The 126 GeV Higgs boson mass and naturalness in (deflected) mirage mediation

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LHC results

- discovery of the 126 GeV Higgs boson

the Higgs boson mass in the MSSM

$$m_h^2 \sim m_Z^2 \cos^2 2\beta + \frac{3v_u^2 y_t^4}{8\pi^2}\left[\log\frac{M_{st}^2}{m_t^2} + \frac{2A_t^2}{M_{st}^2}\left(1 - \frac{A_t^2}{12M_{st}^2}\right)\right]$$

$\longrightarrow$ heavy stop mass ($\gtrsim$ 1 TeV)

- no SUSY signatures

$\longrightarrow$ heavy SUSY particles ($\gtrsim$ 1 TeV)

126 GeV Higgs boson

no SUSY signature

high-scale SUSY ?

high-scale SUSY vs naturalness

high-scale SUSY is disfavored from naturalness

- EWSB vacuum

$$m_Z^2 \simeq -2\mu(m_Z)^2 + 2|m_{H_u}^2(m_Z)|$$

high-scale SUSY leads the fine-tuning problem

- degree of tuning the μ parameter

$$\Delta_\mu^{-1} \times 100\ \% \quad \text{where} \quad \Delta_\mu = \left| \frac{\partial \ln m_Z}{\partial \ln \mu_0} \right|$$

e.g.) CMSSM ($A_0 = 0$)

126 GeV Higgs boson $\xrightarrow{\text{RGE}}$ 10^{-3} % fine-tuning

126 GeV Higgs boson

no SUSY signature

high-scale SUSY ?

126 GeV Higgs boson

no SUSY signature

unnatural SUSY ?

RG effects to soft parameters

this argument is based on RG−effects

- naturalness $m_Z^2 \simeq -2\mu(m_Z)^2 + 2|m_{H_u}^2(m_Z)|$

$$m_{H_u}^2(m_Z) \simeq +0.17M_2^2 - 0.20M_2M_3 - 3.09M_3^2 - 0.23m_0^2$$

GUT scale

- the Higgs boson mass

$$m_h^2 \sim m_Z^2 \cos^2 2\beta + \frac{3v_u^2 y_t^4}{8\pi^2}\left[\log\frac{M_{st}^2}{m_t^2} + \frac{2A_t^2}{M_{st}^2}\left(1 - \frac{A_t^2}{12M_{st}^2}\right)\right]$$

$$m_{\tilde{t}_R}^2(m_Z) \simeq -0.21M_2^2 + 4.61M_3^2 + 0.19m_0^2$$

$$A_t(m_Z) \simeq -0.21M_2 - 1.90M_3 + 0.18A_0$$

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GUT scale

- the Higgs boson mass

$$m_h^2 \sim m_Z^2\cos^2 2\beta + \frac{3v_u^2y_t^4}{8\pi^2}\left[\log\frac{M_{st}^2}{m_t^2} + \underline{\frac{2A_t^2}{M_{st}^2}\left(1-\frac{A_t^2}{12M_{st}^2}\right)}\right]$$

stop–mixing

$$m_{\tilde{t}_R}^2(m_Z) \simeq -0.21M_2^2 + \underline{4.61M_3^2} + 0.19m_0^2$$

$$A_t(m_Z) \simeq -0.21M_2 - \underline{1.90M_3} + 0.18A_0$$

RG effects are dominated by the gluino mass

RG effects to soft parameters

- $M_2 \sim M_3$ (universal gaugino masses)

$$
\begin{aligned}
m_{H_u}^2(m_Z) &\simeq +0.17M_2^2 - 0.20M_2M_3 - 3.09M_3^2 - 0.23m_0^2 \\
&\sim -3.12M_3^2 + \cdots
\end{aligned}
$$

severe fine-tuning when M_{SUSY} increases

$$
m_{\tilde{t}_R}^2(m_Z) \simeq -0.21M_2^2 + 4.61M_3^2 + 0.19m_0^2 \sim 4.61M_3^2 + \cdots
$$

$$
A_t(m_Z) \simeq -0.21M_2 - 1.90M_3 + 0.18A_0 \sim -1.90M_3 + \cdots
$$

$\longrightarrow \quad \left| \frac{A_t}{M_{stop}} \right| < 1$ small stop mixing

RG effects to soft parameters

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$$m_{H_u}^2(m_Z) \simeq +0.17M_2^2 - 0.20M_2M_3 - 3.09M_3^2 - 0.23m_0^2$$
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severe fine–tuning when M_{SUSY} increases

$$m_{\tilde{t}_R}^2(m_Z) \simeq -0.21M_2^2 + 4.61M_3^2 + 0.19m_0^2 \sim 4.61M_3^2 + \cdots$$
$$A_t(m_Z) \simeq -0.21M_2 - 1.90M_3 + 0.18A_0 \sim -1.90M_3 + \cdots$$

→ $\left|\frac{A_t}{M_{stop}}\right| < 1$ small stop mixing

→ heavy stop mass

RG effects to soft parameters

- $M_2 \sim 5 \times M_3$

$$m_{H_u}^2(m_Z) \simeq +0.17M_2^2 - 0.20M_2M_3 - 3.09M_3^2 - 0.23m_0^2$$
$$\sim 0 \times M_3^2 + \cdots$$

$\longrightarrow$ the fine−tuning is relaxed even when M_{SUSY} increases

$$m_{\tilde{t}_R}^2(m_Z) \simeq -0.21M_2^2 + 4.61M_3^2 + 0.19m_0^2 \sim -0.2M_3^2 + \cdots$$
$$A_t(m_Z) \simeq -0.21M_2 - 1.90M_3 + 0.18A_0 \sim -3.0M_3 + \cdots$$

$\longrightarrow$ $\left|\frac{A_t}{M_{stop}}\right| \sim \sqrt{3}$ -$\sqrt{6}$ the Higgs boson mass is increased

more detailed analysis can be seen in ref. [1]

[1] H. Abe, J. K. and H. Otsuka, PTEP **2013**, 013B02 (2013).

