A Light Higgs Scenario from TeV-scale SUSY Strong Dynamics

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Introduction

Extended Higgs Sector with Large Couplings in SUSY Models

$\lambda_u,\ \lambda_d$: Large

$$\mathcal{L} = \int \mathrm{d}^2\theta \, \{ \, \lambda_u H_u \mathcal{O}_u + \lambda_d H_d \mathcal{O}_d + f(\mathcal{O}_u, \, \mathcal{O}_d) \, \} + \text{h.c.},$$

(but no NH_uH_d coupling.)

"Large coupling" :=
Landau pole exists somewhere below Planck scale.

- **Enhance the mass of the SM-like Higgs boson w/o large soft SUSY breaking mass.**
- Realize strongly 1st order EW phase transition for EW baryogenesis.

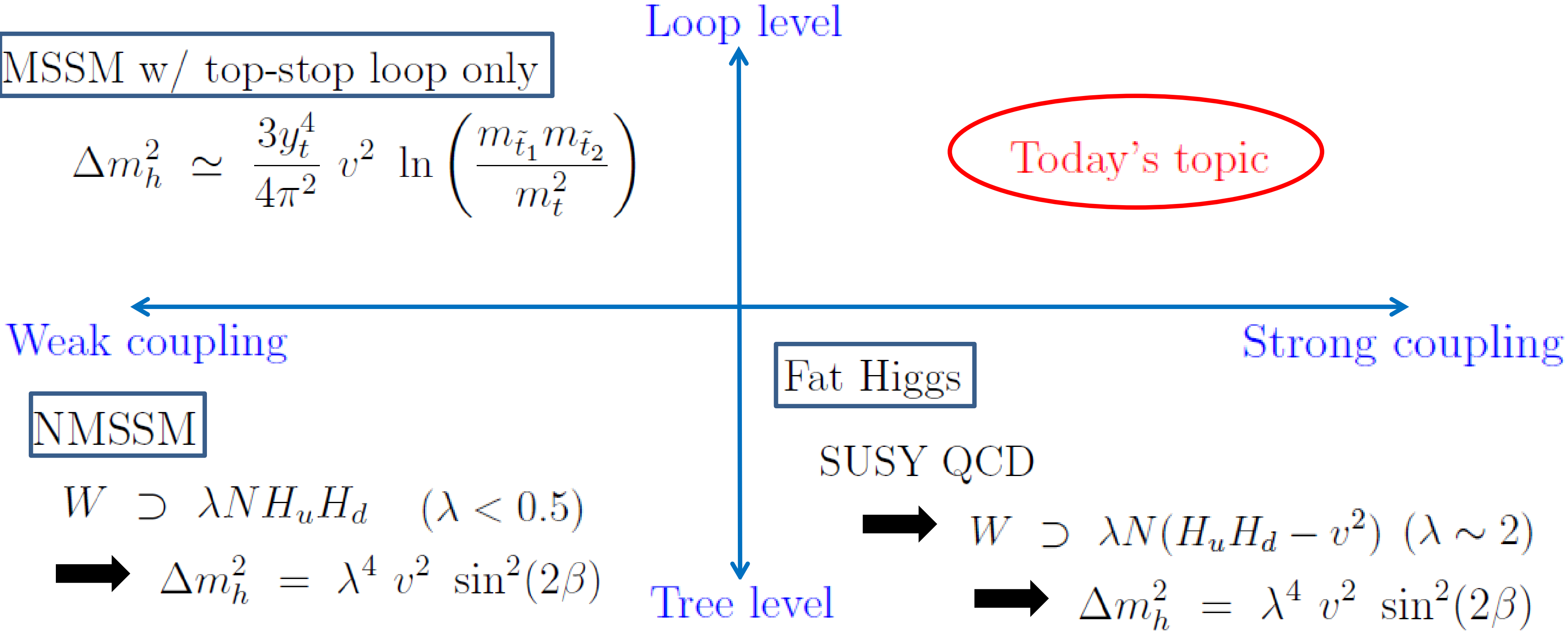
Kanemura, Shindou, Senaha (2011)

125 GeV Higgs with SUSY Standard Models

- ATLAS and CMS SM Higgs search suggests 125 GeV Higgs boson.
- In MSSM, $m_h|_{tree} \leq M_Z^2 \cos^2(2\beta)$.

