Vector-like leptons and Large A-term for 126 GeV Higgs boson

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- ATLAS and CMS have announced the discovery of the SM(-like) Higgs in the 125-126 GeV invariant mass range.

- So far no evidence beyond the SM has appeared yet.

→ Theoretical puzzles raised in the SM still remain unsolved.

- 126 GeV is too large for the MSSM Higgs mass, since it requires a too heavy stop mass (> a few TeV), which compels the soft parameters to be finely tuned to match M_Z.

- For naturalness of the Higgs mass, the stop should be relatively light. At the moment , (fortunately) $m_t^2 > (6\text{-}700\ \text{GeV})^2$, which provides just $\Delta m_h^2|_{top} > (76\ \text{GeV})^2$.

→ $\Delta m_h^2|_{new} > (84 \text{ -- } 43\ \text{GeV})^2$ for $\tan\beta = 2 - 50$ needed.

Radiative Correction

(1. Radiative mass & 2. Renormalization)

The top and stop make contributions to

1. the radiative Higgs mass :
2. the renormalization of m_2^2 :

$$\Delta m_h^2|_{\rm top} \approx 3\frac{v_h^2 \sin^4\beta}{4\pi^2}|y_t|^4 \log\left(\frac{m_t^2+\widetilde{m}_t^2}{m_t^2}\right) = \frac{3m_t^4}{4\pi^2 v_h^2}\log\left(\frac{m_t^2+\widetilde{m}_t^2}{m_t^2}\right)$$

$$\Delta m_2^2|_{\rm top} \approx 3\frac{|y_t|^2}{8\pi^2}\underline{\widetilde{m}_t^2}\,\log\left(\frac{\widetilde{m}_t^2}{M_G^2}\right)$$

$$m_2^2|_{\rm EW} + |\mu|^2_{\rm EW} \approx m_3^2|_{\rm EW}\ \cot\beta + \frac{M_Z^2}{2}\cos 2\beta$$

Vector-like Leptons

With the extra vector-like lepton doublets $\{L, L^c\}$,

and the (lepton) singlets $\{N, N^c\}$,

$$W = y_N L h_u N^c + \mu_L L L^c + \mu_N N N^c$$

$(|\mu_L| > |\mu_N|)$

Vector-like Leptons

With the extra vector-like lepton doublets $\{L, L^c\}$,

...ts $\{N, N^c\}$,

No 2 photons enhancement !

$$W = y_N L h_u N^c + \mu_L L L^c + \mu_N N N^c$$

$(|\mu_L| > |\mu_N|)$

Vector-like Leptons

With the extra vector-like lepton doublets $\{L, L^c\}$

and the lepton si

$L \longrightarrow N^c$ + SM fermions (+ LSP)

$$W = y_N L h_u N^c + \mu_L L L^c + \mu_N N N^c$$

$(|\mu_L| > |\mu_N|)$

Radiative Correction

(1. Radiative mass & 2. Renormalization)

As the (s)top, Vec.-like leptons make contributions to

1. the radiative Higgs mass :
2. the renormalization of m_2^2 :

$$\Delta m_h^2|_{L,N^c} \approx N_V \frac{|y_N|^4}{4\pi^2} v_h^2 \sin^4\beta \, \log\left(\frac{M^2+\widetilde{m}^2}{M^2}\right),$$

$$\Delta m_2^2|_{L,N^c} \approx N_V \frac{|y_N|^2}{8\pi^2} \left[f_Q(M^2+\widetilde{m}_l^2) - f_Q(M^2)\right]_{Q=M_G},$$

[N_V=2 for $SU(2)_Z$]

$$M^2 \equiv |\mu_L|^2 + |y_N|^2 v_h^2 \sin^2\beta \qquad f_Q(m^2) \equiv m^2\{\log(\tfrac{m^2}{Q^2}) - 1\}$$

Radiative Correction
(Radiative mass)