126 GeV Higgs boson

no SUSY signature

unnatural SUSY ?

non-universal gaugino masses → **No !!**

How explain the non-universal gaugino masses ?

SUSY breaking mediation

soft parameters are determined by mediation mechanisms

➢ SUSY breaking mediations

- gravity mediation ··· higher dimensional interactions
- anomaly mediation ··· super–Weyl anomaly
- gauge mediation ··· gauge interactions

➢ assumptions

- single modulus T is a mediator for the gravity mediation
- minimal gauge mediation with N_{mess} pairs of messengers

$$W_{\mathrm{mess}} = W_1(X) + \lambda X \Psi \overline{\Psi}$$

X : SM gauge singlet

Ψ : $\mathbf{5}$ of $SU(5)$

gaugino mass ratios

- gravity mediation

$$\int d^2\theta \; T \times \mathcal{W}^a \mathcal{W}^a \quad \longrightarrow \quad M_a(M_{\rm GUT}) = \frac{F^T}{T+\overline{T}} \equiv m_0$$

gauge coupling unification

universal gaugino masses

gaugino mass ratios

- gravity mediation $\longrightarrow$ $M_1 : M_2 : M_3 = 1 : 1 : 1$

gaugino mass ratios

- gravity mediation $\longrightarrow$ $M_1 : M_2 : M_3 = 1 : 1 : 1$

- anomaly mediation

$$M_a(M_{\rm GUT}) = \frac{g_0^2}{16\pi^2} b_a \frac{F^C}{C} \equiv \; g_0^2 b_a \times \alpha_m m_0$$

where $(b_1, b_2, b_3) = (\frac{33}{5}, 1, -3)$ for $U(1)_Y$,$SU(2)_L$,$SU(3)_C$

$$\longrightarrow \; M_1 : M_2 : M_3 = \frac{33}{5} : 1 : -3$$

gaugino mass ratios

- gravity mediation $\longrightarrow$ $M_1 : M_2 : M_3 = 1 : 1 : 1$
- anomaly mediation $\longrightarrow$ $M_1 : M_2 : M_3 = \frac{33}{5} : 1 : -3$

gaugino mass ratios

- gravity mediation $\longrightarrow$ $M_1 : M_2 : M_3 = 1 : 1 : 1$
- anomaly mediation $\longrightarrow$ $M_1 : M_2 : M_3 = \frac{33}{5} : 1 : -3$
- gauge mediation

$$M_a(M_{\rm mess}) = N_{\rm mess} \frac{g_a^2(M_{\rm mess})}{16\pi^2} \frac{F^X}{X} \equiv N_{\rm mess}\ g_a^2(M_{\rm mess})\ \alpha_g \alpha_m m_0$$

where $M_{\rm mess} = \lambda X$

$\longrightarrow$ $M_3 > M_2$ at any scale

gaugino mass ratios

- gravity mediation $\longrightarrow$ $M_1 : M_2 : M_3 = 1 : 1 : 1$
- anomaly mediation $\longrightarrow$ $M_1 : M_2 : M_3 = \frac{33}{5} : 1 : -3$
- gauge mediation $\longrightarrow$ $M_3 > M_2$ at any scale

gaugino mass ratios

- gravity mediation $\longrightarrow$ $M_1 : M_2 : M_3 = 1 : 1 : 1$
- anomaly mediation $\longrightarrow$ $M_1 : M_2 : M_3 = \frac{33}{5} : 1 : -3$
- gauge mediation $\longrightarrow$ $M_3 > M_2$ at any scale

large M_2/M_3 can't be obtained

(deflected) mirage mediation

we should consider mixed mediations

- parameterization

m_0 ･･･ gravity mediated contributions

α_m ･･･ anomaly / gravity

α_g ･･･ gauge / anomaly

- mixed mediations

$\alpha_m \simeq \mathcal{O}(1), \alpha_g \simeq 0$ → mirage mediation [2]

$\alpha_m, \alpha_g \simeq \mathcal{O}(1)$ → deflected mirage mediation [3]

[2] K. Choi, K. S. Jeong, T. Kobayashi and K. -i. Okumura, Phys. Rev. D **75**, 095012 (2007).
R. Kitano and Y. Nomura, Phys. Lett. B **631** (2005) 58.
[3] L. L. Everett, I. -W. Kim, P. Ouyang and K. M. Zurek, Phys. Rev. Lett. **101**, 101803 (2008).

TeV scale (deflected) mirage mediation

➢ gaugino masses at the GUT scale

$$M_a(M_{\rm GUT}) = \frac{F^T}{T+\overline{T}} + \frac{g_0^2}{16\pi^2} b_a \frac{F^C}{C}$$
$$\simeq m_0 \left(1 + \frac{1}{4} g_0^2 b_a \alpha_m\right)$$

where $(b_1, b_2, b_3) = (\frac{33}{5}, 1, -3)$

if $\alpha_m \sim 2$ → $M_2/M_3 \sim 5$ at the GUT scale

TeV scale mirage mediation [2]

➢ threshold corrections

$$\Delta M_a(M_{\rm mess}) = -N_{\rm mess} \frac{g_a^2(M_{\rm mess})}{16\pi^2} \left(\frac{F^C}{C} + \frac{F^X}{X}\right)$$

→ various patterns of gaugino masses

[2] K. Choi, K. S. Jeong, T. Kobayashi and K. -i. Okumura, Phys. Rev. D **75**, 095012 (2007).
R. Kitano and Y. Nomura, Phys. Lett. B **631** (2005) 58.

moduli stabilization

m_0, α_m, α_g are determined by moduli stabilization scenarios

- the KKLT–type moduli stabilization
  - the original KKLT model predicts $\alpha_m = 1$ [3]
  - similar setups can lead various $O(1)$ values [4]
  - value of α_m could depend on only discrete parameters

winding numbers, # of fluxes, e.t.c.

