2013/2/15@Toyama

Higgs boson mass in low energy SUSY models with vector-like matters

Norimi Yokozaki (Kavli IPMU)

Endo, Hamaguchi, Iwamoto, N.Y.; 2011, 2012

Nakayama N.Y.; 2011

Sato, Tobioka, N.Y.; 2011

Endo, Hamaguchi, Ishikawa, Iwamoto, N.Y.; 2012

Good things of low-energy SUSY

- Radiative Electroweak symmetry breaking
- Better fine-tuning (focus point-**like** behavior can relax it more)
- Muon g-2 deviation (>3σ) can be explained (Sho's talk)

Good things of low-

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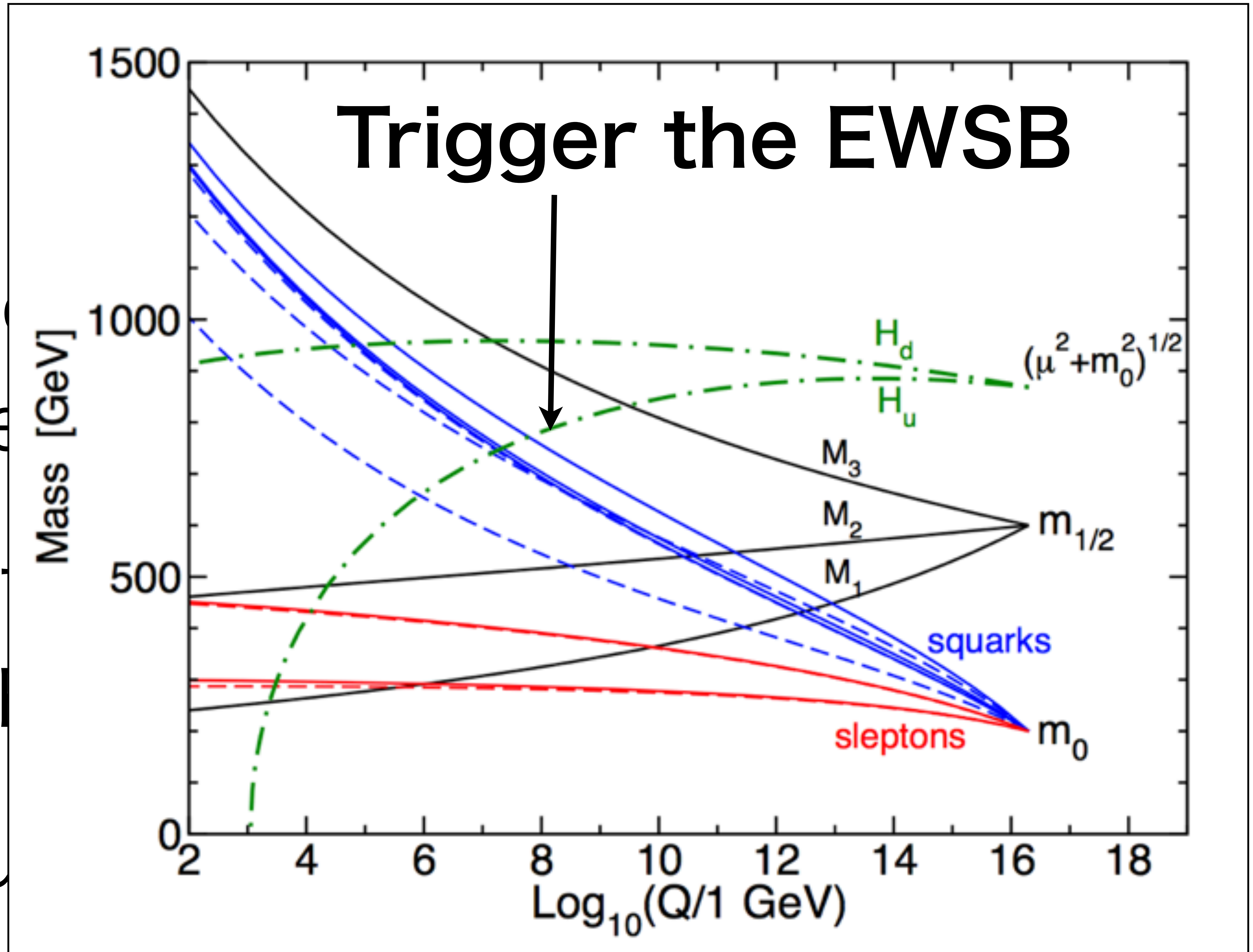
- Mu
  explained (Sho's talk)



[Figures from SUSY primer]

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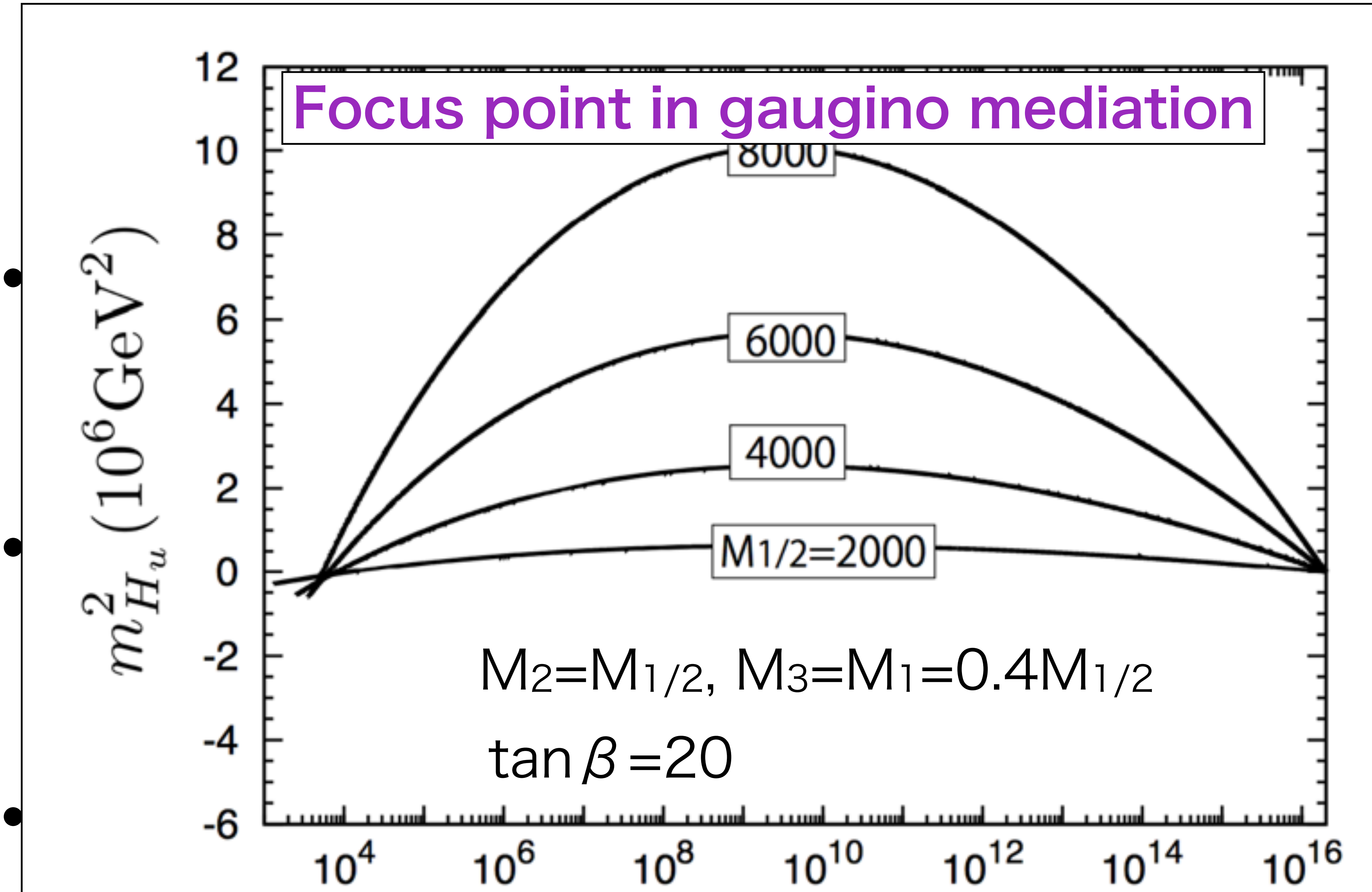

