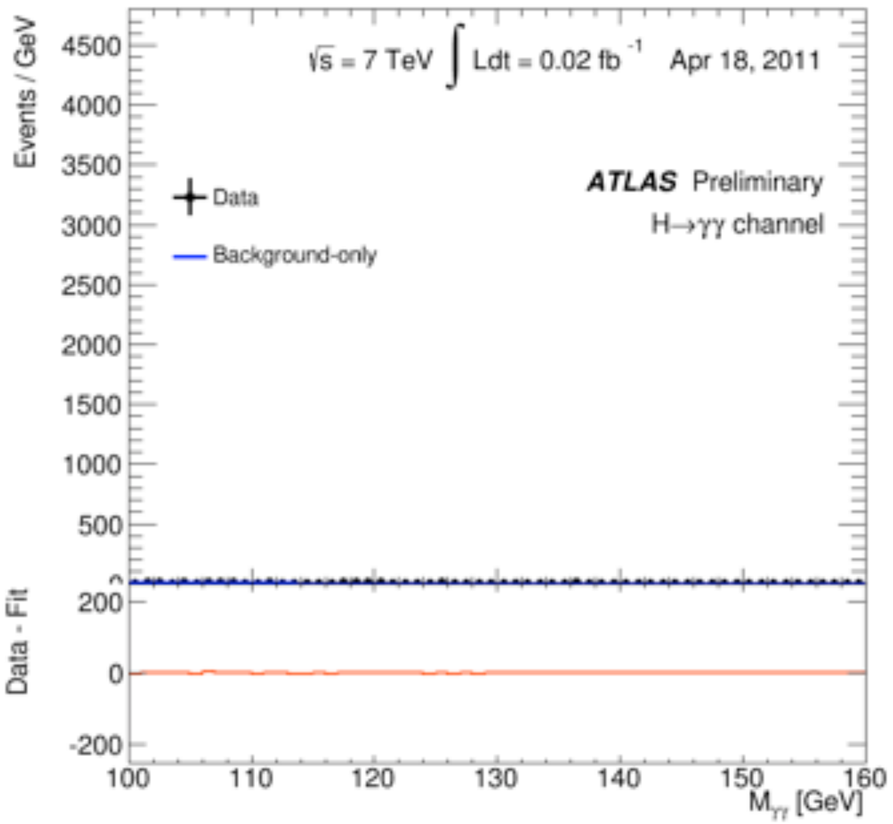
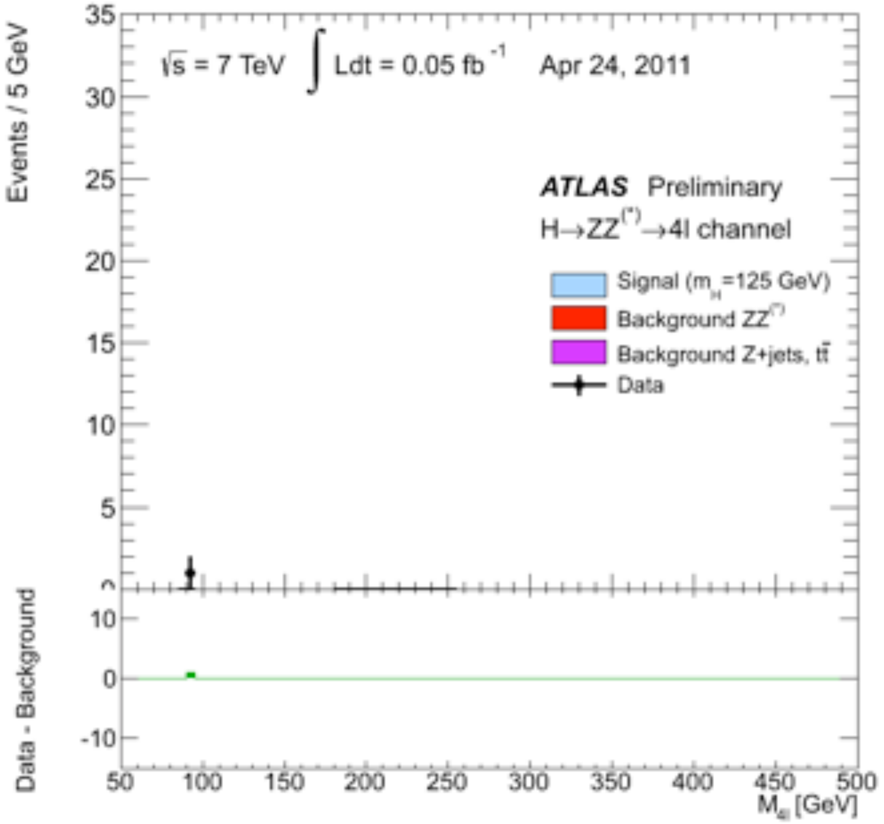
Supersymmetry after Higgs discovery

Koichi Hamaguchi (University of Tokyo)

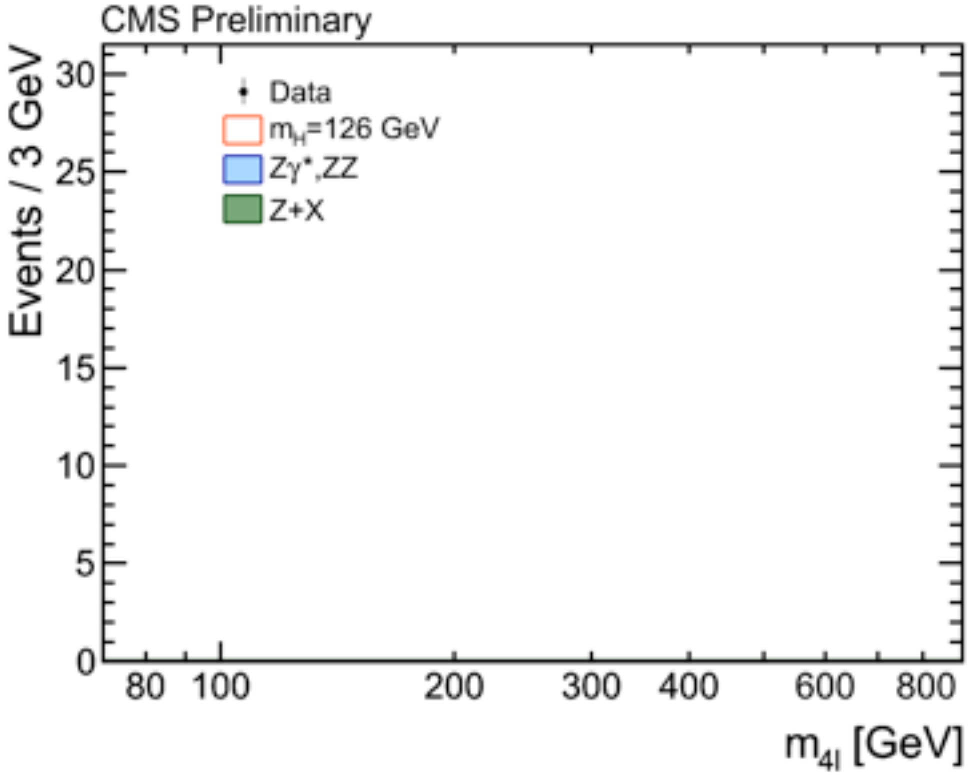
@ “Higgs and Beyond”, Tohoku-U., June 6

a Higgs boson was discovered !



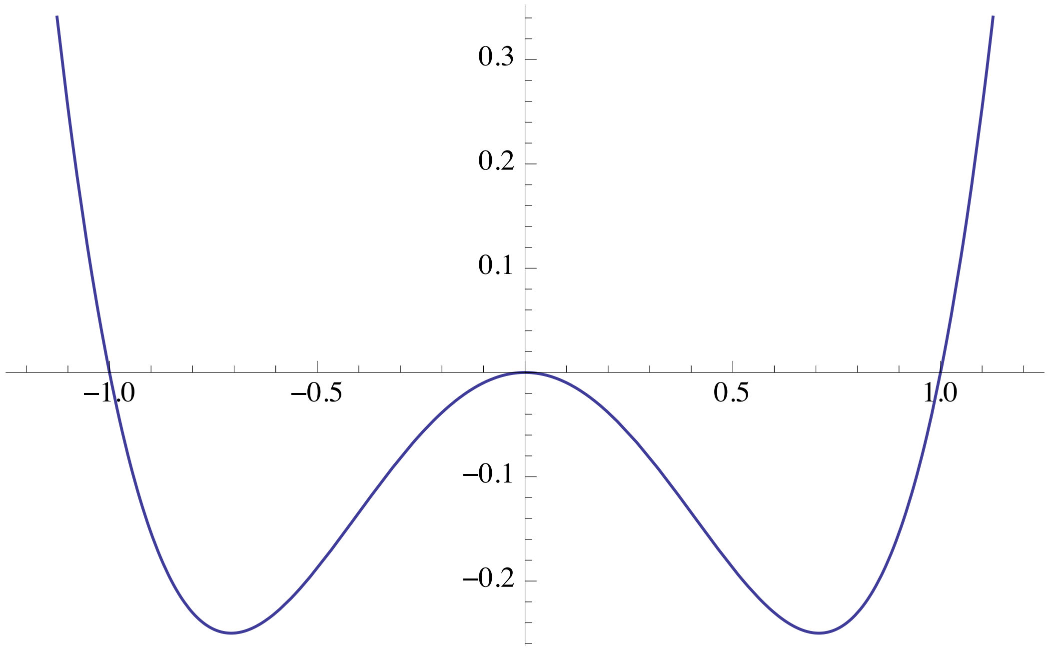


I couldn't find
CMS version of
H → γγ animation



126 GeV Higgs

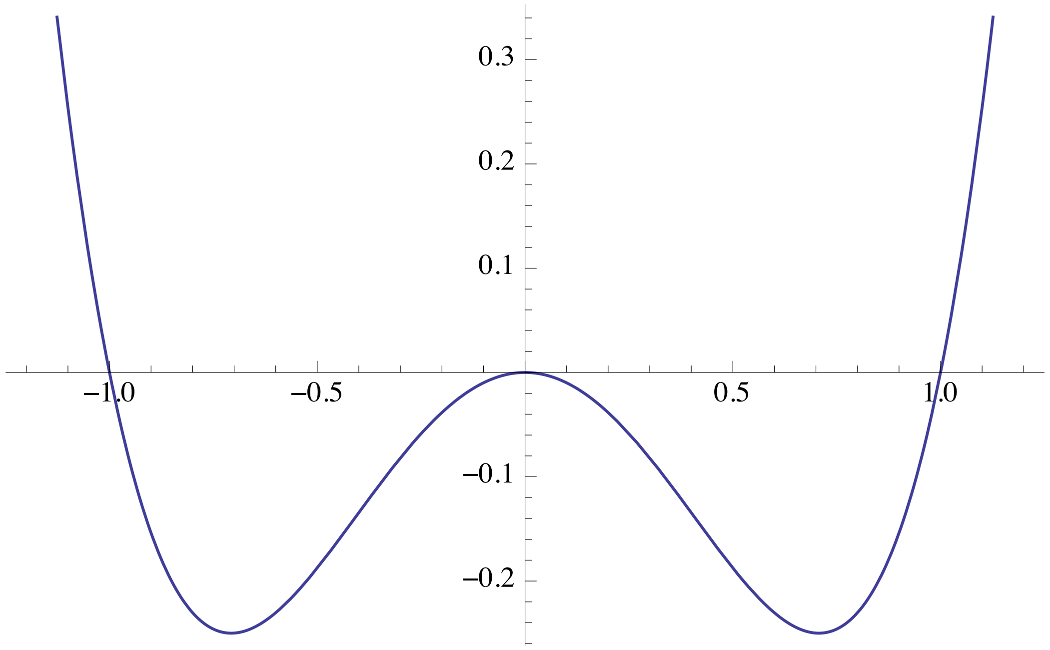
$$V(H) = -m^2(H^\dagger H) + \lambda_\mathrm{H}(H^\dagger H)^2$$



126 GeV Higgs

$$V(H) = -m^2(H^\dagger H) + \lambda_{\mathrm{H}}(H^\dagger H)^2$$

$$\rightarrow \begin{cases} \langle H \rangle^2 = \dfrac{m^2}{2\,\lambda_{\mathrm{H}}} \\ m^2_{\mathrm{Higgs}} = 2\,m^2 \end{cases}$$

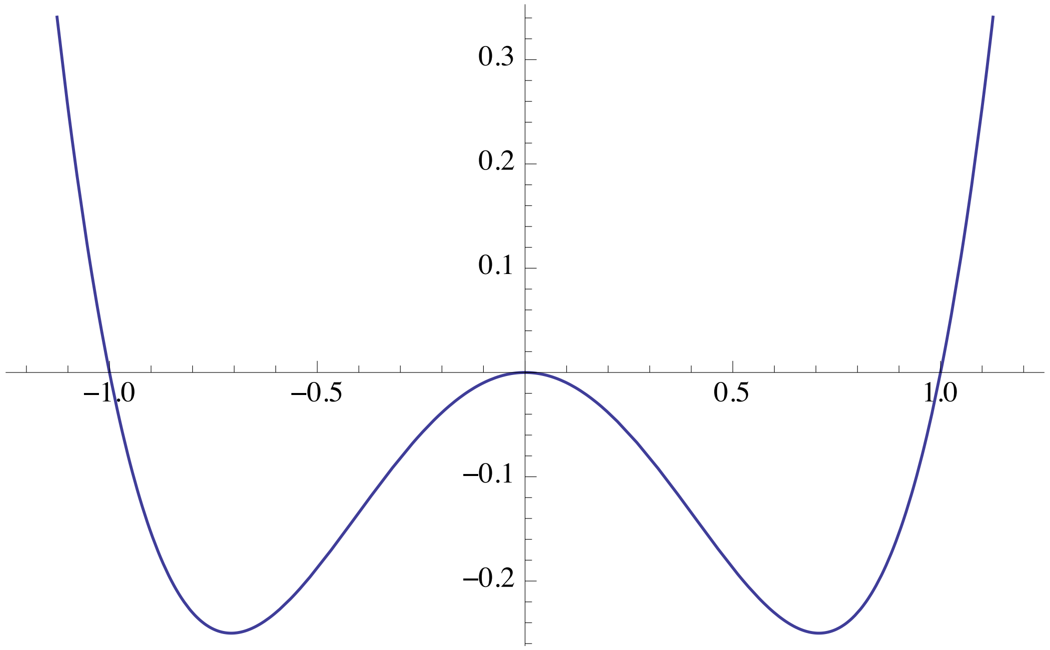


126 GeV Higgs

$$V(H) = -m^2(H^\dagger H) + \lambda_{\mathrm{H}}(H^\dagger H)^2$$

We knew...

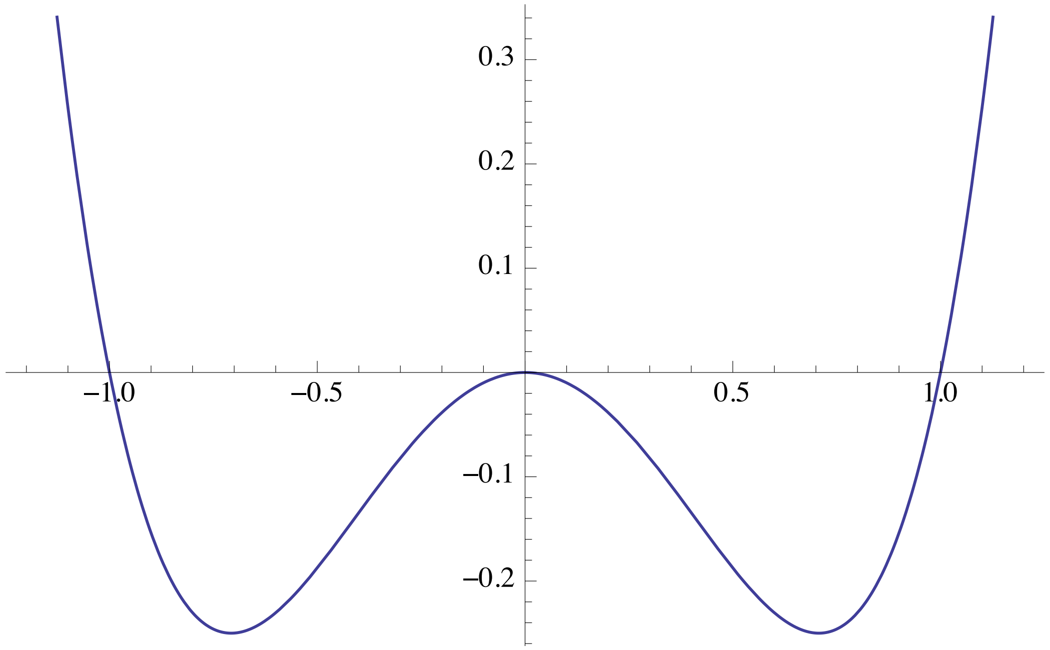
$$\to \begin{cases} \langle H \rangle^2 = \dfrac{m^2}{2\,\lambda_{\mathrm{H}}} = \dfrac{1}{2\sqrt{2}\,G_F} \simeq (174\ \mathrm{GeV})^2 \\ m_{\mathrm{Higgs}}^2 = 2\,m^2 \end{cases}$$



126 GeV Higgs

$$V(H) = -m^2 (H^\dagger H) + \lambda_{\mathrm{H}} (H^\dagger H)^2$$

$$\to \begin{cases} \langle H \rangle^2 = \dfrac{m^2}{2\,\lambda_{\mathrm{H}}} \overset{\text{We knew...}}{=} \dfrac{1}{2\sqrt{2}\,G_F} \simeq (174\ \mathrm{GeV})^2 \\[2em] m^2_{\mathrm{Higgs}} = 2\,m^2 \overset{\text{Now we also know}}{\simeq} \mathbf{(126\ GeV)^2} \end{cases}$$



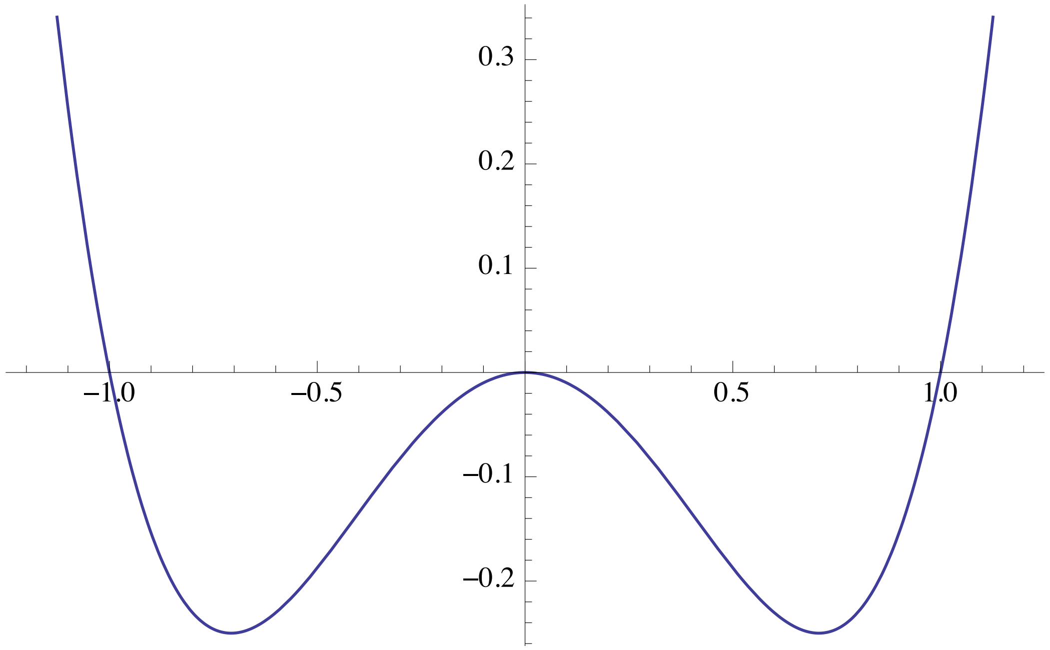
126 GeV Higgs

$$V(H) = -m^2 (H^\dagger H) + \lambda_{\mathrm{H}} (H^\dagger H)^2$$

We knew…

Now we also know

$$\rightarrow \begin{cases} \langle H \rangle^2 = \dfrac{m^2}{2\,\lambda_{\mathrm{H}}} = \dfrac{1}{2\sqrt{2}\,G_F} \simeq (174\ \mathrm{GeV})^2 \\ \\ m_{\mathrm{Higgs}}^2 = 2\,m^2 \simeq (\mathbf{126\ GeV})^2 \end{cases}$$



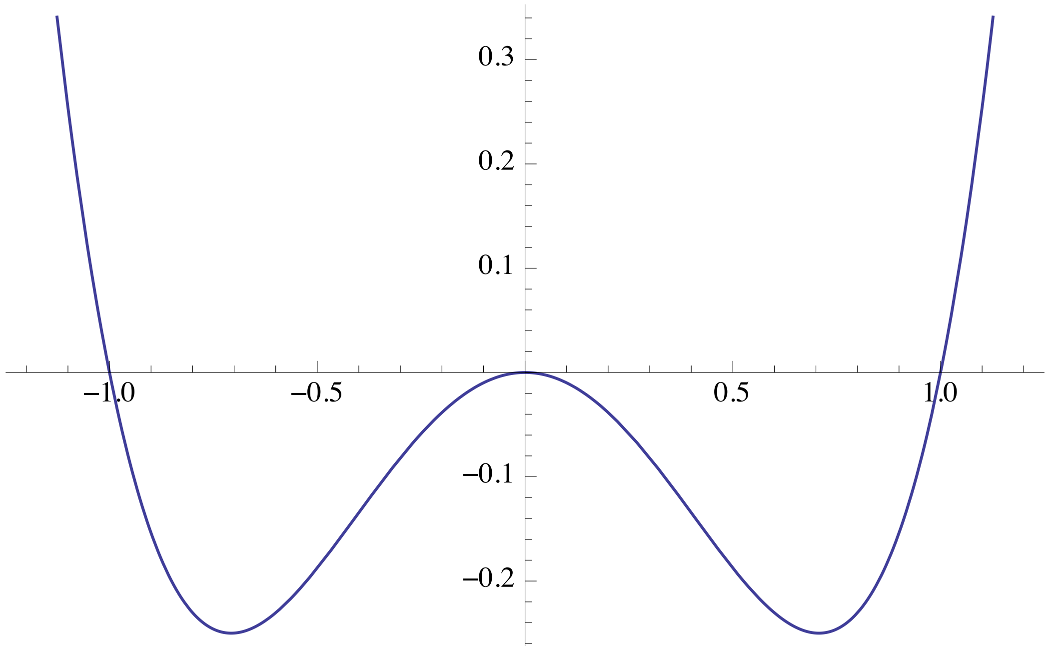
$$\rightarrow \begin{cases} m^2 = \dfrac{m_{\mathrm{Higgs}}^2}{2} \simeq (\mathbf{89\ GeV})^2 \\ \\ \lambda_{\mathrm{H}} = \dfrac{m_{\mathrm{Higgs}}^2}{4\langle H \rangle^2} \simeq \mathbf{0.13} \end{cases}$$

126 GeV Higgs

$$V(H) = -m^2(H^\dagger H) + \lambda_{\mathrm{H}}(H^\dagger H)^2$$

$$(\mathbf{89\ GeV})^2 \qquad \mathbf{0.13}$$

completely determined !



$$\rightarrow \begin{cases} m^2 = \dfrac{m_{\mathrm{Higgs}}^2}{2} \simeq (\mathbf{89\ GeV})^2 \\ \\ \lambda_{\mathrm{H}} = \dfrac{m_{\mathrm{Higgs}}^2}{4\langle H\rangle^2} \simeq \mathbf{0.13} \end{cases}$$

126 GeV Higgs

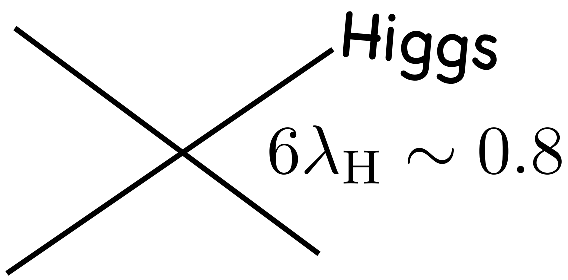
$$V(H) = -m^2(H^\dagger H) + \lambda_\mathrm{H}(H^\dagger H)^2$$

$$\mathbf{(89\ GeV)^2} \qquad \mathbf{0.13}$$

It seems...

Higgs sector is also described by weakly coupled, perturbative QFT.

(at least no sign of strong interaction, so far...)



126 GeV Higgs

By the way...

perturbative, weakly coupled Higgs sector
is consistent with the existence of

heavy right-handed neutrinos

which are (weakly) coupled to Higgs.

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\overline{N_R}(i\partial\!\!\!/ + M_R)N_R + y_\nu \underset{\text{R.H.neutrino}}{\overline{N_R}}\ell_L \underset{\text{Higgs}}{H} + h.c.$$

(1) small neutrino masses

(2) matter unification
in 16 of SO(10)

(3) Leptogenesis

... implying weakly coupled, perturbative Higgs sector
up to right-handed neutrino scale. (say, > 10^{10} GeV.)

126 GeV

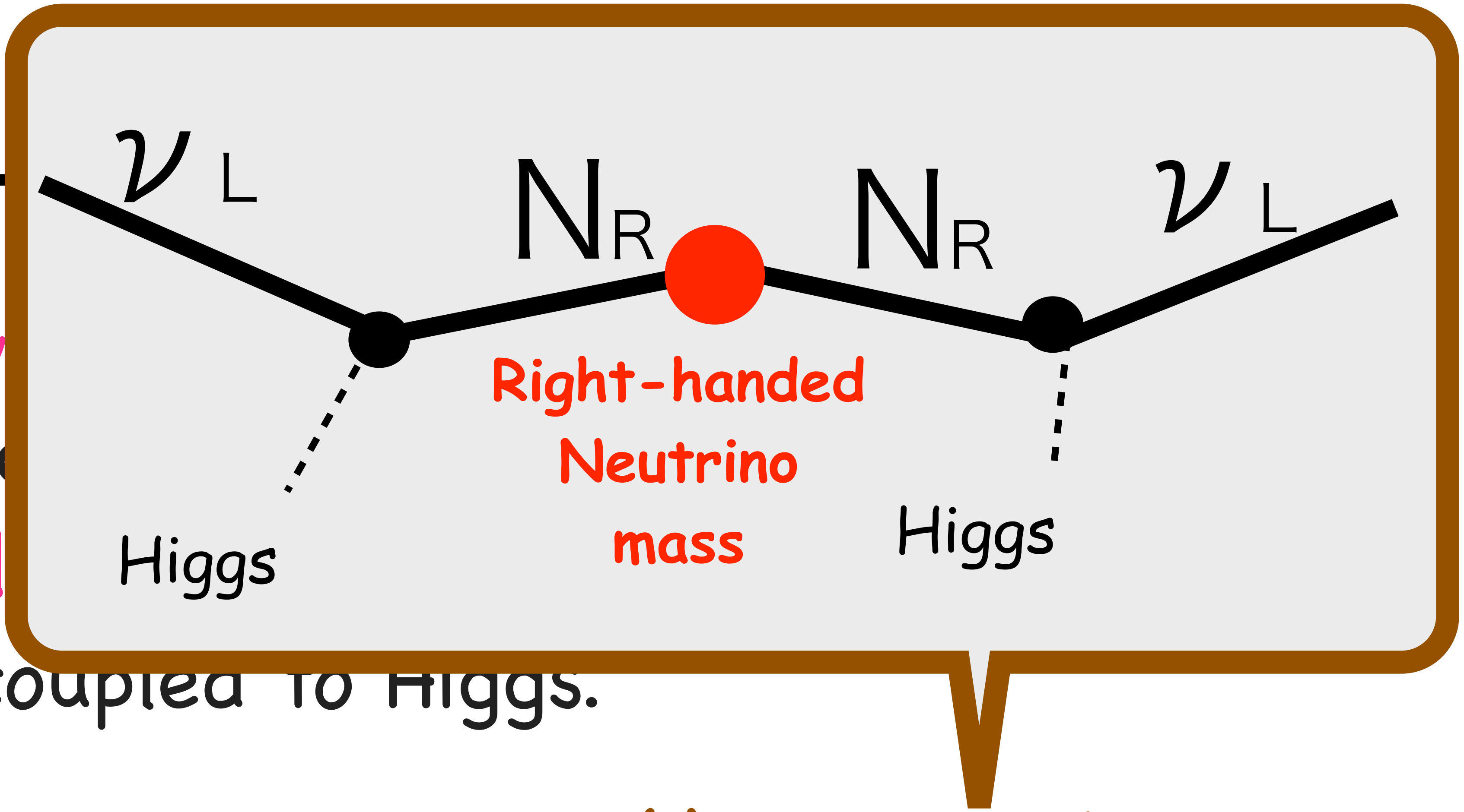
By the way...

perturbative, weakly

is consistent with the

heavy right-hand

which are (weakly) coupled to Higgs.



(1) small neutrino masses

(2) matter unification in 16 of SO(10)

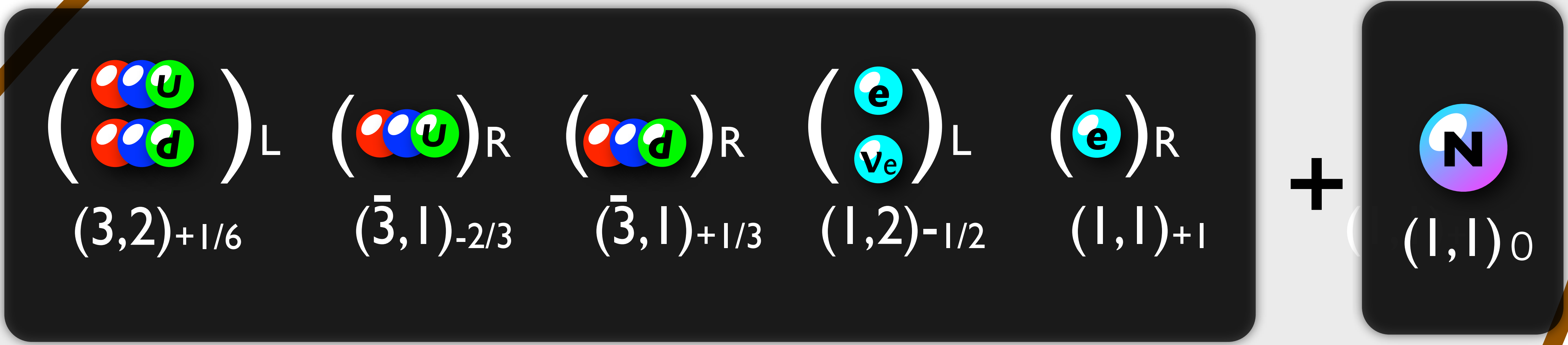
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\overline{N_R}(i\partial\!\!\!/ + M_R)N_R + y_\nu \overline{N_R}\ell_L H + h.c.$$

Higgs

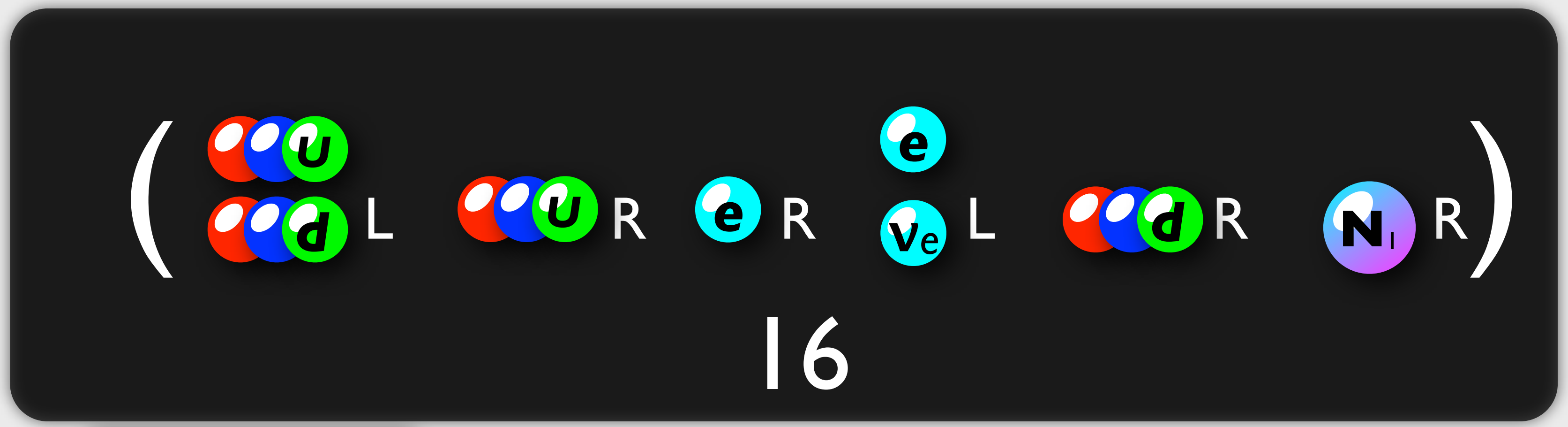
(3) Leptogenesis

R.H.neutrino

... implying weakly coupled, perturbative Higgs sector up to right-handed neutrino scale. (say, > 10^{10} GeV.)



=



=

(↑↓ ↓↓↑)
(↑↓ ↓↑↓)
(↑↓ ↑↓↓)
(↓↑ ↓↓↑)
(↓↑ ↓↑↓)
(↓↑ ↑↓↓)
(↑↑ ↑↑↓)
(↑↑ ↑↓↑)
(↑↑ ↓↑↑)
(↓↓ ↑↑↓)
(↓↓ ↑↓↑)
(↓↓ ↓↑↑)
(↑↓ ↑↑↑)
(↓↑ ↑↑↑)
(↑↑ ↓↓↓)
(↓↓ ↓↓↓)

neutrino masses

(2) matter unification in 16 of SO(10)

$h.c.$

Higgs

R.H.neutrino

(3) Leptogenesis

pled, perturbative Higgs sector

ed neutrino scale. (say, > 10^{10} GeV.)

126 GeV Higgs

By the way...

perturbative, weakly coupled Higgs sector is consistent with the existence of

heavy right-handed neutrinos

which are (weakly) coupled to Higgs.

(1) small neutrino masses

(2) matter unification in 16 of SO(10)

$h.c.$

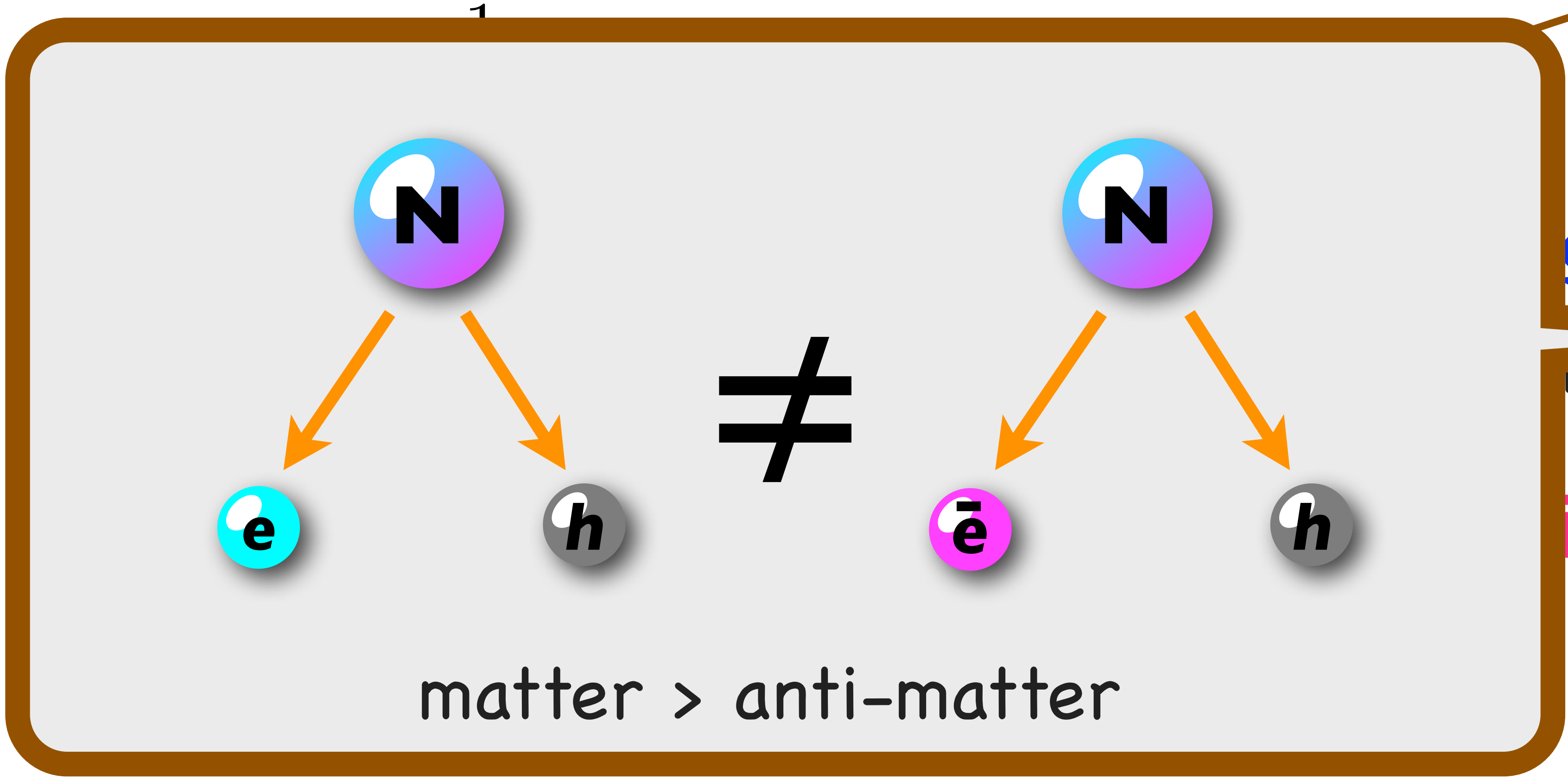
ggs

(3) Leptogenesis

rino

ive Higgs sector

y, > 10^{10} GeV.)



matter > anti-matter

126 GeV Higgs

By the way...

perturbative, weakly coupled Higgs sector
is consistent with the existence of

heavy right-handed neutrinos

which are (weakly) coupled to Higgs.