→ we can take $\alpha_m \sim 2$

- stabilization of X [5]

e.g.) $W_1(X) = \frac{X^n}{\Lambda^{n-3}}, \ (n < 0 \text{ or } n > 3)$ → $\alpha_g = -\frac{2}{n-1}$

→ gauge mediation can also be comparable

[3] S. Kachru, R. Kallosh, A. D. Linde and S. P. Trivedi, Phys. Rev. D **68**, 046005 (2003).
[4] H. Abe, T. Higaki and T. Kobayashi, Phys. Rev. D **73**, 046005 (2006), Nucl. Phys. B **742**, 187 (2006).
[5] L. L. Everett, I. -W. Kim, P. Ouyang and K. M. Zurek, JHEP **0808**, 102 (2008). A. Pomarol and R. Rattazzi, JHEP **9905**, 013 (1999).

input parameters

eight input parameters

$$(m_0, \alpha_m, \alpha_g, n_Q, n_H, N_{\rm mess}, M_{\rm mess}, \tan\beta)$$

input parameters

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$$(m_0, \alpha_m, \alpha_g, n_Q, n_H, N_{\rm mess}, M_{\rm mess}, \tan\beta)$$

size of mediation

input parameters

eight input parameters

$$(\underline{m_0, \alpha_m, \alpha_g}, n_Q, n_H, N_{\rm mess}, M_{\rm mess}, \tan\beta)$$

size of mediation

- modular weights n_i

$$a^{ijk}|_{\rm modulus} = m_0 \sum_{l=i,j,k} (1-n_l), \quad {m^2}_i^{\ j}|_{\rm modulus} = m_0^2(1-n_i)\delta_i^{\ j}$$

we assume universal values for quarks/leptons (n_Q) and Higgses (n_H), respectively

input parameters

eight input parameters

$$(\underline{m_0, \alpha_m, \alpha_g}, \underline{n_Q, n_H}, N_{\rm mess}, M_{\rm mess}, \tan\beta)$$

size of mediation

modular weight

input parameters

eight input parameters

$$(\underbrace{m_0, \alpha_m, \alpha_g}_{\text{size of mediation}}, \underbrace{n_Q, n_H}_{\text{modular weight}}, \underbrace{N_{\text{mess}}, M_{\text{mess}}}_{\text{messenger sector}}, \tan\beta)$$

size of mediation

messenger sector

modular weight

input parameters

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$$(\underbrace{m_0, \alpha_m, \alpha_g}_{\text{size of mediation}}, \underbrace{n_Q, n_H}_{\text{modular weight}}, \underbrace{N_{\rm mess}, M_{\rm mess}}_{\text{messenger sector}}, \underbrace{\tan\beta}_{v_u/v_d})$$

size of mediation

messenger sector

modular weight

v_u/v_d

input parameters

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$$(m_0, \alpha_m, \alpha_g, n_Q, n_H, N_{\rm mess}, M_{\rm mess}, \tan\beta)$$

UV model setups $\longrightarrow$ $n_Q, n_H, N_{\rm mess}$

moduli stabilization $\longrightarrow$ $m_0, \alpha_m, \alpha_g, M_{\rm mess}$

μ, b–term are chosen to realize m_Z and $\tan\beta = 15$

input parameters

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$$(m_0, \alpha_m, \alpha_g, n_Q, n_H, N_{\rm mess}, M_{\rm mess}, \tan\beta)$$

UV model setups $\longrightarrow$ $n_Q, n_H, N_{\rm mess}$

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μ, b–term are chosen to realize m_Z and $\tan\beta = 15$

- EWSB vacuum

$$m_Z^2 = -2\mu(M_{\rm EW})^2 + \underbrace{\left[\frac{|m_{H_d}^2(M_{\rm EW}) - m_{H_u}^2(M_{\rm EW})|}{\sqrt{1-\sin 2\beta}} - m_{H_u}^2(M_{\rm EW}) - m_{h_d}^2(M_{\rm EW})\right]}_{\text{moduli stabilization}}$$

$\longrightarrow$ we focus on the tuning of the μ parameter

How explain the non-universal gaugino masses ?