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[Yanagida, N.Y, 2013]

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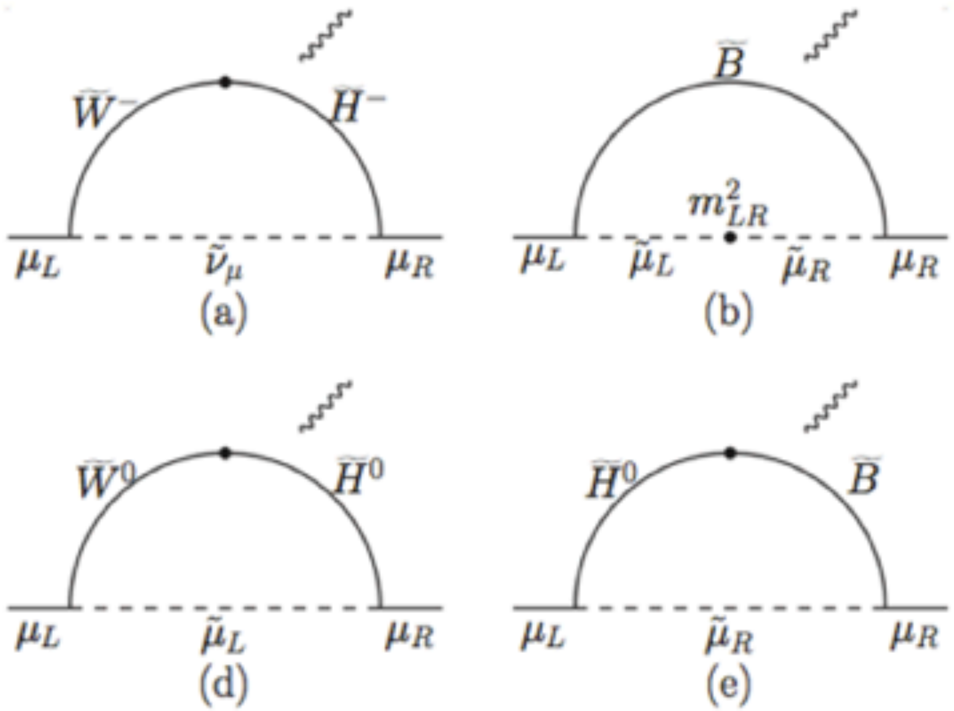
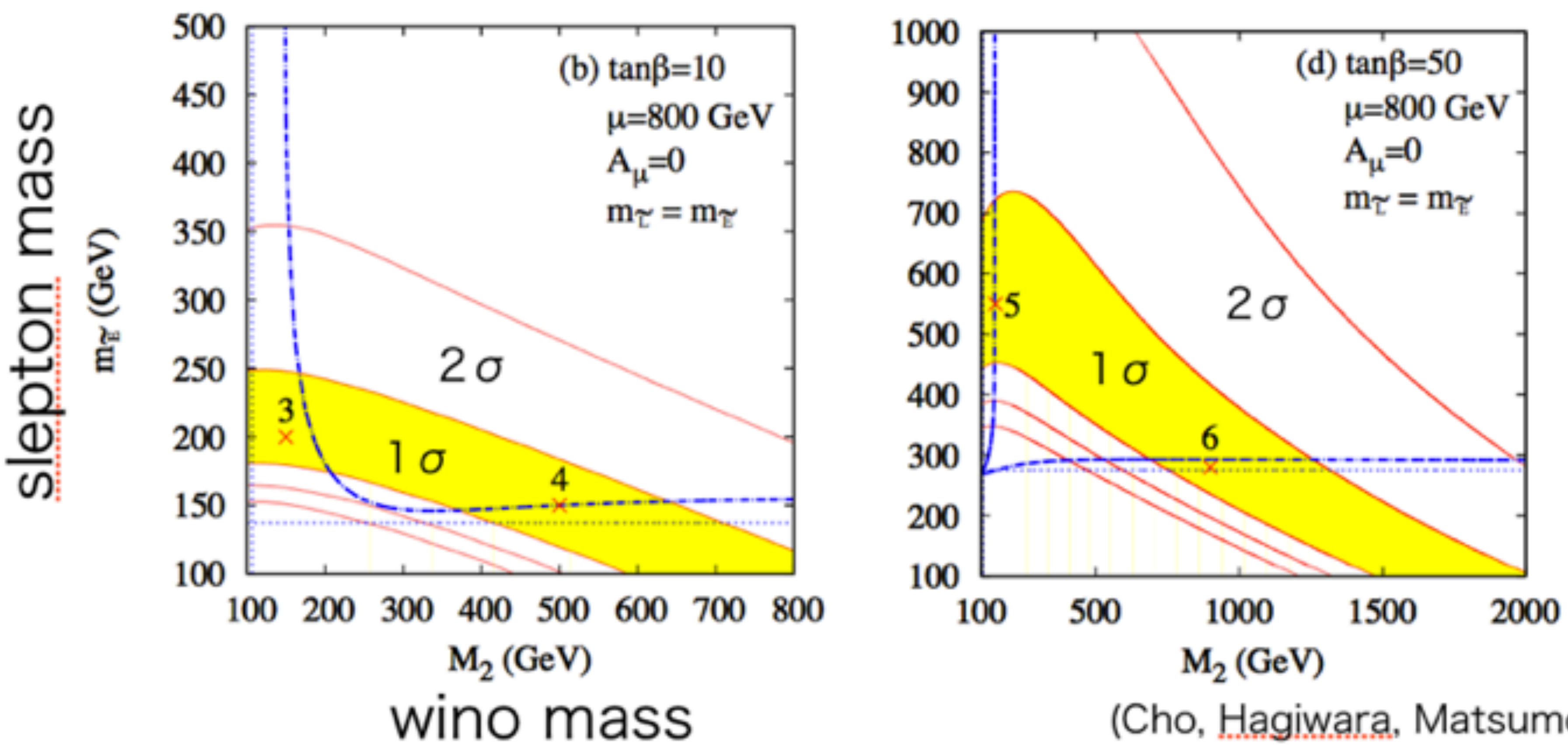


$$\Delta a_\mu(\chi^\pm) \simeq \frac{\alpha_2 m_\mu^2}{8\pi m_{\rm soft}^2}\mathrm{sgn}(\mu M_2)\,\underline{\tan\beta},$$

$$\Delta a_\mu(\chi^0) \simeq \frac{\alpha_Y m_\mu^2}{24\pi m_{\rm soft}^2}\mathrm{sgn}(\mu M_1)\,\underline{\tan\beta} + \cdots,$$



(Cho, Hagiwara, Matsumoto, Nomura, 2011)

sleptons and neutralino/chargino should be light enough

hγγ is possibly enhanced

If the SUSY particles are light, **gauge mediation models** are attractive

Gravity mediation with O(1) TeV gravitino

Flavor changing neutral current
The cosmological Polonyi problem
(spoiling BBN, dilution BAU)

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Gravity mediation with O(1) TeV gravitino

Flavor changing neutral current The cosmological Polonyi problem (spoiling BBN, dilution BAU)

