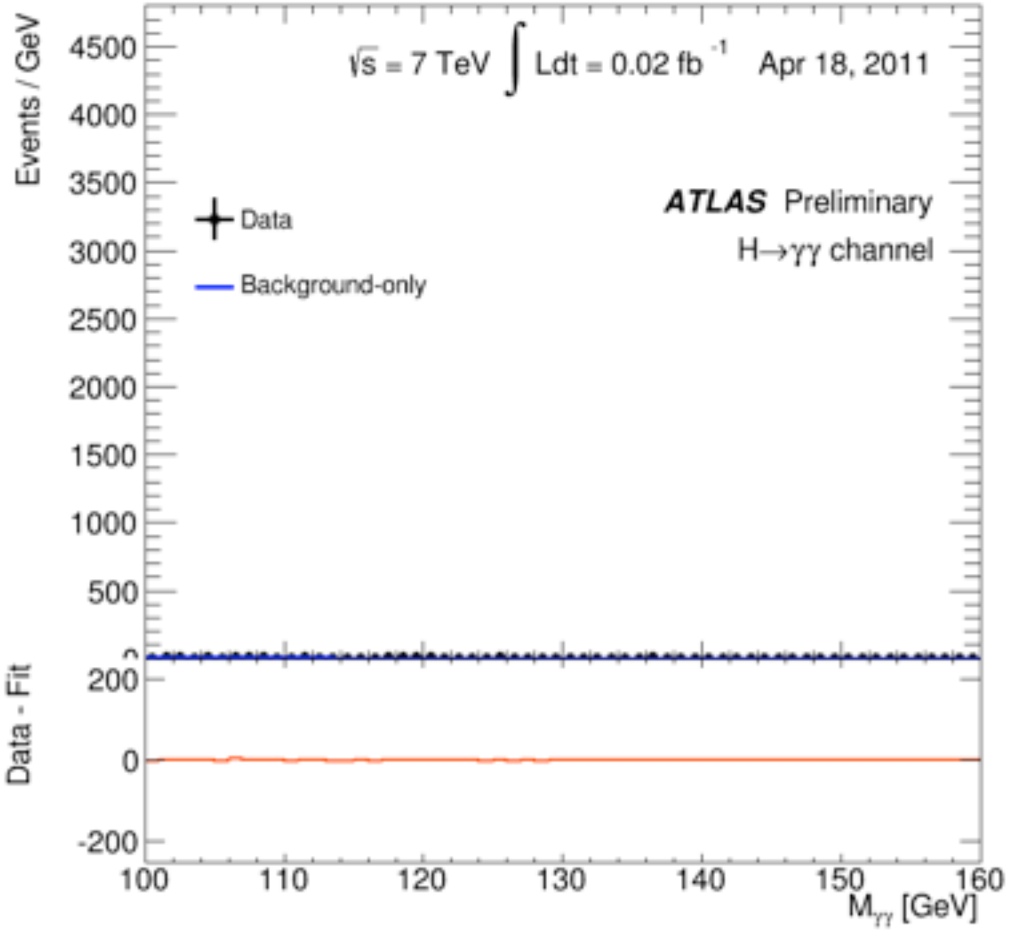
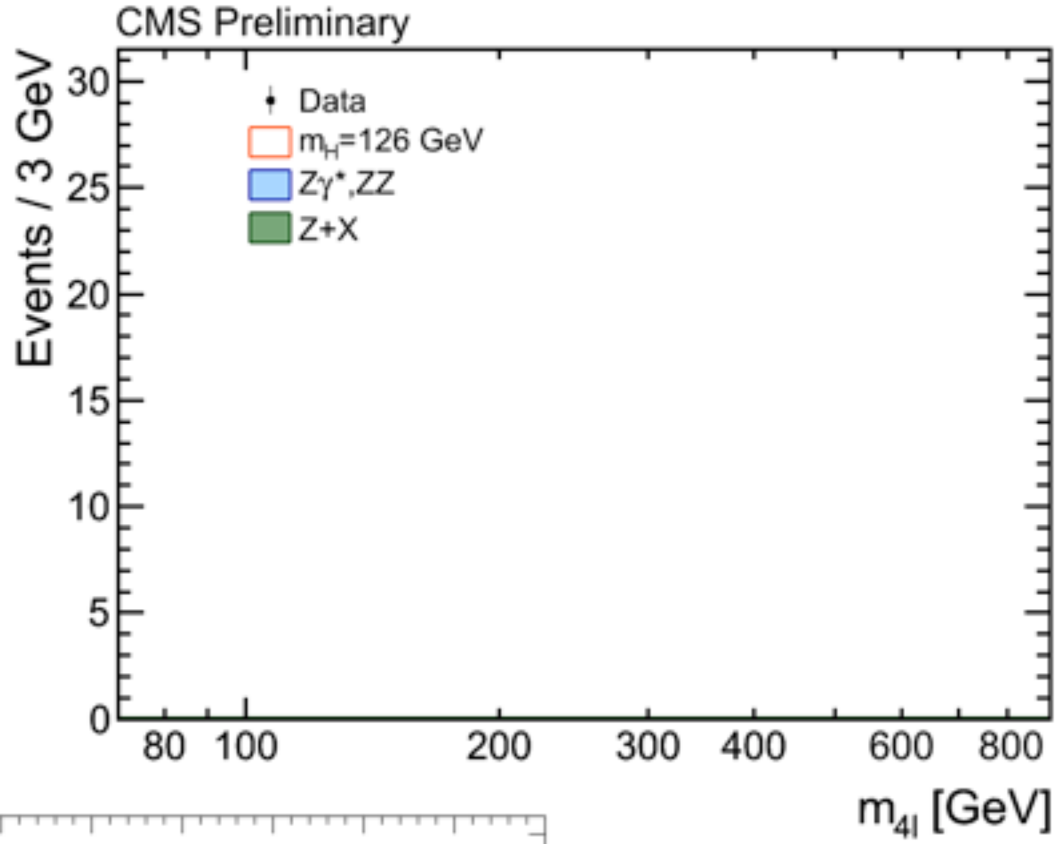
Supersymmetry after Higgs discovery

