The Lightest Higgs Boson Mass in the MSSM with Strongly Coupled Spectators

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Outline

The Supersymmetric Higgs Boson

- SM like Higgs boson mass log. dependent on M_{SUSY}.

$$m_{h^0}^2 \simeq m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} y_t^2 m_t^2 \sin^2\beta \left(\log \frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}}^2} - \frac{A_t^4}{12 m_{\tilde{t}}^4} \right)$$

- 125 GeV Higgs boson in the MSSM
  - $m_{\tilde{t}} \gtrsim 10$ TeV, $\quad A_t \simeq 0$
  - $m_{\tilde{t}} \gtrsim 1$ TeV, $\quad A_t \sim \sqrt{6} m_{\tilde{t}}$

Fine-Tuning in the MSSM

- Two possible fine-tunings in the Higgs sector
  - Weak scale tuning: Higgs soft mass and the μ-term

$$-\frac{1}{2}m_Z^2 = |\mu|^2 + m_{H_u}^2 + \Delta$$

  - High scale tuning: Higgs RG mass

$$\beta_{m_{H_u}^2} \sim \frac{1}{8\pi^2}\left(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + |A_t|^2 - 3g_2^2 M_2^2\right) + 2 - \mathrm{loop}$$

- Quasi-Natural
  - Model that is not weak scale tuned.

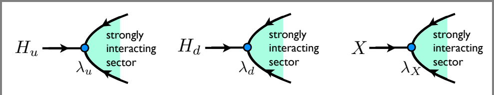
$$m_{\tilde{t}} < 500 \text{ GeV} \quad \mu < 300 \text{ GeV} \quad B < 300 \text{ GeV} \quad |m_{H_u}| < 300 \text{ GeV}$$

Quasi-Natural Supersymmetry

- TYPE I: *D*-term hard breaking
  - U(1) $\rightarrow$ additional contributions to the quartic coupling
    - Arises from new gauge interactions
    - $\Lambda_{U(1)} \lesssim 1$ TeV or radiative corrections to $|m^2_{H_u}|$ are too large
- TYPE II: Additional tree-level Higgs quartic coupling
  - NMSSM: $\lambda S H_u H_d$ $\rightarrow$larger quartic couplings
    - $\lambda \lesssim 0.7$ or Landau pole arise
    - $\tan\beta \sim 1$.
    - MSSM parameters mildly affected (High Scale Tuning)
- TYPE III: Strongly coupled spectators.
  - The model we present here

Outline

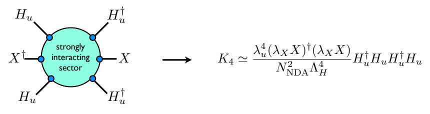
Strongly Coupled Spectators



- Couple Higgs to the strongly coupled sector

$$W_H = \lambda_u H_u \mathcal{O}_u + \lambda_d H_d \mathcal{O}_d + \lambda_X X \mathcal{O}_X \ .$$

- Kähler potential corrections

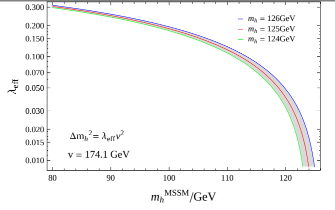


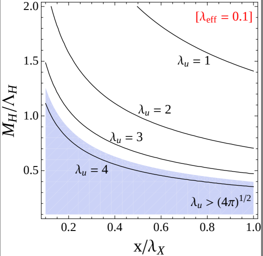
- Higgs potential corrections
  ($X = M_X + F_X \theta^2$, $x = F_X / M_X^2$, and $M_H = \lambda_X M_X$)

$$V \simeq \frac{\lambda_{\rm eff}}{4} |h^\dagger h|^2 \quad \lambda_{\rm eff} \simeq \frac{4 \lambda_u^4}{N_{\rm NDA}^2} \frac{M_H^4}{\Lambda_H^4} \frac{x^2}{\lambda_X^2} \sin^4 \beta$$

Higgs Quartic Couplings to the Hidden Sector

- LHC constraints on the Higgs couplings





- Higgs quartic coupling

$$\lambda_{\rm eff} = 0.025 \times \lambda_u^4 \left(\frac{4\pi}{N_{\rm NDA}}\right)^2 \frac{M_H^4}{\Lambda_H^4} \frac{x^2}{\lambda_X^2} \,,$$