(1) small neutrino masses

(2) matter unification in 16 of SO(10)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\overline{N_R}(i\not{\partial} + M_R)N_R + y_\nu \overline{N_R}\ell_L H + h.c.$$

Higgs

R.H.neutrino

(3) Leptogenesis

... implying weakly coupled, perturbative Higgs sector
up to right-handed neutrino scale. (say, > 10^{10} GeV.)

126 GeV Higgs

Perturbative Higgs sector up to intermediate scale?

... then, **Supersymmetry** is the most attractive candidate for BSM physics.

- **naturalness**

fine-tuning problem

$$m_H^2 = m_{H,0}^2 + \Lambda^2 \qquad (\Lambda \gg m_H)$$

(fine tuning like 1.0000000000000001 - 1)

"little"

~~no~~ fine-tuning

$$-\frac{1}{2}m_{\rm Higgs}^2 \simeq |\mu|^2 + m_{H_u}^{2\,({\rm tree})} + m_{H_u}^{2\,({\rm loop})}$$

("little" fine tuning **1.01-1 or 1.001-1 or...**)

- **gauge coupling unification**
- **DM**
- **muon g-2**

Supersymmetry
after
Higgs discovery

126 GeV Higgs and SUSY

Let's recall the motivations of TeV scale SUSY.....

naturalness

muon g-2

Dark Matter

Coupling Unification

.....

126 GeV Higgs and SUSY

Let's recall the motivations of
TeV scale SUSY.....

126 GeV Higgs + **naturalness**

126 GeV Higgs + **muon g-2**

126 GeV Higgs + **Dark Matter**

126 GeV Higgs + **Coupling Unification**

.....

126 GeV Higgs and SUSY

Let's recall the motivations of TeV scale SUSY.....

126 GeV Higgs + **naturalness**

126 GeV Higgs + **muon g-2**

126 GeV Higgs + **Dark Matter**

126 GeV Higgs + **Coupling Unification**

.....

126 GeV Higgs and naturalness

126 GeV Higgs and naturalness

$$V(H) = -\underbrace{m^2}_{(\mathbf{89\ GeV})^2}(H^\dagger H) + \underbrace{\lambda_{\rm H}}_{\mathbf{0.13}}(H^\dagger H)^2$$

in SUSY...

126 GeV Higgs and naturalness

$$V(H) = -m^2(H^\dagger H) + \lambda_{\mathrm{H}}(H^\dagger H)^2$$

$(89\ \mathbf{GeV})^2$

0.13

$$= \lambda_H^{\text{tree}} + \delta\lambda_H^{\text{loop}}$$

in SUSY...

$$\frac{g^2 \cos^2 2\beta}{8\cos^2\theta_W} \simeq \mathbf{0.069}\ \cos^2 2\beta$$

too small...

126 GeV Higgs and naturalness

$$V(H) = -\underset{(89\ \mathrm{GeV})^2}{m^2}(H^\dagger H) + \underset{0.13}{\lambda_{\mathrm{H}}}(H^\dagger H)^2$$

$$= \lambda_H^{\mathrm{tree}} + \delta\lambda_H^{\mathrm{loop}}$$

in SUSY...

$$\frac{g^2\cos^2 2\beta}{8\cos^2\theta_W} \simeq \mathbf{0.069}\ \cos^2 2\beta$$

$$\frac{3y_t^4}{16\pi^2}\left(\log\left(\frac{m_{\mathrm{stop}}^2}{m_t^2}\right) + \alpha^2 - \frac{\alpha^4}{12}\right) + \cdots$$

for large $\tan\beta$. $(\alpha \simeq A_t/m_{\mathrm{stop}})$

...requires **heavy stop**

and/or **large A-term**

126 GeV Higgs and naturalness

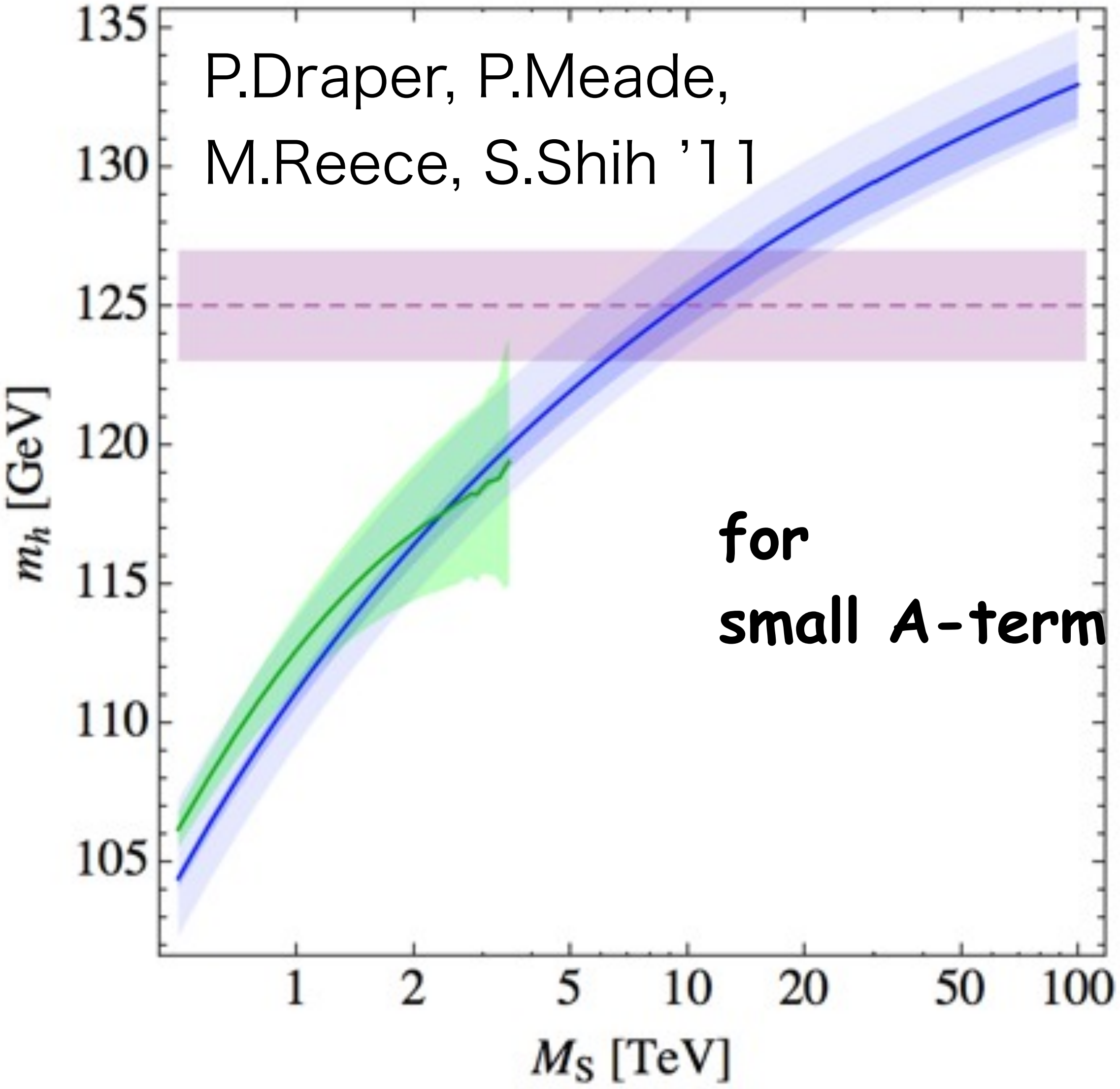
$$V(H) = -m^2(H^\dagger H) + \lambda_{\rm H}(H^\dagger H)^2$$

$(89\ \mathrm{GeV})^2$

0.13

$$= \lambda_H^{\rm tree} + \delta\lambda_H^{\rm loop}$$

in SUSY...



$$\frac{g^2\cos^2 2\beta}{8\cos^2\theta_W} \simeq 0.069\ \cos^2 2\beta$$

$$\frac{3y_t^4}{16\pi^2}\left(\log\left(\frac{m_{\rm stop}^2}{m_t^2}\right) + \alpha^2 - \frac{\alpha^4}{12}\right) + \cdots$$

for large $\tan\beta$. $(\alpha \simeq A_t/m_{\rm stop})$

...requires heavy stop

and/or large A-term

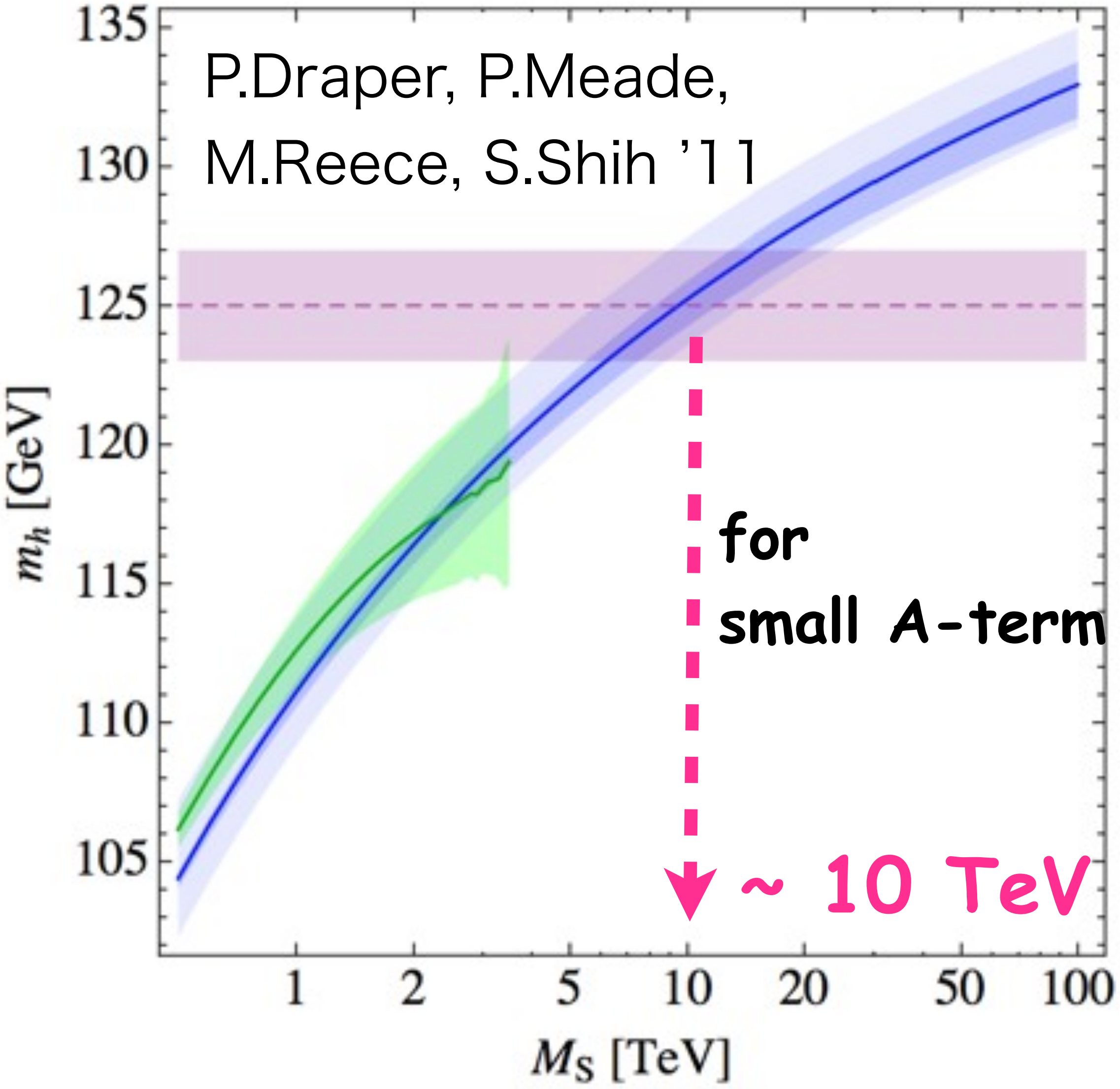
126 GeV Higgs and naturalness

$$V(H) = -m^2 (H^\dagger H) + \lambda_{\mathrm{H}} (H^\dagger H)^2$$

$$m^2 = (89\ \mathrm{GeV})^2 \qquad \lambda_{\mathrm{H}} = 0.13$$

$$= \lambda_H^{\mathrm{tree}} + \delta\lambda_H^{\mathrm{loop}}$$

in SUSY...



P.Draper, P.Meade, M.Reece, S.Shih '11

for small A-term

~ 10 TeV

$$\lambda_H^{\mathrm{tree}}: \quad \frac{g^2 \cos^2 2\beta}{8 \cos^2 \theta_W} \simeq 0.069 \cos^2 2\beta$$

$$\delta\lambda_H^{\mathrm{loop}}: \quad \frac{3y_t^4}{16\pi^2}\left(\log\left(\frac{m_{\mathrm{stop}}^2}{m_t^2}\right) + \alpha^2 - \frac{\alpha^4}{12}\right) + \cdots$$

for large $\tan\beta$. $(\alpha \simeq A_t/m_{\mathrm{stop}})$

...requires **heavy stop**

and/or **large A-term**

126 GeV Higgs and naturalness

$$V(H) = -m^2(H^\dagger H) + \lambda_H (H^\dagger H)^2$$

$$(89\ \mathbf{GeV})^2 \qquad \mathbf{0.13}$$

on the other hand

$$= \lambda_H^{\text{tree}} + \delta\lambda_H^{\text{loop}}$$

$$\frac{g^2 \cos^2 2\beta}{8\cos^2\theta_W} \simeq \mathbf{0.069}\cos^2 2\beta$$

$$\frac{3y_t^4}{16\pi^2}\left(\log\left(\frac{m_{\text{stop}}^2}{m_t^2}\right) + \alpha^2 - \frac{\alpha^4}{12}\right) + \cdots$$

for large $\tan\beta$. $(\alpha \simeq A_t/m_{\text{stop}})$

...requires **heavy stop**

and/or **large A-term**

126 GeV Higgs and naturalness

$$V(H) = -m^2(H^\dagger H) + \lambda_{\rm H}(H^\dagger H)^2$$

$$(89\ \mathrm{GeV})^2 \qquad\qquad 0.13$$

$$= \lambda_H^{\rm tree} + \delta\lambda_H^{\rm loop}$$

on the other hand

$$-m^2 \simeq |\mu|^2 + m_{H_u}^{2\,(\rm tree)} + \delta m_{H_u}^{2\,(\rm loop)}$$

up to $\mathcal{O}\left(\frac{1}{\tan^2\beta}\right)$

Higgsino mass

soft mass for
up-type Higgs

$$\frac{g^2\cos^2 2\beta}{8\cos^2\theta_W} \simeq \mathbf{0.069}\cos^2 2\beta$$

$$\frac{3y_t^4}{16\pi^2}\left(\log\left(\frac{m_{\rm stop}^2}{m_t^2}\right) + \alpha^2 - \frac{\alpha^4}{12}\right) + \cdots$$

for large $\tan\beta$. $(\alpha \simeq A_t/m_{\rm stop})$

...requires **heavy stop**

and/or **large A-term**

126 GeV Higgs and naturalness

$$V(H) = -m^2(H^\dagger H) + \lambda_{\rm H}(H^\dagger H)^2$$

$(89\ \mathrm{GeV})^2$

0.13

$$= \lambda_H^{\rm tree} + \delta\lambda_H^{\rm loop}$$

on the other hand

$$-m^2 \simeq |\mu|^2 + m_{H_u}^{2\,(\rm tree)} + \delta m_{H_u}^{2\,(\rm loop)}$$

up to $\mathcal{O}\left(\frac{1}{\tan^2\beta}\right)$

large μ -----> fine-tuning.

e.g., $\simeq (1000\ \mathrm{GeV})^2 - (1004\ \mathrm{GeV})^2$

for $|\mu| \simeq 1\ \mathrm{TeV}$

requires **Light Higgsino**

to avoid a fine-tuning.

$$\frac{g^2\cos^2 2\beta}{8\cos^2\theta_W} \simeq \mathbf{0.069}\cos^2 2\beta$$

$$\frac{3y_t^4}{16\pi^2}\left(\log\left(\frac{m_{\rm stop}^2}{m_t^2}\right) + \alpha^2 - \frac{\alpha^4}{12}\right) + \cdots$$

for large $\tan\beta$. $(\alpha \simeq A_t/m_{\rm stop})$

...requires **heavy stop**

and/or **large A-term**

126 GeV Higgs and naturalness

$$V(H) = -m^2 (H^\dagger H) + \lambda_{\rm H} (H^\dagger H)^2$$

$(89\ \mathbf{GeV})^2$

0.13

$$= \lambda_H^{\rm tree} + \delta\lambda_H^{\rm loop}$$

on the other hand

$$-m^2 \simeq |\mu|^2 + m_{H_u}^{2\,({\rm tree})} + \delta m_{H_u}^{2\,({\rm loop})}$$

Moreover,

$$\delta m_{H_u}^{2\,({\rm loop})} \sim \frac{-3y_t^2}{8\pi^2} \underline{\left(m_{\widetilde{t}_L}^2 + m_{\widetilde{t}_R}^2 + |A_t|^2\right)} \log\left(\frac{M_{\rm mess}}{m_{\widetilde{t}}}\right) + \cdots$$

requires Light stop and small A-term to avoid a fine-tuning.

$$\frac{g^2 \cos^2 2\beta}{8\cos^2\theta_W} \simeq \mathbf{0.069} \cos^2 2\beta$$

$$\frac{3y_t^4}{16\pi^2}\left(\log\left(\boxed{\frac{m_{\rm stop}^2}{m_t^2}}\right) + \boxed{\alpha^2 - \frac{\alpha^4}{12}}\right) + \cdots$$

for large $\tan\beta$. $(\alpha \simeq A_t/m_{\rm stop})$

...requires heavy stop and/or large A-term

126 GeV Higgs and naturalness

$$V(H) = -m^2(H^\dagger H) + \lambda_H (H^\dagger H)^2$$

$(89\ \mathbf{GeV})^2$

$\mathbf{0.13}$

$$= \lambda_H^{\text{tree}} + \delta\lambda_H^{\text{loop}}$$

on the other hand

$$-m^2 \simeq |\mu|^2 + m_{H_u}^{2\ (\text{tree})} + \delta m_{H_u}^{2\ (\text{loop})}$$

Moreover,

$$\delta m_{H_u}^{2\ (\text{loop})} \sim \frac{-3y_t^2}{8\pi^2}\left(m^2_{\widetilde{t_L}} + m^2_{\widetilde{t_R}} + |A_t|^2\right)\log\left(\frac{M_{\text{mess}}}{m_{\tilde{t}}}\right) + \cdots$$

requires **Light stop and small A-term** to avoid a fine-tuning.

$$\frac{g^2\cos^2 2\beta}{8\cos^2\theta_W} \simeq \mathbf{0.069}\cos^2 2\beta$$

$$\frac{3y_t^4}{\pi^2}\left(\log\left(\frac{m_{\text{stop}}^2}{m_t^2}\right) + \alpha^2 - \frac{\alpha^4}{12}\right) + \cdots$$

for large $\tan\beta$. $(\alpha \simeq A_t/m_{\text{stop}})$

...requires **heavy stop** and/or **large A-term**

inconsistent !!

126 GeV Higgs and naturalness

difficult to reconcile within MSSM

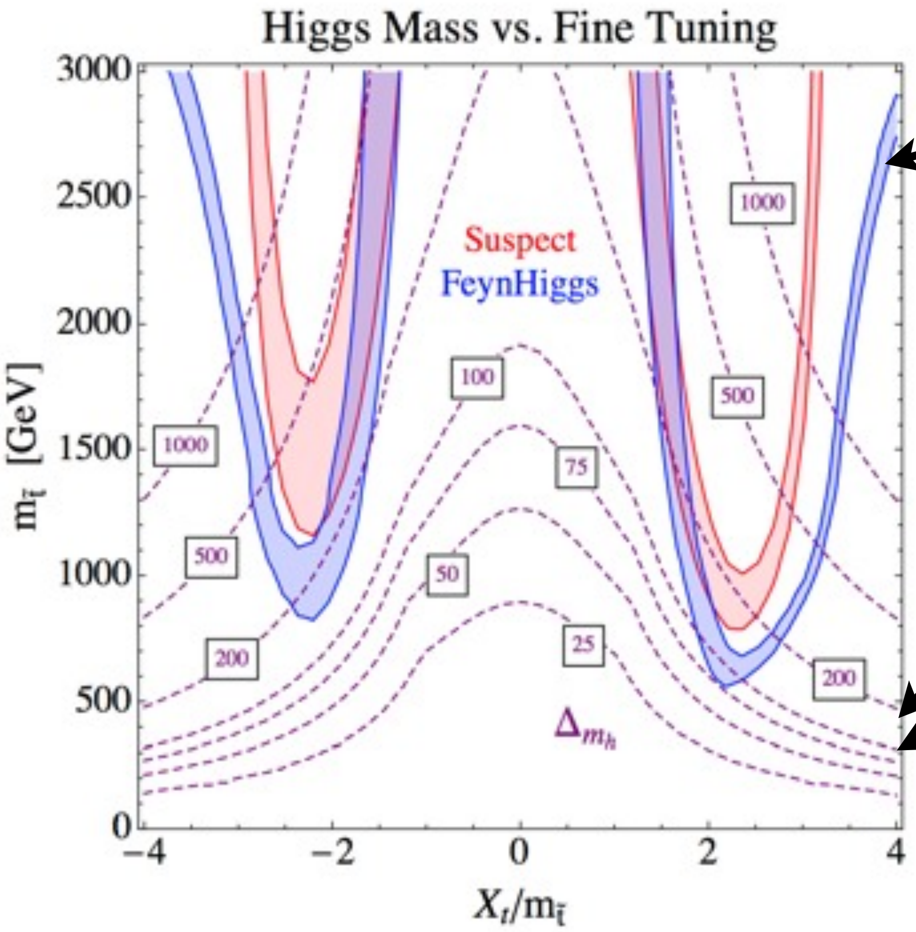
Fine-tuning worse than 1% seems unavoidable in MSSM.

126 GeV Higgs and naturalness

difficult to reconcile within MSSM

Fine-tuning worse than 1% seems unavoidable in MSSM.

L.J.Hall, D.Pinner, J.T.Ruderman, 1112.2703
(Λ_{mess} = 10 TeV is assumed.)



mh = 124-126 GeV

fine tuning 0.5 %

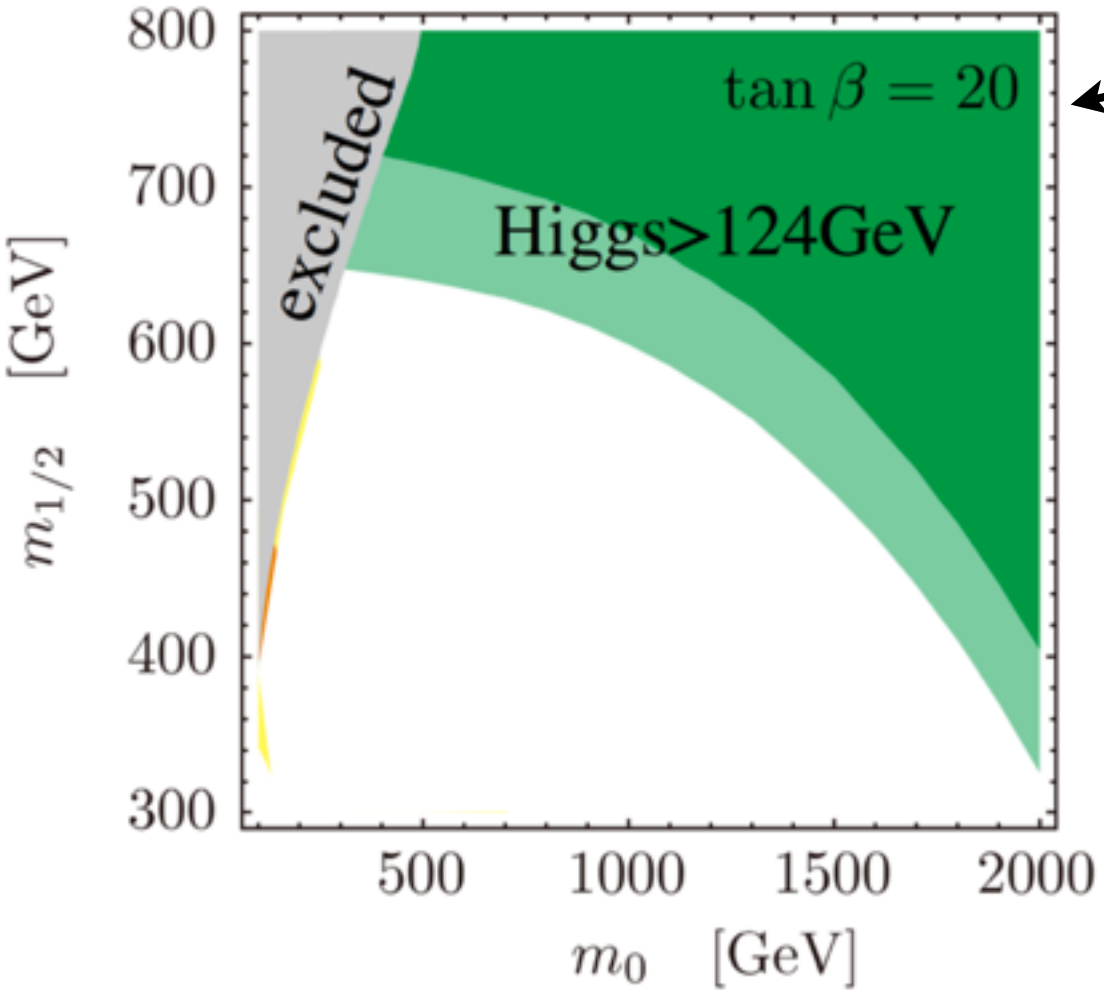
fine tuning 1%

(Exception: **Focus-point (-like) models:**
fine-tuning w.r.t. dimensionful parameters can be
ameliorated by "tuning" dimensionless parameters.)

126 GeV Higgs and naturalness

difficult to reconcile within MSSM

Fine-tuning worse than 1% seems unavoidable in MSSM.



example: CMSSM/mSUGRA
126 GeV Higgs can be realized
with light stop,
if maximally enhanced by A-term.
But,......

$$\delta m^2_{\rm Higgs} \propto \lambda_{\rm H}$$
$$\propto \frac{3y_t^4}{16\pi^2}\left(\log\left(\frac{m^2_{\rm stop}}{m_t^2}\right)+\alpha^2-\frac{\alpha^4}{12}\right)+\cdots$$

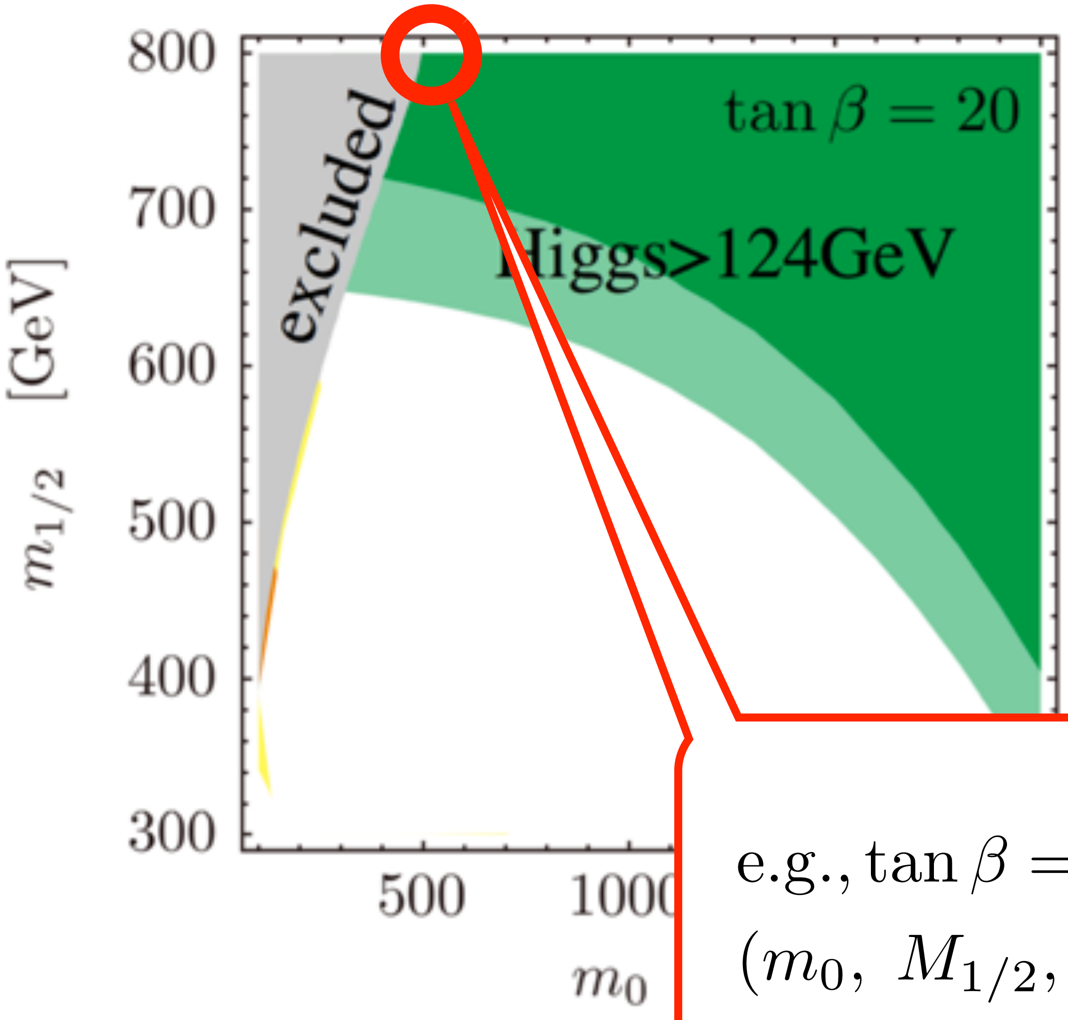
CMSSM/mSUGRA example: Higgs mass is maximized by A-term, while b -> sγ constraint is satisfied. (Thanks to Motoi Endo)

[See M.Endo, KH, S.Iwamoto, K.Nakayama, N.Yokozaki '11]

126 GeV Higgs and naturalness

difficult to reconcile within MSSM

Fine-tuning worse than 1% seems unavoidable in MSSM.



example: CMSSM/mSUGRA
126 GeV Higgs can be realized
with light stop,
if maximally enhanced by A-term.
But,…… **fine-tuned.**

e.g., $\tan\beta = 20,\ \mu > 0$

$(m_0,\ M_{1/2},\ A_0) = (500,\ 800,\ -2500)$ GeV,

$\rightarrow m_{\rm Higgs} = \mathbf{125.6 \pm 2.3}$ GeV (FeynHiggs) with $m_{\tilde{t}_1} = \mathbf{847}$ GeV

but $\mu = \mathbf{1520}$ GeV $\rightarrow$ **tuning $< 0.1\%$**

CMSSM/mSUGRA exampl
while b -> sγ constrain
[See M.Endo, KH, S.Iw

126 GeV Higgs and naturalness

difficult to reconcile within MSSM

Fine-tuning worse than 1% seems unavoidable in MSSM.

implies **Beyond MSSM models.**

126 GeV Higgs and naturalness

difficult to reconcile within MSSM

Fine-tuning worse than 1% seems unavoidable in MSSM.

implies **Beyond MSSM models.**

example: NMSSM $W_{\rm NMSSM} = \lambda_{\rm NMSSM} S H_u H_d$

$$\delta m^2_{\rm Higgs} \propto \lambda_{\rm H} \; (\simeq 0.13)$$

$$= \lambda_{\rm H}^{\rm (tree)} + \delta\lambda_{\rm H}^{\rm (loop)}$$

$$\lambda_{\rm H}^{\rm tree} \simeq \mathbf{0.069} \cos^2 2\beta + \frac{\lambda^{\mathbf{2}}_{\rm NMSSM}}{4} \sin^2 2\beta$$

can be large if $\begin{cases} \lambda^2_{\rm NMSSM} > O(0.1) \\ \text{and } \tan\beta \sim O(1) \end{cases}$

126 GeV Higgs and naturalness

difficult to reconcile within MSSM

Fine-tuning worse than 1% seems unavoidable in MSSM.

implies **Beyond MSSM models.**

example: NMSSM $W_{\rm NMSSM} = \lambda_{\rm NMSSM} S H_u H_d$

$$\delta m^2_{\rm Higgs} \propto \lambda_{\rm H} \; (\simeq 0.13)$$

$$= \lambda_{\rm H}^{\rm (tree)} + \delta\lambda_{\rm H}^{\rm (loop)}$$

$$\lambda_{\rm H}^{\rm tree} \simeq \mathbf{0.069} \cos^2 2\beta + \frac{\lambda^{\mathbf{2}}_{\rm NMSSM}}{4} \sin^2 2\beta$$

$$\text{can be large if} \begin{cases} \lambda^2_{\rm NMSSM} > O(0.1) \\ \text{and } \tan\beta \sim O(1) \end{cases}$$

See next talk by Kwang Sik Jeong!

126 GeV Higgs and naturalness

$$V(H) = -m^2 (H^\dagger H) + \lambda_{\mathrm{H}} (H^\dagger H)^2$$

$(89\ \mathrm{GeV})^2$

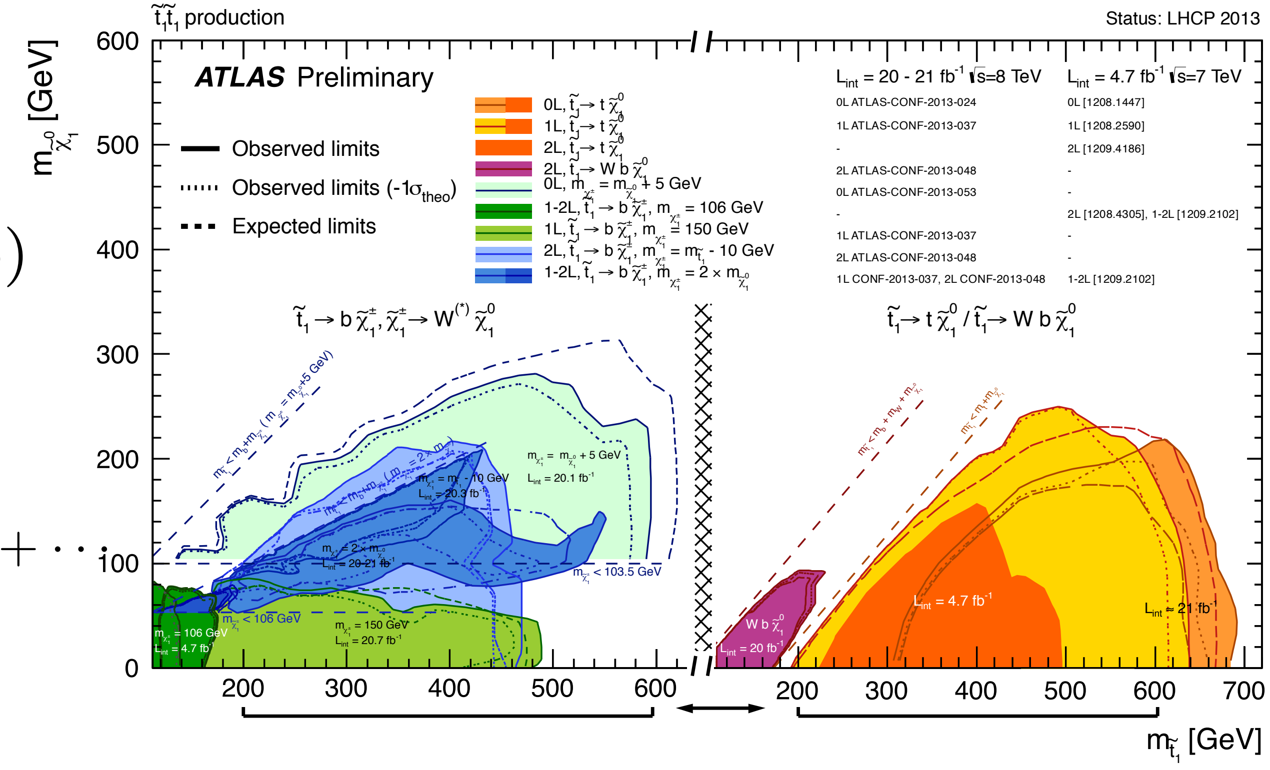
0.13

e.g., by NMSSM

In any case,...

$$-m^2 \simeq \underbrace{|\mu|^2}_{} + m_{H_u}^{2\,(\mathrm{tree})} + \delta m_{H_u}^{2\,(\mathrm{loop})}$$

$$\delta m_{H_u}^{2\,(\mathrm{loop})} \sim \frac{-3y_t^2}{8\pi^2}\underbrace{\left(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + |A_t|^2\right)}_{} \log\left(\frac{M_{\mathrm{mess}}}{m_{\tilde{t}}}\right) + \cdots$$



Naturalness requires **light Higgsino and light stop,** which are searched for at the **LHC**.