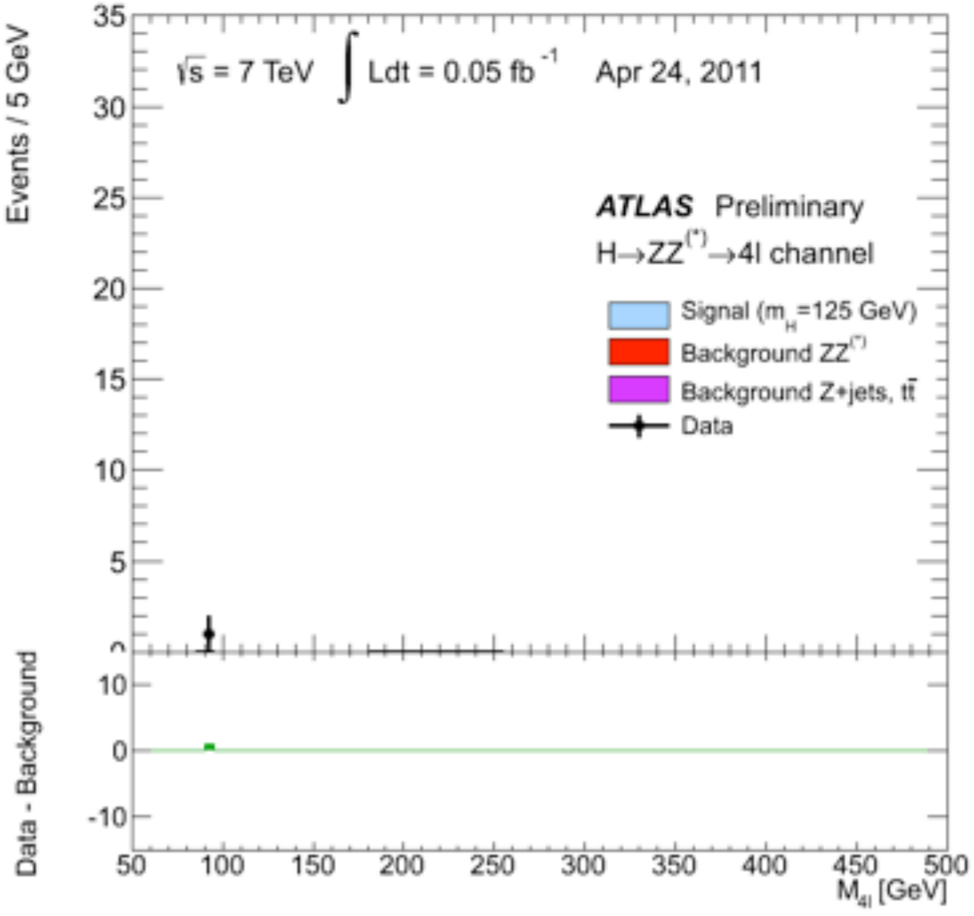
Koichi Hamaguchi (University of Tokyo)