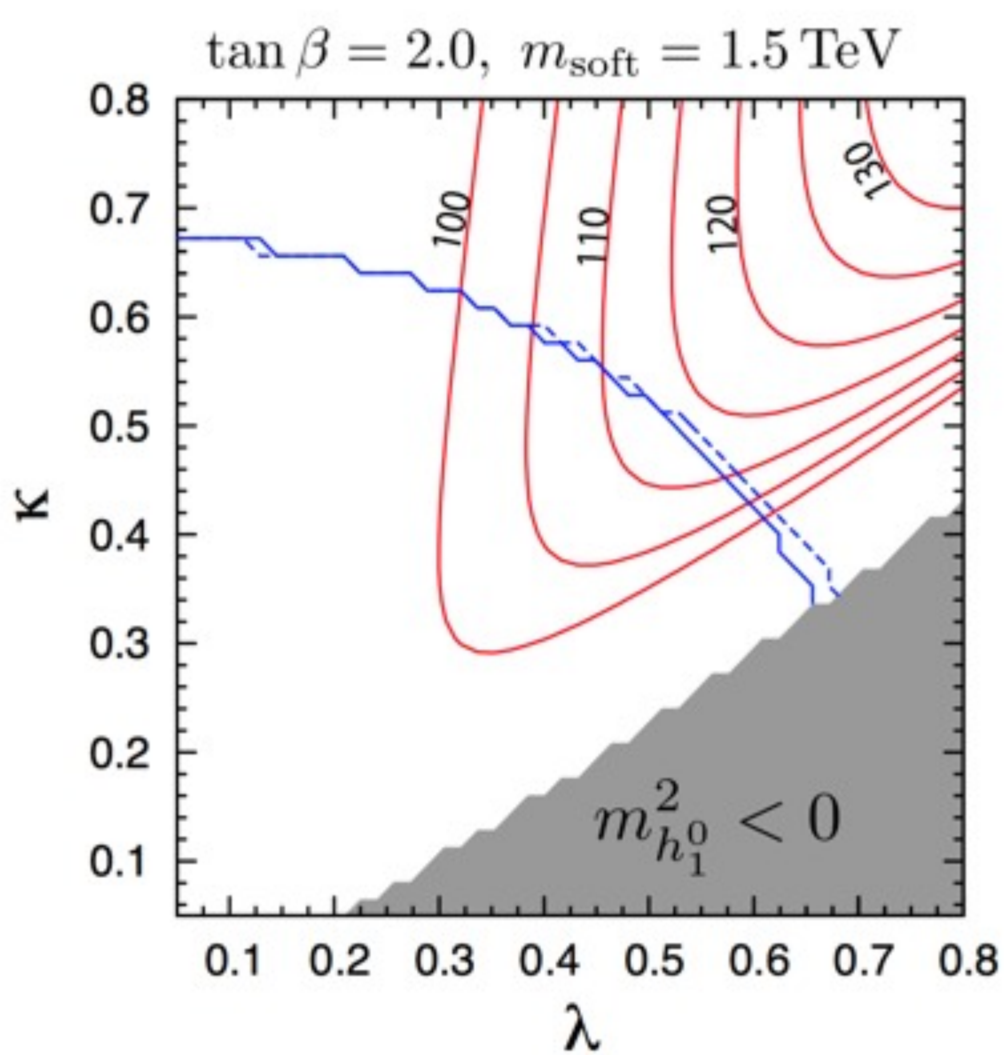
However, the Higgs mass of ~125 GeV is challenging

Gauge Mediation + **Extra Contribution** to Higgs mass is attractive possibility in Low-energy SUSY

Most famous example is NMSSM

NMSSM -> not good in GMSB

(Difficult to realize EWSB, Landau pole, Muon g-2 deviation can not be explained)



$$\lambda S H_u H_d + \kappa S^3/3$$

with A_λ~0

[Figure from Yanagida, Yonekura, N.Y., 2012]

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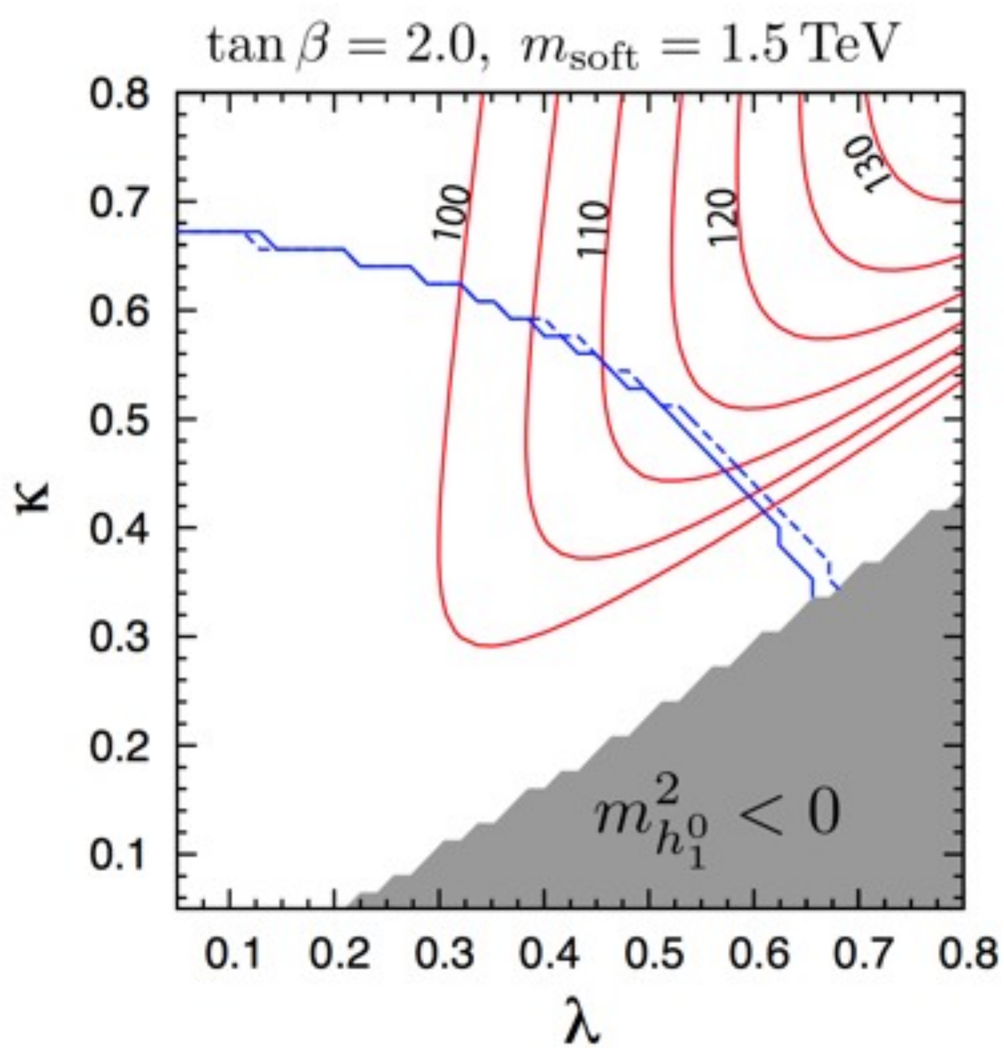


