A Natural Higgs mass in Supersymmetry with Non-decoupling Effects

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Introduction

Tension 1 [MSSM vs 125GeV Higgs mass]

The most critical information from LHC: discovery of a Higgs at 125GeV --MSSM requires large radiative corrections to the Higgs mass, which requires fine-tuning of O(1)%.

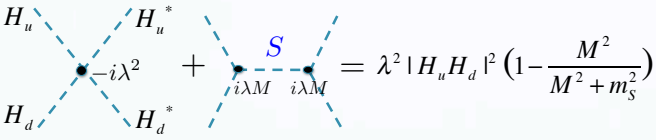
Additional tree-level contribution?

If weak-scale Supersymmetry is a solution to the naturalness problem, one possibility is an extended Higgs sector which has additional Higgs quartic by Non-decoupling *F*-term or *D*-term to accommodate m_h=125GeV.

- Simple and known example: NMSSM

$$W = \lambda S H_u H_d + \frac{M}{2} S^2 + \mu H_u H_d.$$

- Need soft-mass of *S* for non-decoupling *F*-term,



$$= \lambda^2 |H_u H_d|^2 \left(1 - \frac{M^2}{M^2 + m_S^2}\right)$$

Tension 2 [Raising Higgs mass vs Naturalness in NMSSM]

Large SUSY breaking $m_s \gg M$ leads a substantial new quartic coupling, but the naturalness is worse since RGE of Higgs soft mass flows faster,

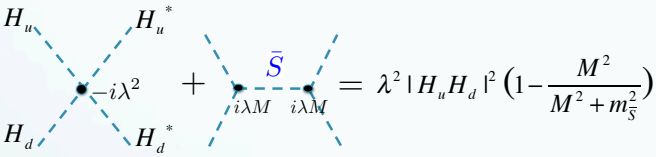
$$\mu \frac{d}{d\mu} m_{H_u}{}^2 = \frac{1}{8\pi^2}\left\{3y_t{}^2(m_{\tilde{Q}_3}{}^2 + m_{\tilde{t}_R}{}^2) + \lambda^2 m_S^2\right\}\ldots$$

★Large Higgs mass and Naturalness seem incompatible in a simple singlet extension of Higgs sector.

Dirac NMSSM

We propose a model with a Dirac mass of singlet. It separates the two issues and can raise Higgs mass without cost of naturalness

$$W = \lambda S H_u H_d + M S \bar{S} + \mu H_u H_d.$$



$$= \lambda^2 |H_u H_d|^2 \left(1 - \frac{M^2}{M^2 + m_{\bar{S}}^2}\right)$$

Basic Idea: Two soft masses of singlet take different roles!

- Higgs mass is raised by very large $m_{sbar} \gg M$
- Naturalness is maintained by small m_S as well as small m_{stop}

Tadpole is adequately small by symmetry arguments, and other singlet involving terms are forbidden or suppressed.

$$W \supset c_{\bar{S}} \cdot \mu M \bar{S} \sim \epsilon_\mu \epsilon_M M_{pl}^2 \bar{S}$$

	matter	H_u	H_d	S	$\bar{S}$	μ	M	ϵ_μ	ϵ_M
$U(1)_{PQ}$	−1/2	1	1	−2	−2	−2	4	−2	4
$U(1)_S$	0	0	0	0	1	0	−1	0	−1

In addition to MSSM potential,

$$\Delta V_{soft} = m_S^2 |S|^2 + m_{\bar{S}}^2 |\bar{S}|^2 + \lambda A_\lambda S H_u H_d + M B_S S\bar{S} + t_{\bar{S}}\bar{S} + t_S S + c.c.$$

Then Higgs mass (in large m_A limit)

$$m_h^2 \simeq m_{h,\mathrm{MSSM}}^2(m_{\tilde{t}}) + \lambda^2 v^2 \left\{ \sin^2 2\beta \left(\frac{m_{\bar{S}}^2}{M^2 + m_{\bar{S}}^2}\right) - \frac{\left|A_\lambda \sin 2\beta - 2\mu_{eff}^*\right|^2}{M^2 + m_S^2} \right\}$$

$$\mu_{eff} \equiv \mu + \lambda v_S$$

Naturalness 1 [RGE]

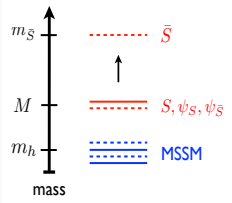
Sbar connects with MSSM+*S* sector only through dimensionful coupling M. By dimensional analysis, RGE of Higgs parameters is independent on m_{sbar} at all orders.
[it must decouple when $M \to 0$]
e.g.) $M m_{sbar}{}^2$ cannot enter in RGE of dim. 2.

