t}{v} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} h_t \\ h_T \\ h_\chi \end{pmatrix},$$

$$M^2_{\text{scalar}} = \begin{pmatrix} (\lambda_1+\lambda_2)v^2 & 0 & (\lambda_1+\lambda_2)u_\chi v \\ 0 & \frac{\lambda_1 w^2 v^2}{2(v_t^2-v_T^2)} & 0 \\ (\lambda_1+\lambda_2)u_\chi v & 0 & (\lambda_1+\lambda_2)u_\chi^2 + \frac{\lambda_1 u_t^2}{2} - \frac{\lambda_1 w^2 v_T}{2(v_t+v_T)} \end{pmatrix}$$

$$M_h^2 \approx \frac{\lambda_1 v^2}{2f^2}\left(u_t^2 - \frac{w^2 v_T}{v_t+v_T}\right) \approx \frac{\lambda_1}{2\xi^2}\left(\frac{y_t^2}{\sin^2\beta} - \frac{m_X^2}{f^2}\frac{2}{1+\tan\beta}\right)v^2$$

EW gauge loops further reduce the Higgs mass.
125 GeV Higgs ($\lambda_h = M_h^2/v^2 = 0.26$) is typically obtained for $m_X \lesssim f$.

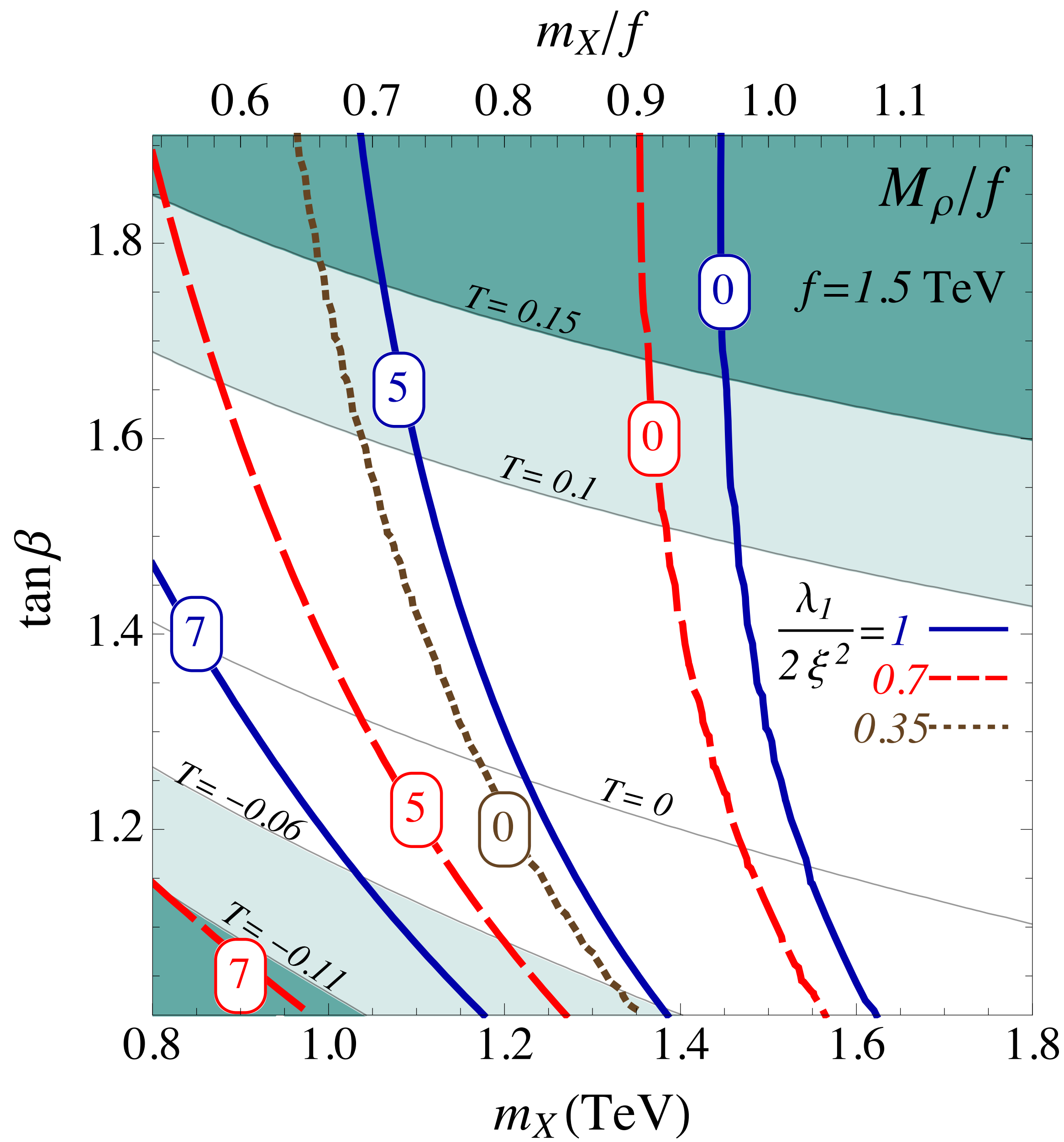
Higgs mass dependence on model parameters



$\xi = 3.6,\ \lambda_1/(2\xi^2) = 0.7,\ \lambda_1/\lambda_2 = 0,$

$\tan\beta = 1.25,\ m_X = 0.9\,\mathrm{TeV},$

$M_\rho = 3f,\ M_{\Sigma_{X,T,t}} = 10f$



$f = 1.5\,\mathrm{TeV}, \xi = 3.6,$

$\lambda_1/\lambda_2 = 0,\ M_{\Sigma_{X,T,t}} = 10f$