$$\lambda S H_u H_d + \kappa S^3/3$$
$$+S q' \bar{q}'$$

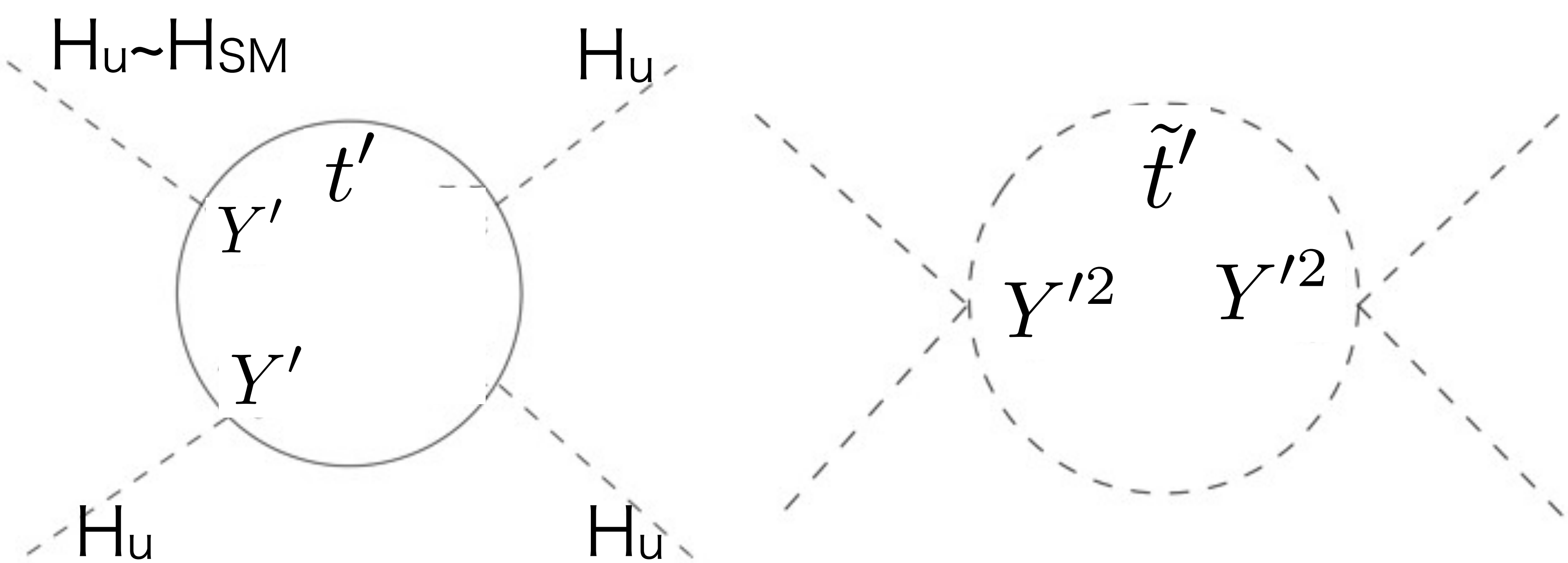
[Gouvea, Friedland, Murayama, 97']

with A_λ~0

[Figure from Yanagida, Yonekura, N.Y., 2012]

Here we consider another possibility

Add top/stop like particles to raise the Higgs mass with vector-like masses



[Okada, Moroi, 92']

10 + 10* is suitable for raising the Higgs mass

(5+1)+(5*+1*)

L' Hu N' ⟷ Hu Hd S

blow-up of Yukawa coupling

scalar masses are light

complete generation

(10+5)+(10*+5*)   Q*' Hu D'

blow-up of gauge coupling (since we need a messenger pair)

Model

$$
\begin{aligned}
10 &= (Q', \bar{U}', \bar{E}') \\
\bar{10} &= (\bar{Q}', U', E')
\end{aligned}
$$

$$
\begin{aligned}
W = W_{\mathrm{MSSM}} \\
&+Y' Q' H_u \bar{U}' + Y'' \bar{Q}' H_d U' \\
&+ M_{Q'} Q' \bar{Q}' + M_{U'} U' \bar{U}' + M_{E'} E' \bar{E}'
\end{aligned}
$$

In addition to the messenger sector

$$
\begin{aligned}
W_{\mathrm{mess}} &= (M_D + F_D \theta^2) \Psi_D \Psi_{\bar{D}} \\
&\quad +(M_L + F_L \theta^2) \Psi_L \Psi_{\bar{L}}
\end{aligned}
$$

If there is no GUT breaking effect

$$
\frac{F_D}{M_D} \simeq \frac{F_L}{M_L} \equiv \Lambda
$$

$$
\begin{aligned}
W &= W_{\mathrm{MSSM}} \\
&\quad + Y' Q' H_u \bar{U}' + Y'' \bar{Q}' H_d U' \\
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10 &= (Q', \bar{U}', \bar{E}') \\
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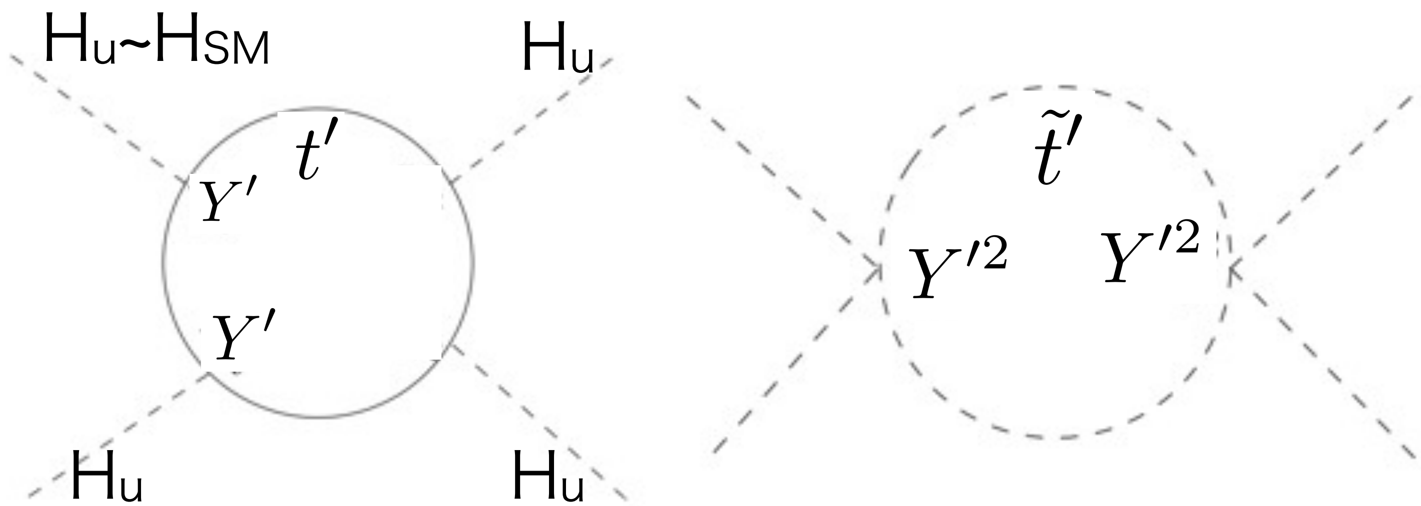
$$

$$
\Delta m_h^2 \sim \frac{3 Y'^4 v^4}{4\pi^2} \ln \frac{m_S^2}{m_F^2}
$$



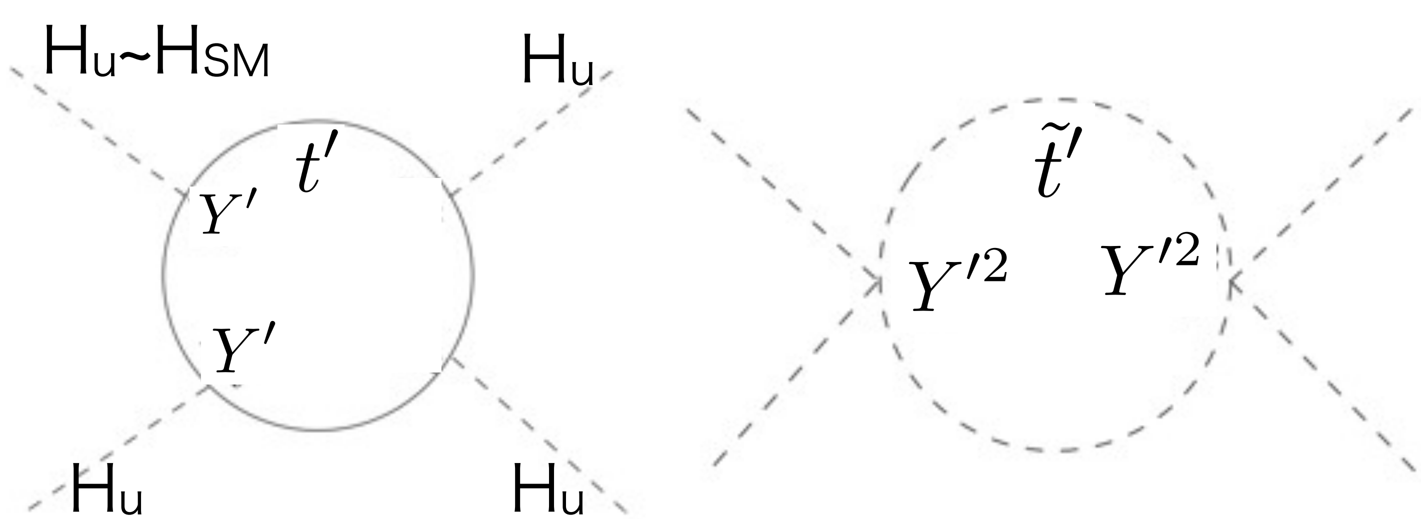
$$10 = (Q', \bar{U}', \bar{E}')$$
$$\bar{10} = (\bar{Q}', U', E')$$