@ ECFA LC 2013, DESY, May 29

a Higgs boson was discovered !

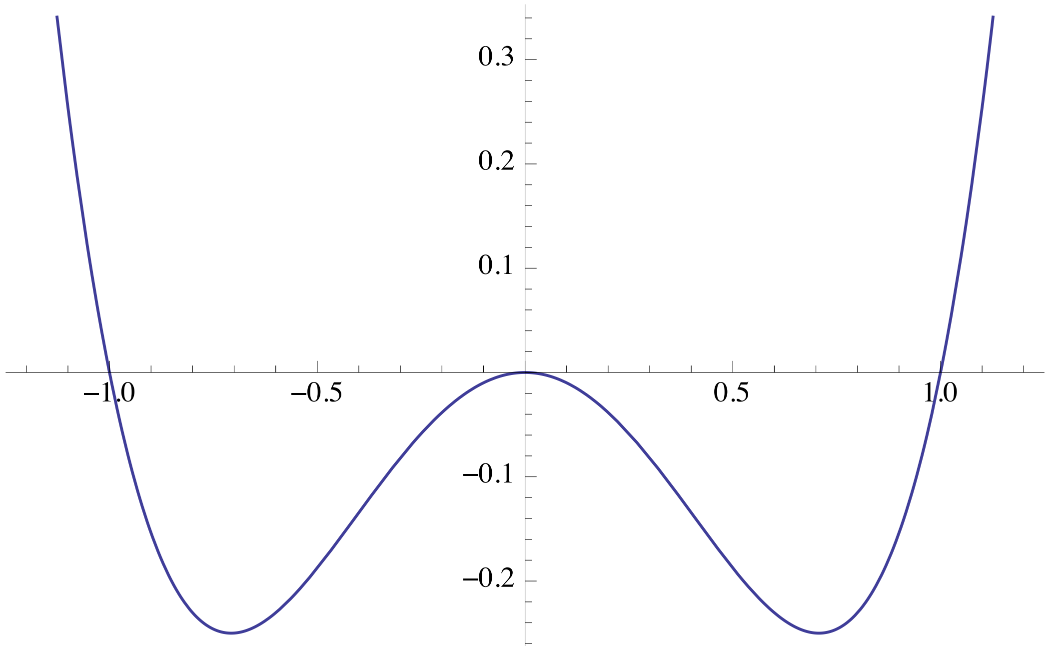






126 GeV Higgs

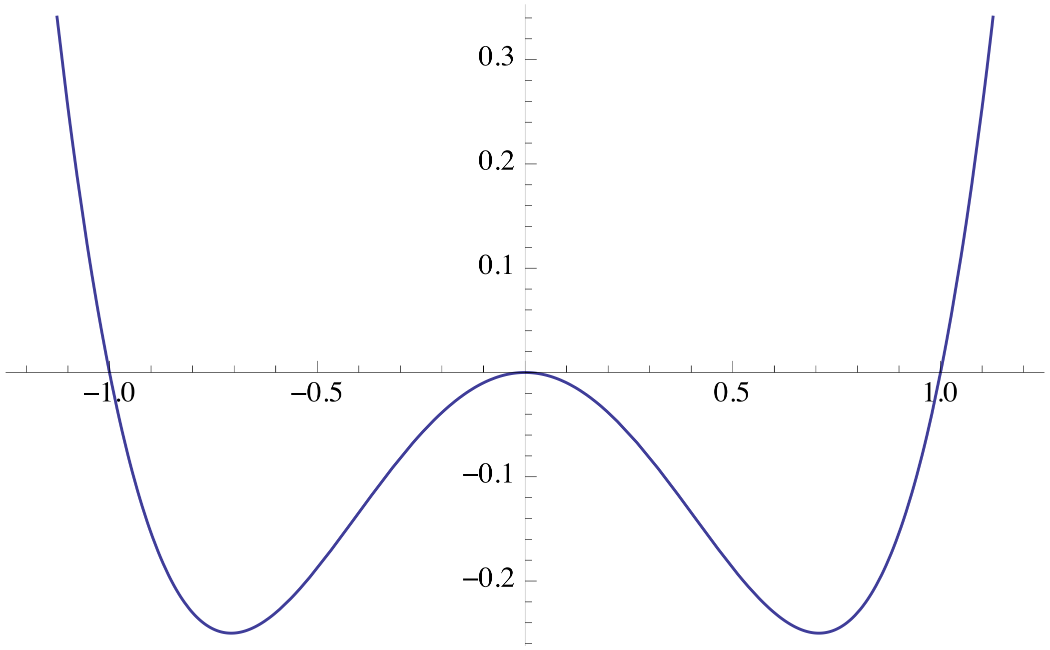
$$V(H) = -m^2(H^\dagger H) + \lambda_{\mathrm{H}}(H^\dagger H)^2$$