VLs contribute to the radiative Higgs mass, Δm_h^2 :

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_h^2|_{\rm top} + \Delta m_h^2|_N \approx (126 \text{ GeV})^2$$

where

$$\Delta m_h^2|_{\rm top} \approx \frac{3 v_h^2 \sin^4\beta}{4\pi^2} |y_t|^4 \log\left(\frac{m_t^2 + \widetilde{m}_t^2}{m_t^2}\right) = \frac{3 m_t^4}{4\pi^2 v_h^2} \log\left(\frac{m_t^2 + \widetilde{m}_t^2}{m_t^2}\right),$$

$$\Delta m_h^2|_N \approx N_V \frac{v_h^2 \sin^4\beta}{4\pi^2} |y_N|^4 \log\left(\frac{M^2 + \widetilde{m}^2}{M^2}\right),$$

$$M^2 \equiv |\mu_L|^2 + |y_N|^2 v_h^2 \sin^2\beta$$

Radiative Correction

(Renormalization)

VLs contribute to the renormalization of $m_2^2(Q)$:

$$f_Q(m^2) \equiv m^2\{\log(\frac{m^2}{Q^2}) - 1\}$$

$$m_2^2(Q) + \frac{3|y_t|^2}{8\pi^2}\left[f_Q(m_t^2 + \widetilde{m}_t^2) - f_Q(m_t^2)\right] + N_V\frac{|y_N|^2}{8\pi^2}\left[f_Q(M^2 + \widetilde{m}^2) - f_Q(M^2)\right]$$

Inserting the RG soln of $m_2^2(Q)$ yields the low energy value of $m_2^2(Q)$, i.e. $m_2^2(Q=E_{EW})$, replacing the Q dependence by M_{GUT} :

[N_V=2 for $SU(2)_Z$]

$$m_2^2|_{\rm EW} \approx m_0^2 + \frac{3|y_t|^2}{8\pi^2}\widetilde{m}_t^2\,\log\left(\frac{\widetilde{m}_t^2}{M_G^2}\right) + N_V\frac{|y_N|^2}{8\pi^2}\left[f_Q(M^2 + \widetilde{m}^2) - f_Q(M^2)\right]_{Q=M_G}$$

Thus, one of the minimum conditions in the Higgs potential is

$$m_2^2|_{\rm EW} + |\mu|^2_{\rm EW} \approx m_3^2|_{\rm EW}\,\cot\beta + \frac{M_Z^2}{2}\cos2\beta$$

Radiative Correction

(Radiative mass & Renormalization)

As the (s)top, Vec.-like leptons make contributions to

1. the radiative Higgs mass :
2. the renormalization of m_2^2 :

$$\Delta m_h^2|_{L,N^c} \approx N_V \frac{|y_N|^4}{4\pi^2} v_h^2 \sin^4\beta \log\left(\frac{M^2+\widetilde{m}^2}{M^2}\right),$$

$$\Delta m_2^2|_{L,N^c} \approx N_V \frac{|y_N|^2}{8\pi^2}\left[f_Q(M^2+\widetilde{m}_l^2) - f_Q(M^2)\right]_{Q=M_G},$$

A larger y_N is preferred → The Landau-pole problem would arise!!

$\{\mu_L^2, m^2\}$ need to be as small as possible. → Vec.-like (s)quarks disfavored.

Radiative Correction

(Renormalization)

To minimize the fine-tuning, we suppose that

the stop mass, m_t^2 is around $(700\ \text{GeV})^2$ or larger,

and

$|\mu_L|^2$ $(>|\mu_N|^2)$, m^2 are smaller than $(700\ \text{GeV})^2$.