  We have to somehow enhance m_h .

- Four ways to enhance the Higgs boson mass :



Loop level

MSSM w/ top-stop loop only

$$\Delta m_h^2 \simeq \frac{3y_t^4}{4\pi^2}\, v^2 \, \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

Today's topic

Weak coupling

Strong coupling

Fat Higgs

NMSSM

$$W \supset \lambda N H_u H_d \quad (\lambda < 0.5)$$

$$\Rightarrow \Delta m_h^2 = \lambda^4 \, v^2 \, \sin^2(2\beta)$$

SUSY QCD

$$\Rightarrow W \supset \lambda N (H_u H_d - v^2) \; (\lambda \sim 2)$$

$$\Rightarrow \Delta m_h^2 = \lambda^4 \, v^2 \, \sin^2(2\beta)$$

Tree level

- We consider an extended Higgs sector with large couplings that contributes to the SM-like Higgs mass through radiative corrections.

What waits beyond the Landau Pole ?

- We want to build a UV-complete model.

- Consider **SUSY SU(2) gauge theory with 3 pairs** of matter superfields (the same setup as "Fat Higgs")

R. Harnik *et al.* (2003)

The theory becomes strongly coupled at an IR scale.

Low-energy effective theory is described by Meson superfields, which have large couplings.

Higgs superfields = Mesons of SUSY gauge theory

Framework

UV Theory

SUSY $\boxed{SU(2)_H}$ gauge theory with six doublets $\boxed{T_1,\ T_2, ...,\ T_6}$, charged under SM gauge groups and a new Z_2-parity.

To suppress FCNCs mediated by extra Higgs doublets.

Field	$SU(2)_L$	$U(1)_Y$	Z_2
$\begin{pmatrix} T_1 \\ T_2 \end{pmatrix}$	2	0	$+$
T_3	1	$+1/2$	$+$
T_4	1	$-1/2$	$+$
T_5	1	$+1/2$	$-$
T_6	1	$-1/2$	$-$

Most general mass term (“current mass”)

$$W_{tree} = m_1 T_1 T_2 + m_3 T_3 T_4 + m_5 T_5 T_6$$

IR Theory

- The gauge theory becomes strongly coupled at Λ_H .
- Below Λ_H , the theory is described by Meson superfields:

  From holomorphy, mesons are given as

$$\boxed{M_{ij} \propto T_i T_j} \quad .$$

  The effective superpotential obeys approximate SU(6) flavor symmetry:

$$\boxed{W_{eff} \propto \epsilon_{ijklmn} M_{ij} M_{kl} M_{mn} + m_1 M_{12} + m_3 M_{34} + m_5 M_{56}}$$

- Kähler potential cannot be determined, but SUSY Naïve Dimensional Analysis suggests