$$W = W_{\rm MSSM} + Y'Q'H_u\bar{U}' + Y''\bar{Q}'H_dU' + M_{Q'}Q'\bar{Q}' + M_{U'}U'\bar{U}' + M_{E'}E'\bar{E}'$$

$$\Delta m_h^2 \sim \frac{3Y'^4 v^4}{4\pi^2}\ln\frac{m_S^2}{m_F^2}$$

m_S : scalar mass
m_F : fermion mass

larger m_s/m_F leads to larger Higgs mass



$$10 = (Q', \bar{U}', \bar{E}')$$
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$$W = W_{\rm MSSM} + Y' Q' H_u \bar{U}' + Y'' \bar{Q}' H_d U' + M_{Q'} Q' \bar{Q}' + M_{U'} U' \bar{U}' + M_{E'} E' \bar{E}'$$

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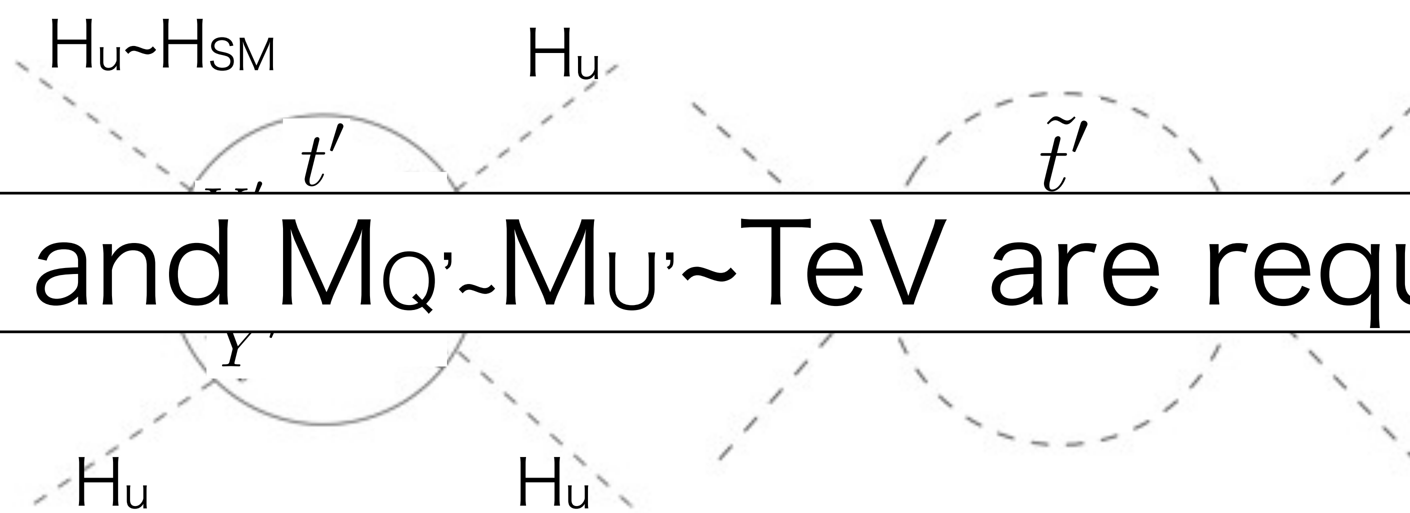

Y'~1 and $M_{Q'}$~$M_{U'}$~TeV are required

$$
\begin{aligned}
W &= W_{\rm MSSM} \\
&\quad + Y' Q' H_u \bar{U}' + Y'' \bar{Q}' H_d U' \\
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$$
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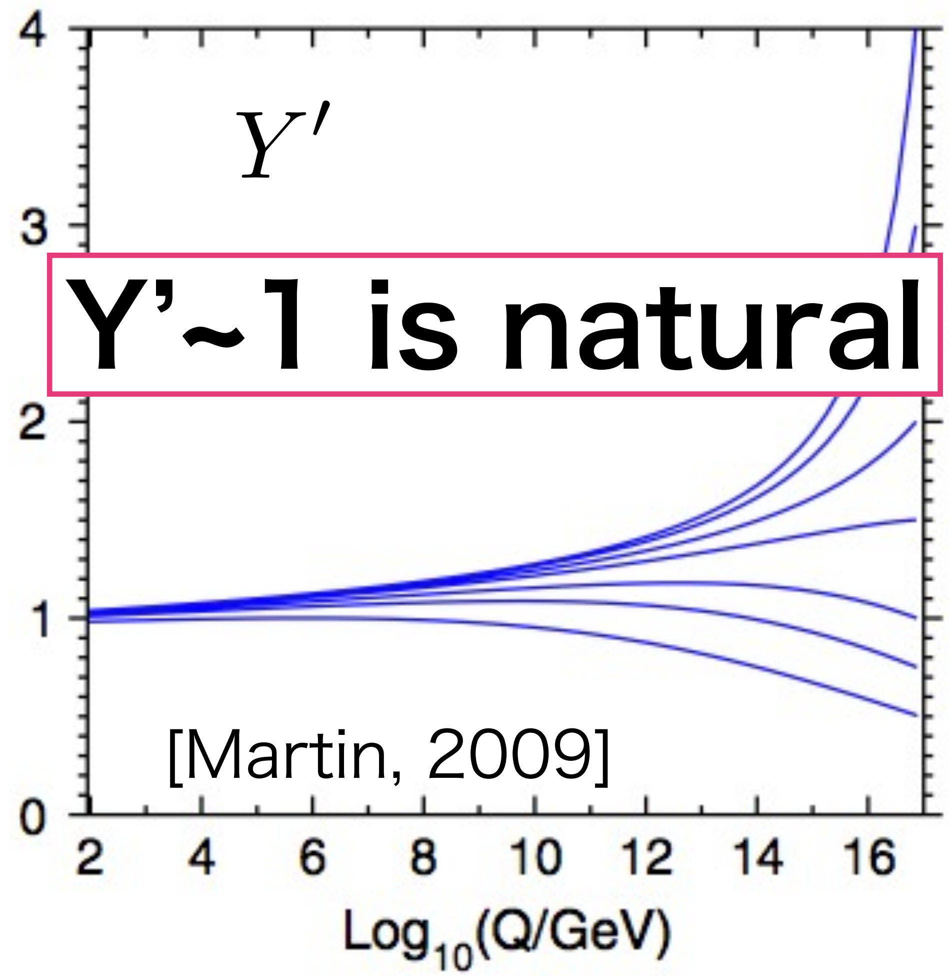
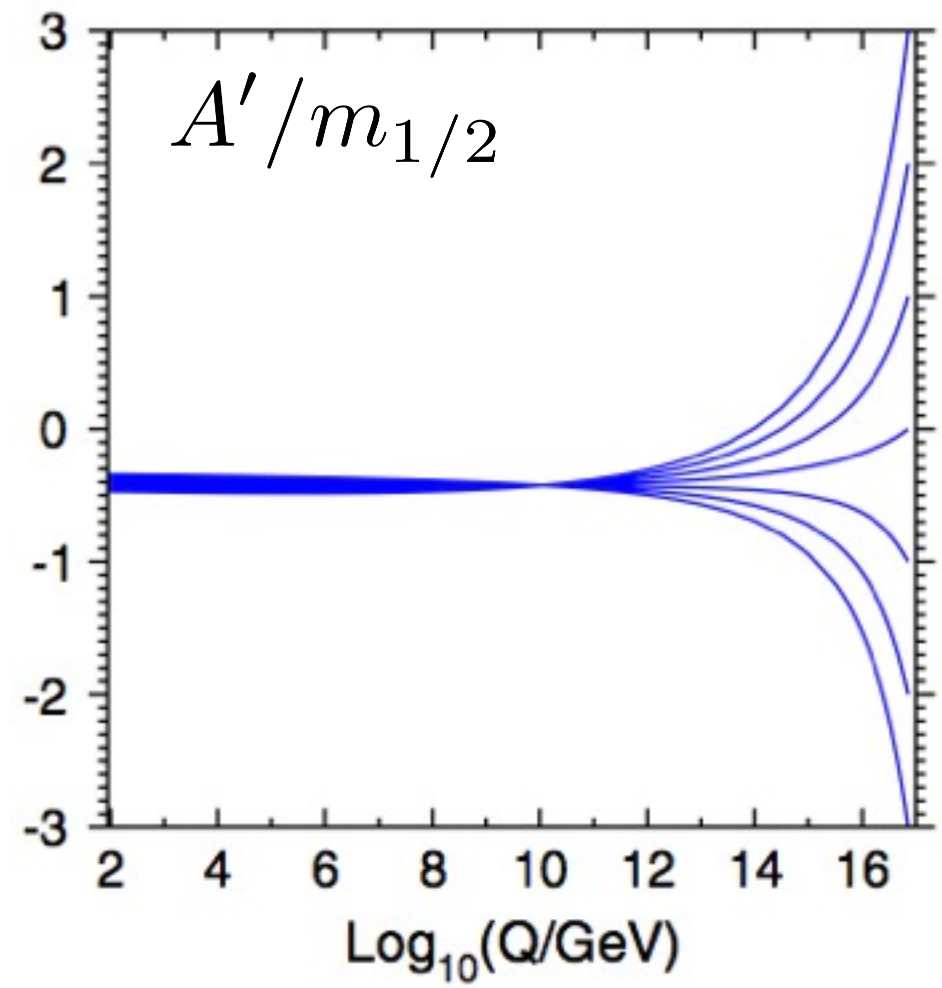
\end{aligned}
$$