Radiative Correction

(Radiative mass)

$$N_V |y_N|^4 \log\left(\frac{M^2+\widetilde{m}^2}{M^2}\right) \lesssim 14.5,\ 5.4,\ 3.7,\ 2.9,\ 2.4$$

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_h^2|_{\mathrm{top}} + \Delta m_h^2|_N \approx (126\ \mathrm{GeV})^2$$

$$2 \times |y_N|^4 \approx 20.9,\ 7.8,\ 5.3,\ 4.2,\ 3.5$$

for $\tan\beta = 2, 4, 6, 10, 50.$

Radiative Correction

(Radiative mass)

$$N_V |y_N|^4 \log\left(\frac{M^2 + \widetilde{m}^2}{M^2}\right) \lesssim 14.5,\ 5.4,\ 3.7,\ 2.9,\ 2.4$$

for $\tan\beta = 2, 4, 6, 10, 50.$

For $N_V = 2$, $|\mu_L|^2 \approx \widetilde{m}^2 \gg v_H^2$,

$$2 \times |y_N|^4 \approx 20.9,\ 7.8,\ 5.3,\ 4.2,\ 3.5$$

for $\tan\beta = 2, 4, 6, 10, 50.$

$y_N \approx 0.7$ (so $|y_N|^4 \approx 0.24$) , which is the **Maximal Value** allowed at the EW scale avoiding the Landau-Pole constraints

can NOT explain 126 GeV Higgs mass.

→ **Need a much larger soft para.**

→ **Fine-Tuning**

Radiative Correction

(Radiative mass)

$$N_V |y_N|^4 \log\left(\frac{M^2+\widetilde{m}^2}{M^2}\right) \lesssim 14.5,\ 5.4,\ 3.7,\ 2.9,\ 2.4$$

for $\tan\beta = 2, 4, 6, 10, 50.$

For $N_V = 2$, $|\mu_L|^2 \approx \widetilde{m}^2 >> v_H^2$,

$$2 \times |y_N|^4 \approx 20.9,\ 7.8,\ 5.3,\ 4.2,\ 3.5$$

< 0.5

for $\tan\beta = 2, 4, 6, 10, 50.$

Model

Superfields	L	L^c	N	N^c	N_H	N_H^c	X
$\mathrm{SU}(2)_Z$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$
$\mathrm{U}(1)_\mathrm{R}$	1	1	1	1	0	2	2
$\mathrm{U}(1)_\mathrm{PQ}$	-1	-1	-3	1	-1	-1	-2

Introduce an extra $SU(2)_Z$ gauge sym. , under which

All the ordinary MSSM superfields including Higgs are Neutral.

Model

Superf	X
SU(2	$\mathbf{1}$
U(1	2
U(1)	-2

No mixing between **MSSM matt.** and **vec.-like leptons**

Introduce an extra **SU(2)$_Z$ gauge sym.**,
under which

All the ordinary **MSSM superfields** including **Higgs**
are **Neutral**.

Model

Superfields	L	L^c	N	N^c	N_H	N_H^c	X
$SU(2)_Z$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_R$	1	1	1	1	0	2	2
$U(1)_{PQ}$	-1	-1	-3	1	-1	-1	-2

$$W = y_N L h_u N^c$$

$$K = (X^\dagger/M_P) [LL^c + NN^c + N_H N_H{}^c] + h.c.$$

$$< F_X > \sim m_{3/2} M_P$$

Model

Superfields	L	L^c	N	N^c	N_H	N_H^c	X
$SU(2)_Z$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_R$	1	1					
$U(1)_{PQ}$	-1	-1					

Higgs for breaking $SU(2)_Z$

$$W = y_N L h_u N^c$$

$$K = (X^\dagger / M_P)[LL^c + NN^c + N_H N_H{}^c] + h.c.$$

$$\langle F_X \rangle \sim m_{3/2} M_P$$

Model

Superfields	L	L^c	N	N^c	N_H	N_H^c	X
$SU(2)_Z$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	
$U(1)_R$	1	1	1				
$U(1)_{PQ}$	-1	-1	-3				

SUSY breaking source

$$W = y_N L h_u N^c$$

$$K = (X^\dagger / M_P)\,[\,L L^c + N N^c + N_H N_H{}^c\,] + h.c.$$

$$\langle F_X \rangle \sim m_{3/2} M_P$$

Model

$1 \times \{ L, L^c ; N, N^c ; N_H, N_H{}^c \}$ are $SU(2)_Z$ doublets.