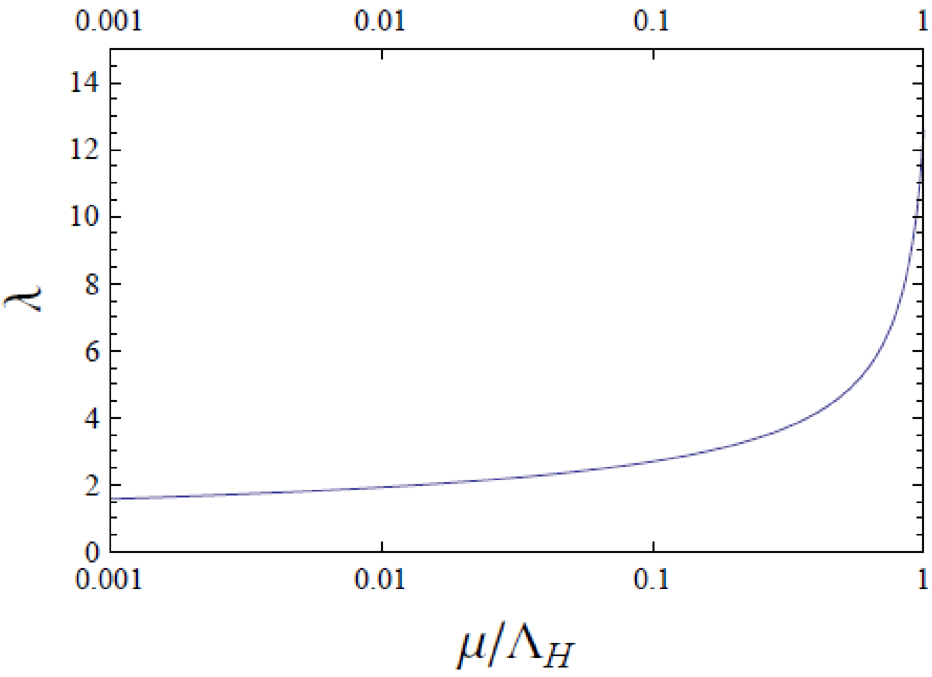
$$\mathcal{L} \simeq \frac{1}{(4\pi)^2} \int \mathrm{d}^4\theta \, \frac{1}{\Lambda_H^2} M_{ij}^\dagger M_{ij} + \frac{1}{(4\pi)^2} \int \mathrm{d}^2\theta \left[\frac{1}{\Lambda_H^3} \epsilon_{ijklmn} M_{ij} M_{kl} M_{mn} + m_1 M_{12} + m_3 M_{34} + m_5 M_{56} \right] .$$

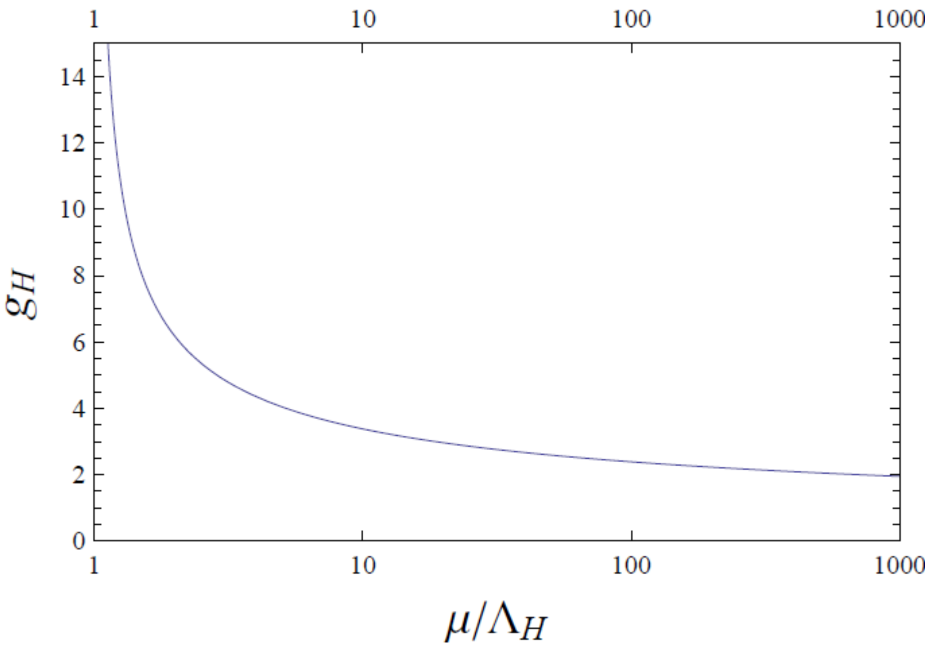
- After canonically normalizing the mesons, we have

$$\boxed{W_{eff} \;\simeq\; -\lambda\, \epsilon^{ijklmn}\, M_{ij} M_{kl} M_{mn} \;+\; \xi_\Omega M_{12} \;+\; \xi_\Phi M_{34} \;+\; \xi M_{56}} \;,$$

with $\lambda(\Lambda_H) \;\simeq\; 4\pi \;,\quad \xi \;\simeq\; \frac{m_1 \Lambda_H}{4\pi}, \;\ldots \quad .$