→ TeV scale (deflected) mirage mediation

modular weights

- mirage unification scenario $(n_Q, n_H) = (1/2, 1)$

If $\sum_{l=i,j,k} (1 - n_l) = 1$ for sizable Yukawa couplings y^{ijk}

→ all soft terms are unified at the "mirage unification scale"

→ small $m_{H_u}^2(M_{\mathrm{EW}})$ can be obtained easily

- large A−term scenario $(n_Q, n_H) = (0, 0)$

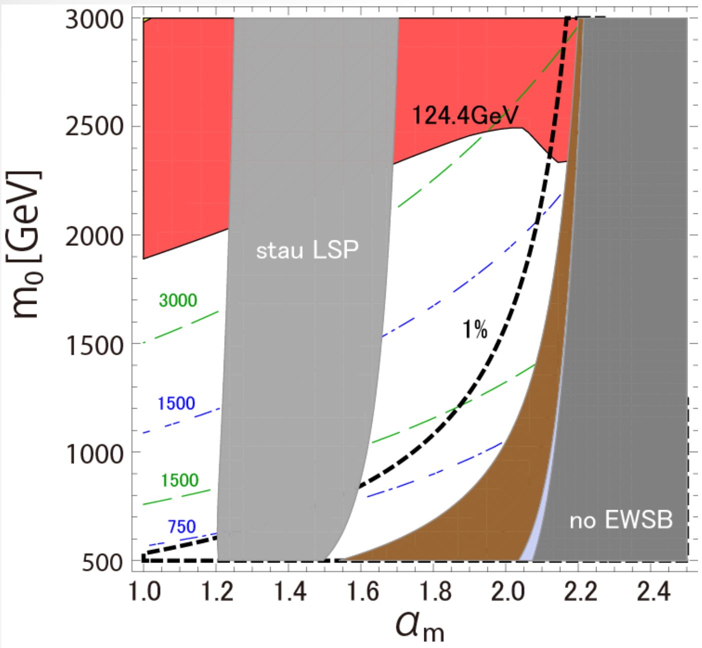
$$a^{ijk}_{\mathrm{moduli}} = m_0 \sum_{l=i,j,k} (1 - n_l), \ \ {m^2}_{i\,\mathrm{moduli}}^{\ j} = m_0^2 (1 - n_i) \delta_i^j$$

→ smaller modular weights will lead the larger stop−mixing

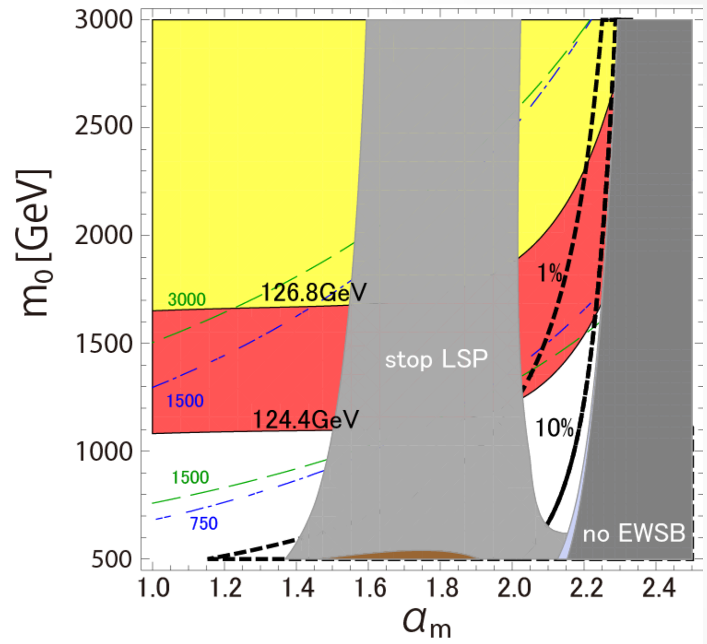
→ increase the Higgs boson mass

mirage mediation $N_{\rm mess} = 0$

mirage unification



large A-term



m_0: SUSY breaking scale

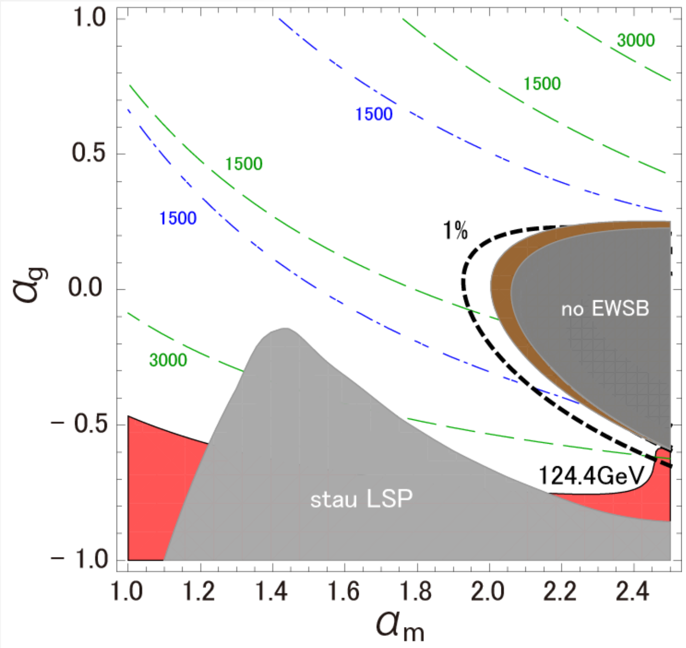
α_m: anomaly/gravity ratio

- large A−term increases the Higgs boson mass
- the tuning is relaxed at $\alpha_m \sim 2$ in **both** cases