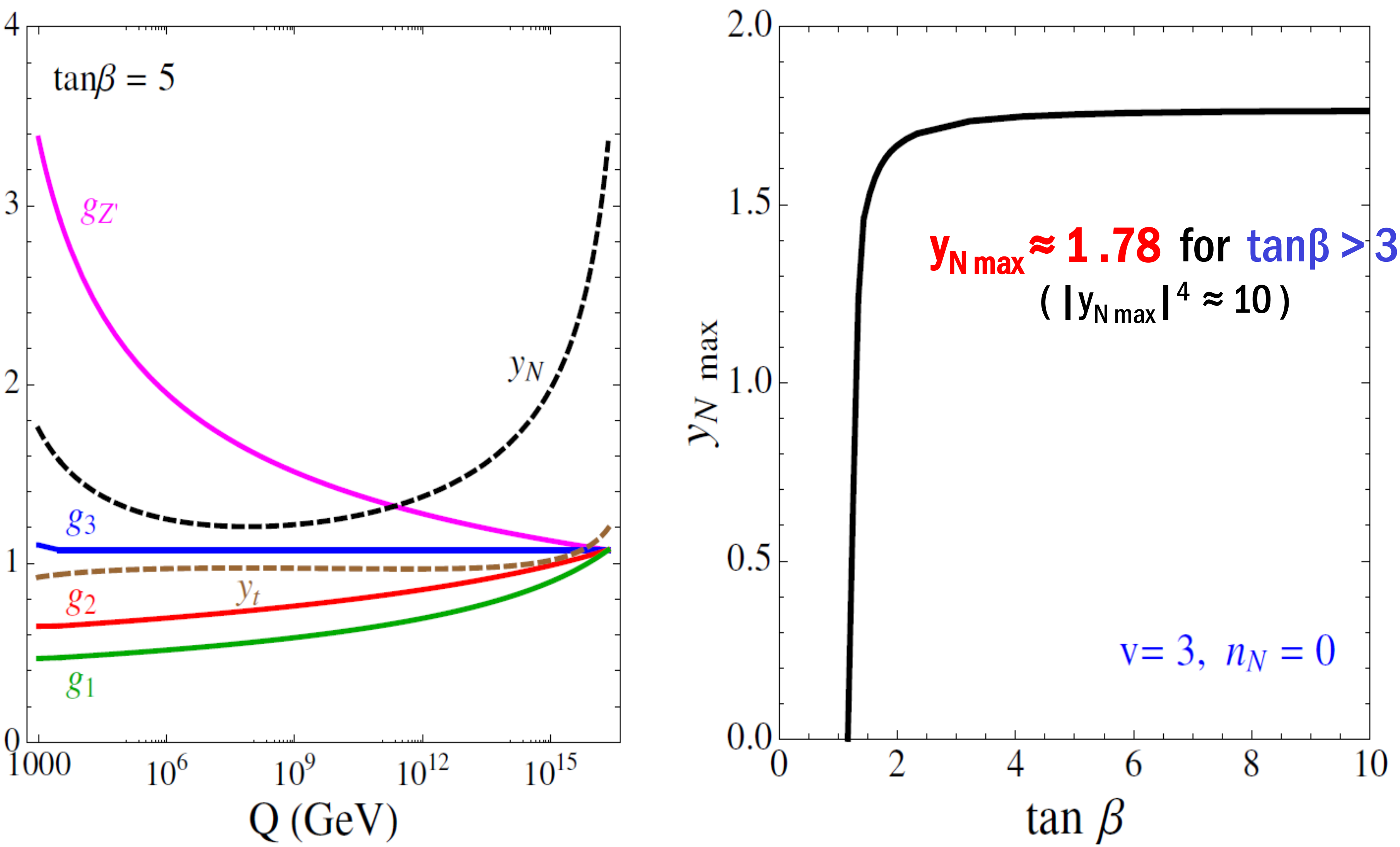
$2 \times \{ D, D^c \}$ are $SU(2)_Z$ singlets.

one more $\{5, 5^*\}$

$\therefore$ in total, $3 \times \{5, 5^*\}$.