Outline

Model of Strongly Coupled Sector

- Supersymmetric QCD with three flavors

$$W_{\rm tree} = \lambda_u H_u \bar{Q}_L Q_0 + \lambda_d H_d Q_L \bar{Q}_0 + \lambda_X X(\bar{Q}_L Q_L + \bar{Q}_N Q_N)$$

	$SU(3)_S$	$SU(2)_L$	$U(1)_Y$
Q_N	$\mathbf{3}$	$\mathbf{1}$	0
Q_L	$\mathbf{3}$	$\mathbf{2}$	$1/2$
$\bar{Q}_N$	$\bar{\mathbf{3}}$	$\mathbf{1}$	0
$\bar{Q}_L$	$\bar{\mathbf{3}}$	$\bar{\mathbf{2}}$	$-1/2$

- Light degrees of freedom below the dynamical scale Λ_H

$$M^i_j \simeq \frac{1}{N_{\rm NDA}} \frac{(Q^i_a \bar{Q}^a_j)}{\Lambda_H} \qquad B = \frac{1}{N_{\rm NDA}} \frac{Q^{i_1}_{[a_1} Q^{i_2}_{a_2} Q^{i_3}_{a_3]}}{\Lambda_H^2} \qquad \bar{B} = \frac{1}{N_{\rm NDA}} \frac{\bar{Q}^{[a_1}_{i_1} \bar{Q}^{a_2}_{i_2} \bar{Q}^{a_3]}_{i_3}}{\Lambda_H^2}$$

Effective Low Scale Theory

- Superpotential after confinement
- Expand around a solution of the deformed moduli constraint

$$
\begin{aligned}
M_0 &\simeq \frac{\sqrt{3}\Lambda_H}{N_{\rm NDA}} + \delta M_0 \\
\mathcal{X} &\simeq -\lambda_X X
\end{aligned}
$$

- The low scale theory becomes

$$
\begin{aligned}
W_{\rm eff} \simeq\ & \frac{\lambda_u}{N_{\rm NDA}}\Lambda_H H_u \mathcal{H}_d + \frac{\lambda_d}{N_{\rm NDA}}\Lambda_H H_d \mathcal{H}_u + \lambda_X X \mathcal{H}_u \mathcal{H}_d \\
& + \frac{\lambda_X}{2} X \mathcal{T}^2 + \frac{\lambda_X}{2} X M_8^2 - \lambda_X X M_0^2 - \lambda_X X B\bar{B} + \cdots ,
\end{aligned}
$$

Generation of μ and B_μ

- Important low scale terms

$$W_{\text{eff}} \simeq \frac{\lambda_u}{N_{\text{NDA}}} \Lambda_H H_u \mathcal{H}_d + \frac{\lambda_d}{N_{\text{NDA}}} \Lambda_H H_d \mathcal{H}_u + \lambda_X X \mathcal{H}_u \mathcal{H}_d$$

- Heavy composites integrated out

$$W \simeq -\frac{\lambda_u \lambda_d}{N_{\text{NDA}}^2} \frac{\Lambda_H^2}{\lambda_X X} H_u H_d$$

- Higgs mass parameters

$$\mu \simeq -\frac{\lambda_u \lambda_d}{N_{\text{NDA}}^2} \frac{\Lambda_H^2}{M_H} \qquad B \simeq x\, M_X = \frac{x}{\lambda_X} M_H$$

Corrections to the Kähler Potential

- Kähler potential corrections to Higgs quartic coupling

$$K \simeq \frac{N_{\rm NDA}^2}{\Lambda_H^2}\mathcal{H}_u^\dagger\mathcal{H}_u\mathcal{H}_u^\dagger\mathcal{H}_u = \frac{\lambda_u^4\Lambda_H^2}{N_{\rm NDA}^2|\lambda_X X|^4}H_u^\dagger H_u H_u^\dagger H_u \quad \rightarrow \quad \lambda_{\rm eff} \simeq \frac{16\lambda_u^4}{N_{\rm NDA}^2}\frac{\Lambda_H^2}{M_H^2}\frac{x^2}{\lambda_X^2}\sin^4\beta$$