Y' and corresponding A parameter (and A_t) have quasi IR fixed point





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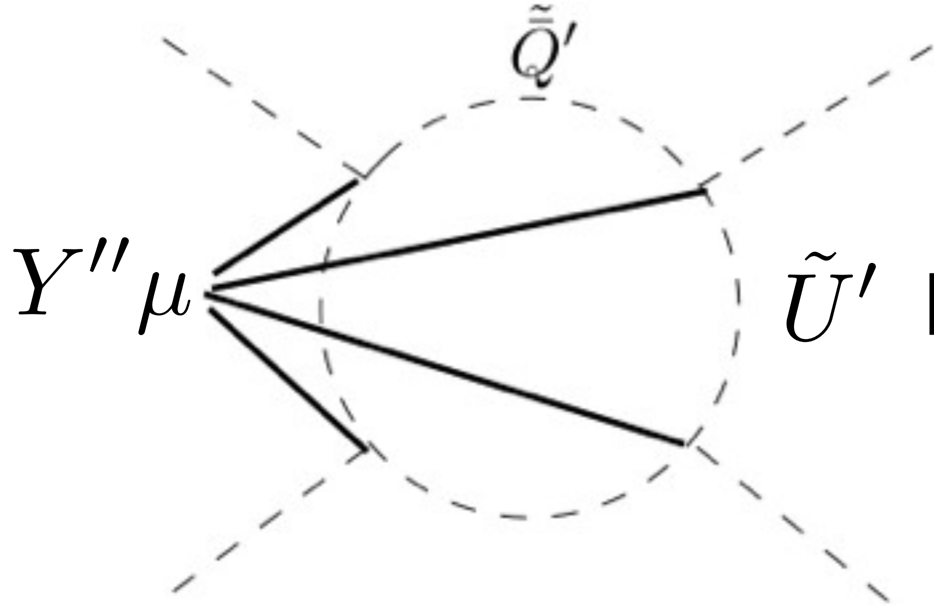
$$+ M_{Q'} Q' \bar{Q}' + M_{U'} U' \bar{U}' + M_{E'} E' \bar{E}'$$

this coupling should be small



$$\Delta m_{h^0}^2 \simeq -\frac{3v^2}{4\pi^2} Y''^4 \sin^4\beta \frac{\mu^4}{12 M_S^4},$$

reducing the Higgs mass (similar to the sbottom loops with large LR mixing)

The correct size of μ-term, $M_{Q'}$ and $M_{U'}$ can be generated by **PQ-symmetry** breaking

$$W_{\rm ext} = \lambda_1 \frac{\phi^2}{M_P} H_u H_d + \frac{\phi^2}{M_P}(\lambda_2 Q' \bar{Q}' + \lambda_3 \bar{U}' U' + \lambda_4 \bar{E}' E')$$

PQ breaking scale: $\langle \phi \rangle \sim 10^{10}{\rm GeV} - 10^{12}{\rm GeV}$

Reduced Plank mass: $M_P \simeq 2.4 \times 10^{18}{\rm GeV}$

$$\mu \sim M_Q \sim M_U \sim M_E$$

$$\sim \frac{\langle \phi \rangle^2}{M_P} \sim 100 - 1000\,{\rm GeV}$$

[Nakayama, N.Y, 2012]

The unwanted interaction is automatically suppressed by **PQ-symmetry**

Requiring that

$$W = \lambda_1 \frac{\phi^2}{M_P} H_u H_d + \frac{\phi^2}{M_P}(\lambda_2 Q' \bar{Q}' + \lambda_3 \bar{U}' U' + \lambda_4 \bar{E}' E')$$
$$+ W_{\mathrm{MSSM},\mu=0} + Y' Q' H_u \bar{U}'$$

$$Y'' \bar{Q}' H_d U' \Rightarrow \Delta m_{h^0}^2 \simeq -\frac{3v^2}{4\pi^2} Y''^4 \sin^4 \beta \frac{\mu^4}{12 M_S^4},$$