Naturalness 2 [Threshold correction]

Threshold corrections logarithmically depend on m_{sbar},

$$\delta m^2_{H_u,H_d} = \frac{(\lambda M)^2}{16\pi^2} \log \frac{M^2 + m_{\bar{S}}^2}{M^2}$$

Large m_{sbar} does not upset naturalness.



Semi-Soft SUSY Breaking

Even after decoupling Sbar for the large SUSY breaking, the effective theory is written by Superfield+ soft SUSY breaking.

- MSSM+*S* sector + new terms:

$$K_{eff} \supset \bar{S}^\dagger \bar{S} + \theta^2\bar{\theta}^2 |M(S + c_{\bar{S}}\mu)|^2,\ W_{eff} \supset M\theta^2 D_\alpha S D^\alpha \bar{S}$$

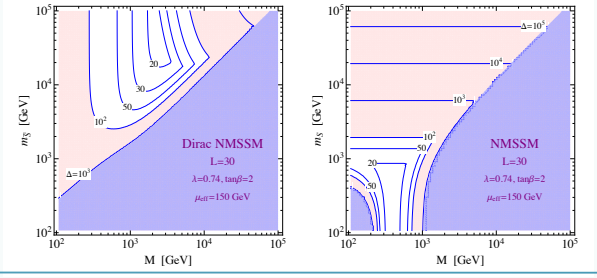
(Scalar and *F*-term of Sbar are reintroduced to form a supefield)

Fine-tuning in Dirac NMSSM and NMSSM

Measure:

$$\Delta = \frac{2}{m_h^2}\max\left(m_{H_u}^2, m_{H_d}^2, \frac{dm_{H_u}^2}{d\ln\mu}L, \frac{dm_{H_d}^2}{d\ln\mu}L, \delta m_H^2, b_{eff}\right)$$

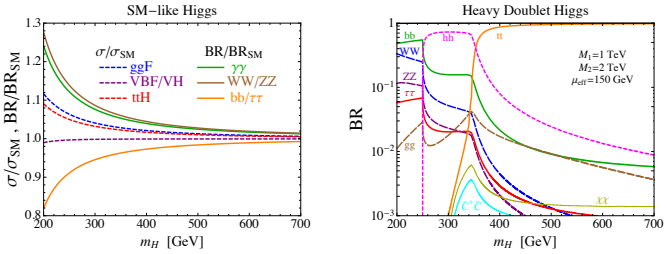
Less fine-tuned in the high-scale m_{sbar} in Dirac NMSSM



Higgs Phenomenology

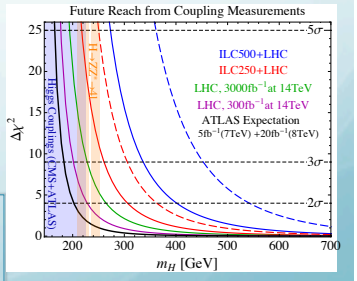
Singlets are too heavy to directly test at colliders, so we focus on nature of the SM-like Higgs(h) and doublet-like Higgs(H).

- Couplings of h to down-type quark and leptons are reduced, while those to up-type quarks are slightly increased
- Non-decoupling quartic leads H→hh decay beyond its threshold



Future Reach at HL-LHC and ILC

We can investigate H up to
m_H=280GeV at HL-LHC
m_H=400GeV at ILC500(consv.)
m_H=580GeV at ILC500(optimistic)
by coupling measurements.
Better accuracy for hbb at ILC



Benchmark parameters
$\lambda = 0.74, \tan\beta = 2,\ \mu_{eff} = 150\,\mathrm{GeV},$
$b_{eff} = (190\,\mathrm{GeV})^2,\ A_\lambda = 0,\ B_s = 100\,\mathrm{GeV},$
$M = 1\,\mathrm{TeV},\ m_{\bar{S}} = 10\,\mathrm{TeV},\ m_S = 800\,\mathrm{GeV}$

Summary

- New singlet extension, *Dirac NMSSM*, make the naturalness and raising Higgs mass compatible
- Interesting mechanism, *semi-soft SUSY breaking*: the model large SUSY breaking behaves as softly-broken theory.
- Discrimination from NMSSM and model-building aspect are yet to be studied