126 GeV Higgs

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

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

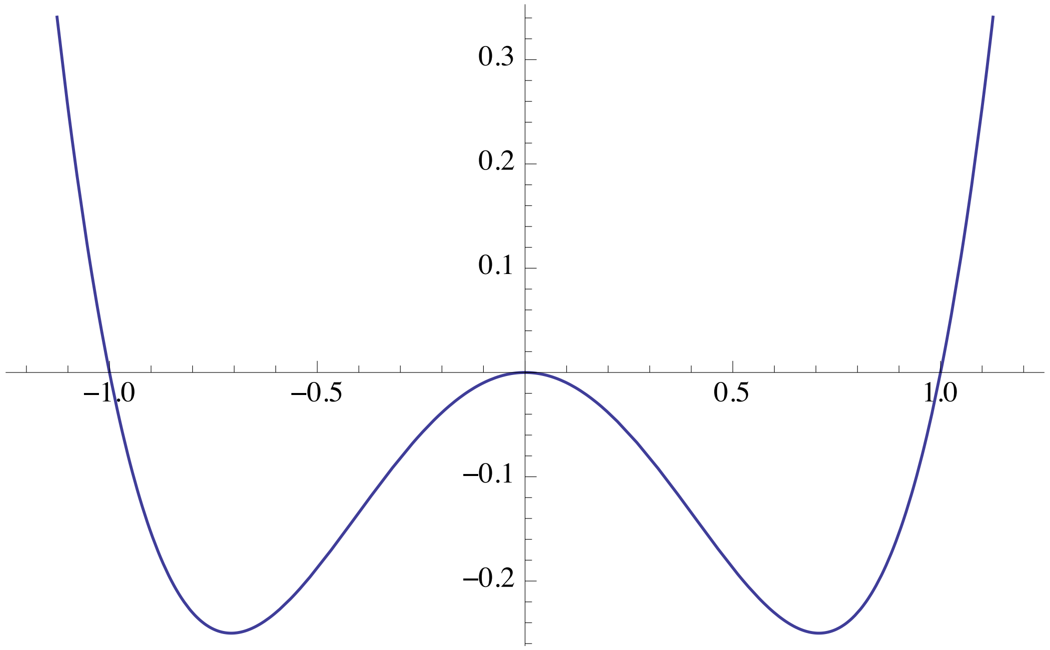


126 GeV Higgs

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

We knew..