RG equations

$$\begin{cases} \dfrac{d|y_N|^2}{dt} = \dfrac{|y_N|^2}{8\pi^2}\left[5|y_N|^2 + 3|y_t|^2 - 3g_2^2 - \frac{3}{5}g_1^2 - 3g_{Z'}^2\right], \\ \dfrac{d|y_t|^2}{dt} = \dfrac{|y_t|^2}{8\pi^2}\left[2|y_N|^2 + 6|y_t|^2 - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{13}{15}g_1^2\right], \end{cases}$$



tanβ = 5
$g_{Z'}$
y_N
g_3
y_t
g_2
g_1
Q (GeV)
$y_{N\,\max}$
$y_{N\,max} \approx 1.78$ for tanβ > 3
($|y_{N\,max}|^4 \approx 10$)
v= 3, $n_N = 0$
tan β

Radiative Correction

(Radiative mass)

$$N_V |y_N|^4 \log\left(\frac{M^2 + \widetilde{m}^2}{M^2}\right) \lesssim 14.5,\ 5.4,\ 3.7,\ 2.9,\ 2.4$$

for $\tan\beta = 2, 4, 6, 10, 50.$

For N_V= 2, $|\mu_L|^2 \approx \widetilde{m}^2$ >> v_H^2,

$$2 \times |y_N|^4 \approx 20.9,\ 7.8,\ 5.3,\ 4.2,\ 3.5$$

< 20

for $\tan\beta = 2, 4, 6, 10, 50.$

Radiative Correction

(Radiative mass)

$N_V |$ … $\left(M^2 + \widetilde{m}^2 \right)$ … $4.5,\ 5.4,\ 3.7,\ 2.9,\ 2.4$

… for $\tan\beta = 2, 4, 6, 10, 50.$

Trivially satisfied!!

126 GeV Higgs mass
easily explained

For $N_V = 2$, $|\mu_L|^2$ … $\widetilde{m}^2 \gg v_H^2$,

$$2 \times |y_N|^4 \approx 20.9,\ 7.8,\ 5.3,\ 4.2,\ 3.5$$

< 20

for $\tan\beta = 2, 4, 6, 10, 50.$

Oblique parameters

require $0.01 < \Delta S < 0.17$ (1σ) for $\Delta T \approx 0.12$, and

$m_h = 125.7 \pm 0.4$ GeV

$m_t = 173.18 \pm 0.94$ GeV

$\Delta T \approx 0.12$ constrains the parameter sp.

[Martin '10]

$$2 \times |y_N|^4 \left(\frac{500\ \text{GeV}}{|\mu_L|}\right)^2 \sin^4\beta \approx 5.56$$

$\mu_L \approx$ 803 GeV, 592 GeV, 517 GeV, 469 GeV, 440 GeV

for $\tan\beta$ = 2, 4, 6, 10, 50

($0.01 < \Delta S < 0.02$)

- $m_{Q1,Q2}$, $M_3 > 1$ TeV at the moment. They don't much affect the Higgs mass. But M_3 heavier than 1 TeV would drive m_t^2 negative at higher energies via RG effect, if $m_t^2 \sim (700\ \text{GeV})^2$.

$\rightarrow$ $m_t^2 \sim (700\ \text{GeV})^2$ is radiatively unstable, if $M_3 > 1$ TeV.