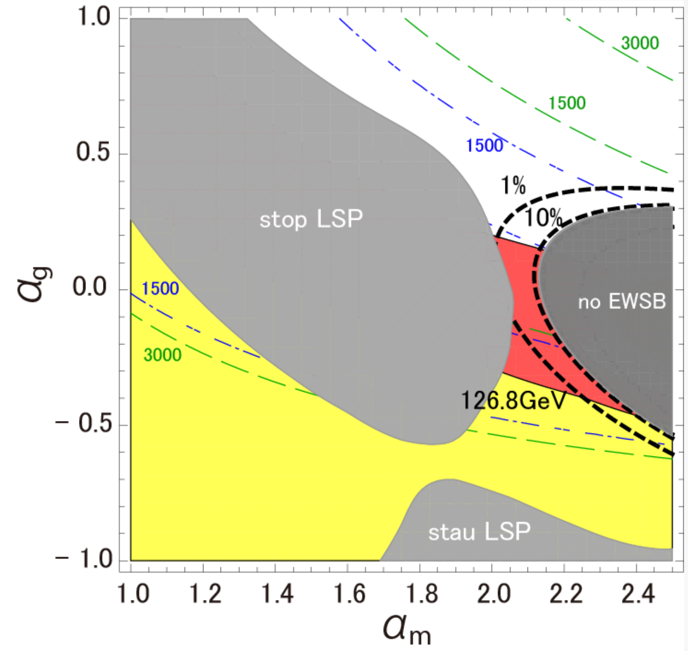
deflected mirage mediation

$m_0 = 2.0[\mathrm{TeV}], N_{\mathrm{mess}} = 3$

mirage unification



large A-term



α_m: anomaly/gravity ratio

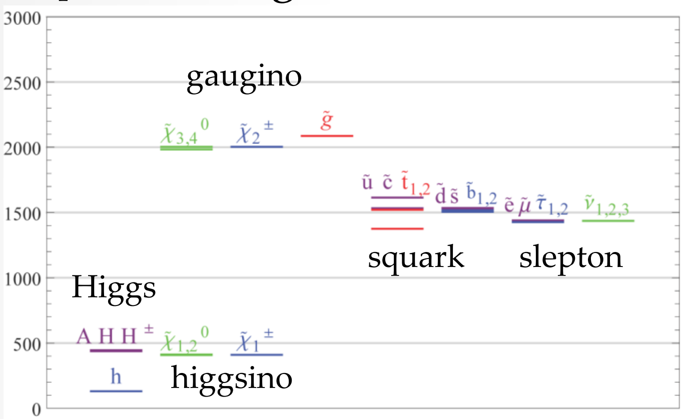
α_g: gauge/anomaly ratio

- large A−term increases the Higgs boson mass
- the tuning is relaxed at $\alpha_m \sim 2,\ \alpha_g \lesssim 0$ in both cases

Typical Natural Mass Spectra

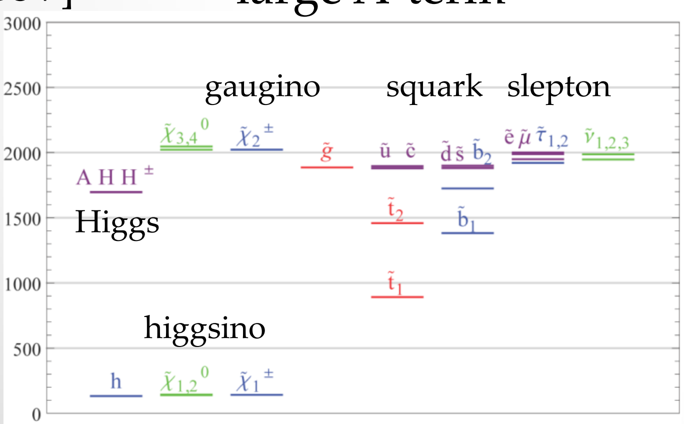
naturalness restricts the parameter space of the DMM

[GeV] mirage unification



$m_h = 123.5\text{GeV}$

[GeV] large A-term



$m_h = 125.4\text{GeV}$

$N_{\text{mess}} = 0, m_0 = 2.0\text{TeV}$

- gaugino masses are roughly degenerate
- the LSP is higgsino
- spectra are similar in the DMM case

conclusions

- 126 GeV Higgs boson and the relaxed tuning
  - $M_2\ /M_3 \sim 5$ at the GUT scale
  - $\alpha_m \sim 2,\ -1 \lesssim \alpha_g \lesssim 0$ in (deflected) mirage mediation
  - small modular weights are favored from the 126 GeV Higgs boson

conclusions

➢ 126 GeV Higgs boson and the relaxed tuning

- $M_2\ /M_3{\sim}5$ at the GUT scale
- $\alpha_m{\sim}2,\ -1 \lesssim \alpha_g \lesssim 0$ in (deflected) mirage mediation
- small modular weights are favored from the 126 GeV Higgs boson

natural SUSY can go !!

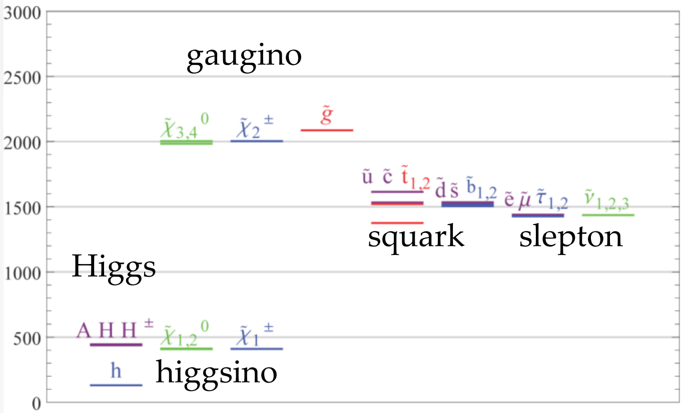
Thank you for your attention

back up

Typical Natural Mass Spectrum

$$N_{\rm mess} = 0, m_0 = 2.0{\rm TeV}$$

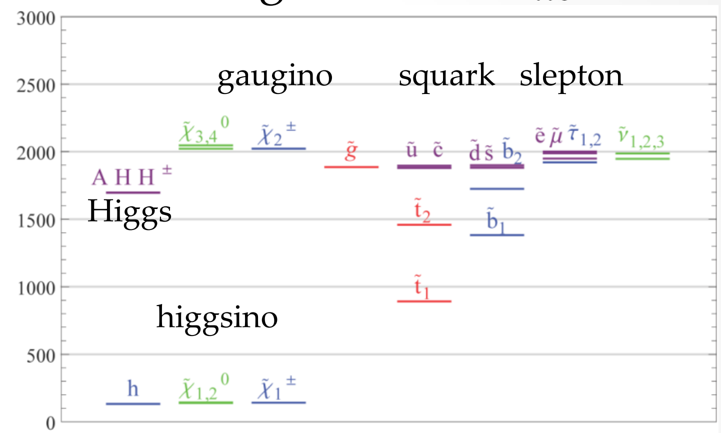
[GeV] mirage unification $\alpha_m = 2.14$