- g_H and λ evolve as follows:





Extended Higgs Sector

Mesons = Higgses

Identify the fifteen mesons with the fields of an extended Higgs sector.

	Field	$SU(2)_L$	$U(1)_Y$	Z_2
MSSM Higgs doublets	H_u	2	$+1/2$	$+$
	H_d	2	$-1/2$	$+$
Extra Higgs doublets	Φ_u	2	$+1/2$	$-$
	Φ_d	2	$-1/2$	$-$
Charged singlets	Ω^+	1	$+1$	$-$
	Ω^-	1	-1	$-$
Z_2-even Neutral singlets	$N,\ N_\Phi,\ N_\Omega$	1	0	$+$
Z_2-odd Neutral singlets	$\zeta,\ \eta$	1	0	$-$

$\Leftrightarrow \quad M_{ij}$

- The superpotential is rewritten as

$$W_{eff} = \lambda \{ N(H_u H_d + v_0^2) + N_\Phi(\Phi_u \Phi_d + v_\Phi^2) + N_\Omega(\Omega^+\Omega^- + v_\Omega^2) - N N_\Phi N_\Omega - N_\Omega \zeta\eta + \zeta H_d \Phi_u + \eta H_u \Phi_d - \Omega^+ H_d \Phi_d - \Omega^- H_u \Phi_u \}$$

Large, $\lambda(M_Z) \sim 2$

Potential Analysis

$$
\begin{aligned}
W_{eff} \;=\;& \lambda \,\{\, N(H_u H_d + v_0^2) \;+\; N_\Phi(\Phi_u \Phi_d + v_\Phi^2) \;+\; N_\Omega(\Omega^+\Omega^- + v_\Omega^2) \\
&- \; N N_\Phi N_\Omega \;-\; N_\Omega \zeta\eta \;+\; \zeta H_d \Phi_u \;+\; \eta H_u \Phi_d \;-\; \Omega^+ H_d \Phi_d \;-\; \Omega^- H_u \Phi_u \,\}
\end{aligned}
$$

Look for charge-conserving vacua.

Focus on SUSY limit.

- VEVs of N, N_Ω, N_Φ arise from tad-pole terms.

  → Effective μ -terms.

- EW symmetry breaking does **not** occur in SUSY limit

  because

$$
\left.
\begin{aligned}
0 &= \frac{1}{\lambda}\frac{\partial W_{eff}}{\partial H_d^0} = -N H_u^0 + \zeta \Phi_u^0 \,, \\
0 &= \frac{1}{\lambda}\frac{\partial W_{eff}}{\partial \Phi_d^0} = -N_\Phi \Phi_u^0 - \eta H_u^0 \\
0 &= \frac{1}{\lambda}\frac{\partial W_{eff}}{\partial N_\Omega} = -N N_\Phi - \zeta\eta + v_\Omega^2
\end{aligned}
\right\} \Rightarrow \quad H_u^0 = \Phi_u^0 = 0
$$

if $v_\Omega \neq 0$.