Small Y'' suppresses contributions to hVV couplings

The Higgs production is almost unchanged

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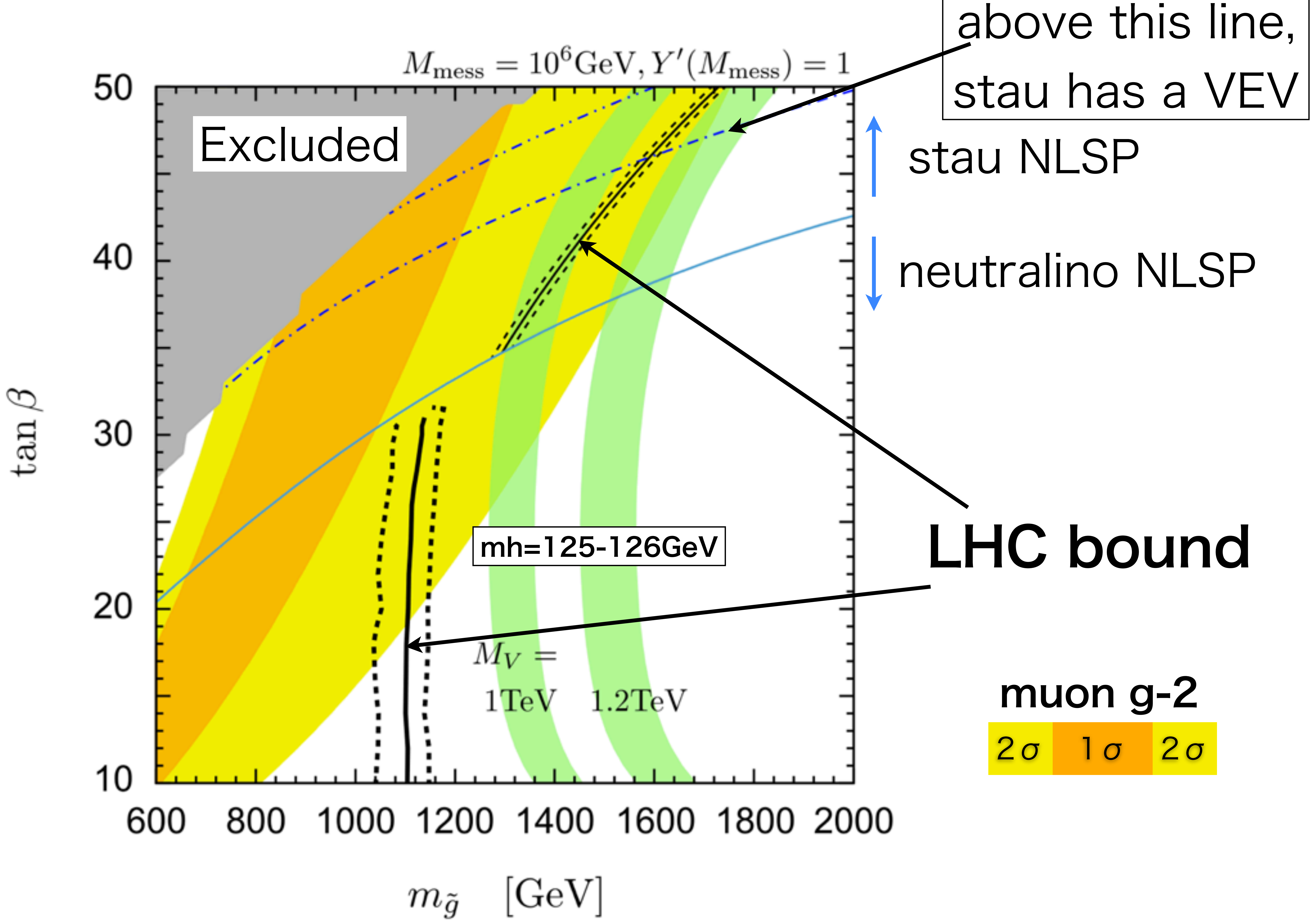
Result



[Endo, Hamaguchi, Ishikawa, Iwamoto, N.Y., 2012]

Oh… it may not be attractive enough

Is it impossible to explain muon g-2 ?

Oh… it may not be attractive enough

Is it impossible to explain muon g-2 ?

Yes, it is possible

The SUSY breaking (invariant) masses of messengers can be split by GUT breaking effects (**GUT is broken!**)

$$W_{\rm mess} = (M_D + F_D\theta^2)\Psi_D\Psi_{\bar{D}} + (M_L + F_L\theta^2)\Psi_L\Psi_{\bar{L}}$$

$$\Lambda_D = \frac{F_D}{M_D} \qquad \Lambda_L = \frac{F_L}{M_L}$$

$\Lambda_D = \Lambda_L$ is not always required

We can take $\Lambda_L < \Lambda_D$

Colored and non-colored SUSY particles become more hierarchical in their masses

$$M_1 \simeq \frac{g_1^2}{16\pi^2} N_5 \left(\frac{2}{5}\Lambda_D + \frac{3}{5}\Lambda_L \right), \quad M_2 \simeq \frac{g_2^2}{16\pi^2} N_5 (\Lambda_L), \quad M_3 \simeq \frac{g_3^2}{16\pi^2} N_5 (\Lambda_D),$$

colored

$$\begin{aligned}
m_{\tilde{Q}}^2 &\simeq N_5 \frac{2}{(16\pi^2)^2} \left[\frac{4}{3} g_3^4 \Lambda_D^2 + \frac{3}{4} g_2^4 \Lambda_L^2 + \frac{3}{5} g_1^4 \left(\frac{2}{5}\Lambda_D^2 + \frac{3}{5}\Lambda_L^2 \right) \frac{1}{6^2} \right], \\
m_{\tilde{U}}^2 &\simeq N_5 \frac{2}{(16\pi^2)^2} \left[\frac{4}{3} g_3^4 \Lambda_D^2 + \frac{3}{5} g_1^4 \left(\frac{2}{5}\Lambda_D^2 + \frac{3}{5}\Lambda_L^2 \right) \left(\frac{2}{3} \right)^2 \right], \\
m_{\tilde{D}}^2 &\simeq N_5 \frac{2}{(16\pi^2)^2} \left[\frac{4}{3} g_3^4 \Lambda_D^2 + \frac{3}{5} g_1^4 \left(\frac{2}{5}\Lambda_D^2 + \frac{3}{5}\Lambda_L^2 \right) \frac{1}{3^2} \right],
\end{aligned}$$

non-colored

$$\begin{aligned}
m_{\tilde{L}}^2 &\simeq N_5 \frac{2}{(16\pi^2)^2} \left[\frac{3}{4} g_2^4 \Lambda_L^2 + \frac{3}{5} g_1^4 \left(\frac{2}{5}\Lambda_D^2 + \frac{3}{5}\Lambda_L^2 \right) \frac{1}{2^2} \right], \\
m_{\tilde{E}}^2 &\simeq N_5 \frac{2}{(16\pi^2)^2} \left[\frac{3}{5} g_1^4 \left(\frac{2}{5}\Lambda_D^2 + \frac{3}{5}\Lambda_L^2 \right) \right], \\
m_{H_u}^2 &= m_{H_d}^2 = m_{\tilde{L}}^2 .
\end{aligned}$$

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$$M_1 \simeq \frac{g_1^2}{16\pi^2} N_5 \left(\frac{2}{5}\Lambda_D + \cancel{\frac{3}{5}\Lambda_L} \right), \quad M_2 \simeq \frac{g_2^2}{16\pi^2} N_5 (\cancel{\Lambda_L}), \quad M_3 \simeq \frac{g_3^2}{16\pi^2} N_5 (\Lambda_D),$$

colored

$$m_{\tilde{Q}}^2 \simeq N_5 \frac{2}{(16\pi^2)^2} \left[\frac{4}{3} g_3^4 \Lambda_D^2 + \cancel{\frac{3}{4} g_2^4 \Lambda_L^2} + \frac{3}{5} g_1^4 \left(\frac{2}{5}\Lambda_D^2 + \cancel{\frac{3}{5}\Lambda_L^2} \right) \frac{1}{6^2} \right],$$

$$m_{\tilde{U}}^2 \simeq N_5 \frac{2}{(16\pi^2)^2} \left[\frac{4}{3} g_3^4 \Lambda_D^2 + \frac{3}{5} g_1^4 \left(\frac{2}{5}\Lambda_D^2 + \cancel{\frac{3}{5}\Lambda_L^2} \right) \left(\frac{2}{3} \right)^2 \right],$$

$$m_{\tilde{D}}^2 \simeq N_5 \frac{2}{(16\pi^2)^2} \left[\frac{4}{3} g_3^4 \Lambda_D^2 + \frac{3}{5} g_1^4 \left(\frac{2}{5}\Lambda_D^2 + \cancel{\frac{3}{5}\Lambda_L^2} \right) \frac{1}{3^2} \right],$$