(If discovered, Higgsinos may be further studied at **ILC**.)

126 GeV Higgs and SUSY

Motivations of TeV scale SUSY.....

126 GeV Higgs + **naturalness**

126 GeV Higgs + **muon g-2**

126 GeV Higgs + **Dark Matter**

126 GeV Higgs + **Coupling Unification**

.....

126 GeV Higgs and SUSY

Motivations of TeV scale SUSY.....

126 GeV Higgs + **naturalness**

126 GeV Higgs + **muon g-2**

126 GeV Higgs + **Dark Matter**

126 GeV Higgs + **Coupling Unification**

.....

126 GeV Higgs and SUSY

Motivations of TeV scale SUSY.....

126 GeV Higgs + **naturalness**

126 GeV Higgs + **muon g-2**

based on recent works

M.Endo, KH, S.Iwamoto, N.Yokozaki, arXiv:**1108.3071, 1112.5653, 1202.2751**

M.Endo, KH, S.Iwamoto, K.Nakayama, N.Yokozaki, arXiv:**1112.6412**

M.Endo, KH, K.Ishikawa, S.Iwamoto, N.Yokozaki, arXiv:**1212.3935**

M.Endo, KH, S.Iwamoto, T.Yoshinaga, arXiv:**1303.4256**

M.Endo, KH, T.Kitahara, T.Yoshinaga, arXiv:**1306.xxxx (to appear soon)**

126 GeV Higgs + muon g-2

126 GeV Higgs + muon g-2

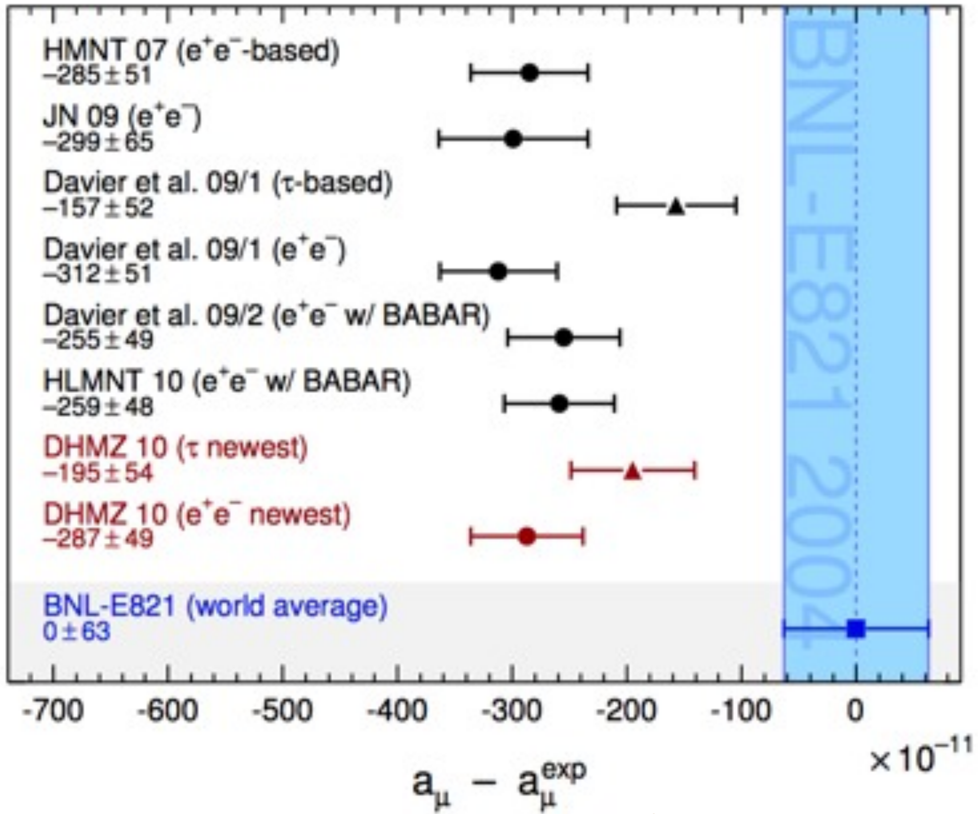
muon g-2

$$a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = (26.1 \pm 8.0) \cdot 10^{-10}$$

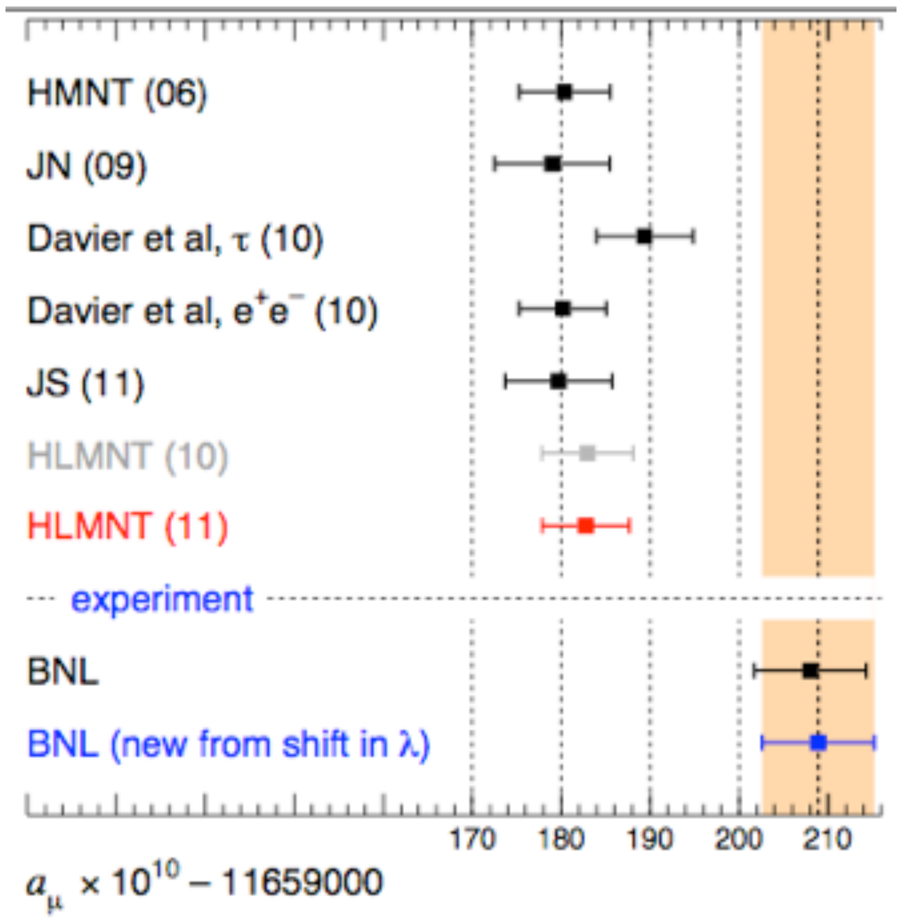
> 3σ deviation !

$$a_\mu^{\mathrm{EXP}} = 116\,592\,089(63) \cdot 10^{-11}$$

$$a_\mu^{\mathrm{SM}} = (11\,659\,182.8 \pm 4.9) \cdot 10^{-10}$$



Davier, Hoecker, Malaescu, Zhang: 1010:4180 + Refs. therein



Hagiwara, Liao, Martin, Nomura, Teubner: 1105.3149 + Refs. therein

126 GeV Higgs + muon g-2

muon g-2

$$a_\mu^{\rm EXP} = 116\,592\,089(63) \cdot 10^{-11}$$

$$a_\mu^{\rm SM} = (11\,659\,182.8 \pm 4.9) \cdot 10^{-10}$$

$$a_\mu^{\rm EXP} - a_\mu^{\rm SM} = (26.1 \pm 8.0) \cdot 10^{-10}$$

> 3σ deviation !

... maybe it's just a statistical fluctuation...

(it's one of many SM tests...)

... and/or maybe theoretical uncertainty is underestimated...

(e.g., hadronic light-by-light contribution...)

... maybe it's a signature of BSM physics !!

126 GeV Higgs + muon g-2

muon g-2

$$a_\mu^{\mathrm{EXP}} = 116\,592\,089(63) \cdot 10^{-11}$$

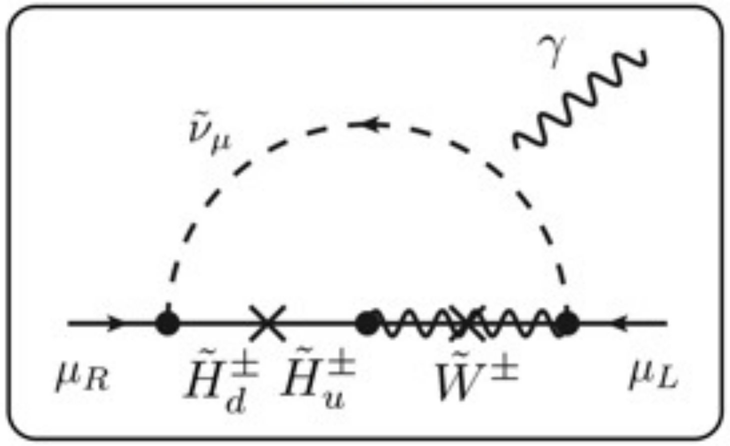
$$a_\mu^{\mathrm{SM}} = (11\,659\,182.8 \pm 4.9) \cdot 10^{-10}$$

$$a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = (26.1 \pm 8.0) \cdot 10^{-10}$$

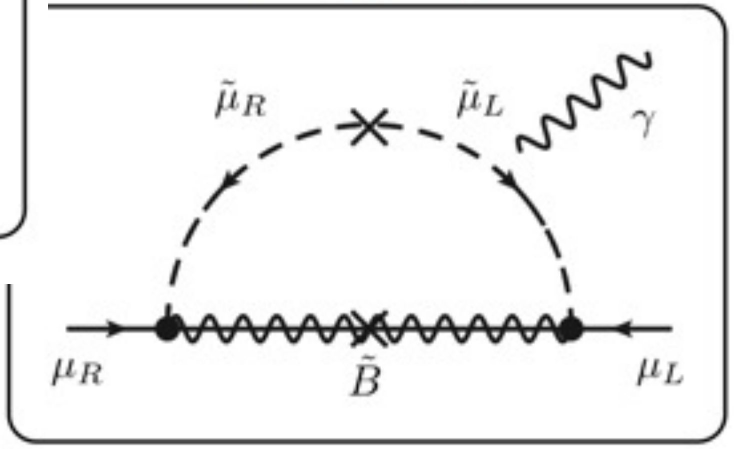
> 3σ deviation !

...can be explained by SUSY.

chargino



neutralino



... if smuon and chargino/neutralino are O(100 GeV).

126 GeV Higgs + muon g-2

However, . . .

heavy stop

light smuon/ inos

difficult to reconcile in typical models

(mSUGRA/GMSB/AMSB/NMSSM (small $\tan\beta$) ...)

126 GeV Higgs + muon g-2

However, ...

heavy stop

light smuon/ inos

difficult to reconcile in typical models

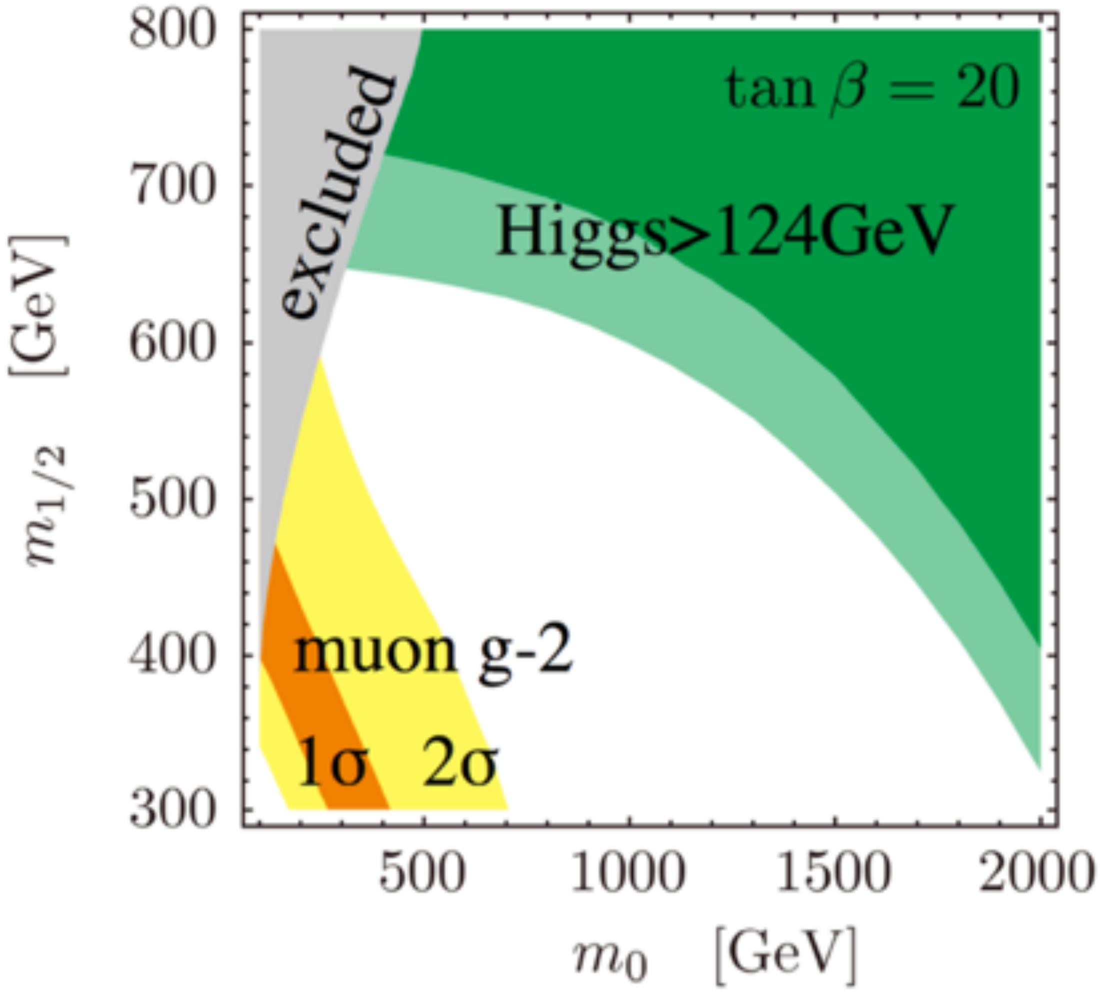
(mSUGRA/GMSB/AMSB/NMSSM (small tanβ) ...)

Example in CMSSM/mSUGRA:

Higgs mass is maximized by A-term, while b -> sγ constraint is satisfied.

(Figure thanks to Motoi Endo.)

[See M.Endo, KH, S.Iwamoto, K.Nakayama, N.Yokozaki '11]



126 GeV Higgs + muon g-2

However, ...

heavy stop

light smuon/ inos

difficult to reconcile in typical models

(mSUGRA/GMSB/AMSB/NMSSM (small tanβ) ...)

2 approaches

(1) general MSSM

(2) model building

126 GeV Higgs + muon g-2

However, . . .

heavy stop

light smuon/ inos

difficult to reconcile in typical models

(mSUGRA/GMSB/AMSB/NMSSM (small tanβ) ...)

2 approaches

(1) general MSSM

(2) model building

"g-2 motivated" MSSM

$$m_{\tilde{q}} \gg m_{\tilde{\ell}},\ m_{\tilde{\chi}^{\pm}},\ m_{\tilde{\chi}^{0}},$$

>> 1 TeV
to explain
Higgs mass

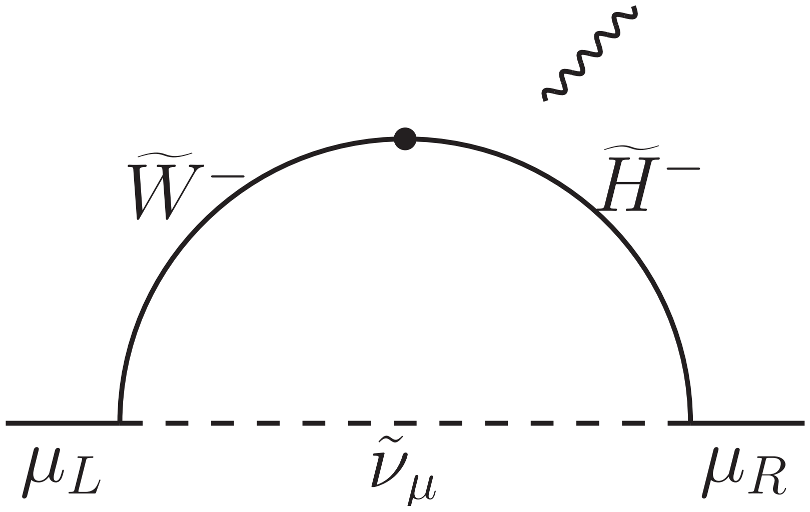
= O(100 GeV)
to explain muon g-2

Can we test it ??

"g-2 motivated" MSSM

two representative parameter regions

Case1



Chargino contribution

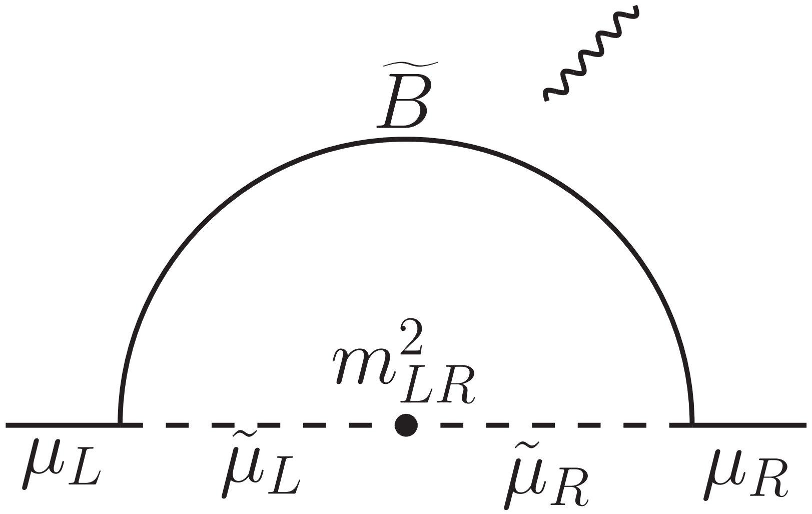
(usually dominant)

enhanced when

Higgsino, Wino, smuon(L)

are light.

Case2



Neutralino contribution

(subdominant)

enhanced when

Bino, smuon(L+R)

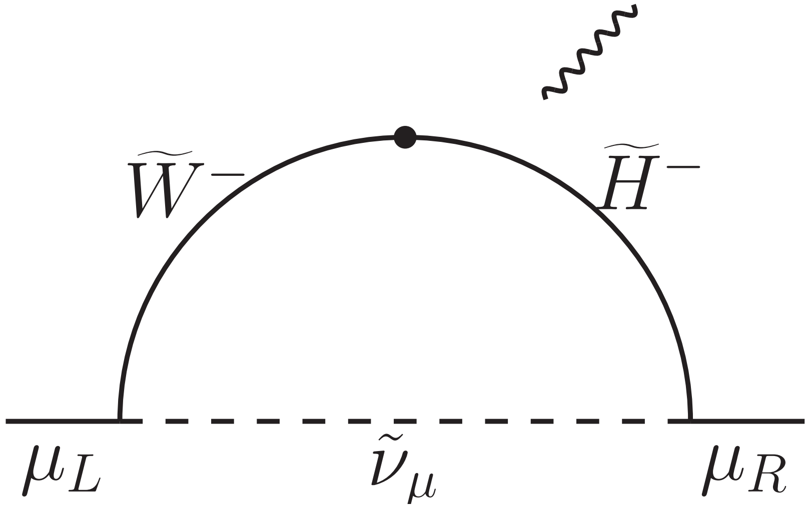
are light

(and μ is large).

“g-2 motivated” MSSM

two representative parameter regions

Case1



Chargino contribution

(usually dominant)

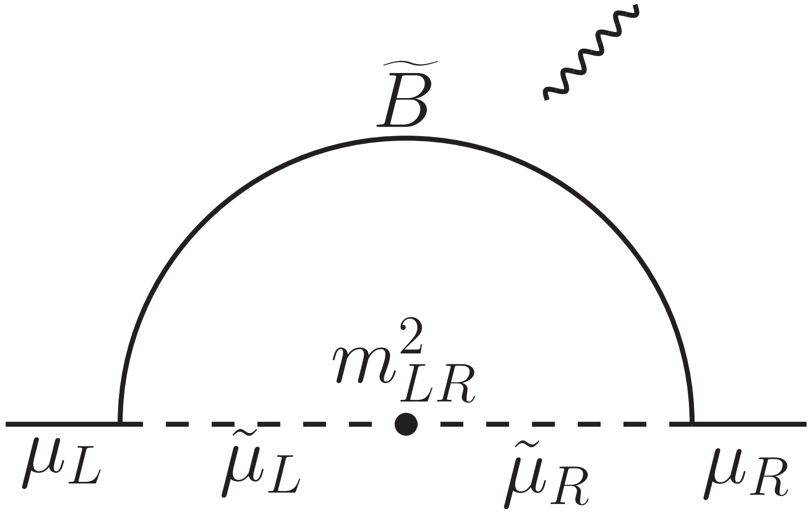
enhanced when

Higgsino, Wino, smuon(L)

are light.

small μ

Case2



Neutralino contribution

(subdominant)

enhanced when

Bino, smuon(L+R)

are light

(and μ is large).

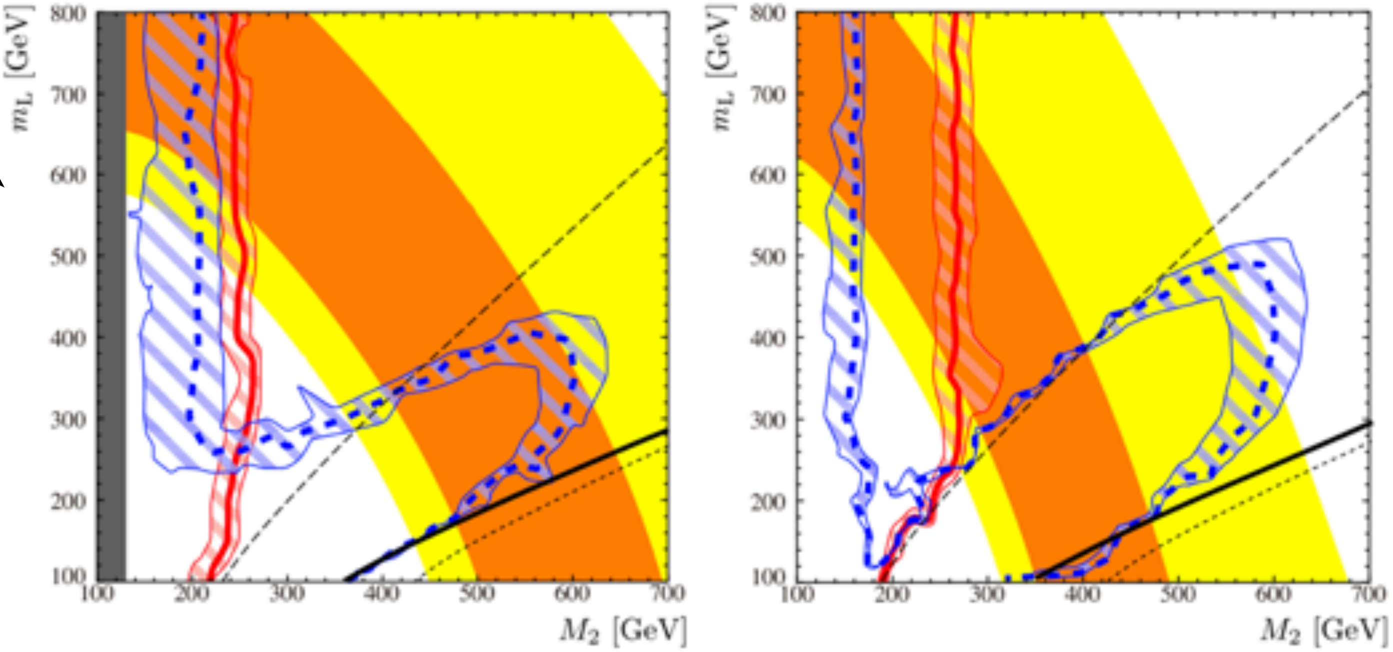
“g-2 motivated” MSSM

M.Endo, KH, S.Iwamoto, T.Yoshinaga [1303.4256]

Results

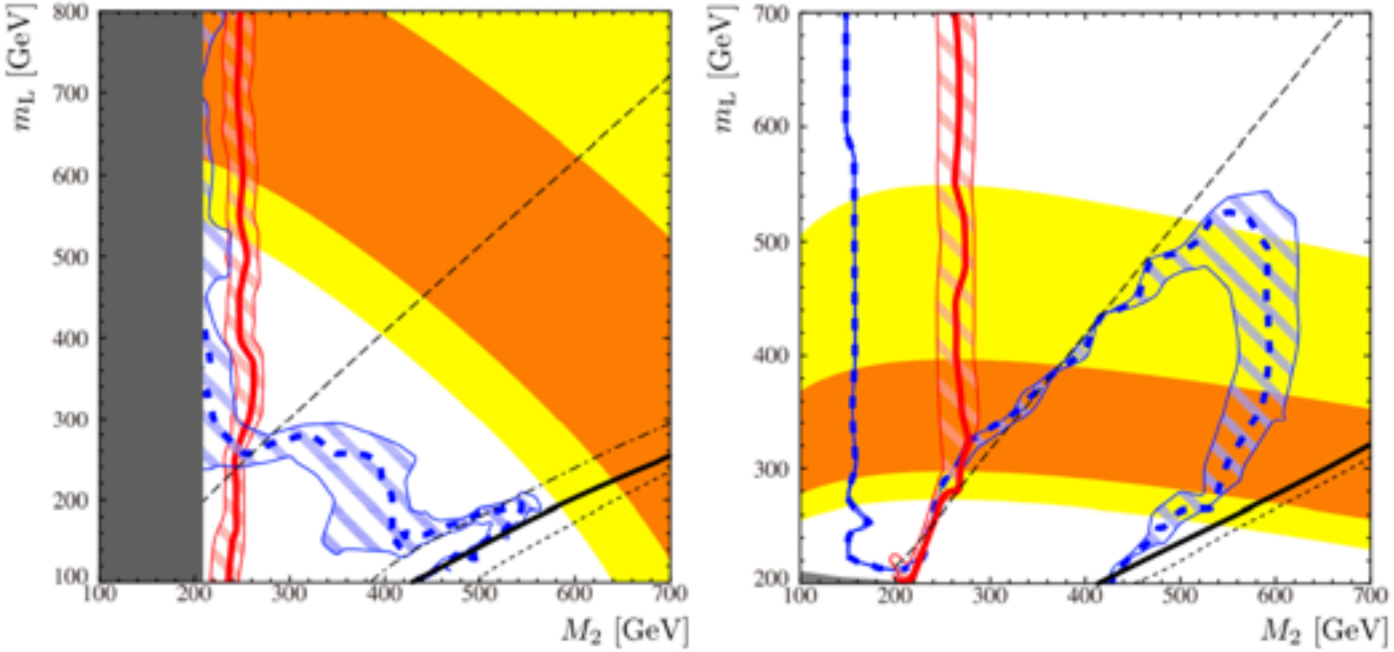
$M_2 = 2M_1$ assumed

slepton_L mass



(a) $\mu = M_2$, $m_R = 3\,\mathrm{TeV}$

(b) $\mu = 2M_2$, $m_R = 3\,\mathrm{TeV}$



(c) $\mu = M_2/2$, $m_R = 3\,\mathrm{TeV}$

(d) $\mu = 2\,\mathrm{TeV}$, $m_R = 1.5m_L$

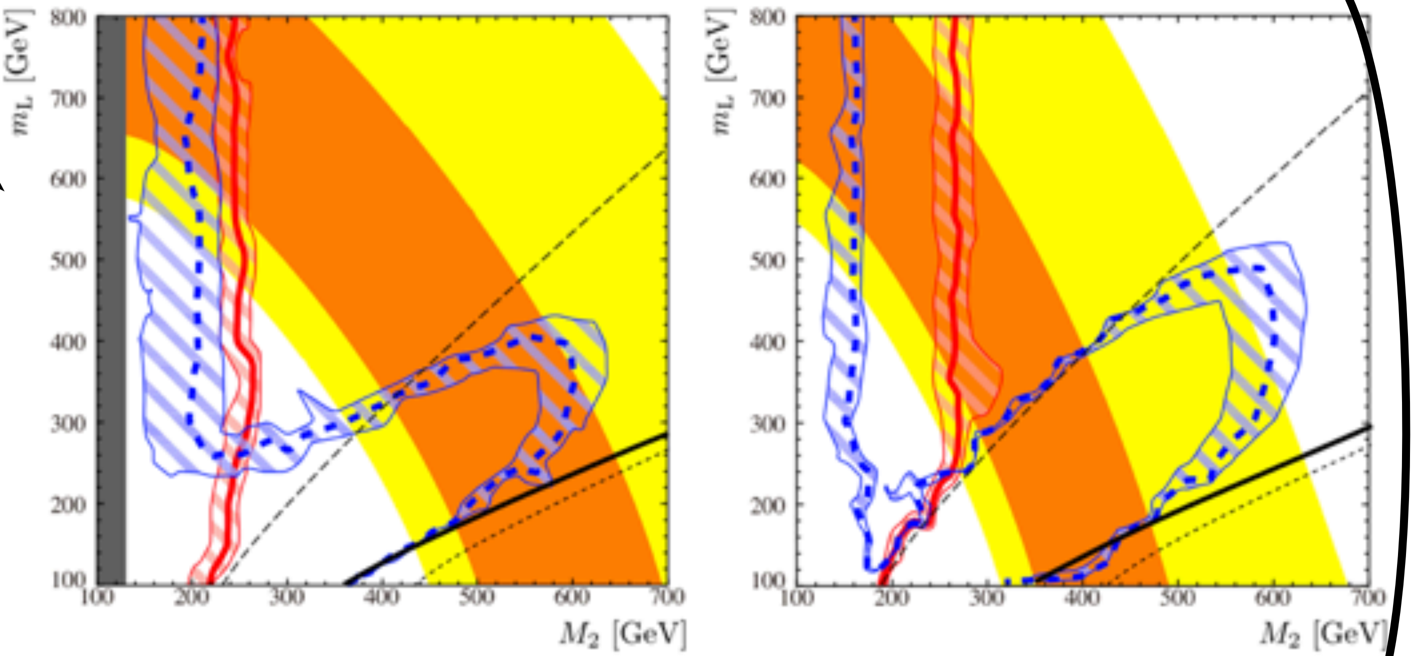
wino mass

“g-2 motivated” MSSM

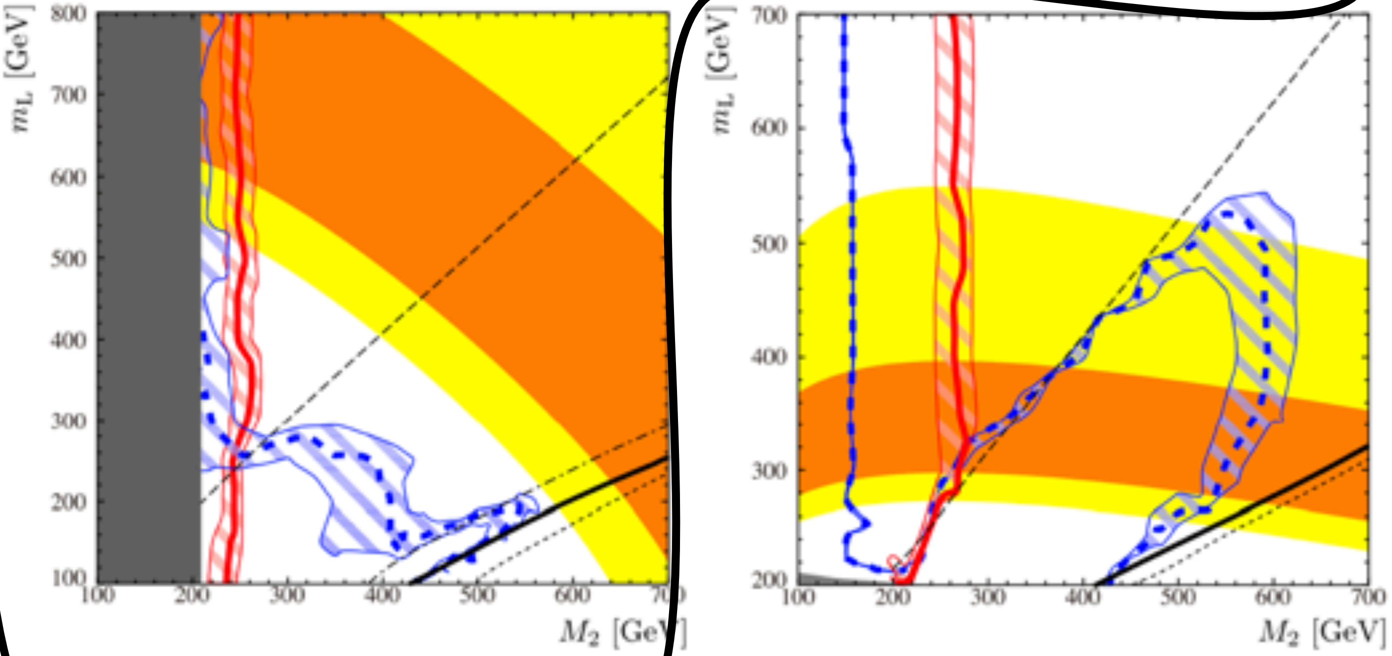
M.Endo, KH, S.Iwamoto, T.Yoshinaga [1303.4256]

Results

$M_2 = 2M_1$ assumed



(a) $\mu = M_2$, $m_R = 3\,\mathrm{TeV}$ (b) $\mu = 2M_2$, $m_R = 3\,\mathrm{TeV}$



(c) $\mu = M_2/2$, $m_R = 3\,\mathrm{TeV}$ (d) $\mu = 2\,\mathrm{TeV}$, $m_R = 1.5m_L$

light

Wino, Higgsino, smuon(L).