We resort to radiative breaking scenario (*c.f.* “Fat Higgs”)

Scale of Λ_H

- “SUSY tadpole problem” puts a constraint on Λ_H .
- Soft SUSY breaking terms contribute to the tadpole terms for N, N_Ω, N_Φ :

Source of SUSY breaking

$$\int \mathrm{d}^4\theta \, \frac{X^\dagger}{M^\dagger} M_{56} + \ldots \Rightarrow \int \mathrm{d}^2\theta \, M_{soft} \frac{\Lambda_H}{4\pi} N + \ldots$$

- In order that these contributions do not spoil the SUSY’s solution to the gauge hierarchy problem,

$$\frac{\Lambda_H}{4\pi} \lesssim 1 \ \mathrm{TeV} \quad .$$

- (Another way to evade SUSY tadpole problem

  → assigning Z_6-parity to $T_1, T_2, \ldots, T_6$.(similar to NMSSM))

Extension with one Singlet

- We add one Z_2-even, $SU(2)_H$ and SM gauge singlet, S .

  Most general superpotential involving S :

$$W_S = (y_1 T_1 T_2 + y_3 T_3 T_4 + y_5 T_5 T_6) S + \frac{M_S}{2} S^2 + \frac{\kappa}{3} S^3$$

$$\boxed{W_S = \left(\frac{y_1}{4\pi} \Lambda_H M_{12} + \frac{y_3}{4\pi} \Lambda_H M_{34} + \frac{y_5}{4\pi} \Lambda_H M_{56} \right) S + \frac{M_S}{2} S^2 + \frac{\kappa}{3} S^3}$$

- We assume $\Lambda_H \sim M_S$ and $O(1) \sim y_1 \gg y_3, \; y_5$.

  y_1 remains perturbative up to the Planck scale.

H. Murayama (2003)

- Integrating S out, and with <u>conformal enhancement</u>,

  we have

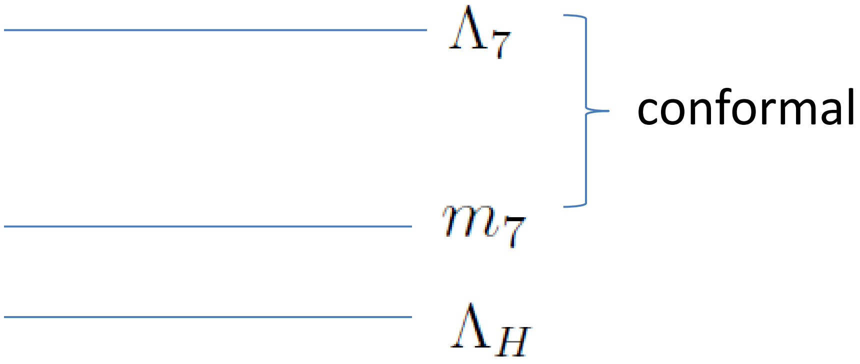
$$\boxed{\Delta W_{eff} = -\frac{M_N}{2} N^2 \quad \text{with } M_N \sim \Lambda_H} \; .$$

“Conformal enhancement”

Introduce two more $SU(2)_H$ doublets, $T_7,\ T_8$, with mass term: $W_7 = m_7 T_7 T_8$ ($m_7 > \Lambda_H$).

The theory above the scale m_7 is in the conformal window.

Assume that the theory approaches to the IR fixed point at the scale $\Lambda_7\ (> m_7)$.



⇒ Couplings y_i are enhanced by $\left(\frac{\Lambda_7}{m_7}\right)^{1/2}$ while running from Λ_7 to m_7 .

This is necessary to derive the O(1) top Yukawa coupling, anyway.

Effective Superpotential

- Since N has the large mass of $M_N \sim \Lambda_H$, we may integrate it out below Λ_H and obtain:

$$\begin{aligned} W_{eff} &= \lambda \, \{ \, N_\Phi(\Phi_u\Phi_d + v_\Phi^2) \; + \; N_\Omega(\Omega^+\Omega^- + v_\Omega^2) \\ &- \; N_\Omega\zeta\eta \; + \; \zeta H_d\Phi_u \; + \; \eta H_u\Phi_d \; - \; \Omega^+ H_d\Phi_d \; - \; \Omega^- H_u\Phi_u \, \} \\ &+ \; \frac{\lambda^2}{2M_N}(H_uH_d + v_0^2 - N_\Phi N_\Omega)^2 \; . \end{aligned}$$