- In eff. SUSY, $m^2_{Q1,Q2}$ heavier than $(22\ \text{TeV})^2$ is known to drive m_t^2 negative at the EW scale via two loop RG effects, if $m_t^2 < (4\ \text{TeV})^2$. [Arkani-Hamed etal. '97]

- To keep the light stop at the EW scale, the radiative correction by M_3 (> 1 TeV) should be properly compensated e.g. by quite heavy $m^2_{Q1,Q2}$, which are experimentally required. [Huh, Kyae '13, ...]

Vector-like Leptons (Dark Matter)

[arXiv: 1307.6568, K.-Y. Choi, B.K., C.S. Shin]

With the extra vector-like lepton doublets $\{L, L^c\}$,
and the lepton singlets $\{N, N^c\}$,

$$W = y_N L h_u N^c + \mu_L L L^c + \mu_N N N^c + \mu_H N_H N_H{}^c$$

$SU(2)_Z$ embeds Z_2 sym., and so $\{N, N^c\}$ can be DM, which can explain AMS-02.
[arXiv: 1307.6568, K.-Y. Choi, B.K., C.S. Shin]

($|\mu_L| > |\mu_N|$)

Conclusion I

- Vector-like Leptons $\{L, L^c; N, N^c\}$ can efficiently enhance the radiative correction to the Higgs mass, explaining 126 GeV Higgs mass with $m_t \sim 700$ GeV, but without large mixing of the stops, if their relevant Yukawa coupling is of order unity. It is possible because the mass bound of the extra leptons are not severe yet.

- The LP problem can be avoided by introducing a (non-) Abelian extra gauge symmetry, under which only the extra vector-leptons are charged.

Higgs mass in the NMSSM

- promote the MSSM μ term to $\lambda S H_u H_d$ in the superpot., introducing a singlet S.

- The Higgs mass can be raised to

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v_H^2 \sin^2 2\beta + \Delta m_h^2$$

- But λ is restricted by the Landau pole constraint:

$$\lambda < 0.7$$

- For $m_t \ll 1$ TeV, $0.6 < \lambda < 0.7$, $1 < \tan\beta < 3$.

Higgs doublet extension of the NMSSM

[arXiv: 1311.XXXX, B.K.]

With the extra Higgs (vector-like lepton) doublets $\{H_u, H_d\}$,

and the (lepton) singlets $\{N, N^c\}$,

$$W = \lambda S h_u h_d + y_N N^c h_u H_d + y_N' N h_d H_u$$

$$+ \mu_H H_u H_d + \mu_N N N^c \; (+ \mu_S S S^c)$$

$(y_N \gg y_N', |\mu_H| > |\mu_N|)$

Higgs doublet extension of the NMSSM

[arXiv: 1311.XXXX, B.K.]

	$H_u,\ N^c,\ (N^c_H)$	$H_d,\ N,\ (N_H)$	MSSM superfields, S
$U(1)'$ charge	q	$-q$	0

$$W = \lambda S h_u h_d + y_N N^c h_u H_d + y_N' N h_d H_u$$

$$+ \mu_H H_u H_d + \mu_N N N^c \ (+ \mu_S S S^c)$$

$(y_N >> y_N',\ |\mu_H| > |\mu_N|)$

Higgs doublet extension of the NMSSM

[arXiv: 1311.XXXX, B.K.]

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v_h^2 \sin^2 2\beta + \Delta m_h^2|_{\rm top} + \Delta m_h^2|_N \approx (126~{\rm GeV})^2$$

$$W = \lambda S h_u h_d + y_N N^c h_u H_d + y_N' N h_d H_u$$

$$+ \mu_H H_u H_d + \mu_N N N^c \ (+ \mu_S S S^c)$$

$$(y_N >> y_N', |\mu_H| > |\mu_N|)$$

Higgs doublet extension of the NMSSM

$$(\mathcal{M}_{\mathcal{B}})^2 \approx \left[\begin{array}{cc|cc} |\mu_H|^2+|y_N h_u|^2 & \mu_N^* y_N h_u & m_B^2 & y_N A_N h_u \\ \mu_N y_N^* h_u^* & |\mu_N|^2 & 0 & 0 \\ \hline m_B^{2*} & 0 & |\mu_H|^2 & \mu_H^* y_N h_u \\ y_N^* A_N^* h_u^* & 0 & \mu_H y_N^* h_u^* & |\mu_N|^2+|y_N h_u|^2 \end{array}\right] + \left[\begin{array}{c} \text{nonholomoriphic} \\ \text{soft mass matrix} \end{array}\right]$$