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



126 GeV Higgs

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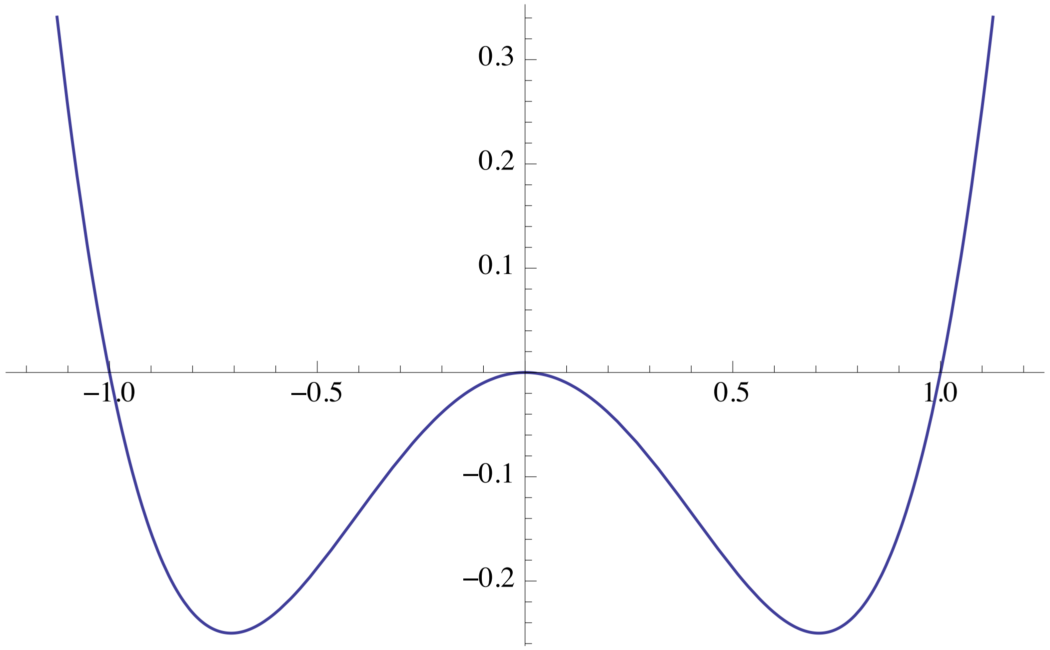

126 GeV Higgs

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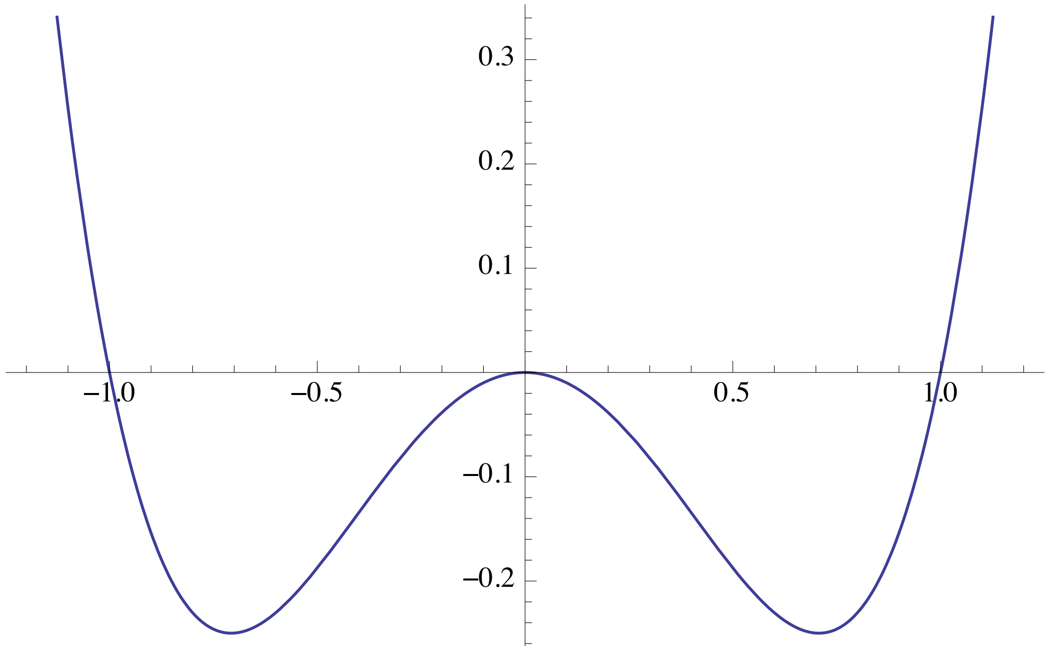