- No three-point superpotential coupling for H_uH_d .
- By taking $\Lambda_H \; > \; m_5 \; \gg \; m_1, \; m_3$,
  we can have O(100) GeV μ-terms for $(H_u, H_d), \; (\Phi_u, \; \Phi_d), \; (\Omega^+, \Omega^-)$
  from the VEVs of N, N_Ω, N_Φ .

$$\begin{aligned} W_{eff} &= -\mu(H_uH_d - n_\Phi n_\Omega) - \mu_\Phi\Phi_u\Phi_d - \mu_\Omega(\Omega^+\Omega^- - \zeta\eta) \\ &+ \; \lambda \, \{ \, H_d\Phi_u\zeta + H_u\Phi_d\eta - H_u\Phi_u\Omega^- - H_d\Phi_d\Omega^+ + n_\Phi\Phi_u\Phi_d + n_\Omega(\Omega^+\Omega^- - \zeta\eta) \, \} \\ &+ \; \cdots \; , \end{aligned}$$

Phenomenology of One-Singlet Extension

SM-like Higgs Boson Mass

- $(\Phi_u,\ \Phi_d),\ (\Omega^+,\Omega^-),\ (\zeta,\eta)$ contribute to the SM-like Higgs mass through loop corrections:

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + (\text{MSSM-loop}) + \boxed{\frac{\lambda^4 v^2}{16\pi^2}} \left(c_\beta^4 \ln \frac{m_{\Omega^+}^2 m_{\Phi_d^\pm}^2 m_{\Phi_u^0}^2 m_\zeta^2}{m_{\tilde{\chi}_1'^\pm}^4 m_{\tilde{\chi}_1'^0}^4} + s_\beta^4 \ln \frac{m_{\Omega^-}^2 m_{\Phi_u^\pm}^2 m_{\Phi_d^0}^2 m_\eta^2}{m_{\tilde{\chi}_2'^\pm}^4 m_{\tilde{\chi}_2'^0}^4} \right)$$

- $\dfrac{\lambda^4 v^2}{16\pi^2}$ with $\lambda \ \sim \ 2$ is of an appropriate magnitude to realize 125 GeV Higgs.

(No large soft SUSY breaking nor tuning of $\tan\beta$ is necessary.)