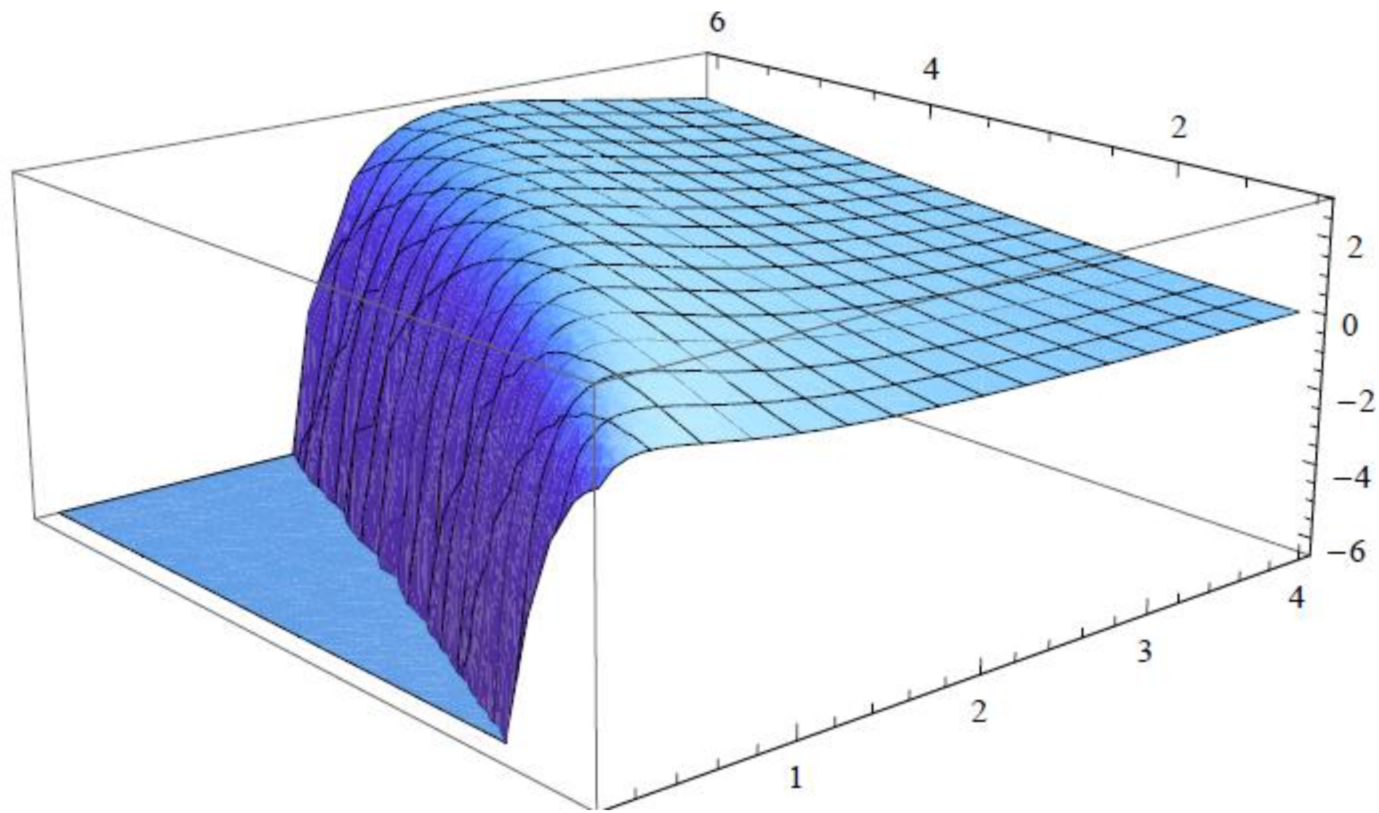
$$\widetilde{m}^2 \ , \ \ |\mu_H|^2 \ \gg \ |m_B|^2 \ \gg \ |\mu_N|^2 \qquad \text{Case I}$$