slepton_L mass

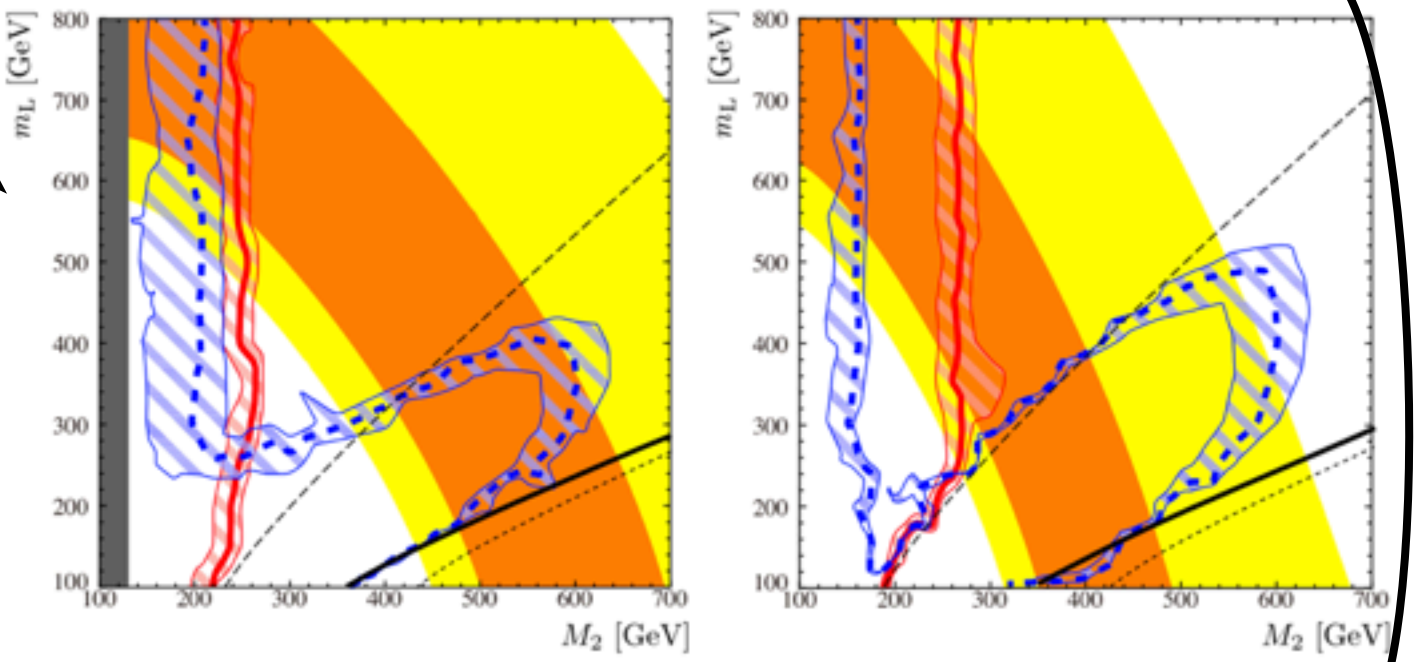
wino mass

"g-2 motivated" MSSM

M.Endo, KH, S.Iwamoto, T.Yoshinaga [1303.4256]

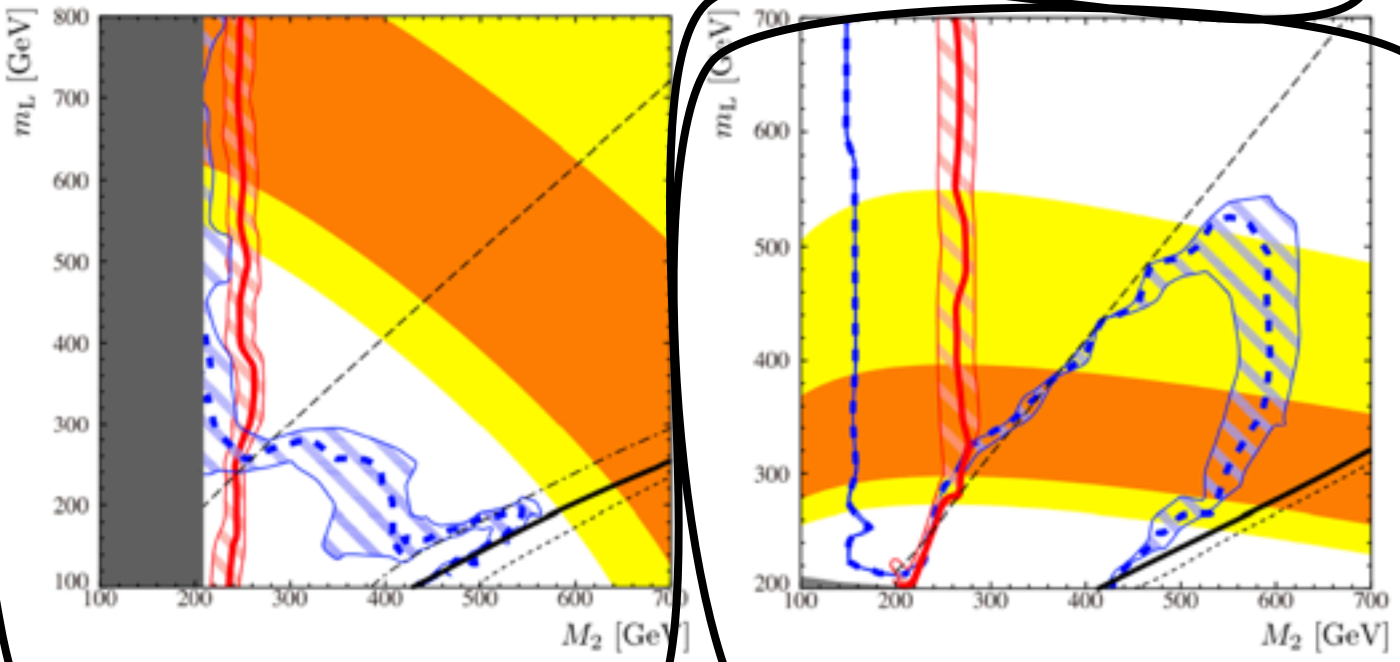
Results

$M_2 = 2M_1$ assumed



(a) $\mu = M_2$, $m_R = 3\,\mathrm{TeV}$

(b) $\mu = 2M_2$, $m_R = 3\,\mathrm{TeV}$



(c) $\mu = M_2/2$, $m_R = 3\,\mathrm{TeV}$

(d) $\mu = 2\,\mathrm{TeV}$, $m_R = 1.5 m_L$

slepton_L mass

wino mass

light

Wino, Higgsino, smuon(L).

light

Bino, smuon(L+R),

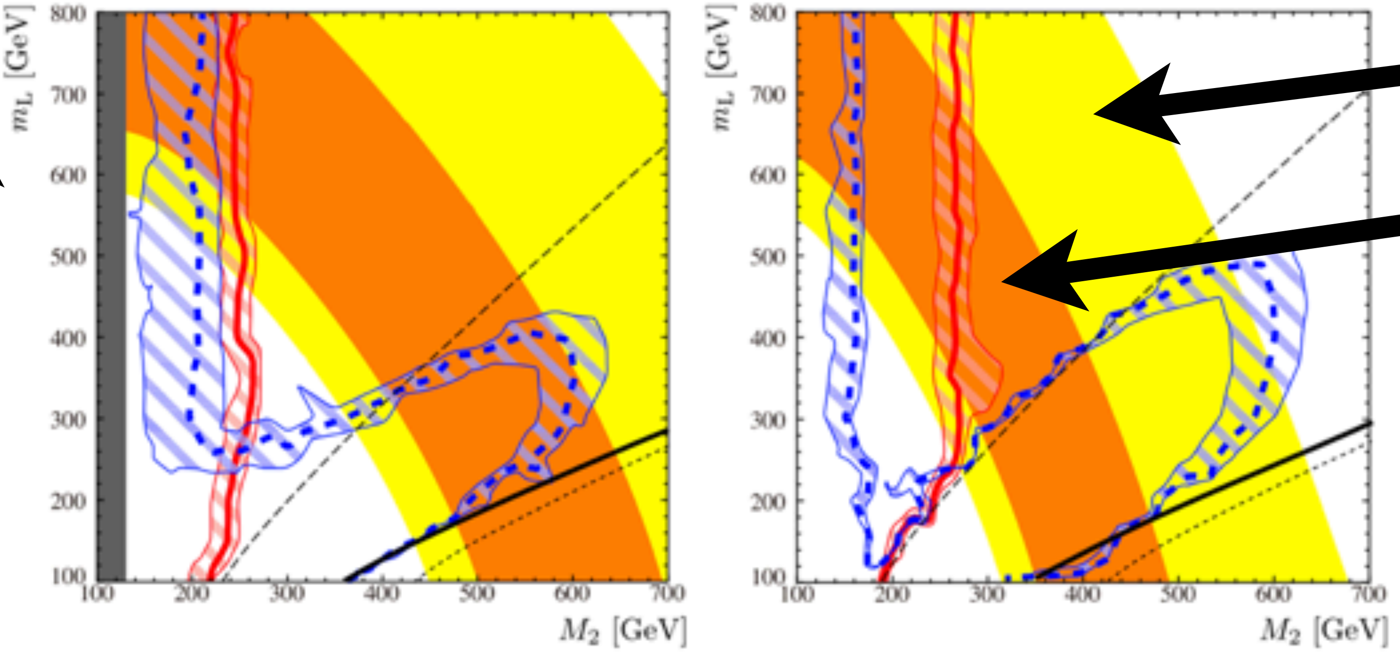
+ large μ.

“g-2 motivated” MSSM

M.Endo, KH, S.Iwamoto, T.Yoshinaga [1303.4256]

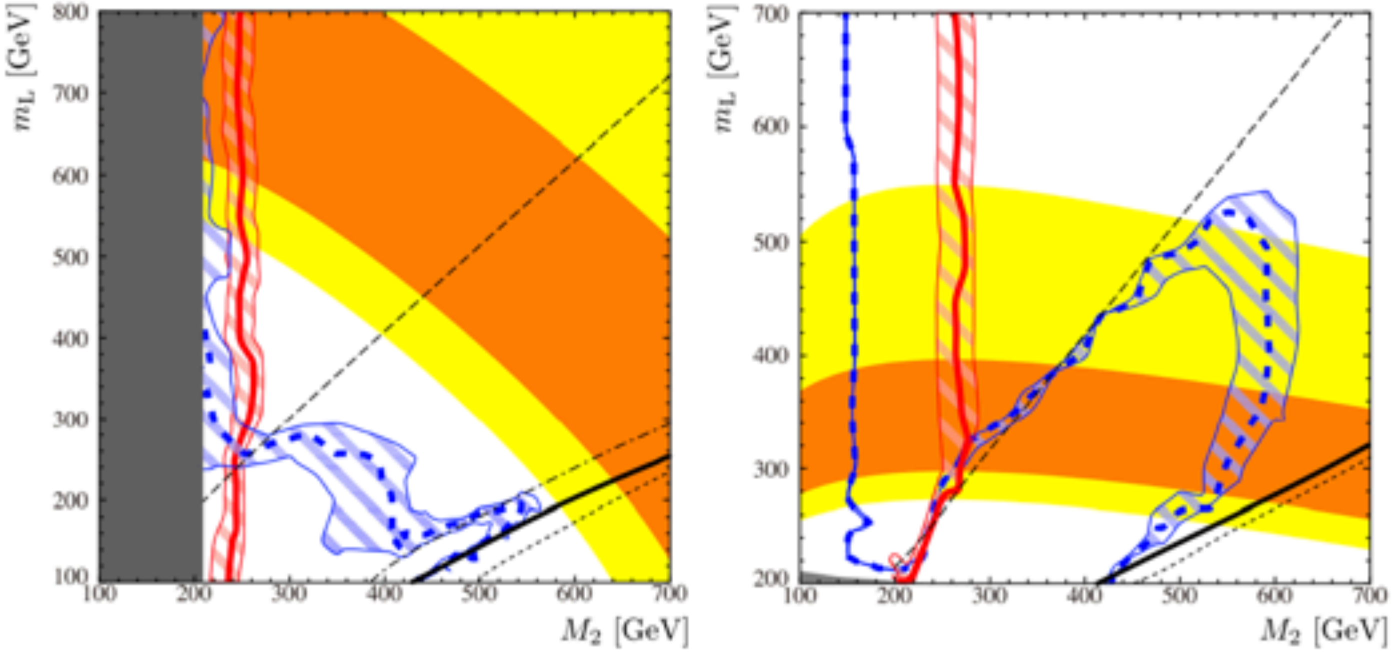
Results

$M_2 = 2M_1$ assumed



(a) $\mu = M_2$, $m_R = 3\,\mathrm{TeV}$

(b) $\mu = 2M_2$, $m_R = 3\,\mathrm{TeV}$



(c) $\mu = M_2/2$, $m_R = 3\,\mathrm{TeV}$

(d) $\mu = 2\,\mathrm{TeV}$, $m_R = 1.5 m_L$

muon g-2: 2σ

1σ

slepton_L mass

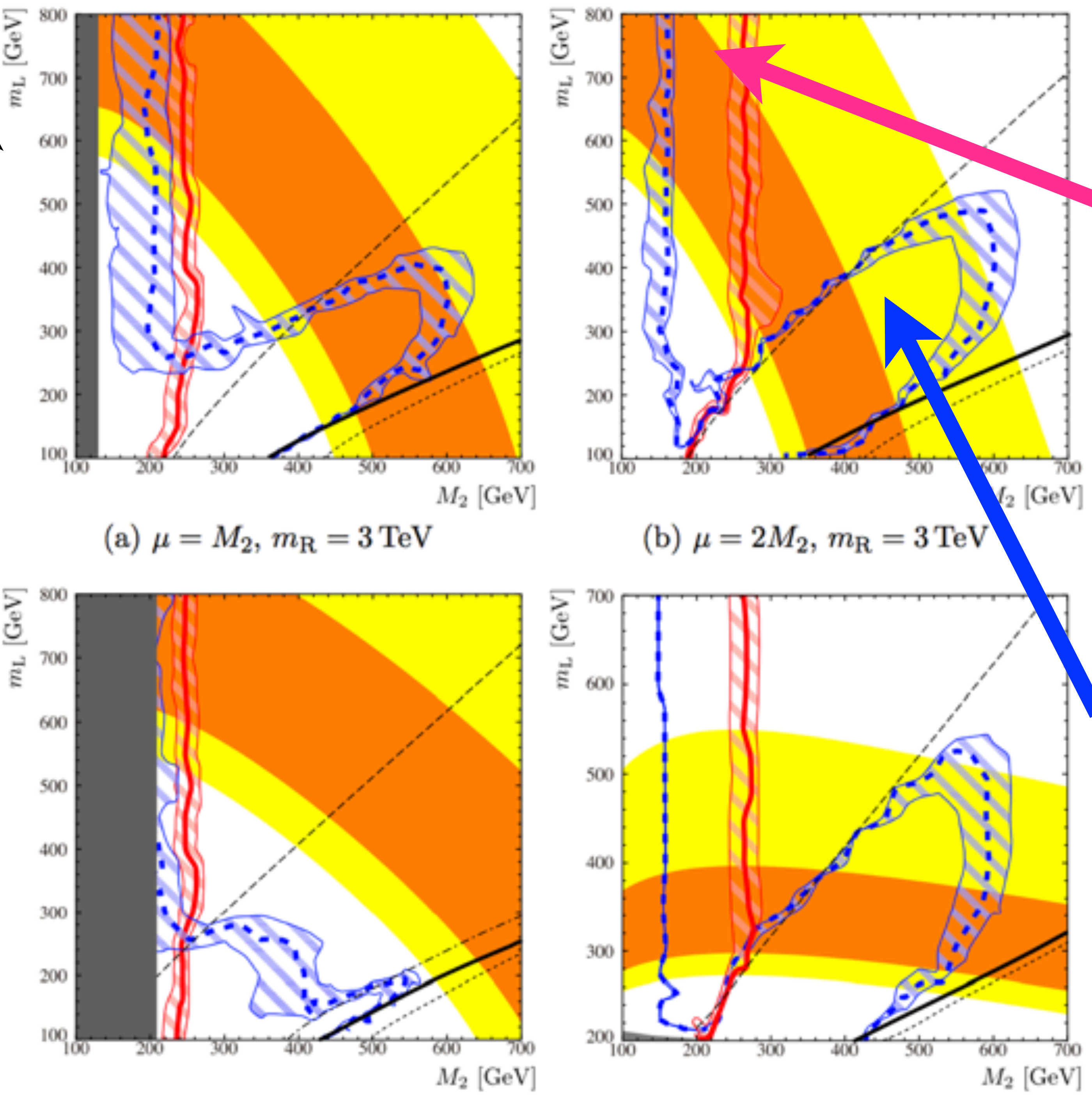
wino mass

“g-2 motivated” MSSM

M.Endo, KH, S.Iwamoto, T.Yoshinaga [1303.4256]

Results

$M_2 = 2M_1$ assumed



(a) $\mu = M_2$, $m_R = 3\,\mathrm{TeV}$

(b) $\mu = 2M_2$, $m_R = 3\,\mathrm{TeV}$

(c) $\mu = M_2/2$, $m_R = 3\,\mathrm{TeV}$

(d) $\mu = 2\,\mathrm{TeV}$, $m_R = 1.5m_L$

slepton_L mass

wino mass

when GUT relation $M_1:M_2:M_3 = 1:2:6$ holds,

this region is excluded by **jets + missing pT search.** (We interpreted ATLAS $5.8\mathrm{fb}^{-1}$@8TeV result.)

even if gluino is heavy

this region is excluded by **3-lepton search.** (ATLAS $13\mathrm{fb}^{-1}$@8TeV.)

$$pp \to \tilde{\chi}\tilde{\chi} \to \ell\tilde{\ell}\,\ell\tilde{\ell} \to \ell\ell\tilde{\chi}\,\ell\ell\tilde{\chi}$$

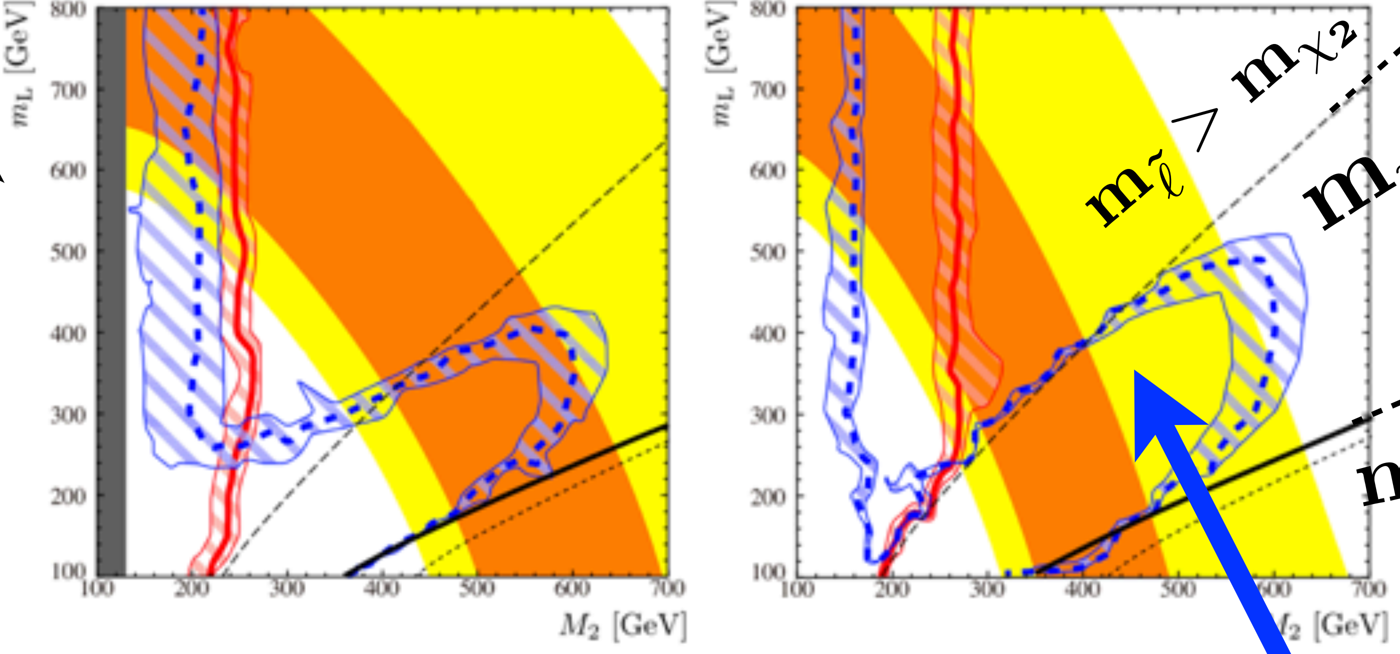
"g-2 motivated" MSSM

M.Endo, KH, S.Iwamoto, T.Yoshinaga [1303.4256]

Results

$M_2 = 2M_1$ assumed

slepton_L mass



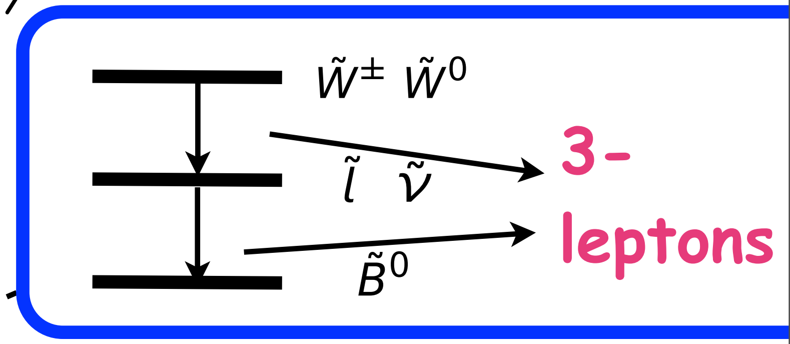
(a) $\mu = M_2,\ m_R = 3\,\mathrm{TeV}$

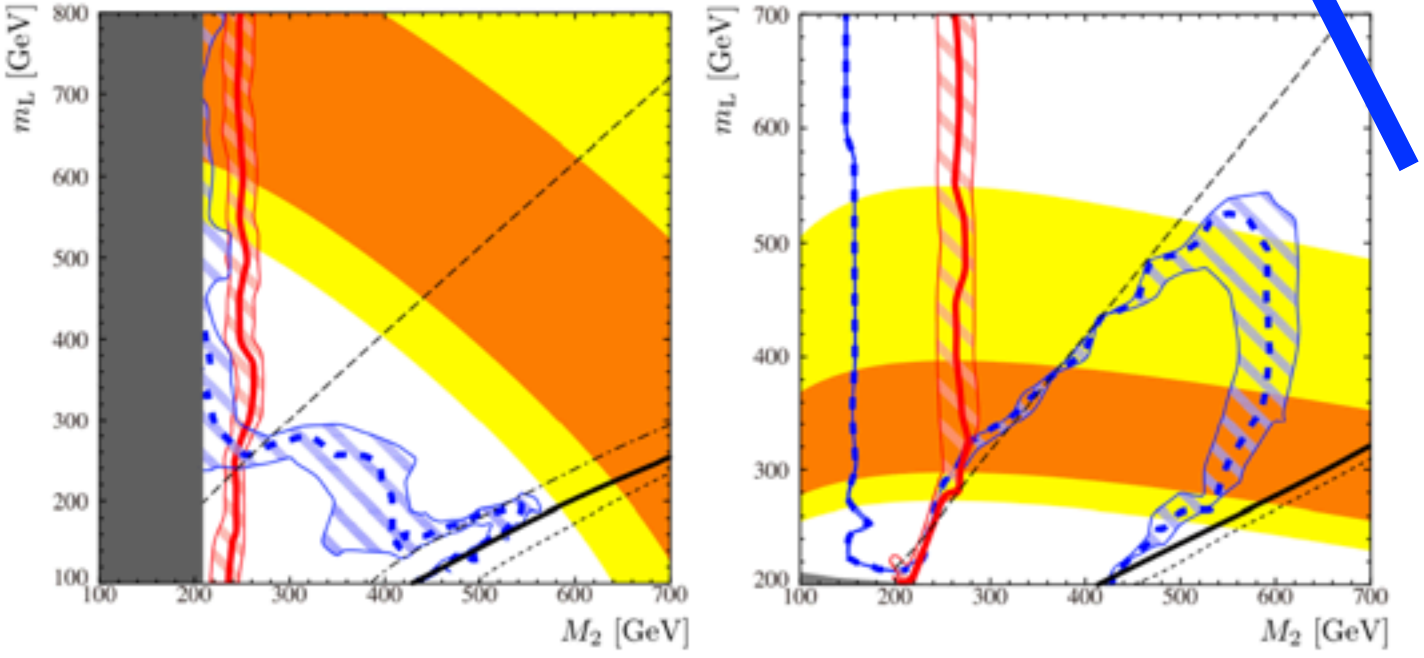
(b) $\mu = 2M_2,\ m_R = 3\,\mathrm{TeV}$

$\mathbf{m_{\tilde{\ell}} > m_{\chi_2} > m_{\chi_1}}$

$\mathbf{m_{\chi_2} > m_{\tilde{\ell}} > m_{\chi_1}}$

$\mathbf{m_{\chi_2} > m_{\chi_1} > m_{\tilde{\ell}}}$





(c) $\mu = M_2/2,\ m_R = 3\,\mathrm{TeV}$

(d) $\mu = 2\,\mathrm{TeV},\ m_R = 1.5m_L$

even if gluino is heavy

this region is excluded by

3-lepton search.

(ATLAS 13fb^{-1}@8TeV.)

$$pp \to \tilde{\chi}\tilde{\chi} \to \ell\tilde{\ell}\,\ell\tilde{\ell} \to \ell\ell\tilde{\chi}\,\ell\ell\tilde{\chi}$$

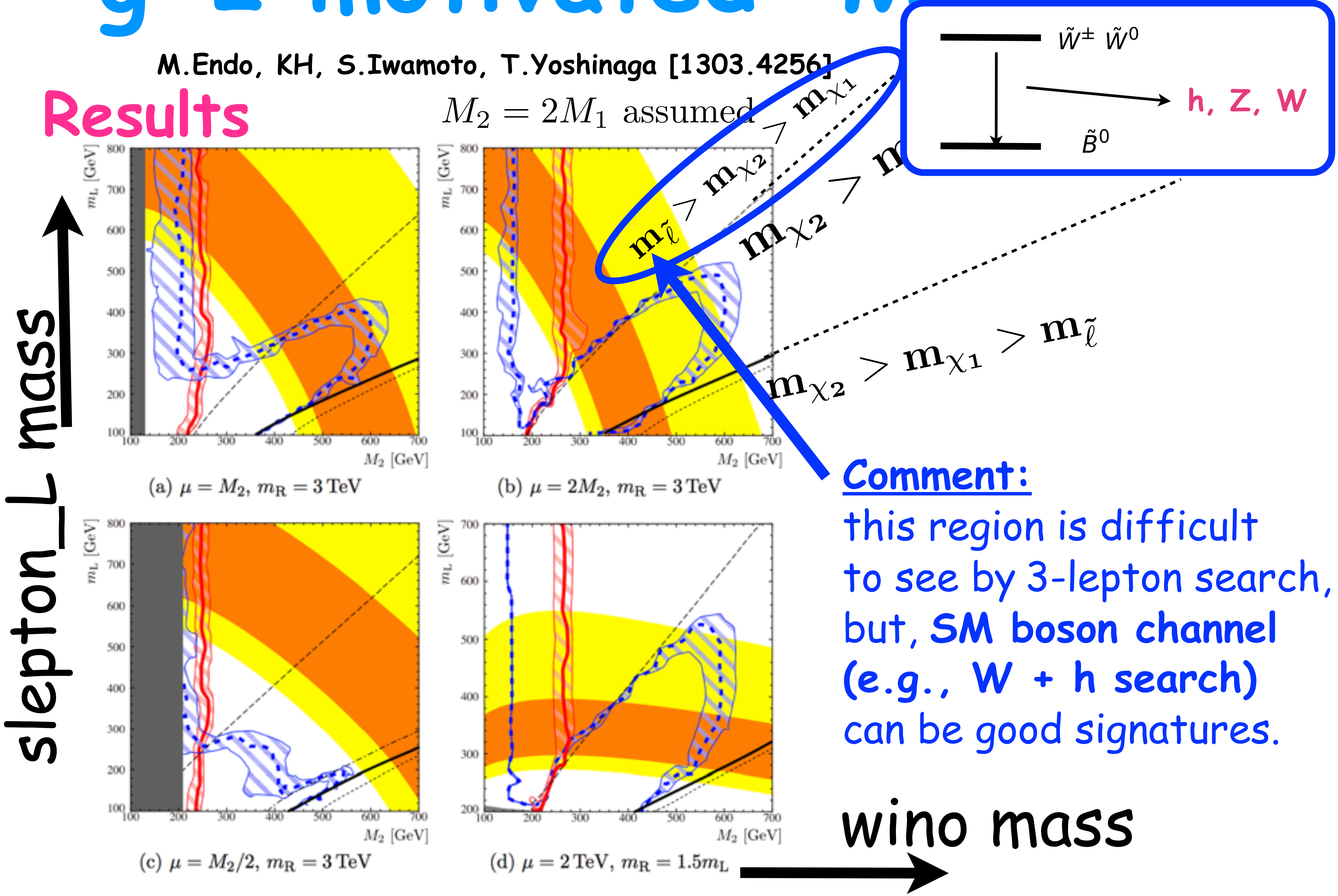
wino mass

“g-2 motivated” MSSM

M.Endo, KH, S.Iwamoto, T.Yoshinaga [1303.4256]

Results

$M_2 = 2M_1$ assumed



(a) $\mu = M_2$, $m_R = 3\,\mathrm{TeV}$

(b) $\mu = 2M_2$, $m_R = 3\,\mathrm{TeV}$

(c) $\mu = M_2/2$, $m_R = 3\,\mathrm{TeV}$

(d) $\mu = 2\,\mathrm{TeV}$, $m_R = 1.5 m_L$

Comment:

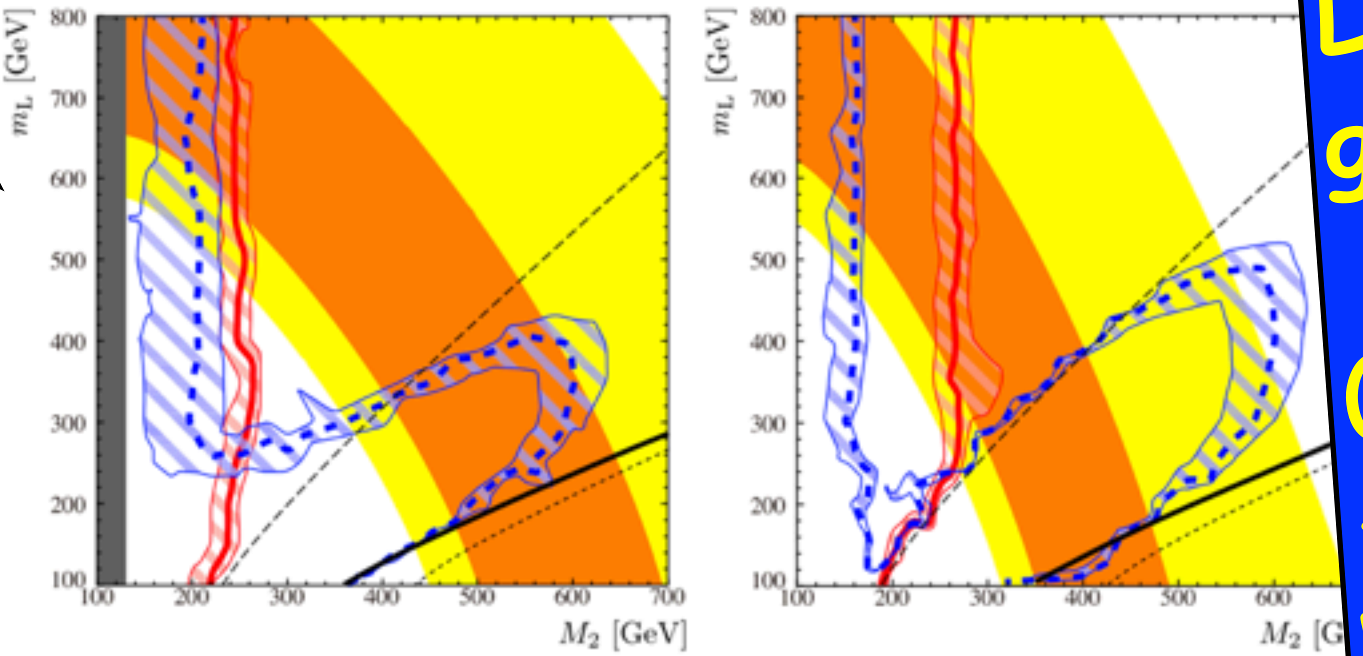
this region is difficult to see by 3-lepton search, but, **SM boson channel (e.g., W + h search)** can be good signatures.

"g-2 motivated" MSSM

M.Endo, KH, S.Iwamoto, T.Yoshinaga [1303.4256]

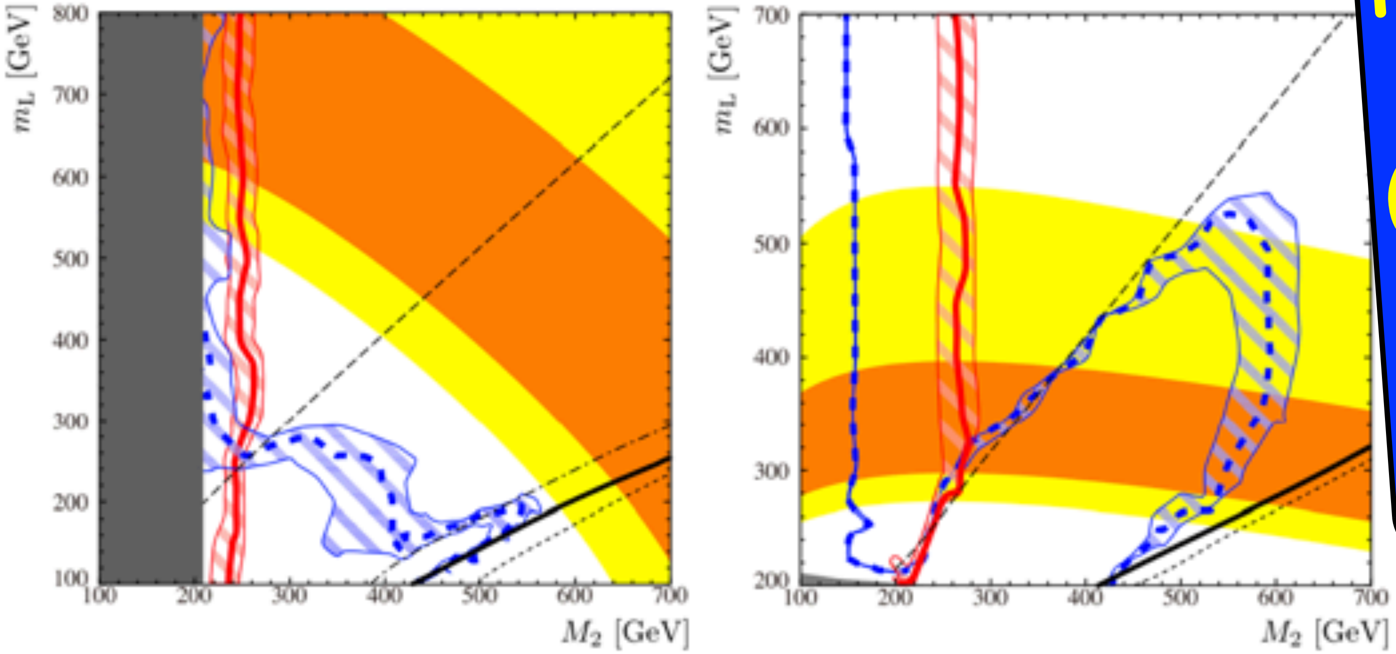
Results

$M_2 = 2M_1$ assume



(a) $\mu = M_2$, $m_R = 3\,\mathrm{TeV}$

(b) $\mu = 2M_2$, $m_R = 3\,\mathrm{TeV}$



(c) $\mu = M_2/2$, $m_R = 3\,\mathrm{TeV}$

(d) $\mu = 2\,\mathrm{TeV}$, $m_R = 1.5 m_L$

slepton_L mass

wino mass

LHC started exclude
g-2 motivated regions !

(1) If discovered at LHC,
--> further test at ILC
whether they are really
responsible for the g-2.

(2) Some regions are
difficult to cover at LHC.
--> ILC may cover them.

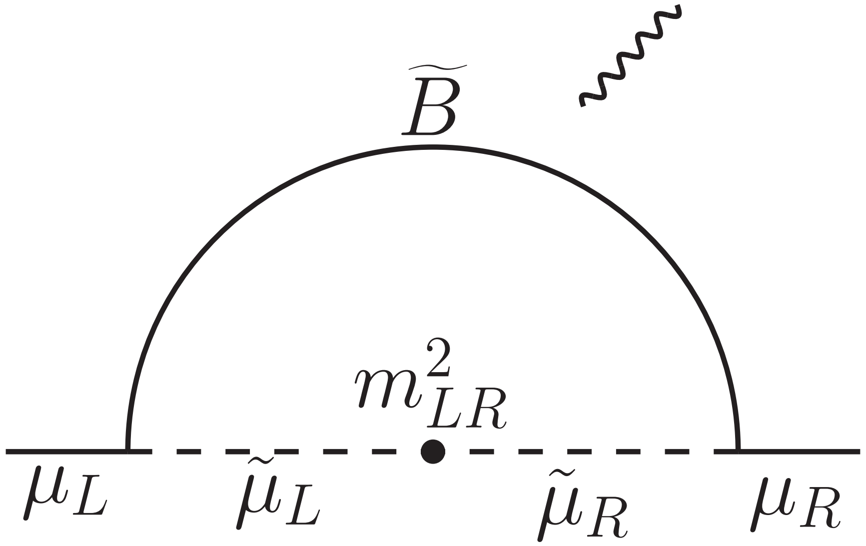
(What is the minimal set of particles that can explain muon g-2 ?)

M.Endo, KH, T.Kitahara, T.Yoshinaga [1306.xxxx]

minimal "g-2 motivated" MSSM

only smuon(L), smuon(R), and Bino are light.