non-colored

$$m_{\tilde{L}}^2 \simeq N_5 \frac{2}{(16\pi^2)^2} \left[\cancel{\frac{3}{4} g_2^4 \Lambda_L^2} + \frac{3}{5} g_1^4 \left(\frac{2}{5}\Lambda_D^2 + \cancel{\frac{3}{5}\Lambda_L^2} \right) \frac{1}{2^2} \right],$$

$$m_{\tilde{E}}^2 \simeq N_5 \frac{2}{(16\pi^2)^2} \left[\frac{3}{5} g_1^4 \left(\frac{2}{5}\Lambda_D^2 + \cancel{\frac{3}{5}\Lambda_L^2} \right) \right],$$

$$m_{H_u}^2 = m_{H_d}^2 = m_{\tilde{L}}^2.$$

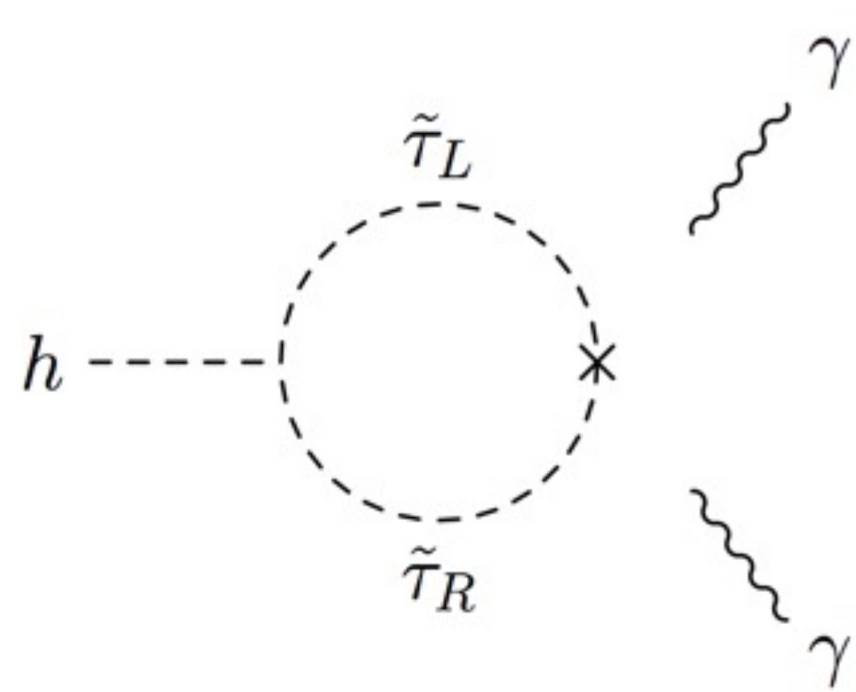
Colored and non-colored SUSY particles become more hierarchical in their masses

Muon g-2 is easier to be explained

Colored and non-colored SUSY particles become more hierarchical in their masses

Muon g-2 is easier to be explained

Stau-loop enhances H$\gamma\gamma$ signal with large LR mixing



[Carena, Gori, Shah, Wagner, 2012]

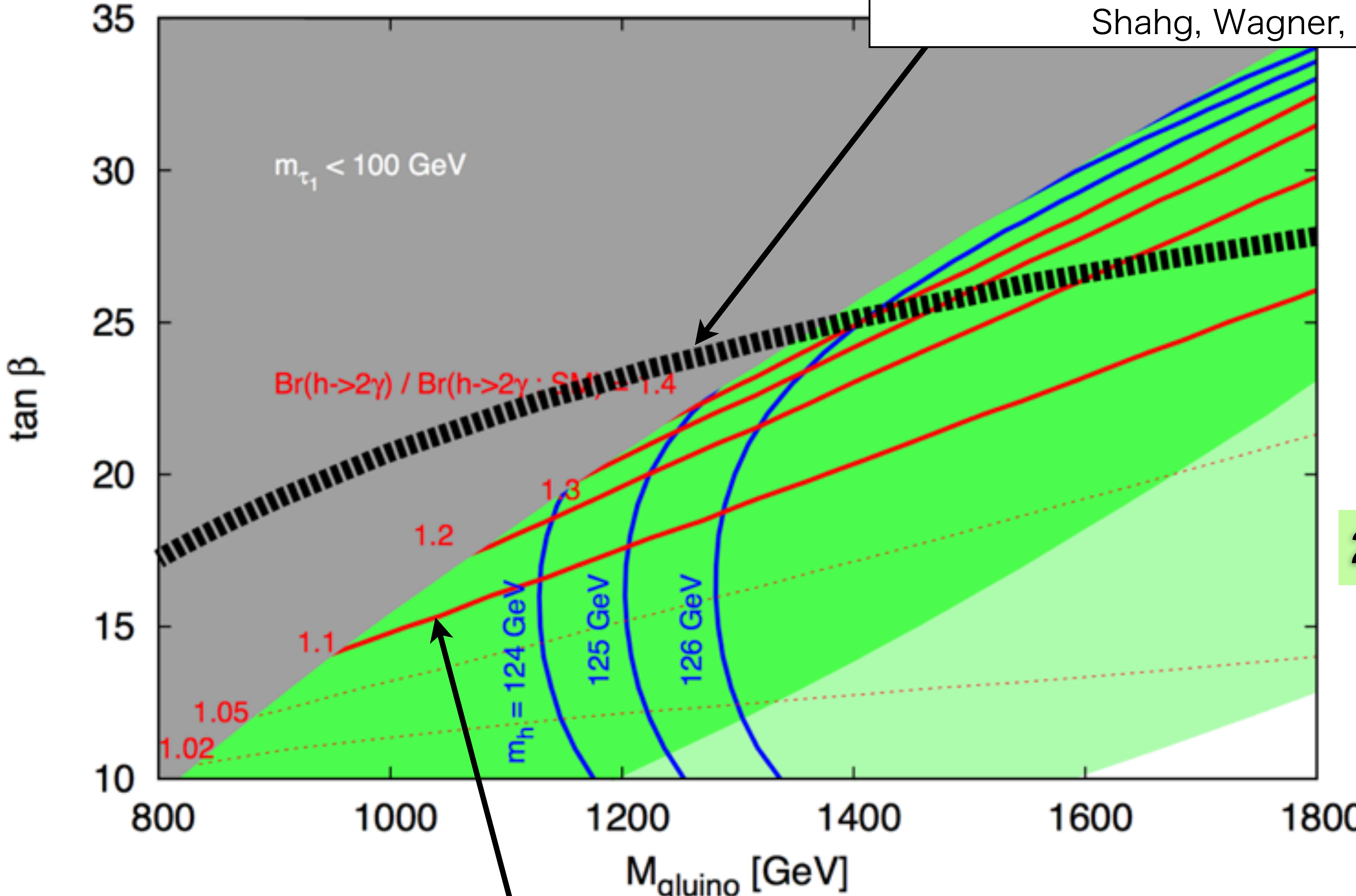
Result 2

$M_Q = M_U = 900$ GeV $\quad \Lambda_L/\Lambda_{\bar{D}} = 0.4$

$M_{\text{mess}} = 4 \times 10^5$ GeV

Vacuum stability bound

[Hisano, Sugiyama, 2010v2; Carena, Gori, Low, Shahg, Wagner, 2012]



muon g-2

2σ	1σ	2σ

$\text{Br}(h \to \gamma\gamma)/\text{Br}(h \to \gamma\gamma)_{\text{SM}}$

[Sato, Tobioka, N.Y, 2012]

Summary

- SUSY SM + vector-like matters in gauge mediation is attractive
- Higgs boson mass, muon g-2 and enhanced di-photon rates (optional) are all explained
- Consistent with perturbative GUT
- Not very large fine-tuning is required compared to high scale SUSY breaking scenarios

Thank you