$$\widetilde{m}^2 \ , \ \ |m_B|^2 \ \gg \ |\mu_H|^2 \ \gg \ |\mu_N|^2 \qquad \text{Case II}$$

Radiative mass & Renormalization

$$\Delta m_h^2|_I \approx \frac{v_h^2 \sin^4\beta}{4\pi^2}|y_N|^4 \left[\log\left(1+z^2\right) - \frac{a_I^4}{2}\log\left(\frac{1+z^2}{z^2}\right) + a_I^2(2+a_I^2)\left\{1 - z^2\log\left(\frac{1+z^2}{z^2}\right)\right\}\right] \equiv \frac{v_h^2 \sin^4\beta}{4\pi^2}|y_N|^4 \times Z_I$$

$$\begin{aligned}\Delta m_2^2|_I \;\approx\; & \frac{|y_N|^2}{8\pi^2}\Big[F_Q(|\mu_H|^2+\widetilde{m}^2) - F_Q(|\mu_H|^2) \\ & + \frac{a_I^2}{2}\left\{F_Q(|\mu_H|^2+\widetilde{m}^2) - F_Q(\widetilde{m}^2)\right\}\Big]_{Q=M_G} \\ \longrightarrow\; & \frac{|y_N|^2}{8\pi^2}\widetilde{m}^2 \log\frac{\widetilde{m}^2}{M_G^2}\left(1+\frac{a_I^2}{2z^2}\right) \qquad \text{for} \quad \widetilde{m}^2 \gg |\mu_H|^2,\end{aligned}$$



6
4
2
2
0
−2
−4
−6
4
3
2
1

RG equations

$$\begin{cases} \frac{d|y_N|^2}{dt} = \frac{|y_N|^2}{8\pi^2}\left[4|y_N|^2 + |\lambda|^2 + 3|y_t|^2 - 3g_2^2 - \frac{3}{5}g_1^2 - \frac{4}{N_Q}g_{Z'}^2\right], \\ \frac{d|\lambda|^2}{dt} = \frac{|\lambda|^2}{8\pi^2}\left[|y_N|^2 + 4|\lambda|^2 + 3|y_t|^2 - 3g_2^2 - \frac{3}{5}g_1^2\right], \\ \frac{d|y_t|^2}{dt} = \frac{|y_t|^2}{8\pi^2}\left[|y_N|^2 + |\lambda|^2 + 6|y_t|^2 - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{13}{15}g_1^2\right]. \end{cases}$$

Conclusion II

- By Higgs doublet extension $\{H_u, H_d ; N, N^c\}$ of the NMSSM and the large A term, the parameter space of the NMSSM can remarkably become larger .
- The LP problem can be avoided by introducing an Abelian extra gauge symmetry, under which only the extra Higgs and singlets are charged.
- For $m_t^2 \approx (700\ \mathrm{GeV})^2$, $\mu_H^2, m_H^2 \ll (1\ \mathrm{TeV})^2$,

  $\tan\beta = 10$: $0 < \lambda < 0.6$, $0.86 > y_N > 0.73$

  $\tan\beta = 6$: $0.3 < \lambda < 0.7$, $0.84 > y_N > 0.61$

  $\tan\beta = 4$: $0.5 < \lambda < 0.6$, $0.81 > y_N > 0.60$