(and μ is large)



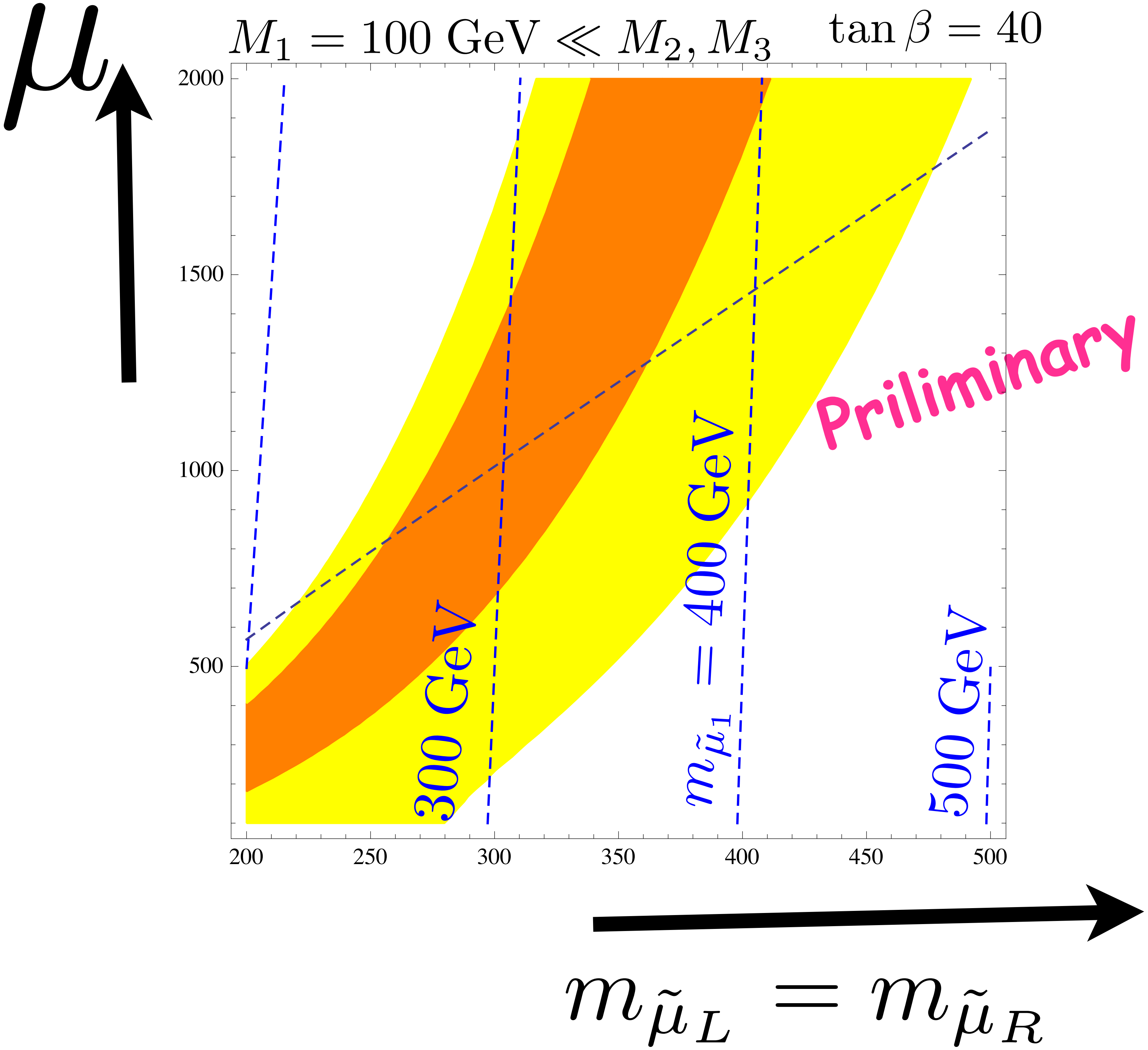
(What is the minimal set of particles that can explain muon g-2 ?)

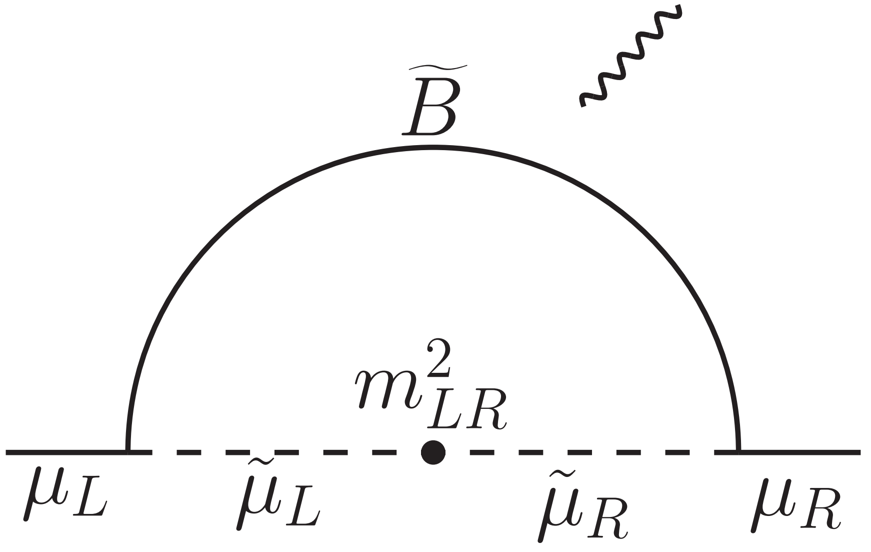
M.Endo, KH, T.Kitahara, T.Yoshinaga [1306.xxxx]

minimal "g-2 motivated" MSSM

only smuon(L), smuon(R), and Bino are light.

(and μ is large)





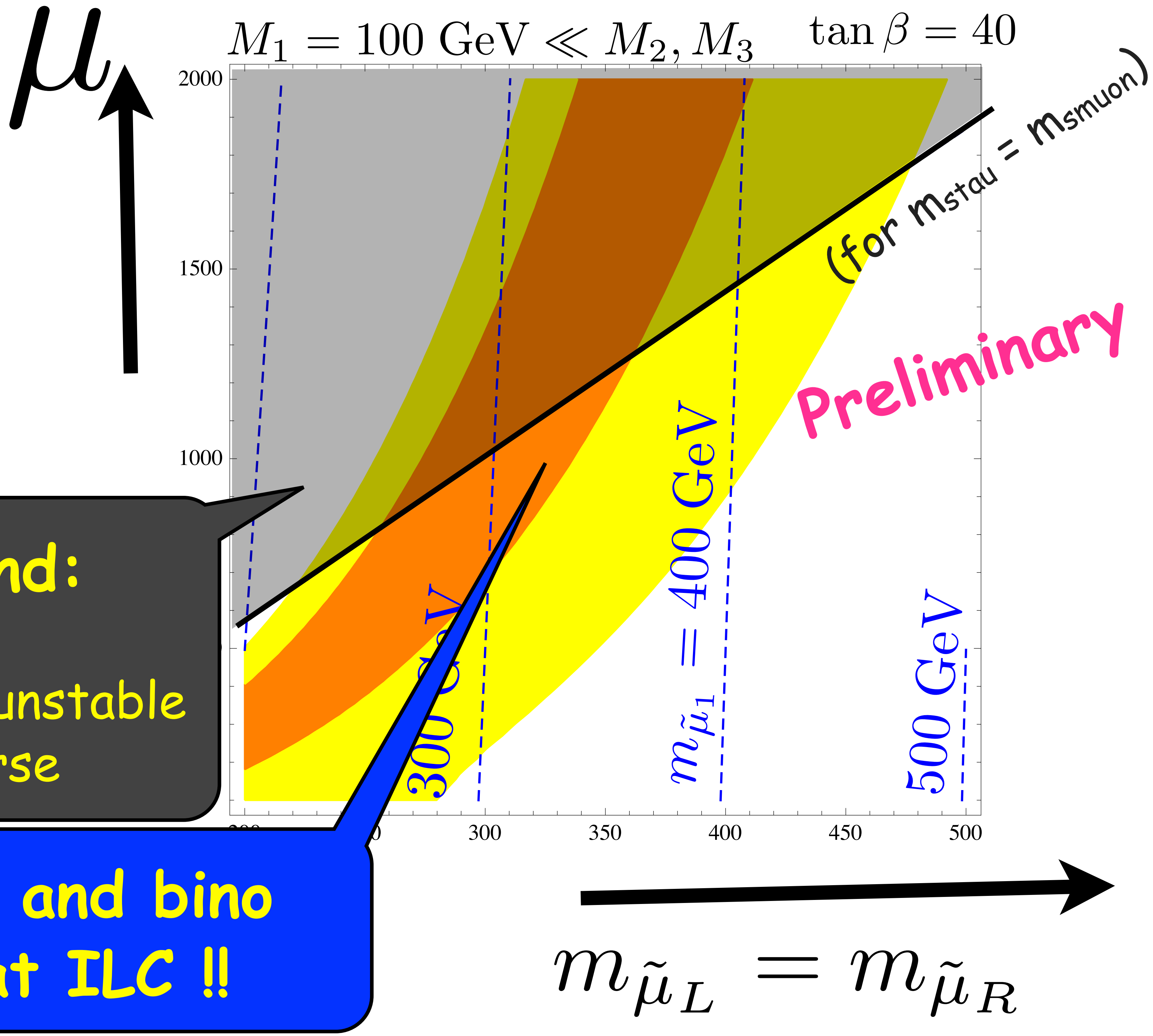
(What is the minimal set of particles that can explain muon g-2 ?)

M.Endo, KH, T.Kitahara, T.Yoshinaga [1306.xxxx]

minimal "g-2 motivated" MSSM

only smuon(L), smuon(R), and Bino are light.

(and μ is large)



Vacuum stability bound:

(too large μ

--> slepton-Higgs potential unstable

--> Lifetime < Age of Universe

O(100 GeV) slepton and bino

... may be tested at ILC !!

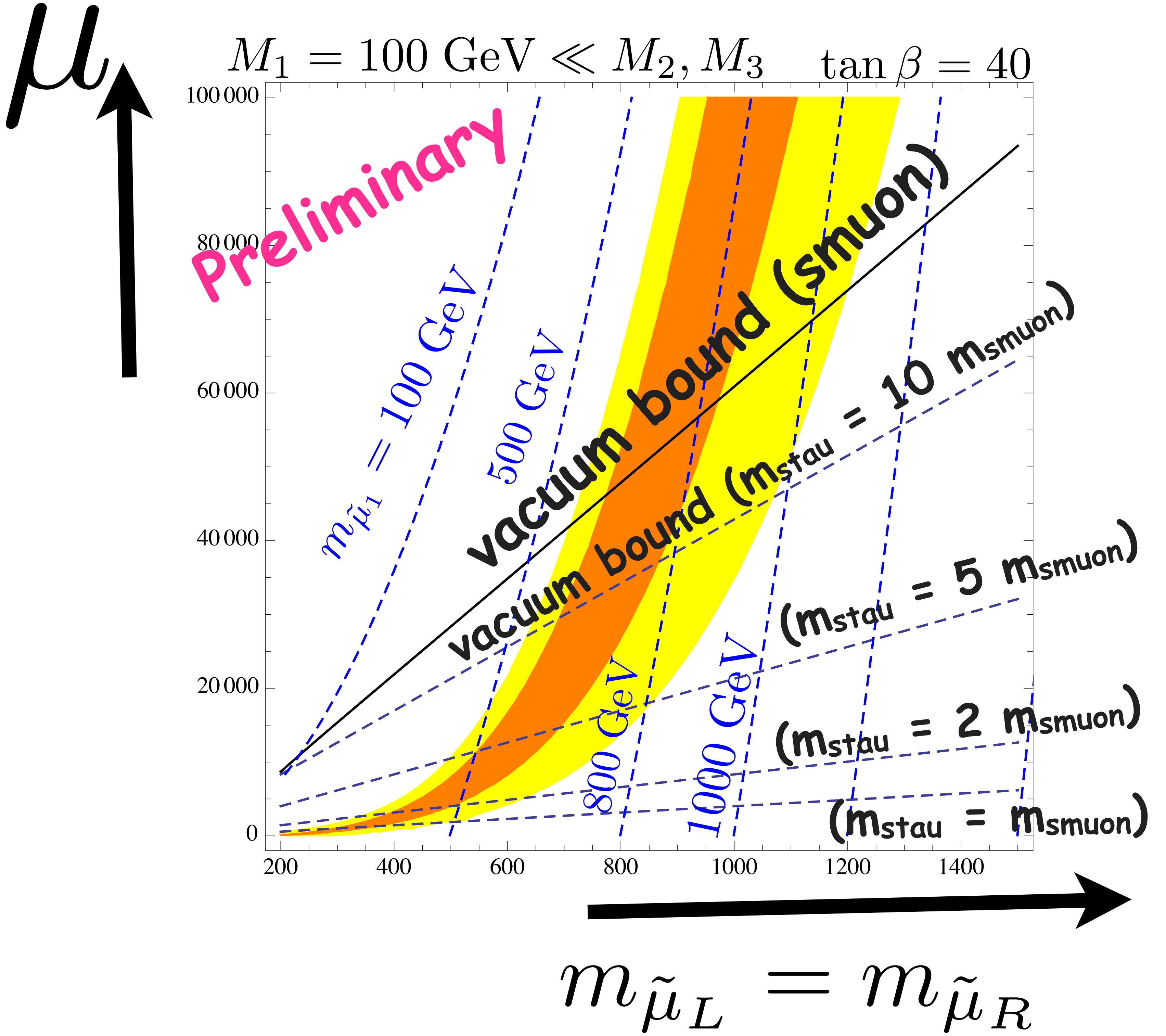
(What is the minimal set of particles that can explain muon g-2 ?)

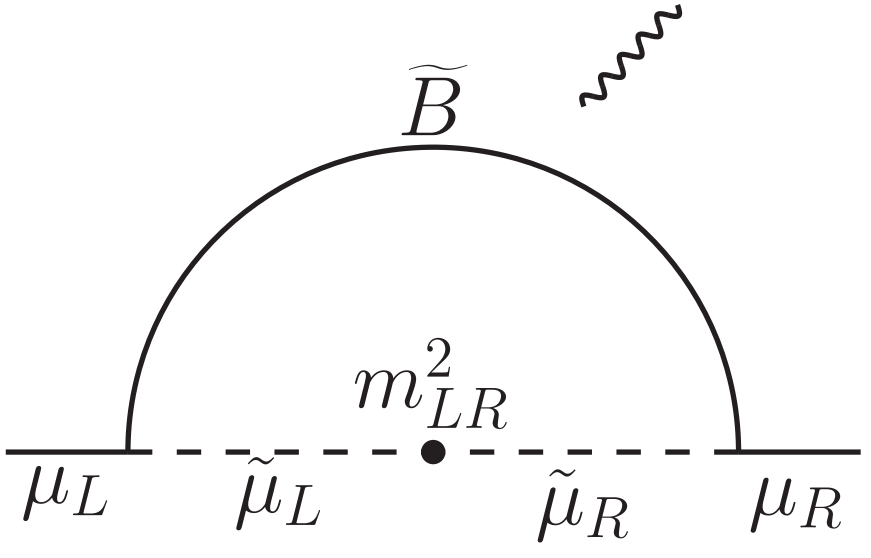
M.Endo, KH, T.Kitahara, T.Yoshinaga [1306.xxxx]

minimal "g-2 motivated" MSSM

only smuon(L), smuon(R), Bino are light.

(and μ is large)





126 GeV Higgs + muon g-2

heavy stop

light smuon/ inos

difficult to reconcile in typical models

(mSUGRA/GMSB/AMSB/NMSSM (small $\tan\beta$) ...)

2 approaches

(1) general MSSM

(2) model building

126 GeV Higgs + muon g-2

heavy stop

light smuon/ inos

difficult to reconcile in typical models

(mSUGRA/GMSB/AMSB/NMSSM (small $\tan\beta$) ...)

2 approaches

(1) general MSSM

(2) model building

126 GeV Higgs + muon g-2

heavy stop

light smuon/ inos

difficult to reconcile in typical models

(mSUGRA/GMSB/AMSB/NMSSM (small tanβ) ...)

(2) model building

MSSM + vector-like matter Endo,KH,Iwamoto,Yokozaki,+Ishikawa,'11-12, Moroi,Sato,Yanagida,'11, Sato,Tobioka,Yokozaki,'12, Nakayama,Yokozaki,'12,...

MSSM + U(1) Endo,KH,Iwamoto,Nakayama,Yokozaki'11,...

split family Ibe,Yanagida,Yokozaki,'13,...

modified GMSB Evans,Ibe,Shirai,Yanagida,'12, Ibe,Matsumoto,Yanagida,Yokozaki'12,...

non-universal gaugino Mohanty,Rao,Roy,'13,...

other models.....

126 GeV Higgs + muon g-2

heavy stop

light smuon/ inos

difficult to reconcile in typical models

(mSUGRA/GMSB/AMSB/NMSSM (small $\tan\beta$) ...)

(2) model building

MSSM + vector-like matter Endo,KH,Iwamoto,Yokozaki,+Ishikawa,'11-12, Moroi,Sato,Yanagida,'11, Sato,Tobioka,Yokozaki,'12, Nakayama,Yokozaki,'12,...

MSSM + U(1) Endo,KH,Iwamoto,Nakayama,Yokozaki'11,...

split family Ibe,Yanagida,Yokozaki,'13,...

modified GMSB Evans,Ibe,Shirai,Yanagida,'12, Ibe,Matsumoto,Yanagida,Yokozaki'12,...

non-universal gaugino Mohanty,Rao,Roy,'13,...

other models.....

126 GeV Higgs + muon g-2

MSSM + vector-like matter

Idea:

In MSSM, Y_{top} (and A_{top}) raises the Higgs mass.

$$W = Y_{top} Q_3 U_3 H u$$

$$\delta m^2_{\rm Higgs} \propto \lambda_{\rm H} \ (\simeq 0.13)$$
$$= \lambda_{\rm H}^{\rm (tree)} + \delta\lambda_{\rm H}^{\rm (loop)} \longleftarrow$$

$$\delta\lambda_{\rm H}^{\rm (loop)} \propto Y_{\rm top}^4 \cdot (\text{top, stop-loop})$$

126 GeV Higgs + muon g-2

MSSM + vector-like matter

Idea:

In MSSM, $Y_{\rm top}$ (and $A_{\rm top}$) raises the Higgs mass.

--> Add **new vector-like matters (10+10bar)**

with a Yukawa coupling to Higgs.

$$W = Y_{\rm top}\, Q_3 U_3 H_u + Y' Q' U' H_u$$

[Okada,Moroi,'92;.....Babu,Gogoladze,Rehman,Shafi,'08; Martin,'09]

$$\delta m^2_{\rm Higgs} \propto \lambda_{\rm H}\ (\simeq 0.13)$$
$$= \lambda_{\rm H}^{\rm (tree)} + \delta\lambda_{\rm H}^{\rm (loop)}$$

$$\delta\lambda_{\rm H}^{\rm (loop)} \propto Y_{\rm top}^4 \cdot (\text{top, stop-loop}) + \mathbf{Y'^4} \cdot (\text{new vector-loop})$$

126 GeV Higgs + muon g-2

MSSM + vector-like matter

Setup

Add vector-like 10=(Q′,U′,E′) and $\overline{10}$=($\overline{Q}'$,$\overline{U}'$,$\overline{E}'$).

$$W = Y'Q'U'H_u + M_{Q'}\overline{Q}'Q' + M_{U'}\overline{U}'U' + M_{E'}\overline{E}'E'$$

(and corresponding soft terms)

---> new contribution to the Higgs mass

$$\boxed{\Delta m_h^2 \simeq \frac{3Y'^4 v^2}{4\pi^2}\left[\ln\frac{m_S^2}{m_F^2} - \frac{1}{6}\left(1-\frac{m_F^2}{m_S^2}\right)\left(5-\frac{m_F^2}{m_S^2}\right) + \frac{A'^2}{m_S^2}\left(1-\frac{m_F^2}{3m_S^2}\right) - \frac{1}{12}\frac{A'^4}{m_S^4}\right]}$$

[mF (mS) are fermion (scalar) masses of vectors.
2-loop effect can be large.]

126 GeV Higgs + muon g-2

MSSM + vector-like matter

$$\Delta m_h^2 \simeq \frac{3Y'^4 v^2}{4\pi^2}\left[\ln\frac{m_S^2}{m_F^2} - \frac{1}{6}\left(1-\frac{m_F^2}{m_S^2}\right)\left(5-\frac{m_F^2}{m_S^2}\right) + \frac{A'^2}{m_S^2}\left(1-\frac{m_F^2}{3m_S^2}\right) - \frac{1}{12}\frac{A'^4}{m_S^4}\right]$$

can be large for mF << mS and Y'≈ 1.

126 GeV Higgs + muon g-2

MSSM + vector-like matter

$$\Delta m_h^2 \simeq \frac{3Y'^4 v^2}{4\pi^2}\left[\ln\frac{m_S^2}{m_F^2} - \frac{1}{6}\left(1-\frac{m_F^2}{m_S^2}\right)\left(5-\frac{m_F^2}{m_S^2}\right) + \frac{A'^2}{m_S^2}\left(1-\frac{m_F^2}{3m_S^2}\right) - \frac{1}{12}\frac{A'^4}{m_S^4}\right]$$

can be large for mF << mS and Y'≈ 1.

comments:

1. vector-like fermion mass mF:

We take $M_{Q'} = M_{U'}\ (= M_{E'}) \sim 1$ TeV.

- Higgs production changes only a few %.
- Corrections to EW precision is small.
- LHC bound is also evaded.

126 GeV Higgs + muon g-2

MSSM + vector-like matter

$$\Delta m_h^2 \simeq \frac{3Y'^4 v^2}{4\pi^2}\left[\ln\frac{m_S^2}{m_F^2} - \frac{1}{6}\left(1-\frac{m_F^2}{m_S^2}\right)\left(5-\frac{m_F^2}{m_S^2}\right) + \frac{A'^2}{m_S^2}\left(1-\frac{m_F^2}{3m_S^2}\right) - \frac{1}{12}\frac{A'^4}{m_S^4}\right]$$

can be large for mF << mS and Y’≈ 1.

comments:

2. RGEs of Y’ and A’ have quasi-fixed points.

12

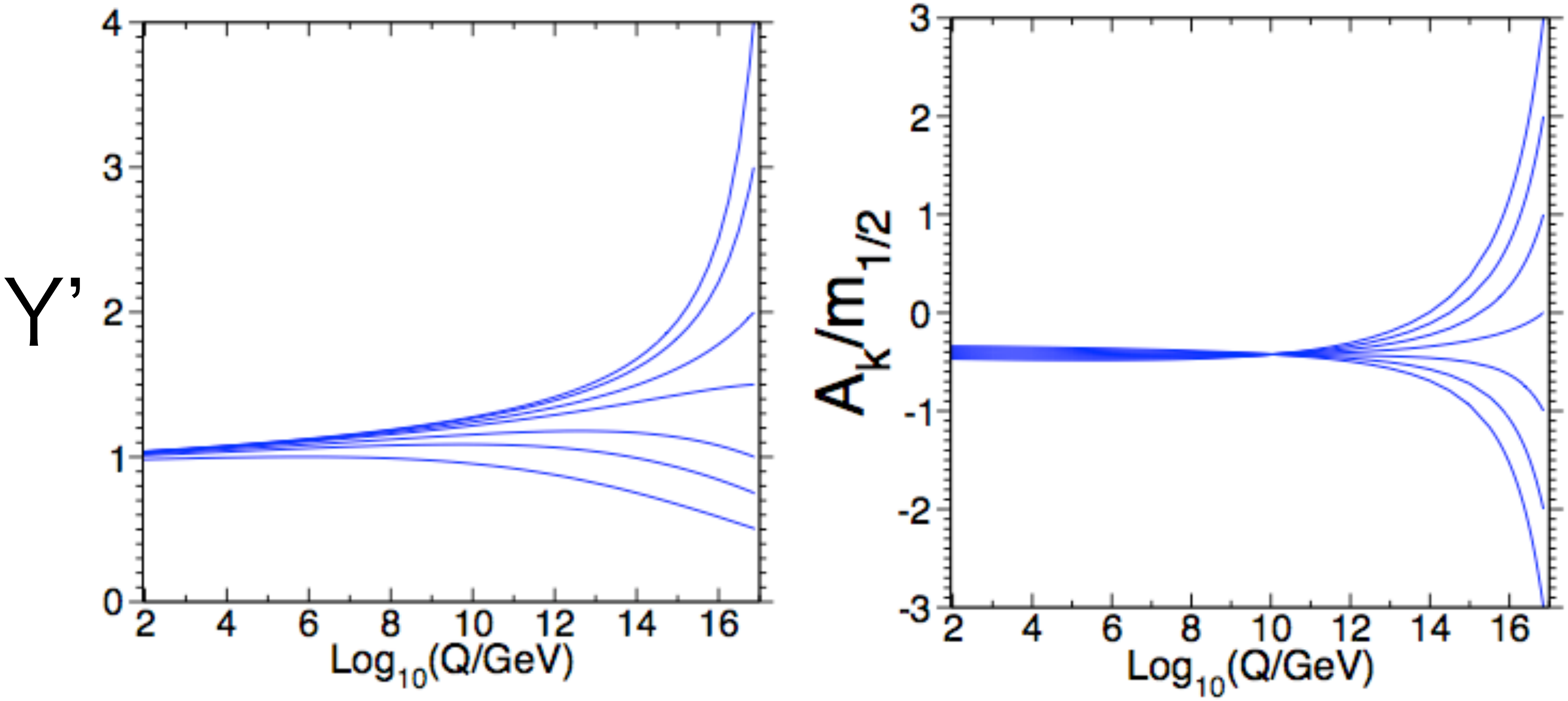
MSSM

$$\Delta m_h^2 \simeq \frac{3Y'^4}{4\pi^2}$$

can be

commen

[S.P.Martin 0910.2732].



2. RGEs of Y and A have quasi-fixed poi ts.

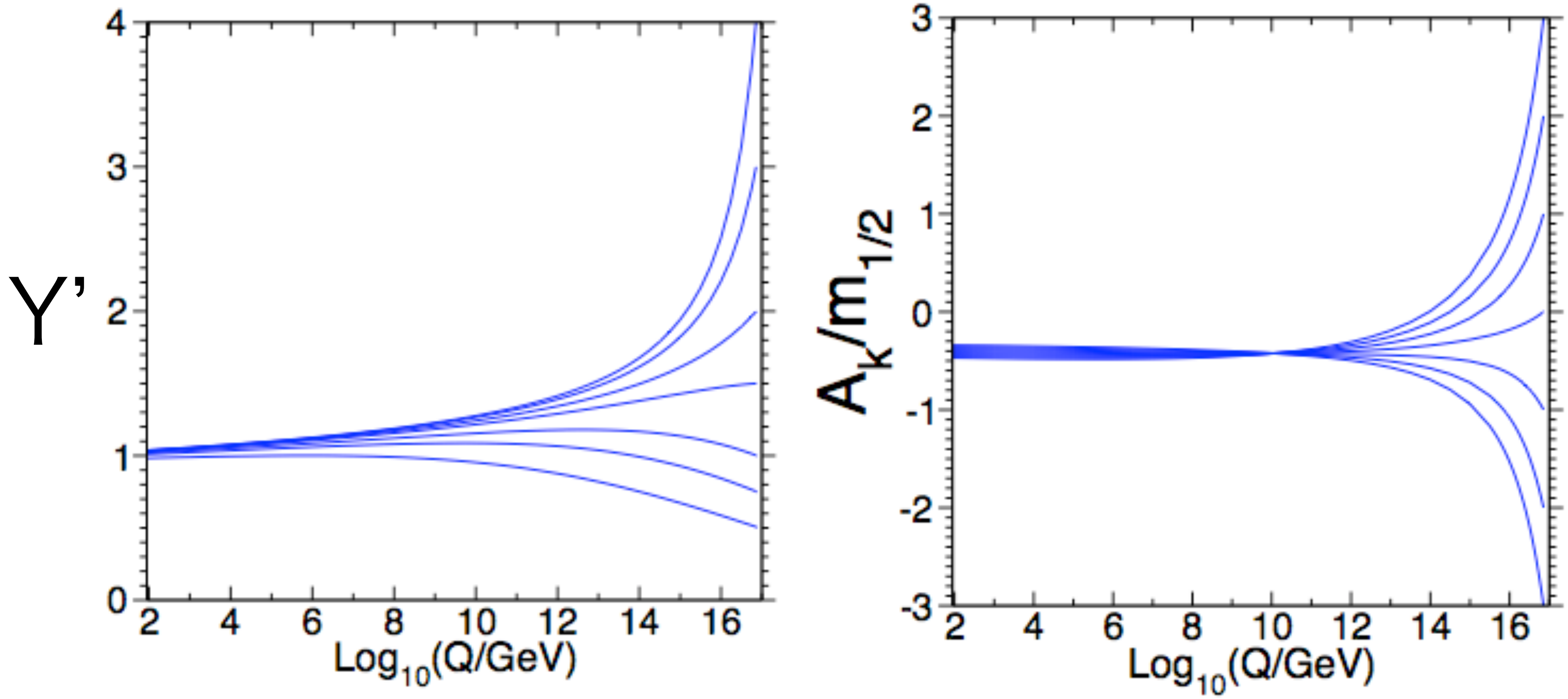
12

MSSM

$$\Delta m_h^2 \simeq \frac{3Y'^4}{4\pi^2}$$

can be

commen



[S.P.Martin 0910.2732].

2. RGEs of Y' and A' have quasi-fixed points.

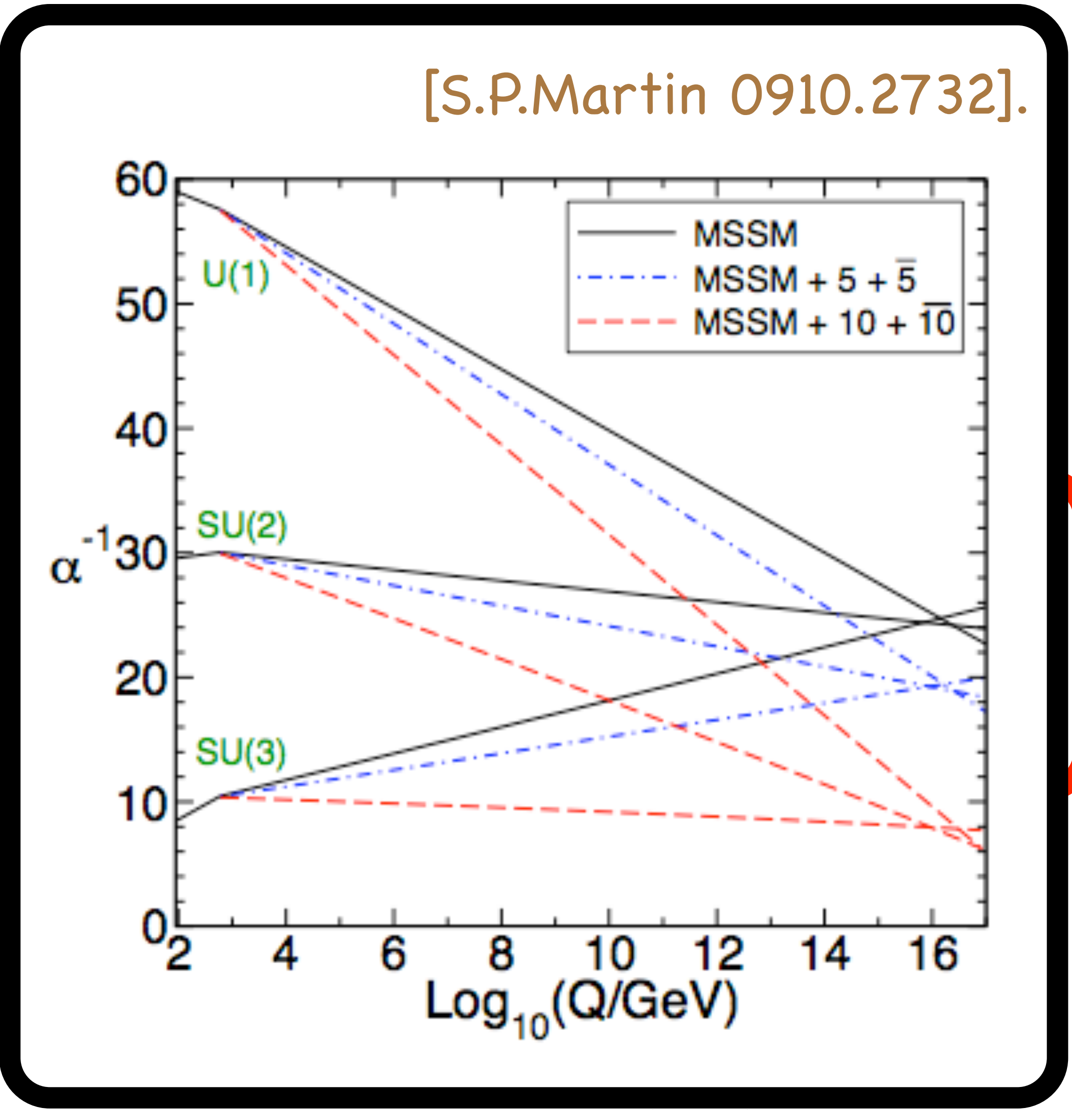
- Y'≈ 1, model independently.
- A'<< m_S. A-term contribution is small.

126 GeV Higgs +

MSSM + vector-like m

$$\Delta m_h^2 \simeq \frac{3Y'^4v^2}{4\pi^2}\Bigg[\ln\frac{m_S^2}{m_F^2} - \frac{1}{6}\left(1-\frac{m_F^2}{m_S^2}\right)\Bigg(5-$$

can be large for mF <<


[S.P.Martin 0910.2732].

comments:

3. 1-loop β-function vanishes for SU(3).

(10+10* corresponds to Nf=3, 3Nc-6-Nf=0)

▶ 2-loop RGE is important, in particular for gluino mass.

126 GeV Higgs + muon g-2

Results

In the following, let's see the results for GMSB models with vector-like matters (= "V-GMSB" models).

M.Endo, KH, S.Iwamoto, N.Yokozaki [1108.3071, 1112.5653, 1202.2751]
M.Endo, KH, K.Ihikawa, S.Iwamoto, N.Yokozaki [1212.3935]
J.L.Evans, M.Ibe, T.T.Yanagida [1108.3437]
S.P.Martin, J.D.Wells [1206.2956]

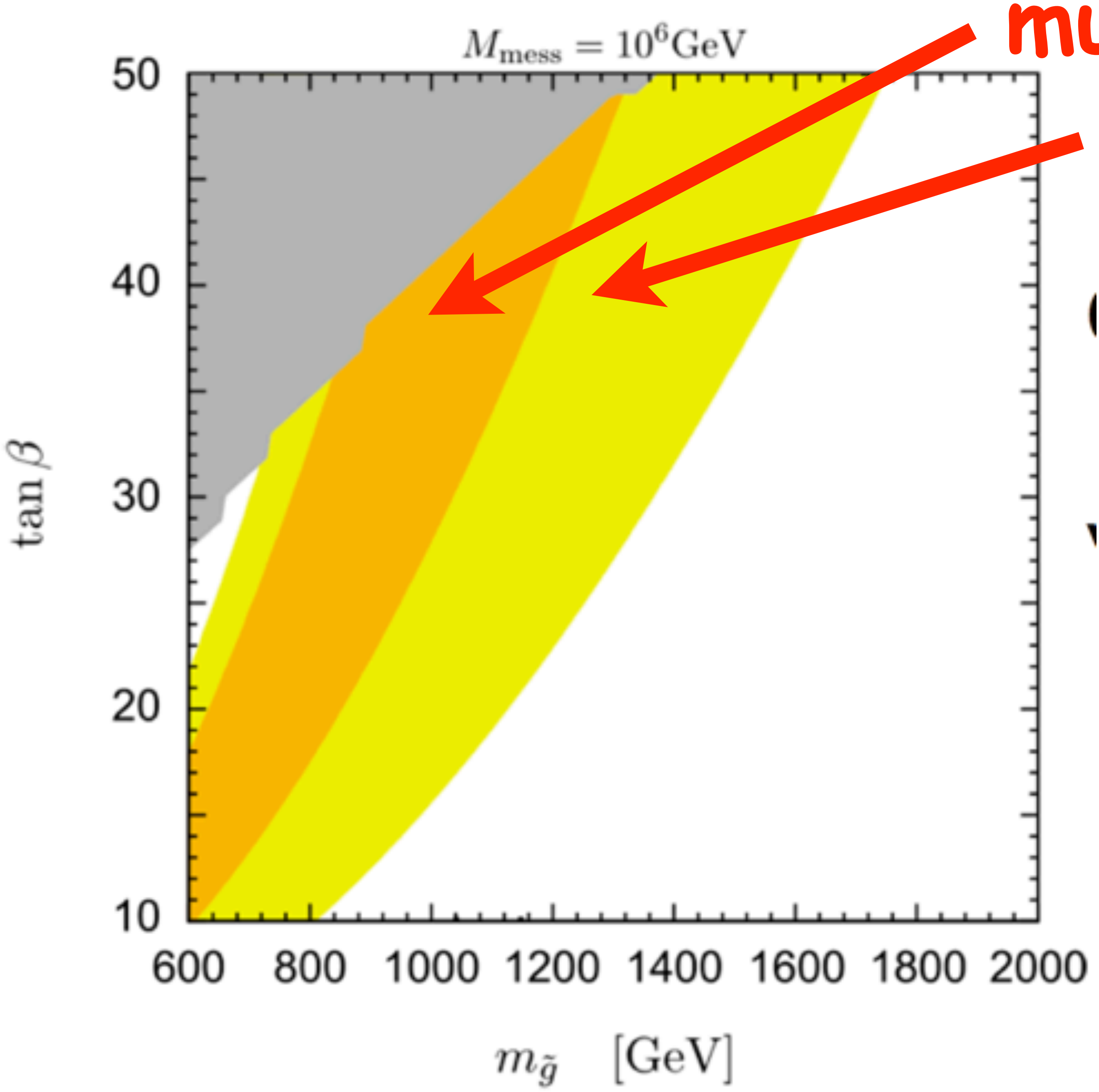
(*) GMSB = Gauge-Mediated SUSY Breaking
..... solves SUSY FCNC/CPV problems.