$$m_h = 123.5 \text{ GeV}$$

$$\Delta_\mu^{-1} \times 100 = 2.31\%$$

[GeV] large A-term $\alpha_m = 2.26$



$$m_h = 125.4 \text{ GeV}$$

$$\Delta_\mu^{-1} \times 100 = 55.6\%$$

- stop can be lighter than 1 TeV in the large A–term case
- heavy Higgs bosons tend to be light in the mirage unification case due to the mirage unification → enhance $BR(b \to s\,\gamma)$

implications of the mass spectra

➢ typical mass spectra

- light colored particles, especially light stop
- uncolored sparticle masses are almost same as colored sparticle masses
- higgsino LSP

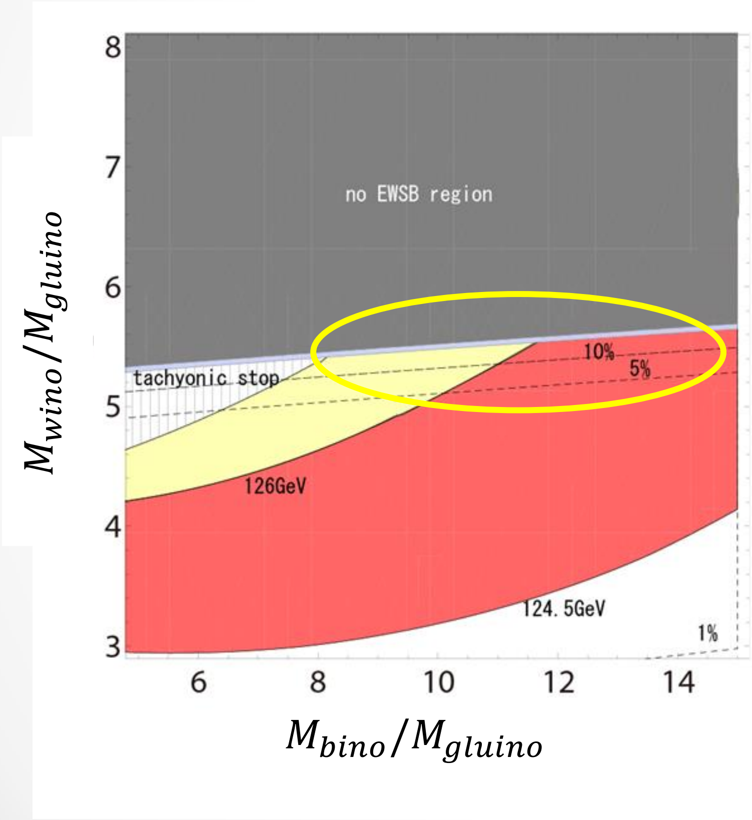
→

- can be tested at the LHC
- will be excluded when some signatures for light uncolored particles are detected
- it's challenging to explain the observations for dark matters

axino LSP, non-minimal cosmological scenario, ･･･

non-universal gaugino masses

[1] H. Abe, J. K. and H. Otsuka, PTEP **2013**, 013B02 (2013).