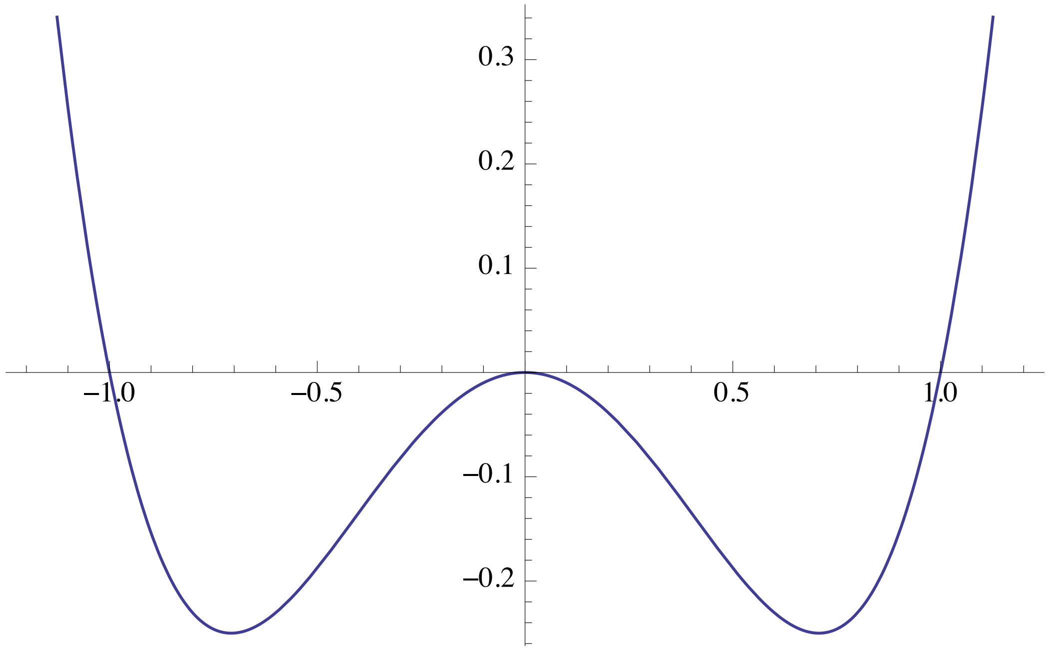
$$\rightarrow \begin{cases} m^2 = \dfrac{m^2_{\mathrm{Higgs}}}{2} \simeq \mathbf{(89\ GeV)^2} \\[2em] \lambda_{\mathrm{H}} = \dfrac{m^2_{\mathrm{Higgs}}}{4\langle H\rangle^2} \simeq \mathbf{0.13} \end{cases}$$

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 !



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126 GeV Higgs

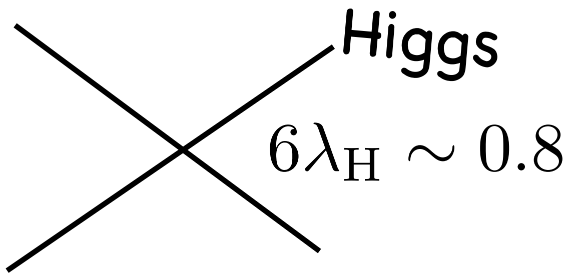
$$V(H) = -m^2(H^\dagger H) + \lambda_{\mathrm{H}}(H^\dagger H)^2$$

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

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.

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

R.H.neutrino

Higgs

(1) small neutrino masses

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

(3) Leptogenesis

... implying weakly coupled, perturbative QFT 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

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

("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.....

Today

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.....

Today

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.....

See also the next
H.Baer's talk

Today

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

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

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

in SUSY...

126 GeV Higgs and naturalness

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

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

0.13

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

in SUSY...

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

too small...