126 GeV Higgs + muon g-2

Results

M.Endo, KH, K.Ishikawa, S.Iwamoto, N.Yokozaki, arXiv:1212.3935

for "V-GMSB"



muon g-2 explained (1σ)

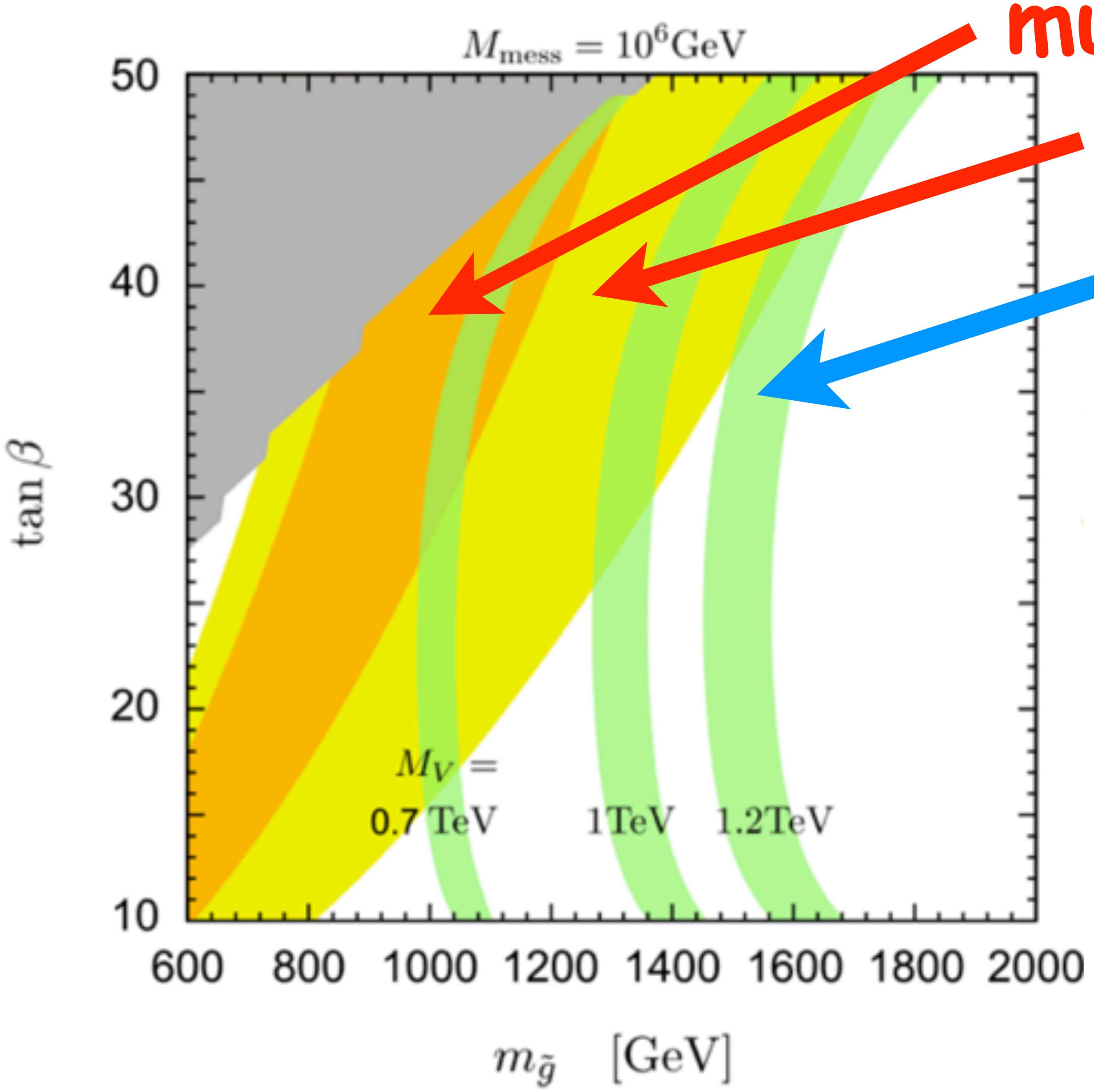
(2σ)

126 GeV Higgs + muon g-2

Results

M.Endo, KH, K.Ishikawa, S.Iwamoto, N.Yokozaki, arXiv:1212.3935

for "V-GMSB"



muon g-2 explained (1σ)

(2σ)

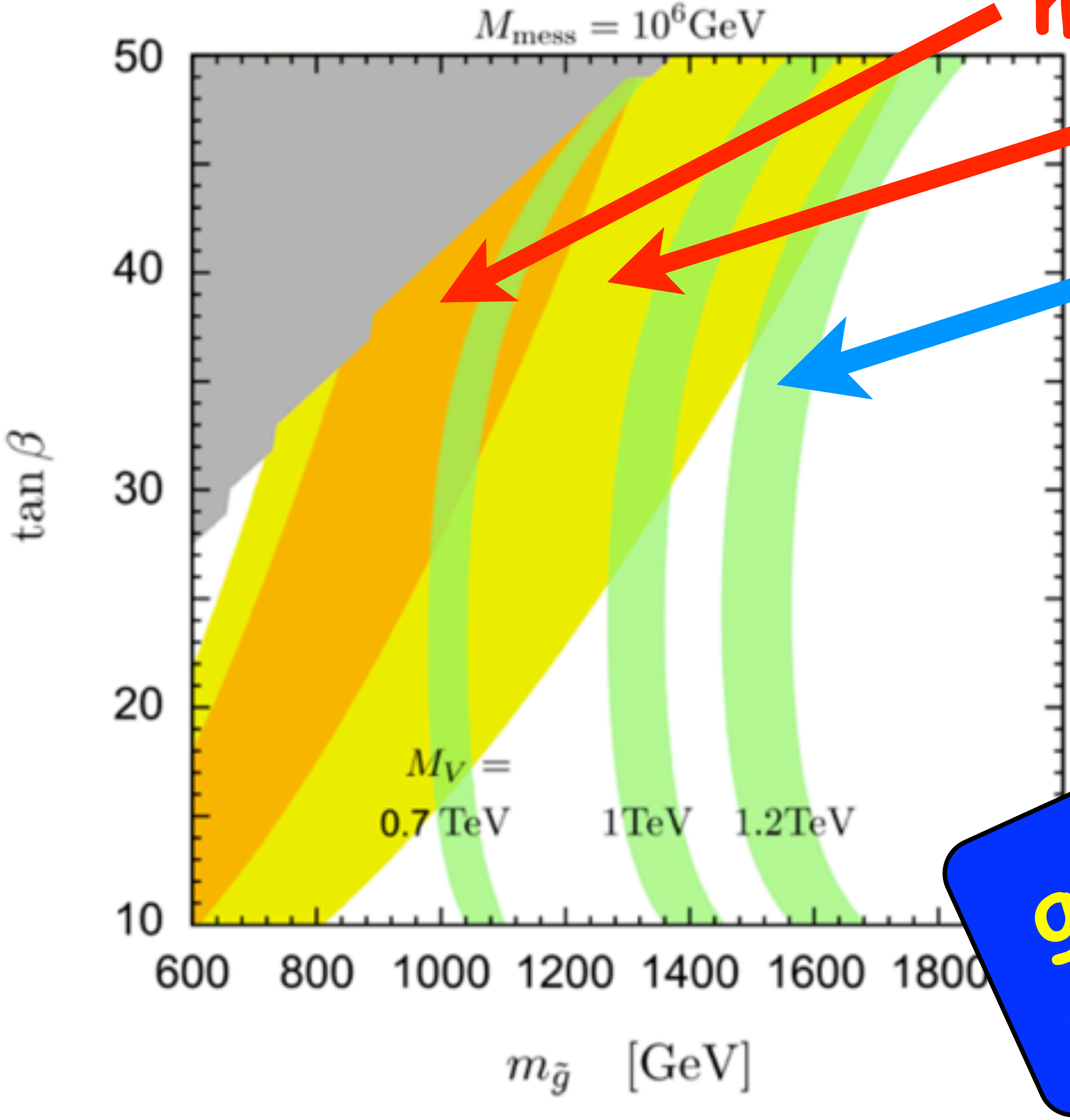
Higgs mass 125-126 GeV

126 GeV Higgs + muon g-2

Results

M.Endo, KH, K.Ishikawa, S.Iwamoto, N.Yokozaki, arXiv:1212.3935

for "V-GMSB"



muon g-2 explained (1σ)

(2σ)

Higgs mass 125-126 GeV

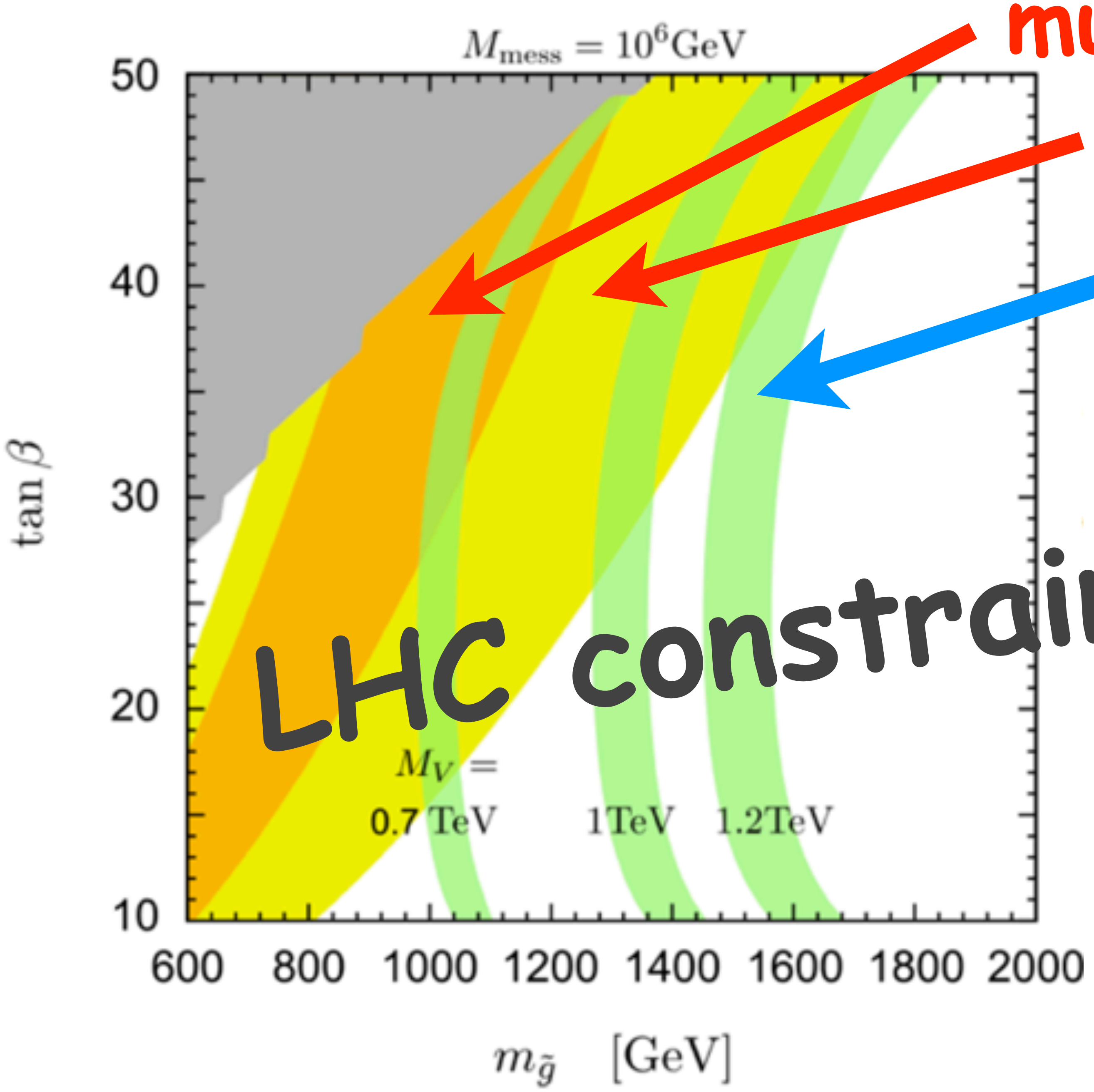
g-2 and Higgs mass are explained simultaneously!

126 GeV Higgs + muon g-2

Results

M.Endo, KH, K.Ishikawa, S.Iwamoto, N.Yokozaki, arXiv:1212.3935

for "V-GMSB"



muon g-2 explained (1σ)

(2σ)

Higgs mass
125-126 GeV

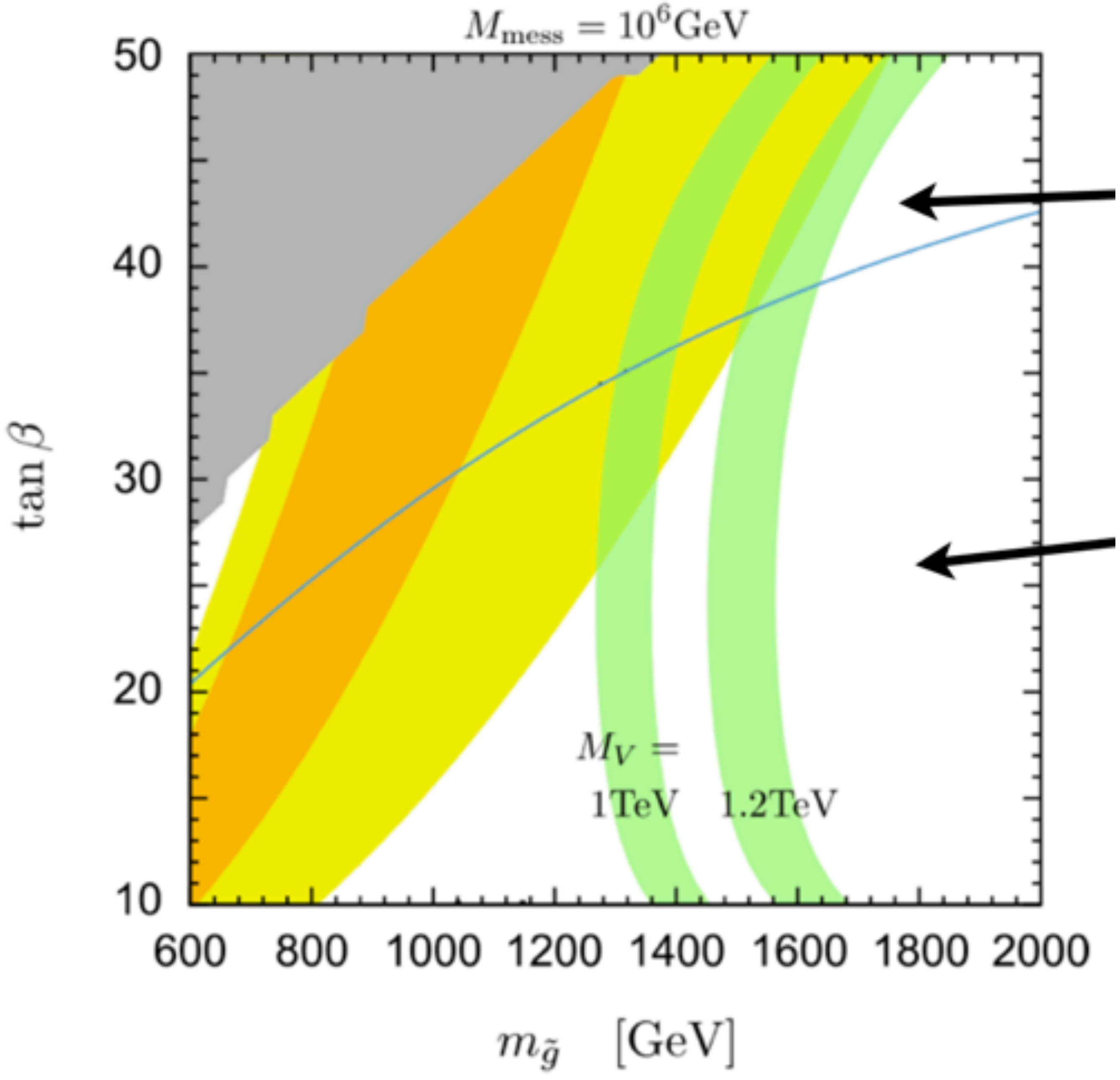
LHC constraints ?

126 GeV Higgs + muon g-2

Results

for "V-GMSB"

M.Endo, KH, K.Ishikawa, S.Iwamoto, N.Yokozaki, arXiv:1212.3935



NLSP = stau

LHC signal

= **long-lived charged particle**

NLSP = neutralino

LHC signal

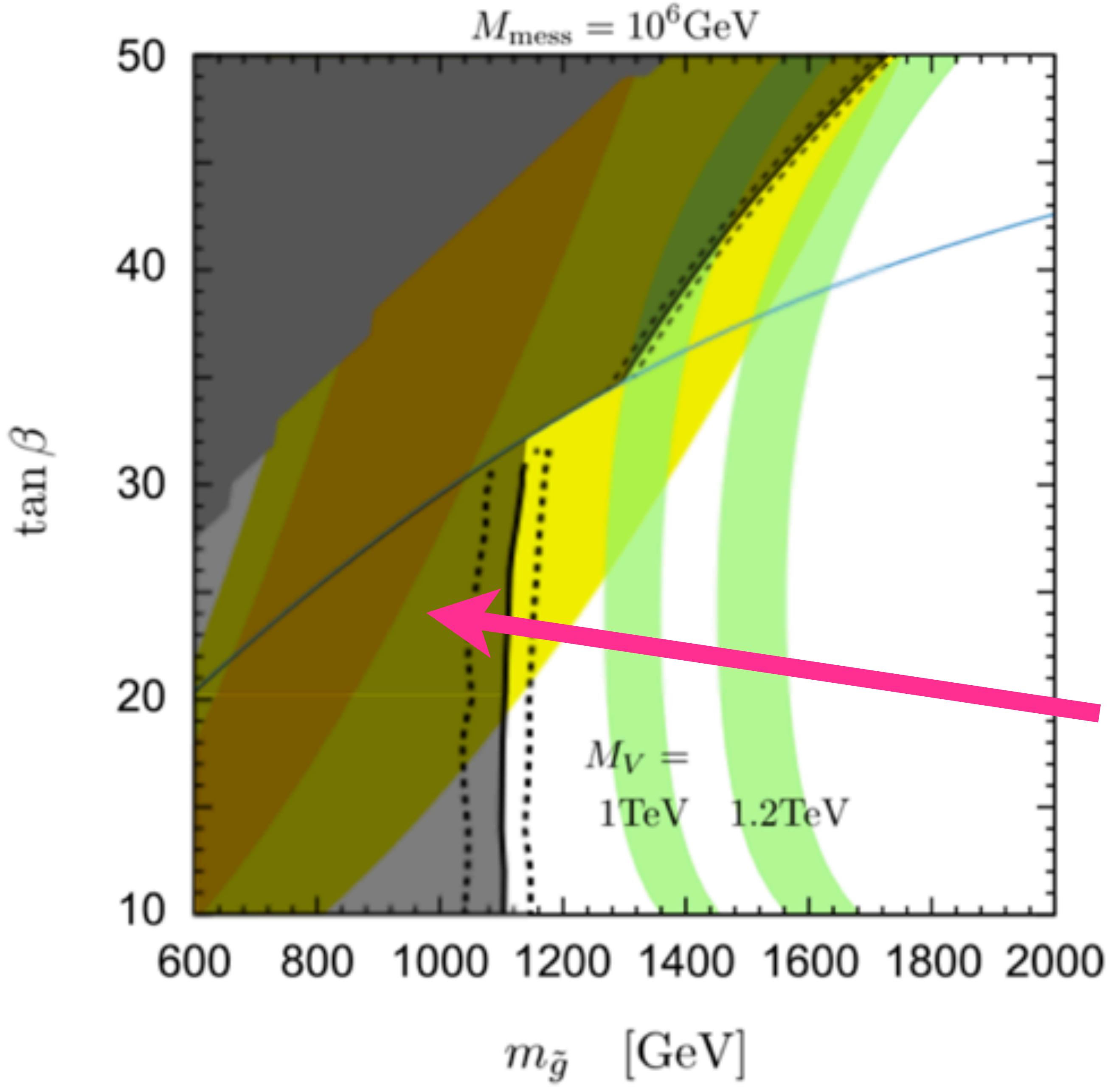
= **jets + missing energy**

126 GeV Higgs + muon g-2

Results

for "V-GMSB"

M.Endo, KH, K.Ishikawa, S.Iwamoto, N.Yokozaki, arXiv:1212.3935



already excluded

[* using
ATLAS result ($5.8{\rm fb}^{-1}$@8TeV)
for jets + missing
and CMS result ($5.0{\rm fb}^{-1}$@7TeV)
for long-lived charged particle.]

126 GeV Higgs + muon g-2

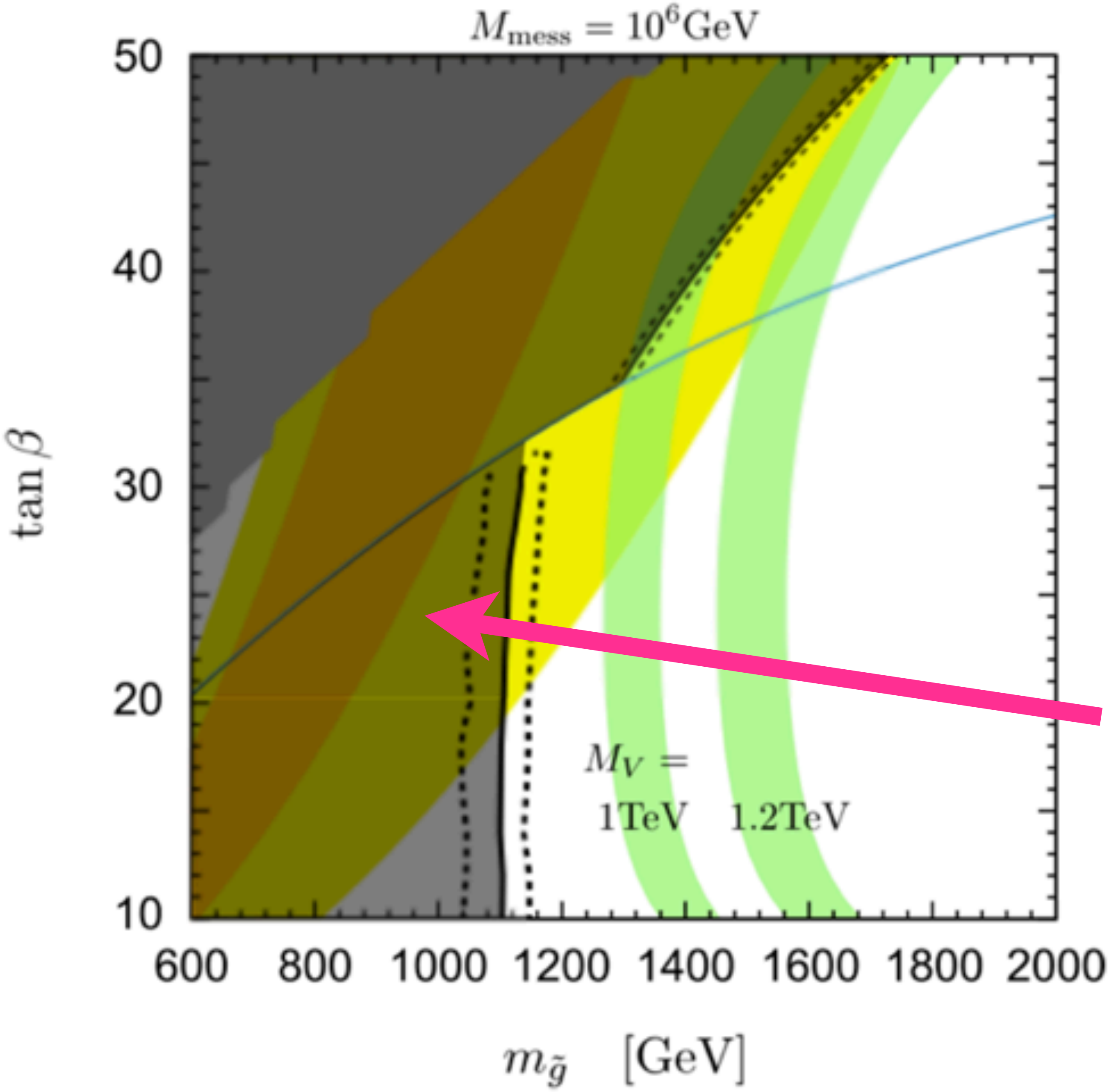
Results

for "V-GMSB"

M.Endo, KH, K.Ishikawa, S.Iwamoto, N.Yokozaki, arXiv:1212.3935

New LHC results

reported after our analysis.



already excluded

[* using
ATLAS result (5.8fb^{-1}@8TeV)
for jets + missing
and CMS result (5.0fb^{-1}@7TeV)
for long-lived charged particle.]

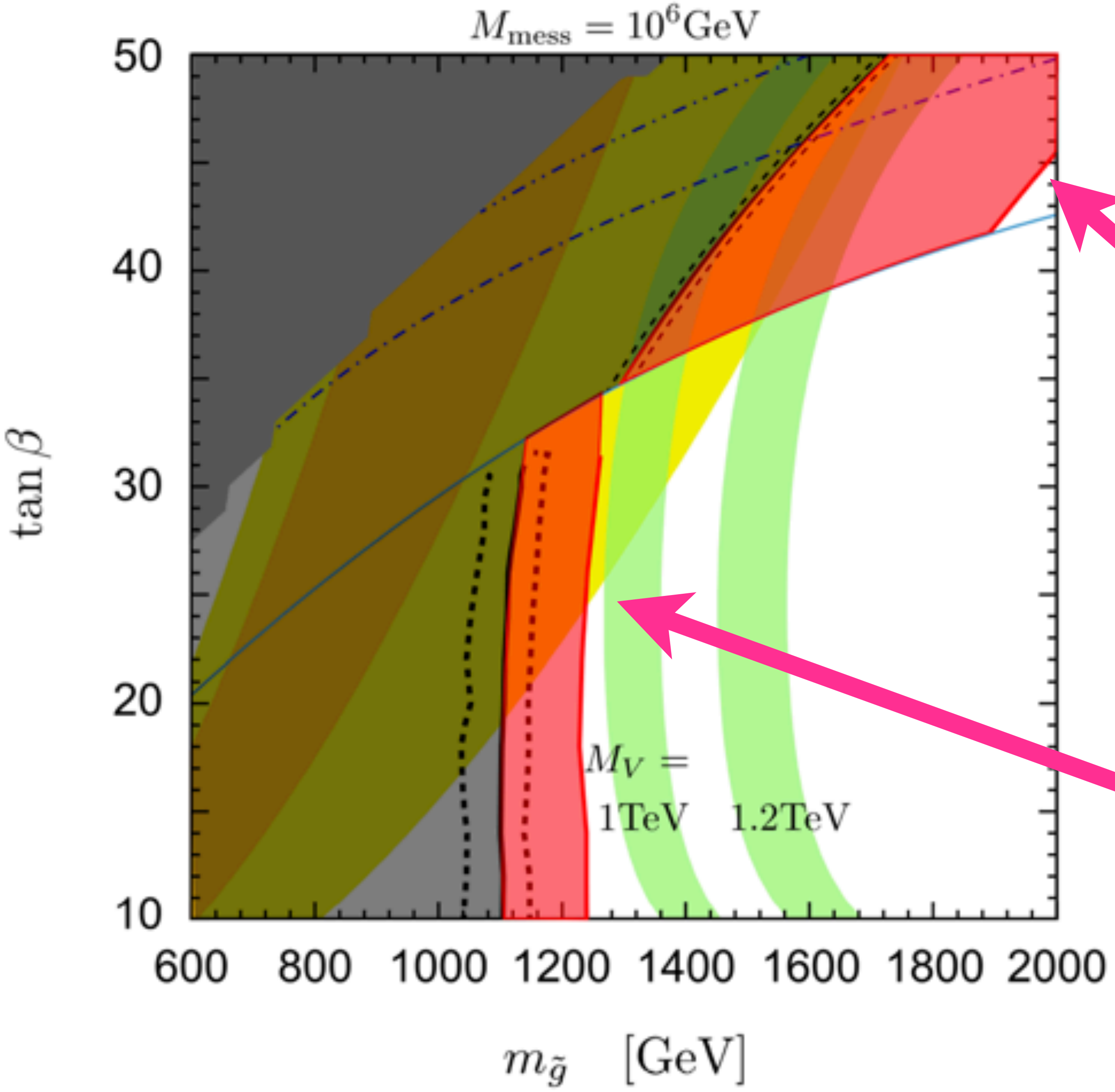
126 GeV Higgs + muon g-2

Results

for "V-GMSB"

M.Endo, KH, K.Ishikawa, S.Iwamoto, N.Yokozaki, arXiv:1212.3935

New LHC results reported after our analysis.



stau NLSP region is completely excluded.

[CMS: m(stau) > 339 GeV with Drell-Yang direct]

neutralino NLSP region is still allowed.

We interpreted 8 TeV 20fb^-1 result [ATLAS-CONF-2013-047]

New analysis: thanks to **Kazuya Ishikawa**.

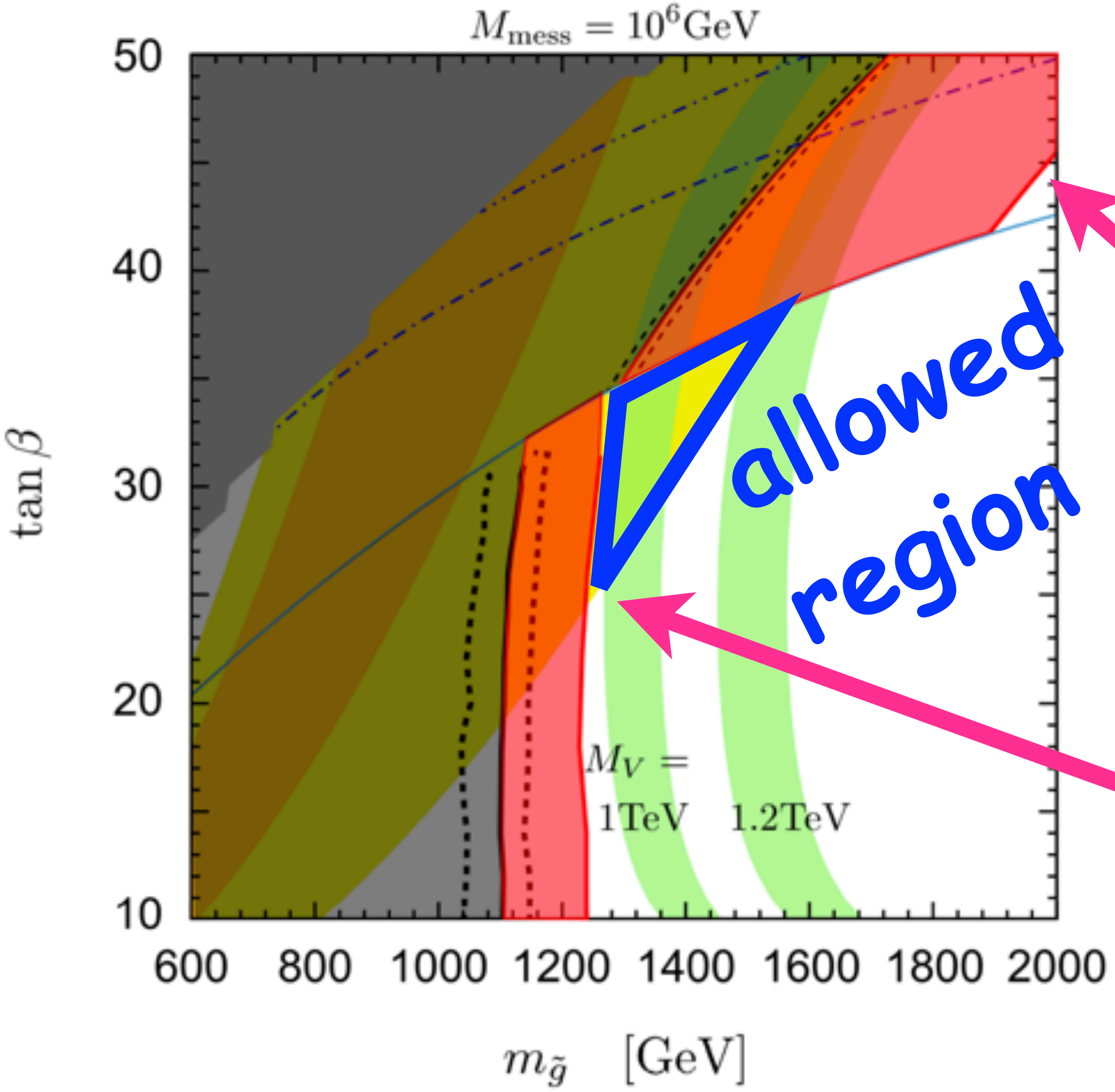
126 GeV Higgs + muon g-2

Results

for "V-GMSB"

M.Endo, KH, K.Ishikawa, S.Iwamoto, N.Yokozaki, arXiv:1212.3935

New LHC results reported after our analysis.



stau NLSP region is completely excluded.

[CMS: m(stau) > 339 GeV with Drell-Yang direct]

neutralino NLSP region is still allowed.

We interpreted 8 TeV 20fb^-1 result [ATLAS-CONF-2013-047]

New analysis: thanks to **Kazuya Ishikawa**.

126 GeV Higgs and SUSY

Motivations of TeV scale SUSY.....

126 GeV Higgs + **naturalness**

126 GeV Higgs + **muon g-2**

126 GeV Higgs + **Dark Matter**

126 GeV Higgs + **Coupling Unification**

.....

126 GeV Higgs and SUSY

Motivations of TeV scale SUSY.....

126 GeV Higgs + **naturalness**

126 GeV Higgs + **muon g-2**

126 GeV Higgs + **Dark Matter**

126 GeV Higgs + **Coupling Unification**

.....

126 GeV Higgs + Dark Matter
126 GeV Higgs + coupling unification

126 GeV Higgs + Dark Matter
126 GeV Higgs + coupling unification

No problem !

126 GeV Higgs + Dark Matter
126 GeV Higgs + coupling unification

No problem !