$$\tan\beta = 15$$

$$M_3 = 385\text{GeV}$$

$$(m_0)_3 = 200\text{GeV}$$

$$(m_0)_{1,2} = 1.5\text{TeV}$$

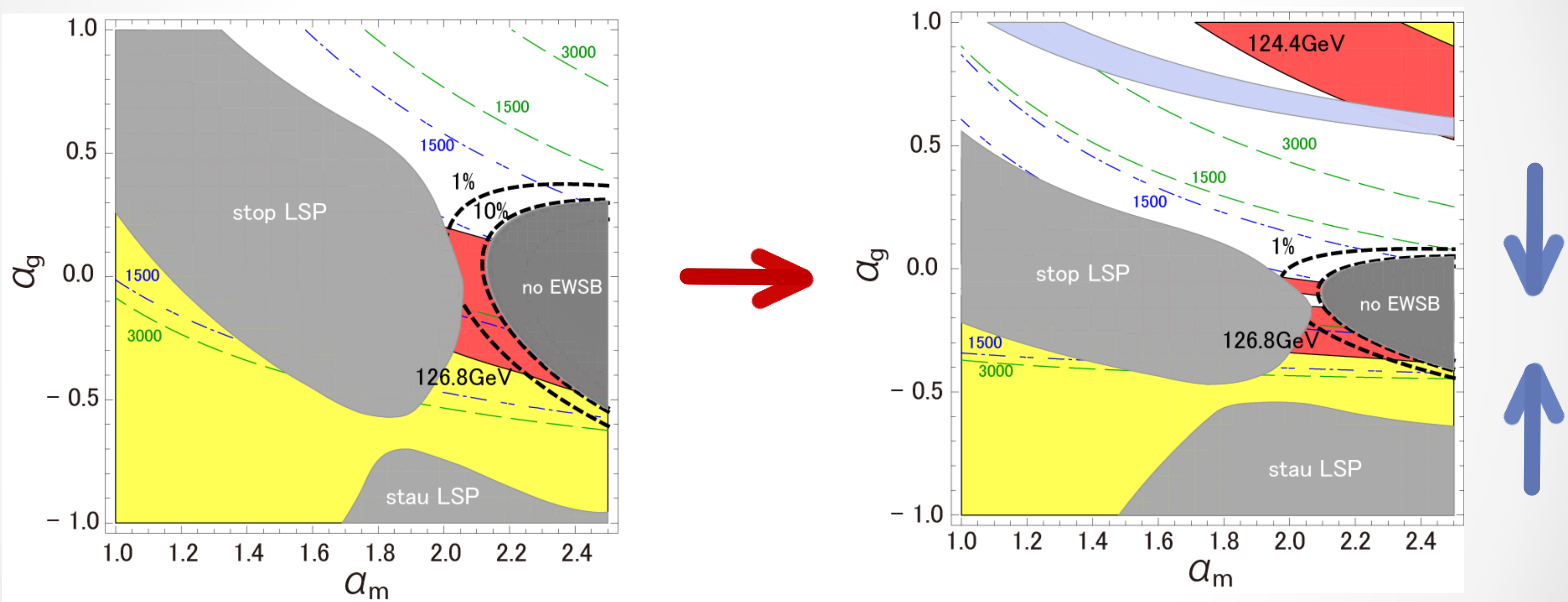
$$A_0 = -400\text{GeV}$$

- relaxed fine-tuning and large stop-mixing

messenger sector dependence

$$m_0 = 2.0\text{TeV}, (n_Q, n_H) = (0, 0)$$

$$N_{\text{mess}} = 3 \rightarrow N_{\text{mess}} = 6$$

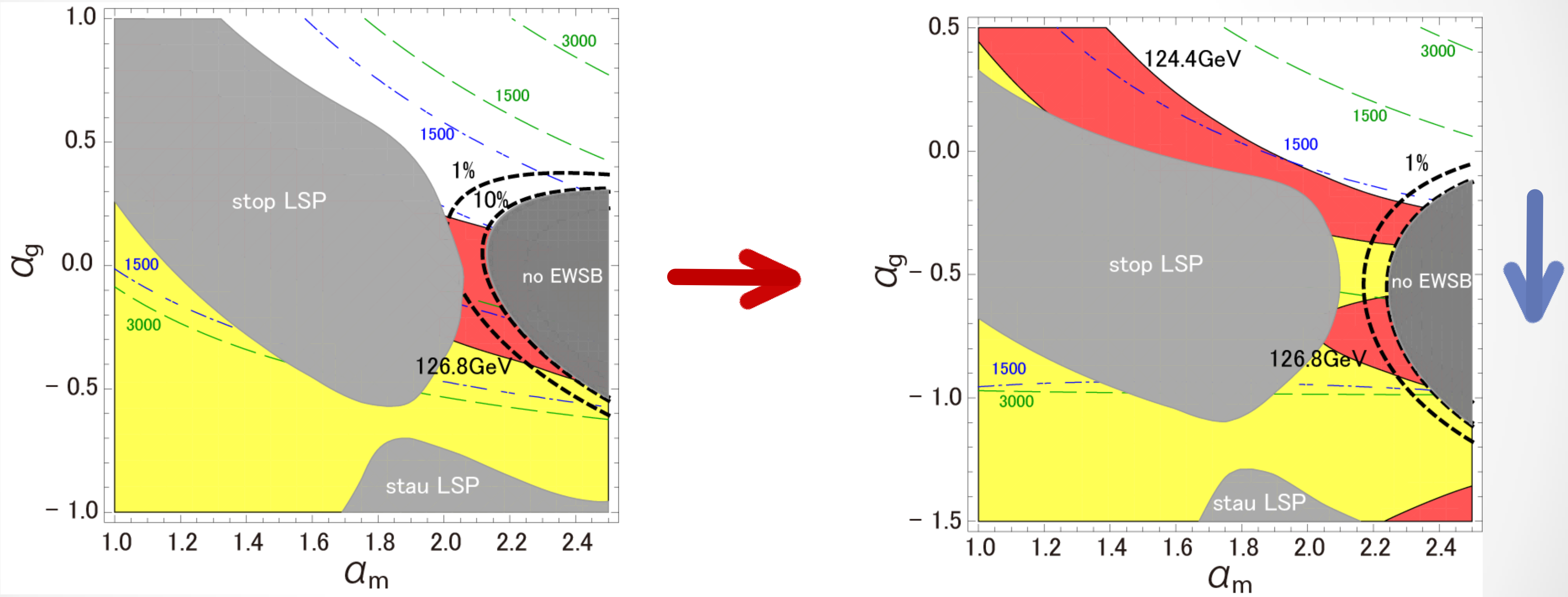


- aimed region is **compressed** along α_g direction

messenger sector dependence

$m_0 = 2.0\text{TeV}, (n_Q, n_H) = (0,0)$

$$M_{\text{mess}} = 10^{12}\text{GeV} \rightarrow M_{\text{mess}} = 10^{6}\text{GeV}$$