- Kähler corrections to the soft terms

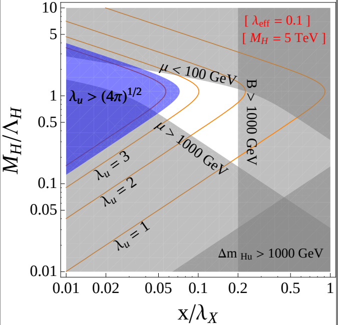
$$K \simeq \frac{\lambda_u^2\Lambda_H^2}{N_{\rm NDA}^2|\lambda_X X|^2}H_u^\dagger H_u \ ,$$

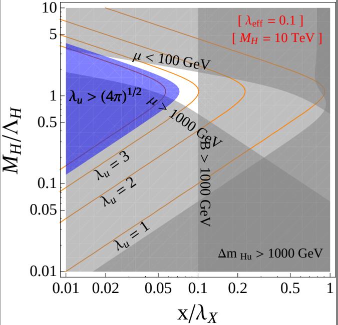
- Higgs soft terms generated by SQCD

$$\mathcal{L} \simeq \frac{\lambda_u^2}{N_{\rm NDA}^2}\frac{x^2}{\lambda_X^2}\Lambda_H^2|H_u|^2 + \frac{\lambda_u^2\Lambda_H^2}{N_{\rm NDA}^2 M_H}\frac{x}{\lambda_X}F_{H_u}^\dagger H_u + \frac{\lambda_u\lambda_d\Lambda_H^4}{N_{\rm NDA}^2 M_H^3}\frac{x^2}{\lambda_X^2}F_{H_d}H_u + h.c.$$

Naturalness Constraints

- Contours of the Higgs mass parameters





- Quasi-Natural points are indeed allowed by these models

Extending into the Conformal Window

- Strongly coupled sector ruins gauge coupling unification
  - 3 additional $SU(2)$ doublets

	$SU(3)_S$	$SU(2)_L$	$U(1)_Y$
Q_N	$\mathbf{3}$	$\mathbf{1}$	0
Q_L	$\mathbf{3}$	$\mathbf{2}$	$1/2$
$\bar{Q}_N$	$\bar{\mathbf{3}}$	$\mathbf{1}$	0
$\bar{Q}_L$	$\bar{\mathbf{3}}$	$\bar{\mathbf{2}}$	$-1/2$

Extending into the Conformal Window

- Strongly coupled sector ruins gauge coupling unification
  - 3 additional $SU(2)$ doublets
- Replace $Q_L \to 5_Q = (Q_{\bar{D}}, Q_L)$
  - Complete multiplets of $SU(5)$
  - The theory is now conformal $3N_c/2 < N_f < 3N_c$

	$SU(3)_H$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
Q_0	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	0
Q_L	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
$Q_{\bar{D}}$	$\mathbf{3}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$
$\bar{Q}_0$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	0
$\bar{Q}_L$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\bar{\mathbf{2}}$	$1/2$
$\bar{Q}_{\bar{D}}$	$\bar{\mathbf{3}}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$

Outline

Conformal Fixed Point

- The anomalous dimensions at one-loop

$$\gamma_{ij} = \frac{1}{32\pi^2}\left(y_{ilm}y^{jlm} - 4g^2 C(r)\right)$$

- Beta functions of the conformal sector

$$\frac{d}{d\ln\mu_R}\frac{1}{\alpha_{3'}} = \frac{1}{2\pi}\frac{9 - \sum(1-2\gamma_i)/2 - \sum(1-2\gamma_{\bar{i}})/2}{1 - 3\alpha_{3'}/2\pi} ,$$

$$\frac{d}{d\ln\mu_R}\alpha_u = 2\alpha_u(\gamma_{H_u} + \gamma_{\bar{L}} + \gamma_0) , \quad \frac{d}{d\ln\mu_R}\alpha_d = 2\alpha_d(\gamma_{H_d} + \gamma_L + \gamma_{\bar{0}}) .$$

- The fixed point couplings (Banks-Zaks)

$$\begin{aligned}
(I):&\quad \lambda_u^2 = \frac{12\pi^2}{7} , &\quad \lambda_d^2 = \frac{12\pi^2}{7} , &\quad g_{3'}^2 = \frac{27\pi^2}{14} , \\
(II):&\quad \lambda_{u,d}^2 = \frac{3\pi^2}{2} , &\quad \lambda_{d,u}^2 = 0 , &\quad g_{3'}^2 = \frac{27\pi^2}{16} , \\
(III):&\quad \lambda_u^2 = 0 , &\quad \lambda_d^2 = 0 , &\quad g_{3'}^2 = \frac{3\pi^2}{2} .
\end{aligned}$$