- e.g., CMSSM/mSUGRA

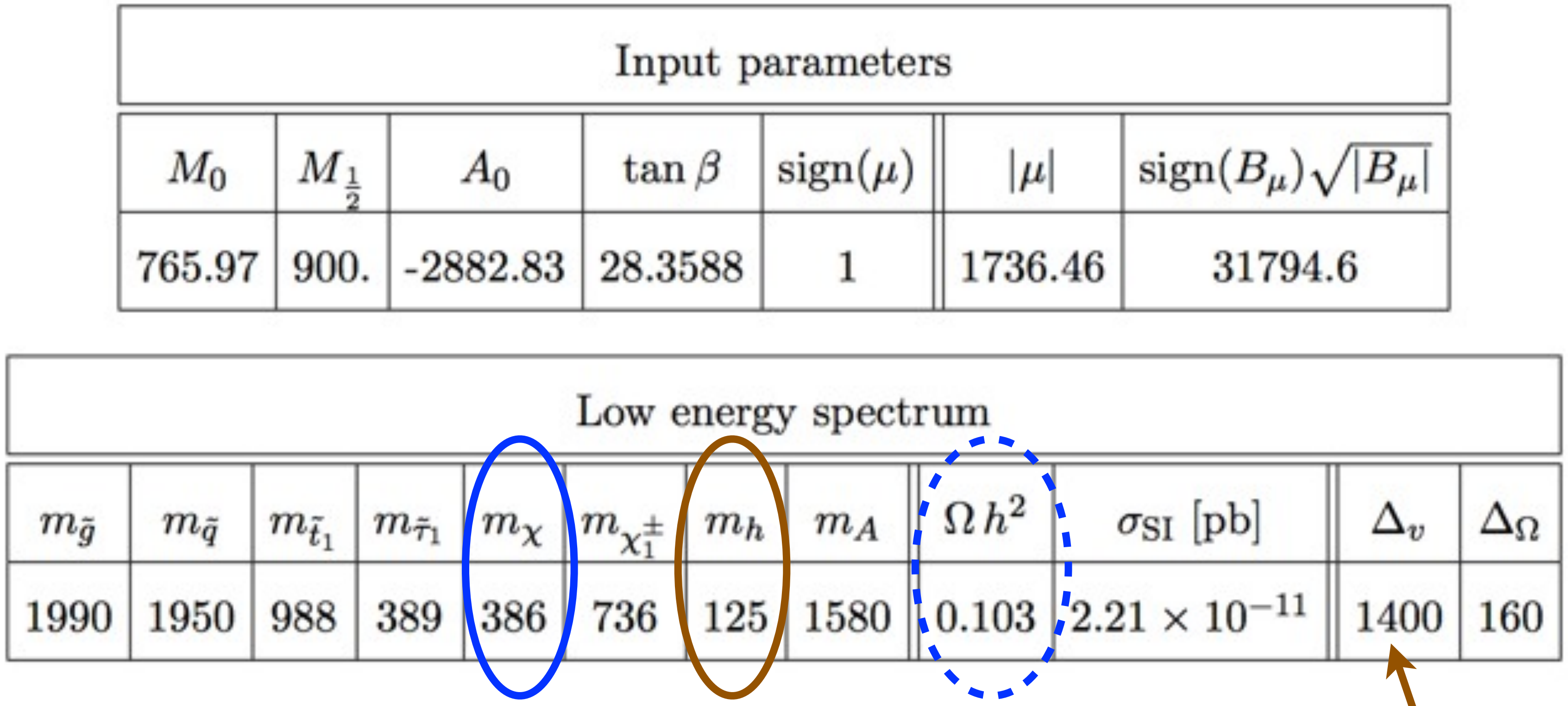
126 GeV Higgs + Dark Matter
126 GeV Higgs + coupling unification

No problem !

- e.g., CMSSM/mSUGRA

Benchmark model points shown in 1305.2914, Cohen Wacker

"Stau coannihilation"



Input parameters						
M_0	$M_{\frac{1}{2}}$	A_0	$\tan\beta$	$\mathrm{sign}(\mu)$	$\|\mu\|$	$\mathrm{sign}(B_\mu)\sqrt{\|B_\mu\|}$
765.97	900.	-2882.83	28.3588	1	1736.46	31794.6

Low energy spectrum											
$m_{\tilde{g}}$	$m_{\tilde{q}}$	$m_{\tilde{t}_1}$	$m_{\tilde{\tau}_1}$	m_χ	$m_{\chi_1^\pm}$	m_h	m_A	Ωh^2	σ_{SI} [pb]	Δ_v	Δ_Ω
1990	1950	988	389	386	736	125	1580	0.103	2.21×10^{-11}	1400	160

neutralino DM

Higgs

fine-tuning

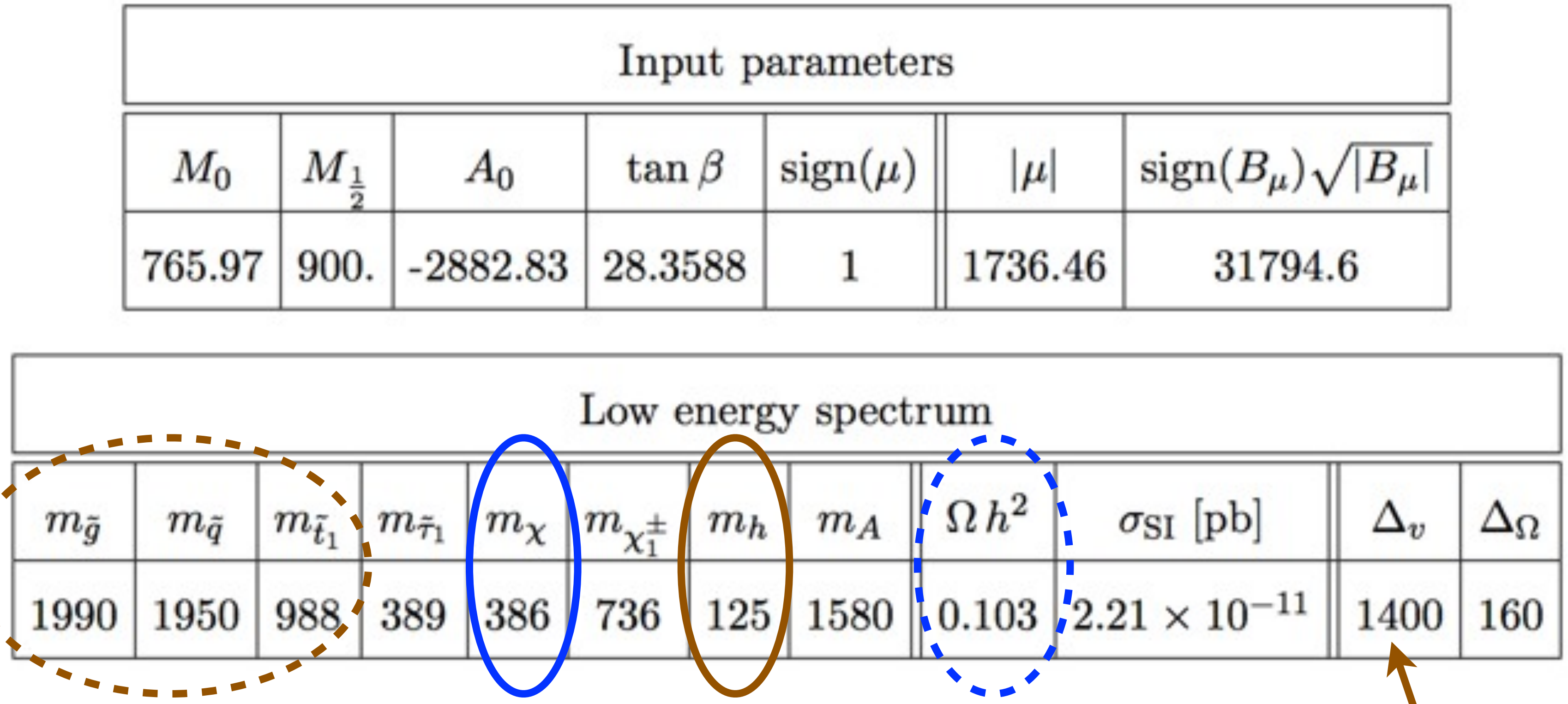
126 GeV Higgs + Dark Matter
126 GeV Higgs + coupling unification

No problem !

- e.g., CMSSM/mSUGRA

Benchmark model points shown in 1305.2914, Cohen Wacker

"Stau coannihilation"



Input parameters						
M_0	$M_{\frac{1}{2}}$	A_0	$\tan\beta$	$\mathrm{sign}(\mu)$	$\lvert\mu\rvert$	$\mathrm{sign}(B_\mu)\sqrt{\lvert B_\mu\rvert}$
765.97	900.	-2882.83	28.3588	1	1736.46	31794.6

Low energy spectrum											
$m_{\tilde{g}}$	$m_{\tilde{q}}$	$m_{\tilde{t}_1}$	$m_{\tilde{\tau}_1}$	m_χ	$m_{\chi_1^\pm}$	m_h	m_A	Ωh^2	σ_{SI} [pb]	Δ_v	Δ_Ω
1990	1950	988	389	386	736	125	1580	0.103	2.21×10^{-11}	1400	160

gluino
squark
stop

neutralino DM

Higgs

fine-tuning

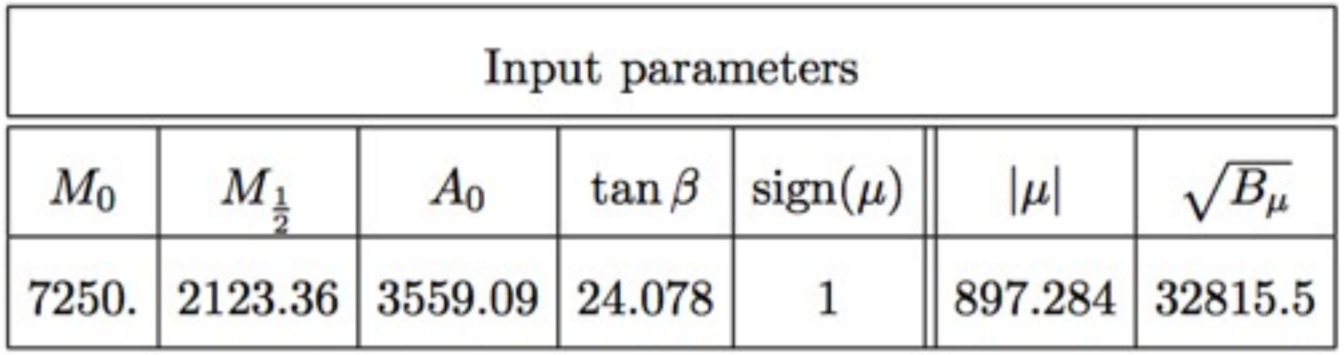
126 GeV Higgs + Dark Matter
126 GeV Higgs + coupling unification

No problem !

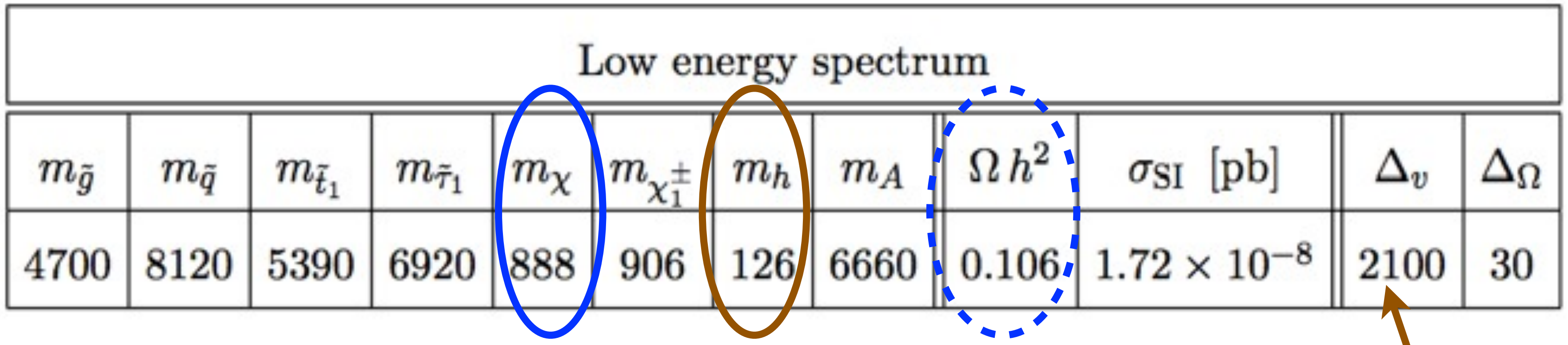
- e.g., CMSSM/mSUGRA

Benchmark model points shown in 1305.2914, Cohen Wacker

"Well tempered"



Input parameters						
M_0	$M_{\frac{1}{2}}$	A_0	$\tan\beta$	$\mathrm{sign}(\mu)$	$\|\mu\|$	$\sqrt{B_\mu}$
7250.	2123.36	3559.09	24.078	1	897.284	32815.5



Low energy spectrum											
$m_{\tilde{g}}$	$m_{\tilde{q}}$	$m_{\tilde{t}_1}$	$m_{\tilde{\tau}_1}$	m_χ	$m_{\chi_1^\pm}$	m_h	m_A	Ωh^2	$\sigma_{\rm SI}$ [pb]	Δ_v	Δ_Ω
4700	8120	5390	6920	888	906	126	6660	0.106	1.72×10^{-8}	2100	30

neutralino DM

Higgs

fine-tuning

126 GeV Higgs + Dark Matter
126 GeV Higgs + coupling unification

No problem !

- e.g., CMSSM/mSUGRA

Benchmark model points shown in 1305.2914, Cohen Wacker

"Well tempered"

Input parameters						
M_0	$M_{\frac{1}{2}}$	A_0	$\tan\beta$	sign(μ)	$\lvert\mu\rvert$	$\sqrt{B_\mu}$
7250.	2123.36	3559.09	24.078	1	897.284	32815.5

Low energy spectrum											
$m_{\tilde{g}}$	$m_{\tilde{q}}$	$m_{\tilde{t}_1}$	$m_{\tilde{\tau}_1}$	m_χ	$m_{\chi_1^\pm}$	m_h	m_A	Ωh^2	$\sigma_{\rm SI}$ [pb]	Δ_v	Δ_Ω
4700	8120	5390	6920	888	906	126	6660	0.106	1.72×10^{-8}	2100	30

gluino
squark
stop

outside the 13 TeV LHC reach

neutralino DM

Higgs

fine-tuning

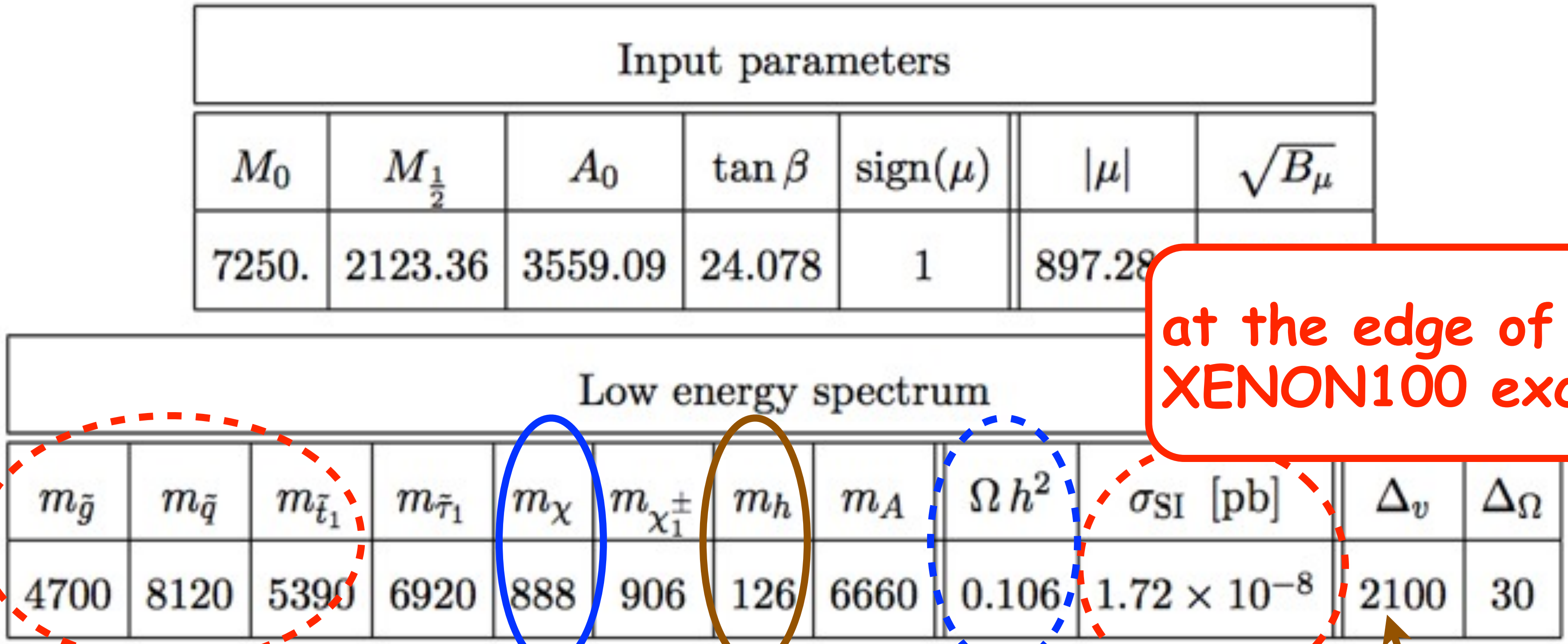
126 GeV Higgs + Dark Matter
126 GeV Higgs + coupling unification

No problem !

- e.g., CMSSM/mSUGRA

Benchmark model points shown in 1305.2914, Cohen Wacker

“Well tempered”



Input parameters						
M_0	$M_{\frac{1}{2}}$	A_0	$\tan\beta$	sign(μ)	$\|\mu\|$	$\sqrt{B_\mu}$
7250.	2123.36	3559.09	24.078	1	897.28	

Low energy spectrum											
$m_{\tilde{g}}$	$m_{\tilde{q}}$	$m_{\tilde{t}_1}$	$m_{\tilde{\tau}_1}$	m_χ	$m_{\chi_1^\pm}$	m_h	m_A	Ωh^2	$\sigma_{\rm SI}$ [pb]	Δ_v	Δ_Ω
4700	8120	5390	6920	888	906	126	6660	0.106	1.72×10^{-8}	2100	30

at the edge of XENON100 exclusion

gluino
squark
stop

outside the 13 TeV LHC reach

neutralino DM

Higgs

fine-tuning

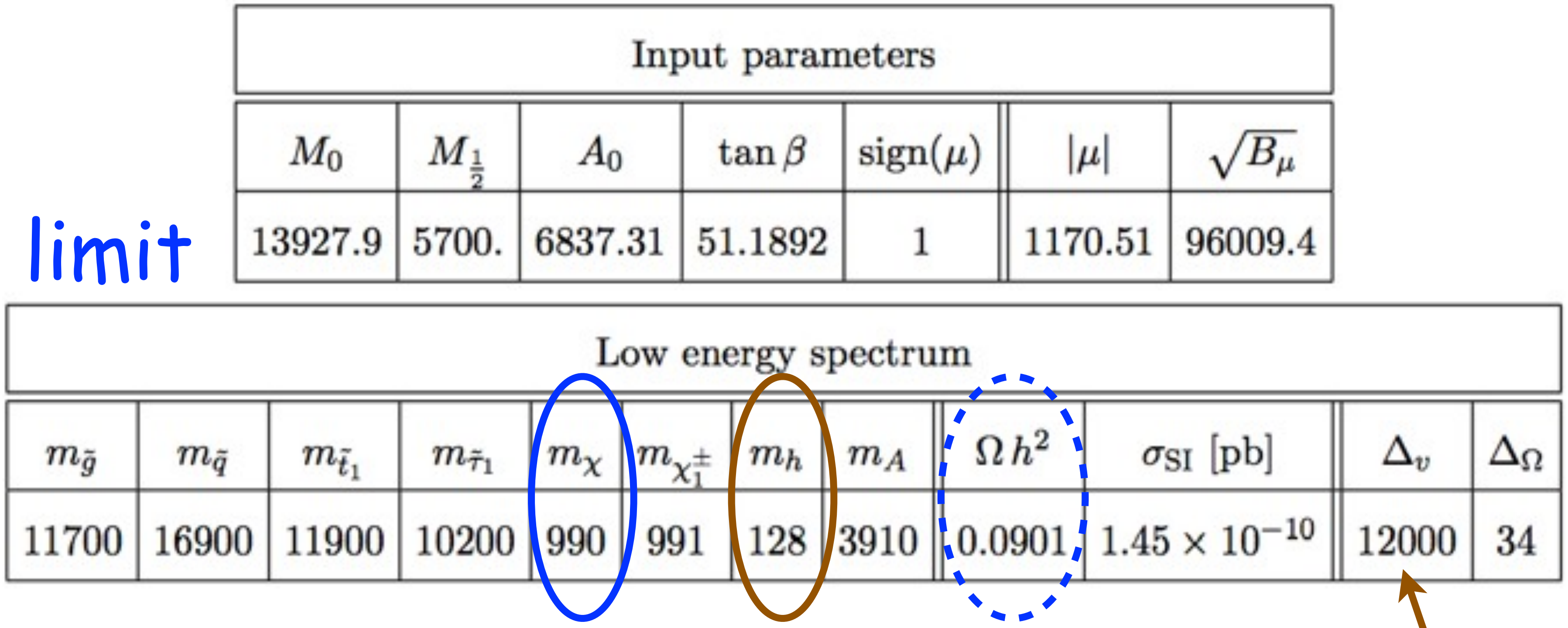
126 GeV Higgs + Dark Matter
126 GeV Higgs + coupling unification

No problem !

- e.g., CMSSM/mSUGRA

Benchmark model points shown in 1305.2914, Cohen Wacker

"Well tempered"
pure Higgsino limit



Input parameters						
M_0	$M_{\frac{1}{2}}$	A_0	$\tan\beta$	$\mathrm{sign}(\mu)$	$\lvert\mu\rvert$	$\sqrt{B_\mu}$
13927.9	5700.	6837.31	51.1892	1	1170.51	96009.4

Low energy spectrum											
$m_{\tilde{g}}$	$m_{\tilde{q}}$	$m_{\tilde{t}_1}$	$m_{\tilde{\tau}_1}$	m_χ	$m_{\chi_1^\pm}$	m_h	m_A	Ωh^2	σ_{SI} [pb]	Δ_v	Δ_Ω
11700	16900	11900	10200	990	991	128	3910	0.0901	1.45×10^{-10}	12000	34

neutralino DM

Higgs

fine-tuning

126 GeV Higgs + Dark Matter

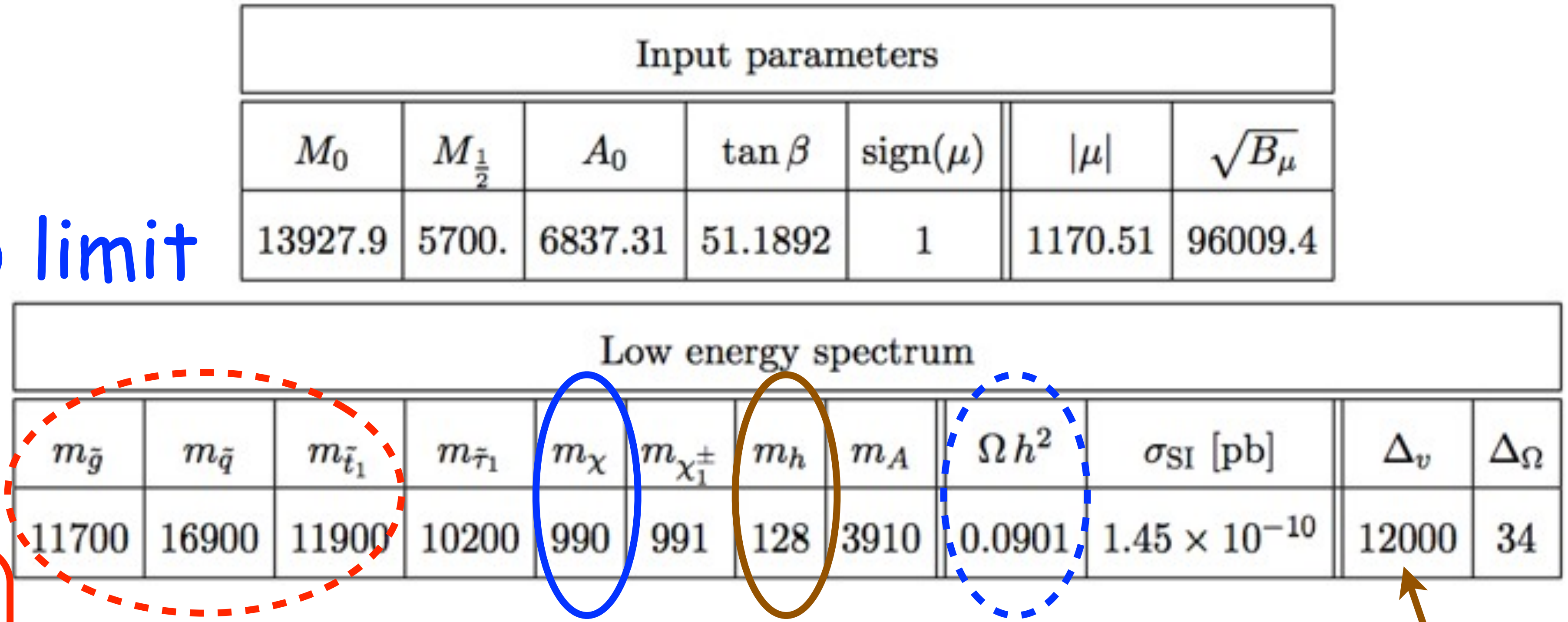
126 GeV Higgs + coupling unification

No problem !

- e.g., CMSSM/mSUGRA

Benchmark model points shown in 1305.2914, Cohen Wacker

"Well tempered" pure Higgsino limit



Input parameters						
M_0	$M_{\frac{1}{2}}$	A_0	$\tan\beta$	$\mathrm{sign}(\mu)$	$\lvert\mu\rvert$	$\sqrt{B_\mu}$
13927.9	5700.	6837.31	51.1892	1	1170.51	96009.4

Low energy spectrum											
$m_{\tilde{g}}$	$m_{\tilde{q}}$	$m_{\tilde{t}_1}$	$m_{\tilde{\tau}_1}$	m_χ	$m_{\chi_1^\pm}$	m_h	m_A	Ωh^2	σ_{SI} [pb]	Δ_v	Δ_Ω
11700	16900	11900	10200	990	991	128	3910	0.0901	1.45×10^{-10}	12000	34

gluino
squark
stop

outside the 13 TeV LHC reach

neutralino DM

Higgs

fine-tuning

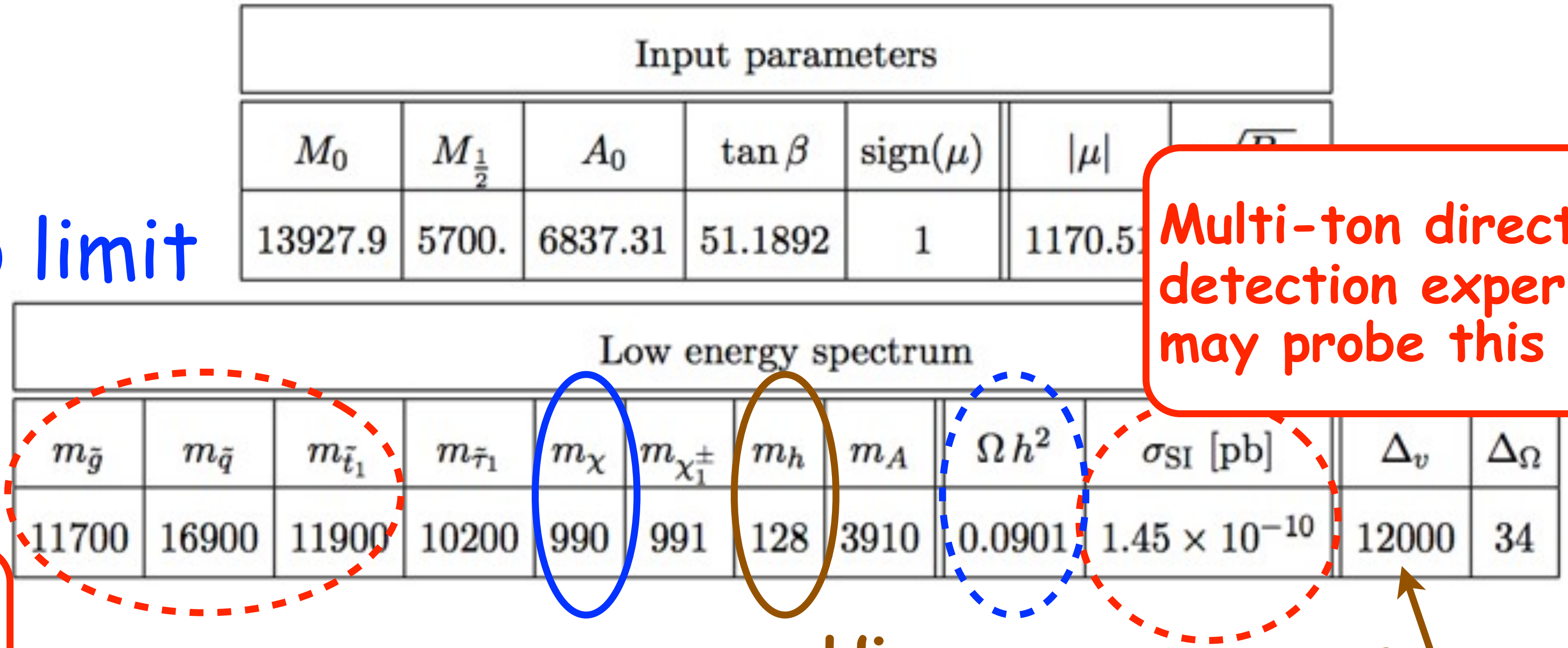
126 GeV Higgs + Dark Matter
126 GeV Higgs + coupling unification

No problem !

- e.g., CMSSM/mSUGRA

Benchmark model points shown in 1305.2914, Cohen Wacker

"Well tempered" pure Higgsino limit



Input parameters					
M_0	$M_{\frac{1}{2}}$	A_0	$\tan\beta$	sign(μ)	$\|\mu\|$
13927.9	5700.	6837.31	51.1892	1	1170.5

Low energy spectrum											
$m_{\tilde{g}}$	$m_{\tilde{q}}$	$m_{\tilde{t}_1}$	$m_{\tilde{\tau}_1}$	m_χ	$m_{\chi_1^\pm}$	m_h	m_A	Ωh^2	$\sigma_{\rm SI}$ [pb]	Δ_v	Δ_Ω
11700	16900	11900	10200	990	991	128	3910	0.0901	1.45×10^{-10}	12000	34

Multi-ton direct detection experiments may probe this point.

gluino
squark
stop

outside the 13 TeV LHC reach

neutralino DM

Higgs

fine-tuning

126 GeV Higgs + Dark Matter
126 GeV Higgs + coupling unification

No problem !

- e.g., CMSSM/mSUGRA
- scalars >> gauginos/Higgsinos

126 GeV Higgs + Dark Matter
126 GeV Higgs + cou

No problem

- e.g., CMSSM/mSUG
- scalars >> gauginos/Higgsinos

Motivated by
126 GeV Higgs
+ no SUSY signal
+ FCNC/CP, cosmology,..

Many many related works recently..... (too many to list all...)

Ibe,Yanagida'11, Ibe,Matsumoto,Yanagida'12,
Bhattacherjee,Feldstein,Ibe,Matsumoto,Yanagida'12,
Hall,Nomura'11, Hall,Nomura,Shirai'12,
Giudice,Strumia'11, Arvanitaki,Craig,Dimopoulos,Villadoro'12
Arkani-Hamed,Gupta,Kaplan,Weiner,Zorawski'12, Ibanez,Valenzuela'13,
Jeong,Shimosuka,Yamaguchi'11, Hisano,Ishiwata,Nagata'12, Sato,Shirai,Tobioka'12,
Moroi,Nagai'13, McKeen,Pospelov,Ritz'13,
Hisano,Kuwahara,Nagata'13, Hisano,Kobayashi,Kuwahara,Nagata'13, etc etc.....

126 GeV Higgs + Dark Matter
126 GeV Higgs + cou

No problem

Motivated by
126 GeV Higgs
+ no SUSY signal
+ FCNC/CP, cosmology,..

- e.g., CMSSM/mSU
- scalars >> gauginos/Higgsinos

Typical DM = Wino DM (AMSB)

* if thermal relic,... 2.7 TeV (>> LHC reach)
(Hisano,Matsumoto,Nagai,Saito,Senami'07)

* if non-thermal, it can be lighter.

* anti-proton @AMS-02 expected ?!

126 GeV Higgs + Dark Matter
126 GeV Higgs + cou

No problem

Motivated by
126 GeV Higgs
+ no SUSY signal
+ FCNC/CP, cosmology,..

- e.g., CMSSM/mSUG
- scalars >> gauginos/Higgsinos

Typical DM = Wino DM (AMSB)

* if thermal reli

* if non-therm

* anti-proton @

See talk by S.Matsumoto tomorrow !!

126 GeV Higgs + Dark Matter
126 GeV Higgs + cou

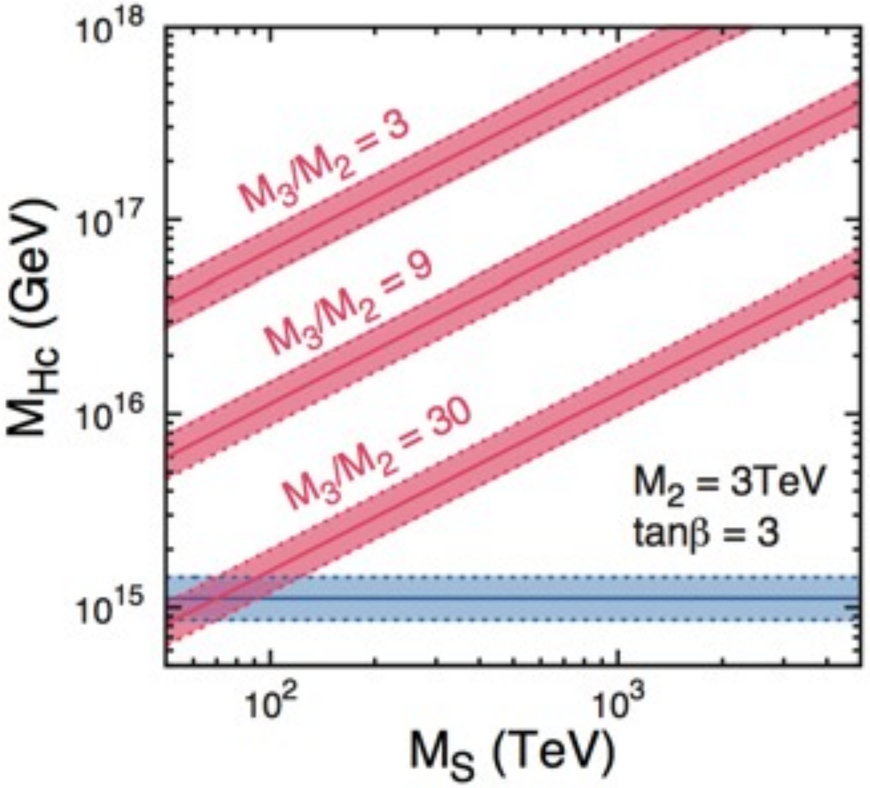
No problem

Motivated by
126 GeV Higgs
+ no SUSY signal
+ FCNC/CP, cosmology,...

- e.g., CMSSM/mSUG
- scalars >> gauginos/Higgsinos

--> makes
coupling unification
better.