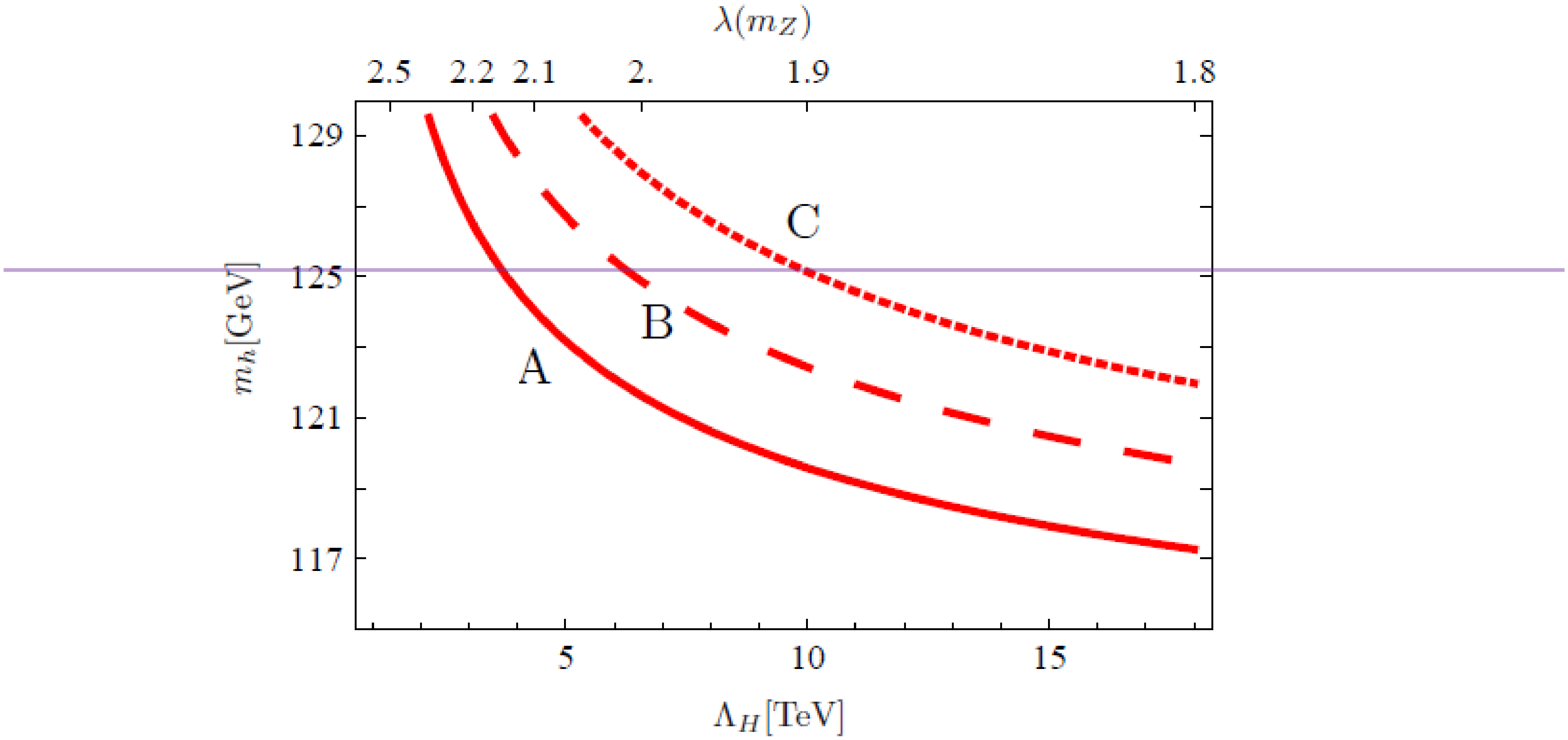
- SM-like Higgs mass at benchmark points.

$\bar m^2_{\tilde t_L} = \bar m^2_{\tilde t_R} = 1000\ \mathrm{GeV}$, $A_t + \mu \cot\beta = 500\ \mathrm{GeV}$, $m_A = 500\ \mathrm{GeV}$, $\tan\beta = 3$

$\mu = 200\ \mathrm{GeV}$, $\mu_\Phi = \mu_\Omega = 0$ (extra-Higgsino masses come from Higgs VEVs),

Soft masses:

Set	$\bar m_{\Phi_u^0} = \bar m_{\Phi_u^\pm}$	$\bar m_{\Phi_d^0} = \bar m_{\Phi_d^\pm}$	$\bar m_{\Omega^-}$	$\bar m_{\Omega^+}$	$\bar m_\zeta$	$\bar m_\eta$
A	50	350	50	350	50	350
B	50	400	50	400	50	400
C	50	450	50	450	50	450



Correction on Partial Width

- $\Gamma(h \to \gamma\gamma)$ is affected by **multiple** extra charged Higgses that couple with SM-like Higgs thru **large** couplings.

➡ The correction can be large.

But large current masses $m_1, \; m_3, \; m_5$ can make the μ-terms for $(\Phi_u, \; \Phi_d), \; (\Omega^+, \Omega^-)$ large (as large as Λ_H), so extra Higgs bosons /Higgsinos can be decoupled.

➡ The correction can be small.

Conclusion

- SUSY **extended Higgs sector** w/ **large couplings** arising from strongly coupled SUSY SU(2) gauge theory.
- Our model is UV-complete.
- Natural realization of 125 GeV SM-like Higgs.
- Strong 1st order EW phase transition is possible.
- Other phenomenological implications …