- the aimed region is **shifted** along the α_g direction

model setup

- effective SUGRA action with single modulus field

$$\mathcal{L} = -\int d^4\theta\ 3|C|^2 e^{-K/3} + \left[\int d^2\theta f_a\ \mathcal{W}^a\mathcal{W}^a + \int d^2\theta C^3 W + \text{h.c.}\right]$$

where

$$f_a = T$$

$$K = -3\ln(T+\overline{T}) + \frac{X\overline{X}}{(T+\overline{T})^{n_X}} + \frac{\Phi_i\overline{\Phi}_i}{(T+\overline{T})^{n_i}}$$

$$W = \underline{W_0(T) + W_1(X)} + \underline{\lambda X\Psi\overline{\Psi}} + W_{\text{MSSM}}$$

stabilize T, X — messenger

T : moduli

C : compensator

X : SM gauge singlet

Φ_i : MSSM matter

Ψ : $\mathbf{5}$ of $SU(5)$

n_i : modular weights

soft parameters in the DMM

- soft parameters at the GUT scale

$$M_a(M_{\rm GUT}) = m_0\left[1+\frac{g_0^2}{16\pi^2}b'_a\alpha_m\ln\frac{M_p}{m_{3/2}}\right]$$

$$a^{ijk}(M_{\rm GUT}) = m_0\left[(3-n_i-n_j-n_k)-\frac{1}{16\pi^2}\left[y^{ljk}\gamma_l{}^i+\text{cyclic}\right]\alpha_m\ln\frac{M_p}{m_{3/2}}\right]$$

$$m^2{}_i{}^j(M_{\rm GUT}) = m_0{}^2\left[(1-n_i)\delta_i{}^j-\frac{2\theta_i{}^j}{16\pi^2}\alpha_m\ln\frac{M_p}{m_{3/2}}-\frac{\dot{\gamma}_i^j}{(16\pi^2)^2}\left(\alpha_m\ln\frac{M_p}{m_{3/2}}\right)^2\right]$$

- threshold corrections at the messenger scale

$$\Delta M_a(M_{\rm mess}) = -m_0 N\frac{g_a^2(M_{\rm mess})}{16\pi^2}\alpha_m(1+\alpha_g)\ln\frac{M_p}{m_{3/2}}$$

$$\Delta m^2{}_i{}^j(M_{\rm mess}) = m_0{}^2\sum_a 2c_a(\Phi_i)N\frac{g_a^4(M_{\rm mess})}{(16\pi^2)^2}\left[\alpha_m(1+\alpha_g)\ln\frac{M_p}{m_{3/2}}\right]^2\delta_i{}^j$$

- parameterization

$$\frac{F^T}{T+\overline{T}}\equiv m_0,\quad \frac{F^C}{C}=m_0\left(\alpha_m\ln\frac{M_p}{m_{3/2}}\right),\quad \frac{F^X}{X}=\alpha_g\frac{F^C}{C}$$

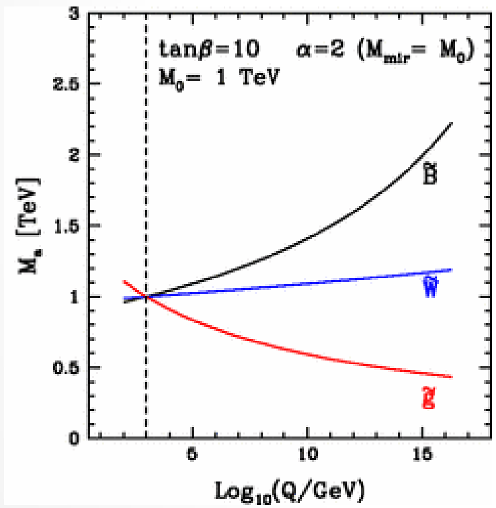
mirage unification

If $\sum_{l=i,j,k}(1-n_l)=1$ for sizable Yukawa couplings y^{ijk}

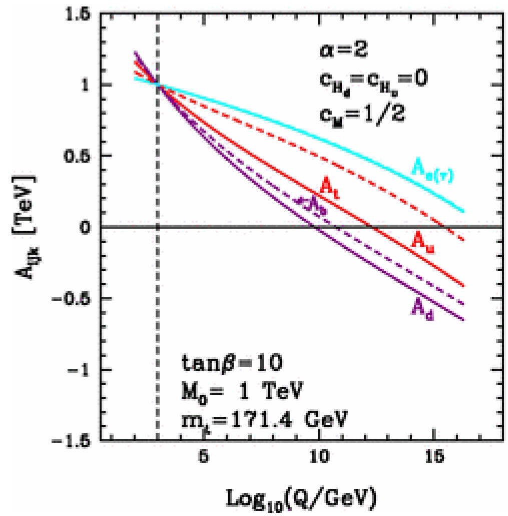
→ all soft terms are unified at the "mirage unification scale"

K. Choi, K. S. Jeong, T. Kobayashi and K. -i. Okumura, Phys. Rev. D **75**, 095012 (2007).

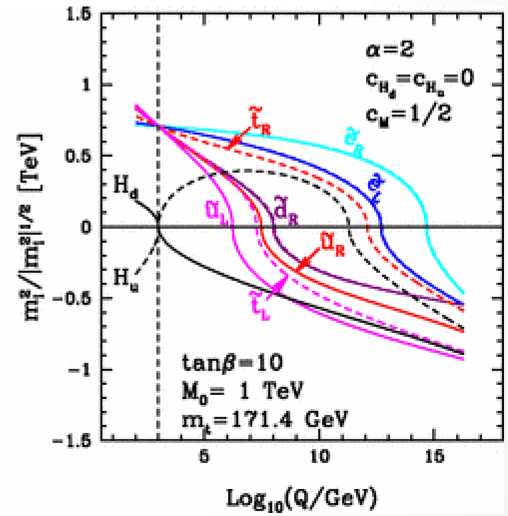
gaugino masses



A-terms



soft masses



always unify

depending on modular weights