[Hisano,Kuwahara,Nagata'13,
Hisano,Kobayashi,Kuwahara,Nagata'13]



SUMMARY

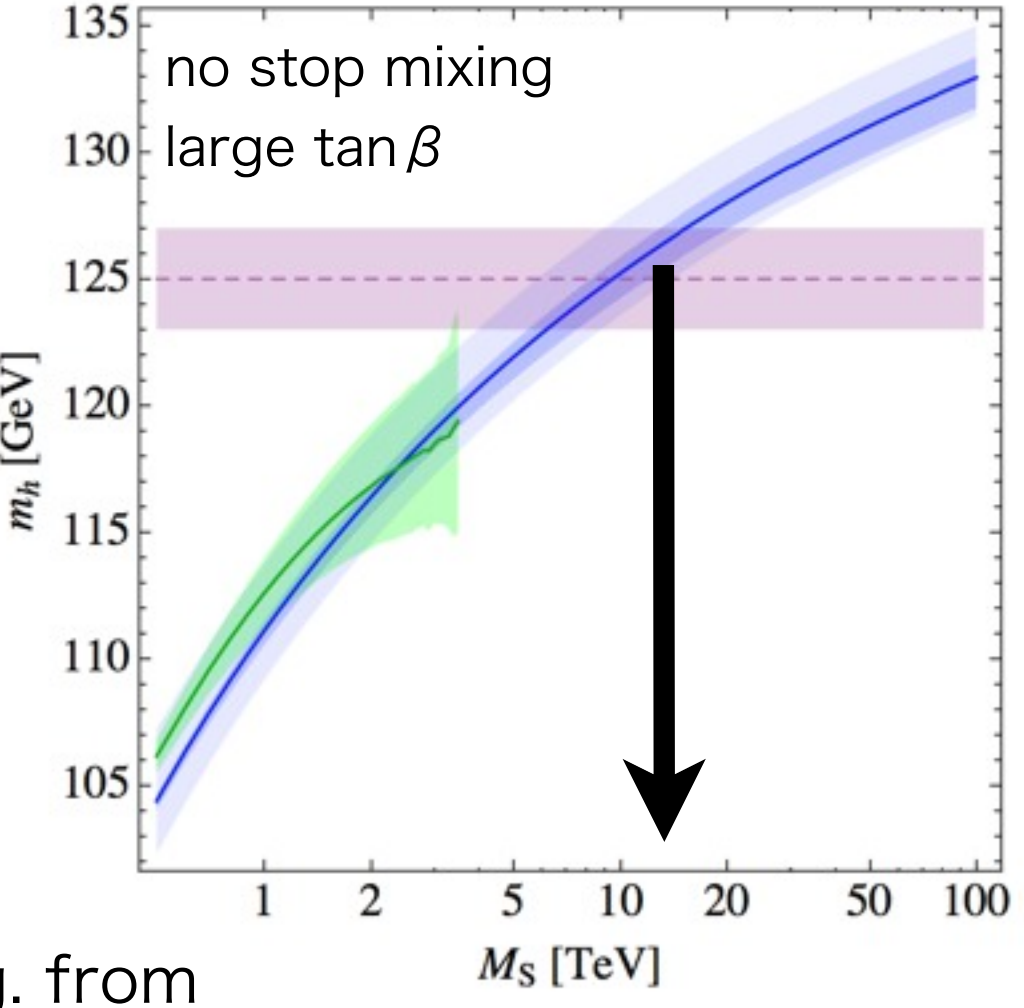
SUSY < O(TeV) after Higgs discovery

<table>
<tr><th>motivations</th><th>model</th><th>LHC/ILC/other signals</th></tr>
<tr><td>126 GeV Higgs
+ naturalness</td><td>implies beyond MSSM
(e.g. NMSSM)
See talk by K.S.Jeong !</td><td>light stop and
light Higgsino.</td></tr>
<tr><td>126 GeV Higgs
+ muon g-2
(>3σ !!)</td><td>difficult in simple models
(1) general MSSM
(2) model building</td><td>(1) “g-2 motivated MSSM”
--> can be tested by non-colored particle search at LHC/ILC.
(2) example: “V-GMSB”
--> barely alive. tested soon.</td></tr>
<tr><td>126 GeV Higgs
+ Dark Matter</td><td colspan="2" rowspan="2">* No problem in simple models (e.g., CMSSM/mSUGRA).
* “light gauginos/Higgsinos + heavy scalars” scenario works well.
Wino Dark Matter See talk by S.Matsumoto !</td></tr>
<tr><td>126 GeV Higgs
+ coupling unification</td></tr>
</table>

- **backup**

126 GeV Higgs and SUSY

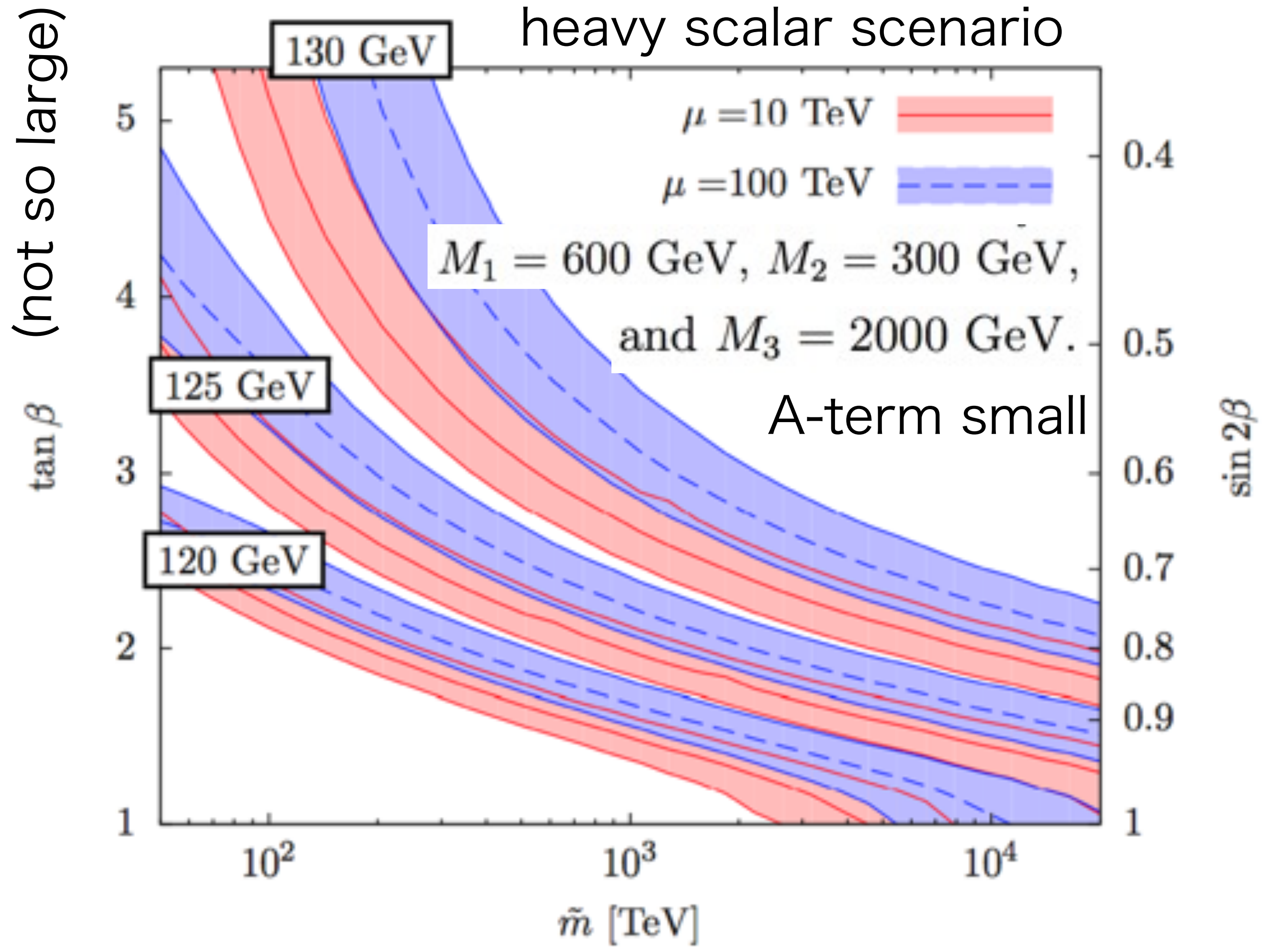
simplest possibility: heavy SUSY



no stop mixing

large tan β

Fig. from
P.Draper, P.Meade, M.Reece, S.Shih '11



(not so large)

heavy scalar scenario

A-term small

Fig. from L.Hall, Y.Nomura, S.Shirai '12

+ many related works

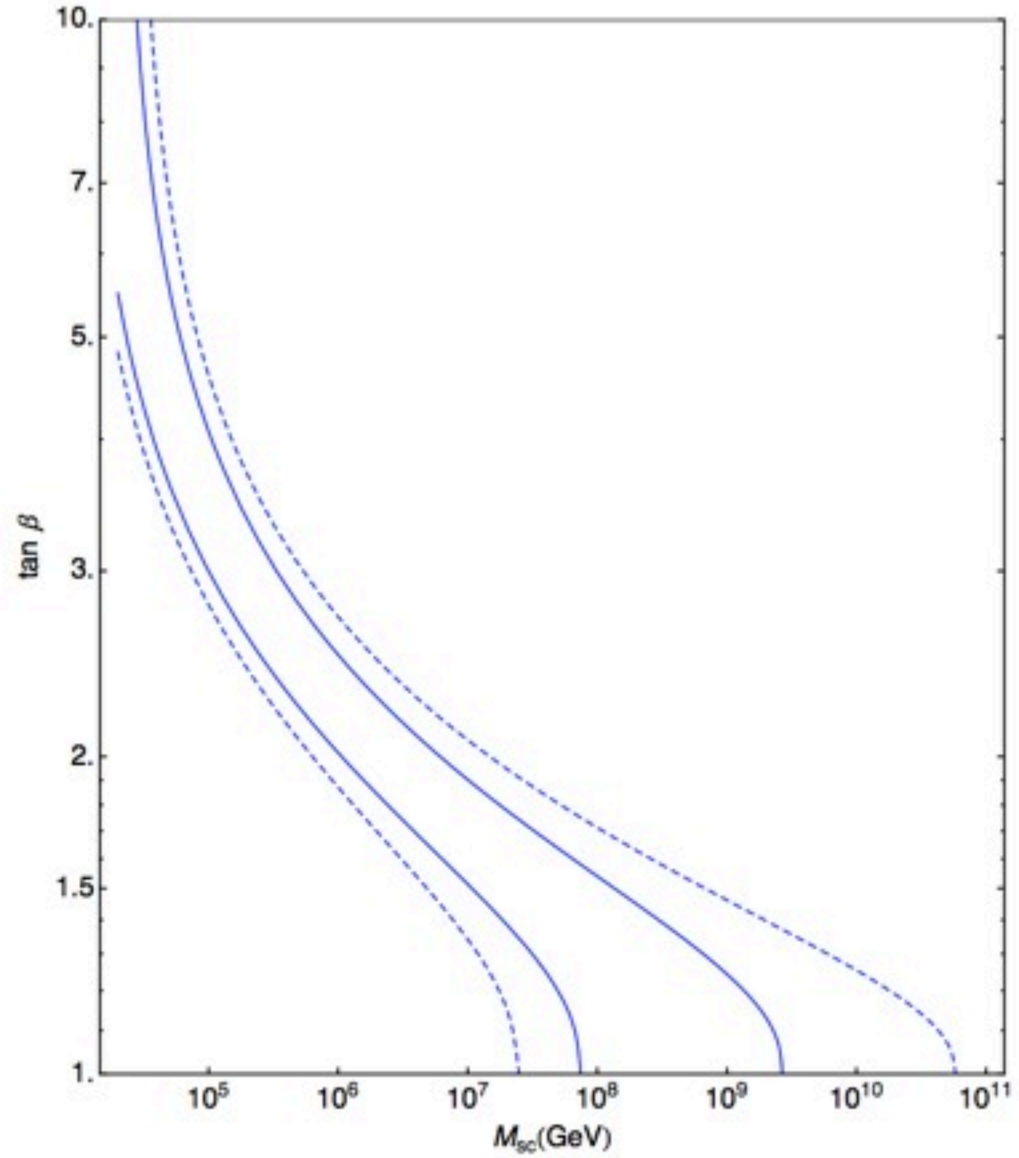
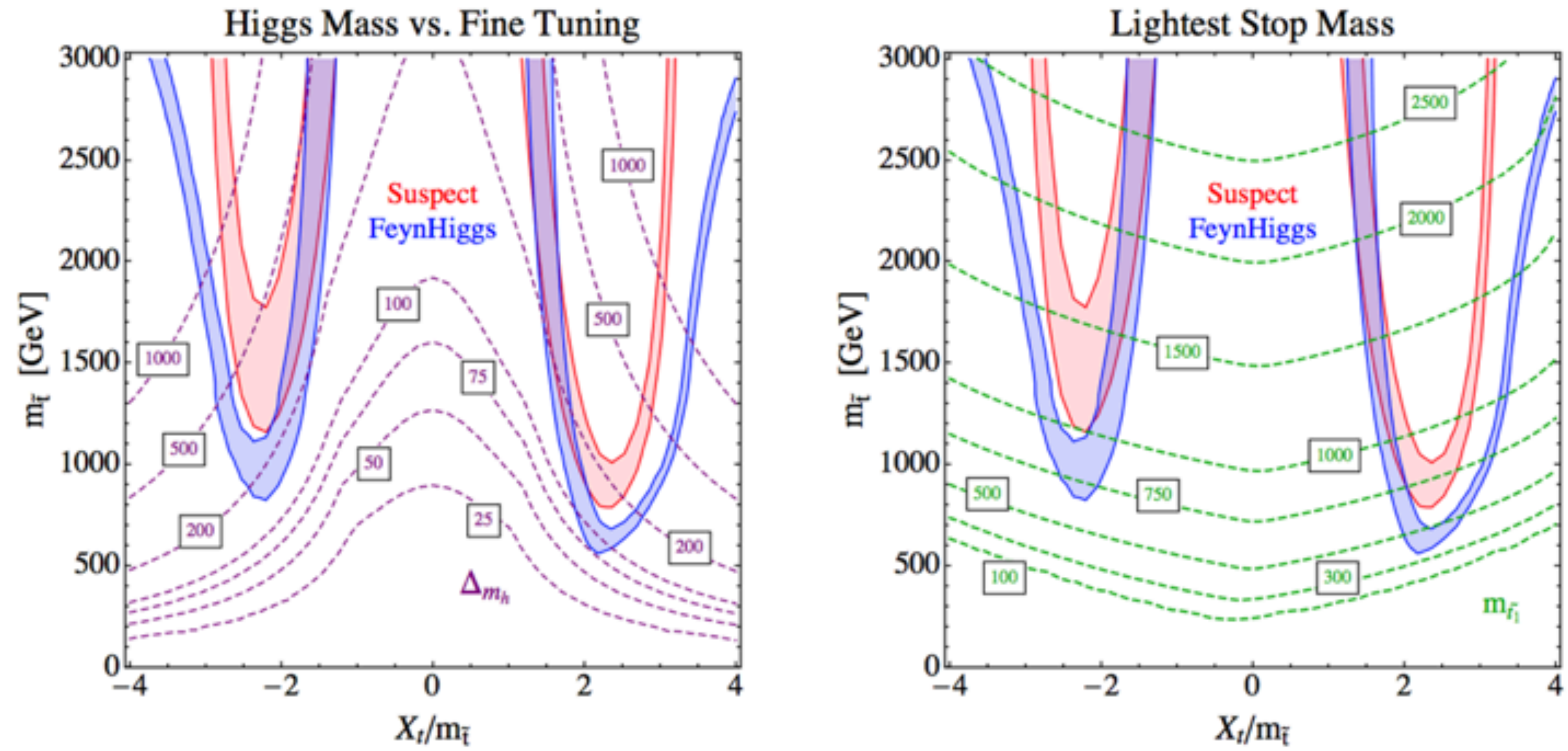


FIG. 3. The allowed parameter space in the $\tan\beta - M_{sc}$ plane for a Higgs mass of 125.7 ± 0.8 GeV, for $\mu = m_{sc}$. The solid blue lines delimit the 2σ uncertainty. The dashed blue lines show the effect of the 1σ uncertainty in the top mass, $m_t = 173.2 \pm 0.9$ GeV [45]. We take the gaugino spectrum predicted by AMSB (including the heavy Higgsino threshold) with the gravitino mass $m_{3/2} = 500$ TeV, resulting in a wino LSP at 2.6 TeV, and a gluino mass of 14.4 TeV. However, the Higgs mass is highly insensitive to the gaugino spectrum, and a gravitino mass of 50 TeV yields essentially the same plot above.

Fig. from

N.Arkani-Hamed, A.Gupta, D.E.Kaplan, N.Weiner, T.Zorawski'12



[L.J.Hall, D.Pinner, J.T.Ruderman, 1112.2703]

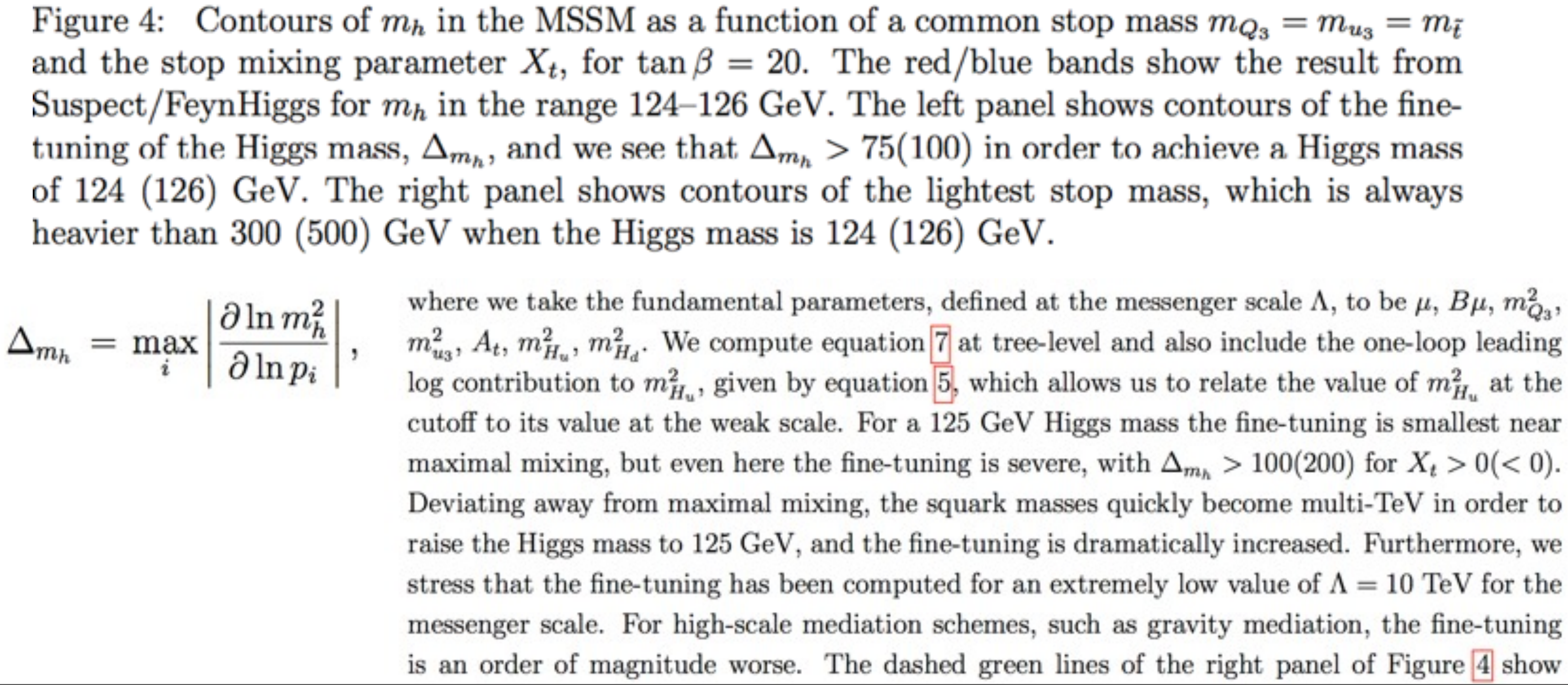


Figure 4: Contours of m_h in the MSSM as a function of a common stop mass $m_{Q_3} = m_{u_3} = m_{\tilde{t}}$ and the stop mixing parameter X_t, for $\tan\beta = 20$. The red/blue bands show the result from Suspect/FeynHiggs for m_h in the range 124–126 GeV. The left panel shows contours of the fine-tuning of the Higgs mass, Δ_{m_h}, and we see that $\Delta_{m_h} > 75(100)$ in order to achieve a Higgs mass of 124 (126) GeV. The right panel shows contours of the lightest stop mass, which is always heavier than 300 (500) GeV when the Higgs mass is 124 (126) GeV.

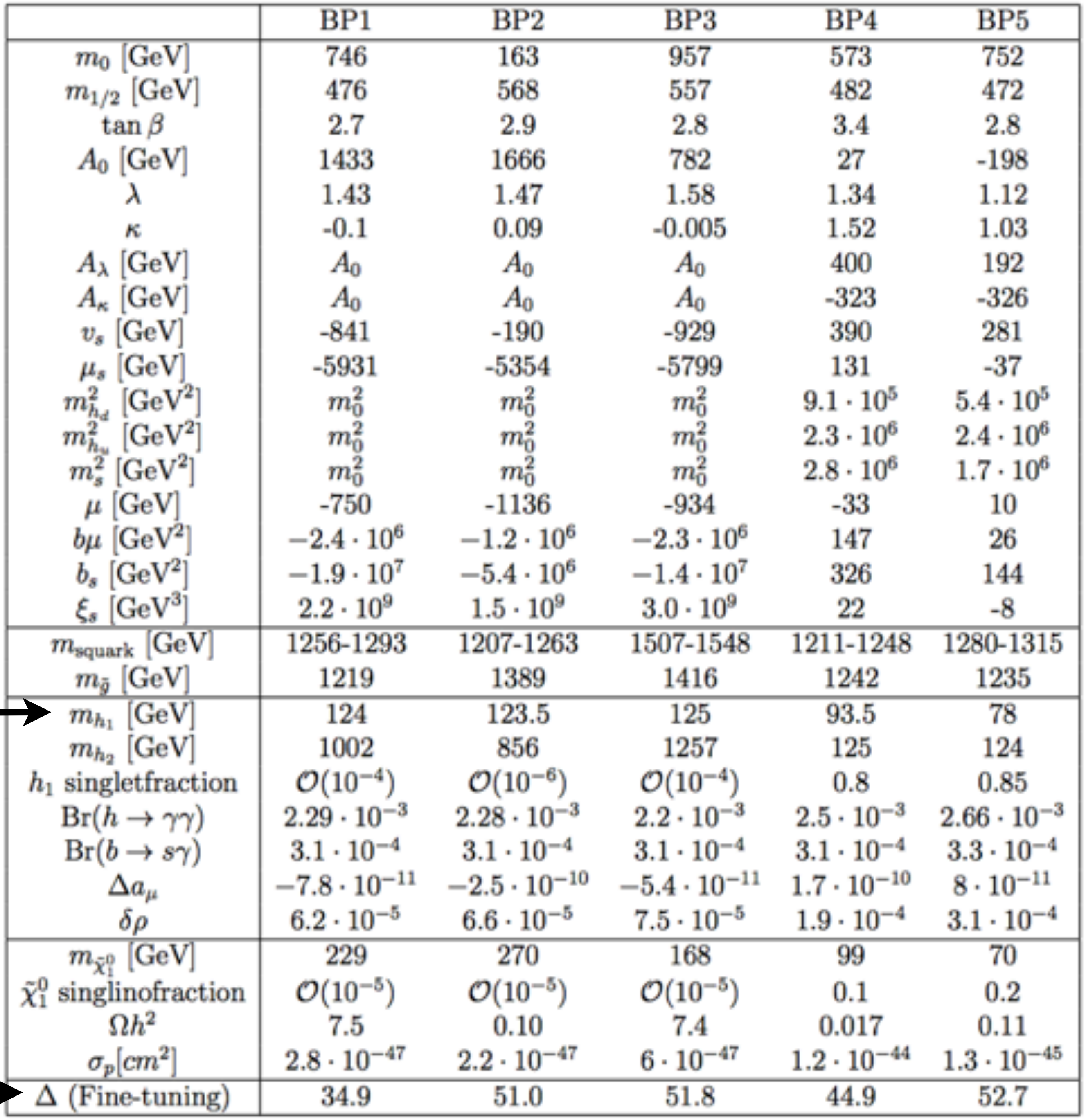
$$\Delta_{m_h} = \max_i \left| \frac{\partial \ln m_h^2}{\partial \ln p_i} \right| ,$$

where we take the fundamental parameters, defined at the messenger scale Λ, to be μ, $B\mu$, $m_{Q_3}^2$, $m_{u_3}^2$, A_t, $m_{H_u}^2$, $m_{H_d}^2$. We compute equation 7 at tree-level and also include the one-loop leading log contribution to $m_{H_u}^2$, given by equation 5, which allows us to relate the value of $m_{H_u}^2$ at the cutoff to its value at the weak scale. For a 125 GeV Higgs mass the fine-tuning is smallest near maximal mixing, but even here the fine-tuning is severe, with $\Delta_{m_h} > 100(200)$ for $X_t > 0(< 0)$. Deviating away from maximal mixing, the squark masses quickly become multi-TeV in order to raise the Higgs mass to 125 GeV, and the fine-tuning is dramatically increased. Furthermore, we stress that the fine-tuning has been computed for an extremely low value of $\Lambda = 10$ TeV for the messenger scale. For high-scale mediation schemes, such as gravity mediation, the fine-tuning is an order of magnitude worse. The dashed green lines of the right panel of Figure 4 show

generalized NMSSM

G.G.Ross,
K.Schmidt-Hoberg,
F.Staub [1205.1509]

$$\begin{aligned}\mathcal{W} &= \mathcal{W}_{\text{Yukawa}} + \frac{1}{3}\kappa S^3 + (\mu + \lambda S)H_u H_d + \xi S + \frac{1}{2}\mu_s S^2 \\ &\equiv \mathcal{W}_{\text{NMSSM}} + \mu H_u H_d + \xi S + \frac{1}{2}\mu_s S^2\end{aligned}$$



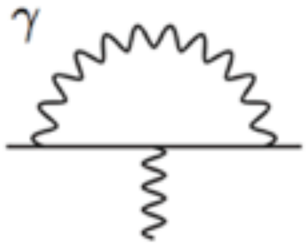
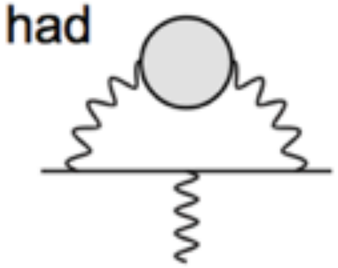
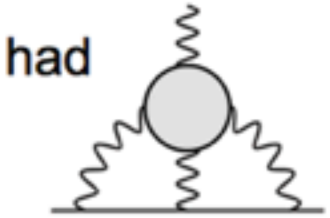
	BP1	BP2	BP3	BP4	BP5
m_0 [GeV]	746	163	957	573	752
$m_{1/2}$ [GeV]	476	568	557	482	472
$\tan\beta$	2.7	2.9	2.8	3.4	2.8
A_0 [GeV]	1433	1666	782	27	-198
λ	1.43	1.47	1.58	1.34	1.12
κ	-0.1	0.09	-0.005	1.52	1.03
A_λ [GeV]	A_0	A_0	A_0	400	192
A_κ [GeV]	A_0	A_0	A_0	-323	-326
v_s [GeV]	-841	-190	-929	390	281
μ_s [GeV]	-5931	-5354	-5799	131	-37
$m^2_{h_d}$ [GeV^2]	m_0^2	m_0^2	m_0^2	$9.1 \cdot 10^5$	$5.4 \cdot 10^5$
$m^2_{h_u}$ [GeV^2]	m_0^2	m_0^2	m_0^2	$2.3 \cdot 10^6$	$2.4 \cdot 10^6$
m^2_s [GeV^2]	m_0^2	m_0^2	m_0^2	$2.8 \cdot 10^6$	$1.7 \cdot 10^6$
μ [GeV]	-750	-1136	-934	-33	10
$b\mu$ [GeV^2]	$-2.4 \cdot 10^6$	$-1.2 \cdot 10^6$	$-2.3 \cdot 10^6$	147	26
b_s [GeV^2]	$-1.9 \cdot 10^7$	$-5.4 \cdot 10^6$	$-1.4 \cdot 10^7$	326	144
ξ_s [GeV^3]	$2.2 \cdot 10^9$	$1.5 \cdot 10^9$	$3.0 \cdot 10^9$	22	-8
m_{squark} [GeV]	1256-1293	1207-1263	1507-1548	1211-1248	1280-1315
$m_{\tilde{g}}$ [GeV]	1219	1389	1416	1242	1235
m_{h_1} [GeV]	124	123.5	125	93.5	78
m_{h_2} [GeV]	1002	856	1257	125	124
h_1 singletfraction	$\mathcal{O}(10^{-4})$	$\mathcal{O}(10^{-6})$	$\mathcal{O}(10^{-4})$	0.8	0.85
$\text{Br}(h \to \gamma\gamma)$	$2.29 \cdot 10^{-3}$	$2.28 \cdot 10^{-3}$	$2.2 \cdot 10^{-3}$	$2.5 \cdot 10^{-3}$	$2.66 \cdot 10^{-3}$
$\text{Br}(b \to s\gamma)$	$3.1 \cdot 10^{-4}$	$3.1 \cdot 10^{-4}$	$3.1 \cdot 10^{-4}$	$3.1 \cdot 10^{-4}$	$3.3 \cdot 10^{-4}$
Δa_μ	$-7.8 \cdot 10^{-11}$	$-2.5 \cdot 10^{-10}$	$-5.4 \cdot 10^{-11}$	$1.7 \cdot 10^{-10}$	$8 \cdot 10^{-11}$
$\delta\rho$	$6.2 \cdot 10^{-5}$	$6.6 \cdot 10^{-5}$	$7.5 \cdot 10^{-5}$	$1.9 \cdot 10^{-4}$	$3.1 \cdot 10^{-4}$
$m_{\tilde{\chi}^0_1}$ [GeV]	229	270	168	99	70
$\tilde{\chi}^0_1$ singlinofraction	$\mathcal{O}(10^{-5})$	$\mathcal{O}(10^{-5})$	$\mathcal{O}(10^{-5})$	0.1	0.2
Ωh^2	7.5	0.10	7.4	0.017	0.11
$\sigma_p[cm^2]$	$2.8 \cdot 10^{-47}$	$2.2 \cdot 10^{-47}$	$6 \cdot 10^{-47}$	$1.2 \cdot 10^{-44}$	$1.3 \cdot 10^{-45}$
Δ (Fine-tuning)	34.9	51.0	51.8	44.9	52.7

Table 1: Benchmark scenarios for the GNMSSM for the universal (BP1-BP3) and the general (BP4-BP5) case. m_{squark} shows the range of squark masses of the first two generations. For the last two points the second lightest Higgs is mostly MSSM-like. All input parameters except $\tan\beta$ and v_s are given at the GUT scale.

Higgs
mass

a few %
fine-tuning

Standard Model Prediction

Exp (E821)		116 592 089 (63) [10^{-11}]	
QED (α^5, Rb)		116 584 718.951 (0.080)	
EW (W/Z/H_{SM}, NLO)		154.0 (1.0)	
Hadronic (leading)	[HLMNT]	6 949.1 (43)*	
	[DHMZ]	6 923 (42)	
Hadronic (α higher)		-98.4 (0.7)	
Hadronic (LbL)	[RdRV]	105 (26)*	
	[NJN]	116 (39)	

$$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (26.0 \pm 8.1) \cdot 10^{-10}$$ > 3σ deviation

from talk by **M.Endo** @ Hokkaido Winter School'13

Hadronic light-by-light scattering in the muon $g-2$: Summary

Some results for the various contributions to $a_\mu^{\mathrm{LbyL;had}} \times 10^{11}$:

Contribution	BPP	HKS, HK	KN	MV	BP, MdRR	PdRV	N, JN	FGW
π^0, η, η'	85 ± 13	82.7 ± 6.4	83 ± 12	114 ± 10	–	114 ± 13	99 ± 16	84 ± 13
axial vectors	2.5 ± 1.0	1.7 ± 1.7	–	22 ± 5	–	15 ± 10	22 ± 5	–
scalars	-6.8 ± 2.0	–	–	–	–	-7 ± 7	-7 ± 2	–
π, K loops	-19 ± 13	-4.5 ± 8.1	–	–	–	-19 ± 19	-19 ± 13	–
π, K loops $+$subl. N_C	–	–	–	$0\pm$[illegible]	–	–	–	–
other	–	–	–	–	–	–	–	0 ± 20
quark loops	21 ± 3	9.7 ± 11.1	–	–	–	2.3	21 ± 3	107 ± 48
Total	83 ± 32	89.6 ± 15.4	80 ± 40	136 ± 25	110 ± 40	105 ± 26	116 ± 39	191 ± 81

$\gtrsim 3\sigma$!

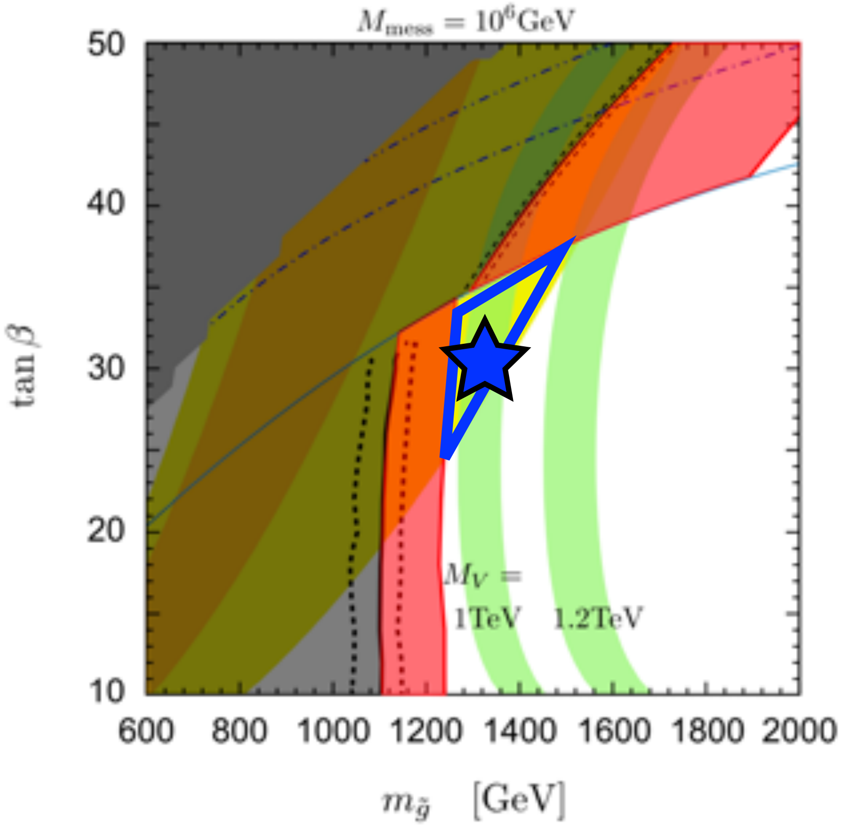
BPP = Bijnens, Pallante, Prades '95, '96, '02; HKS = Hayakawa, Kinoshita, Sanda '95, '96; HK = Hayakawa, Kinoshita '98, '02; KN = Knecht, Nyffeler '02; MV = Melnikov, Vainshtein '04; BP = Bijnens, Prades '07; MdRR = Miller, de Rafael, Roberts '07; PdRV = Prades, de Rafael, Vainshtein '09; N = Nyffeler '09, JN = Jegerlehner, Nyffeler '09; FGW = Fischer, Goecke, Williams '10, '11 (used values from arXiv:1009.5297v2 [hep-ph], 4 Feb 2011)

- Pseudoscalar-exchange contribution dominates numerically (except in FGW). But other contributions are not negligible. Note cancellation between π, K-loops and quark loops !
- PdRV: Do not consider dressed light quark loops as separate contribution ! Assume it is already taken into account by using short-distance constraint of MV '04 on pseudoscalar-pole contribution. Added all errors in quadrature ! Like HK(S). Too optimistic ?
- N, JN: New evaluation of pseudoscalars. Took over most values from BPP, except axial vectors from MV. Added all errors linearly. Like BPP, MV, BP, MdRR. Too pessimistic ?
- FGW: new approach with Dyson-Schwinger equations. Is there some double-counting ? Between their dressed quark loop (largely enhanced !) and the pseudoscalar exchanges.

Nyffeler, INT workshop on "The Hadronic LbL Contribution to the Muon Anomaly"

Results

for "V-GMSB"



M.Endo, KH, K.Ishikawa, S.Iwamoto, N.Yokozaki,

arXiv:1212.3935

```
3    3.00000000e+01   # tanb
4    1.00000000e+00   # sign(mu)
1    1.65000000e+05   # lambda
2    1.00000000e+06   # M_mess
5    1.00000000e+00   # N5

1    1.00000000e+03   # MQ'(SUSY)
2    1.00000000e+03   # MU'(SUSY)
3    1.00000000e+03   # ME'(SUSY)
4    1.00000000e+00   # Y'(input)
5    0.00000000e+00   # Y''(input)
```

```
Block VECTORMASS
  8000001     9.19246145e+02   # t_1'
  8000002     1.08784791e+03   # t_2'
  8000003     1.00000000e+03   # b'
  8000004     1.00000000e+03   # tau'
  8000005     2.04454519e+03   # ~t_1'
  8000006     2.20498371e+03   # ~t_2'
  8000007     2.35226167e+03   # ~t_3'
  8000008     2.47452620e+03   # ~t_4'
  8000009     2.20345618e+03   # ~b_1'
  8000010     2.46108407e+03   # ~b_2'
  8000011     1.04125672e+03   # ~tau_1'
  8000012     1.05215246e+03   # ~tau_2'
```

```
Block MASS                  # Mass spectrum
   25     1.25297e+02   # h0
    35     1.66854258e+03   # H0
    36     1.66853938e+03   # A0
    37     1.67070990e+03   # H+
 1000021     1.30320381e+03   # ~g
 1000022     2.24794391e+02   # ~neutralino(1)
 1000023     4.42870366e+02   # ~neutralino(2)
 1000024     4.43014726e+02   # ~chargino(1)
 1000025    -1.60827881e+03   # ~neutralino(3)
 1000035     1.60992366e+03   # ~neutralino(4)
 1000037     1.61068696e+03   # ~chargino(2)
 1000001     2.20271713e+03   # ~d_L
 1000002     2.20134932e+03   # ~u_L
 1000003     2.20270645e+03   # ~s_L
 1000004     2.20133863e+03   # ~c_L
 1000005     2.05190037e+03   # ~b_1
 1000006     1.90874207e+03   # ~t_1
 1000011     6.53371235e+02   # ~e_L
 1000012     6.48048188e+02   # ~nue_L
 1000013     6.53263452e+02   # ~mu_L
 1000014     6.48034900e+02   # ~numu_L
 1000015     2.51278423e+02   # ~stau_1
 1000016     6.39706366e+02   # ~nu_tau_L
 2000001     2.11013140e+03   # ~d_R
 2000002     2.11698121e+03   # ~u_R
 2000003     2.11011126e+03   # ~s_R
 2000004     2.11697894e+03   # ~c_R
 2000005     2.10255419e+03   # ~b_2
 2000006     2.09034095e+03   # ~t_2
 2000011     3.17876514e+02   # ~e_R
 2000013     3.17821740e+02   # ~mu_R
 2000015     6.60554188e+02   # ~stau_2
```