Banks-Zaks approximation

- Fixed point couplings are large
- Is the Banks-Zaks approximation valid?

$$\gamma_0 \simeq -0.18 \,, \quad \gamma_L \simeq -0.23 \,, \quad \gamma_{\bar{D}} \simeq -0.29 \,, \quad \gamma_{H_u} \simeq 0.41 \,,$$

- *a*-maximization gives us the non-perturbative anomalous dimensions

$$\gamma_0 \simeq -0.11 \,, \quad \gamma_L \simeq -0.21 \,, \quad \gamma_{\bar{D}} \simeq -0.32 \,, \quad \gamma_{H_u} \simeq 0.32 \,.$$

- Less than 30 percent deviation

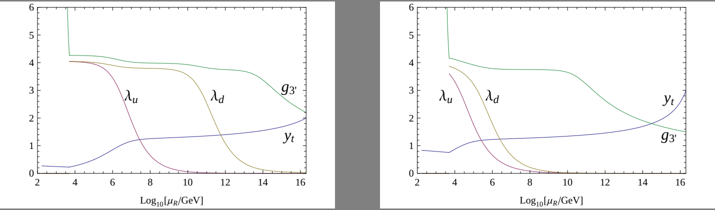
Outline

Top Yukawa Running

- Top running is deflected by the conformal sector

$$\frac{d}{d\ln\mu} y_t = \frac{y_t}{16\pi^2}\left(6y_t^2 + 3\lambda_u^2 - \frac{13}{15}g_1^2 - 3g_2^2 - \frac{16}{3}g_3^2\right)$$

- Fixed point couplings are large $\lambda_u \sim 4.1$
- y_t is drastically suppressed for λ_u at fixed point



Stable Baryons and BBN

- Low-Energy theory respects $U(1)_B$
- Baryons are charged under EW theory
- Baryons symmetry broken by Plank-suppressed operators

$$W = \frac{1}{M_P} 5_Q 5_Q 5_Q 10$$

- Seems lifetime is too long
- Anomalous dimensions of 5_Q are rather large $\gamma_{5_Q} \sim 0.25$.
- RG running enhances operator giving a much smaller effective cut-off

Conclusions

- Quasi-natural SUSY models are still allowed
- Strong sector enhances the Higgs quartic couplings
- Strong sector does not destroy quasi-naturalness
- Higgs mixing generates the μ-term
- Extending to GUT consist model $\rightarrow$ conformal theory
- Naturally generated couplings from conformal theory

Electroweak Precision Measurements

- Corrections to the T parameter

$$K \simeq \frac{\lambda_u^4}{N_{\rm NDA}^2 \Lambda_H^2} H_u^\dagger H_u H_u^\dagger H_u \,, \to \mathcal{L} \simeq \frac{\lambda_u^4}{N_{\rm NDA}^2 \Lambda_H^2} \sin^4\beta |h^\dagger D_\mu h|^2 \,,$$

$$|T| \simeq 0.08 \times \left(\frac{4\pi}{N_{\rm NDA}}\right)^2 \left(\frac{\lambda_u}{3}\right)^4 \left(\frac{5\rm TeV}{\Lambda_H}\right)^2 \sin^4\beta < 0.05 \pm 0.12$$

- Corrections to the S parameter

$$K \simeq \frac{\lambda_u^2}{N_{\rm NDA}^2 \Lambda_H^2} (\nabla^{\dagger 2} H_u^\dagger e^{-2V})(\nabla^2 H_u) \to \mathcal{L} \simeq \frac{\lambda_u^2 g g'}{N_{\rm NDA}^2 \Lambda_H^2} \sin^2 (h^\dagger W_{\mu\nu} h) B^{\mu\nu} \,,$$

$$|S| \simeq 0.007 \times \left(\frac{4\pi}{N_{\rm NDA}}\right)^2 \left(\frac{\lambda_u}{3}\right)^2 \left(\frac{5\,\rm TeV}{\Lambda_H}\right)^2 \sin^2\beta < 0.02 \pm 0.11$$