126 GeV Higgs and naturalness

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

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

$\mathbf{0.13}$

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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

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

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

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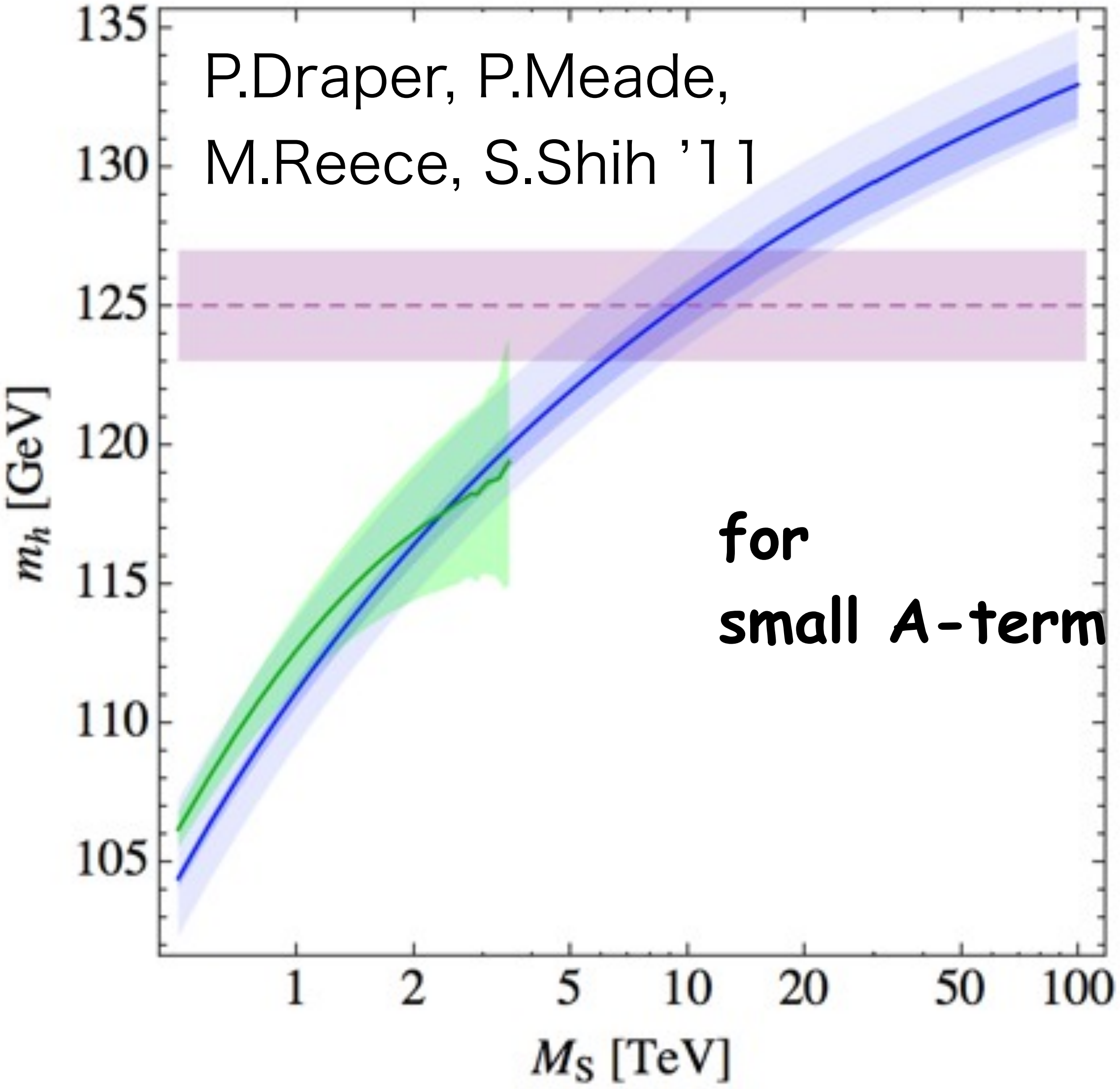


P.Draper, P.Meade, M.Reece, S.Shih '11

for small A-term

126 GeV Higgs and naturalness

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

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

λ_H: 0.13

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

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

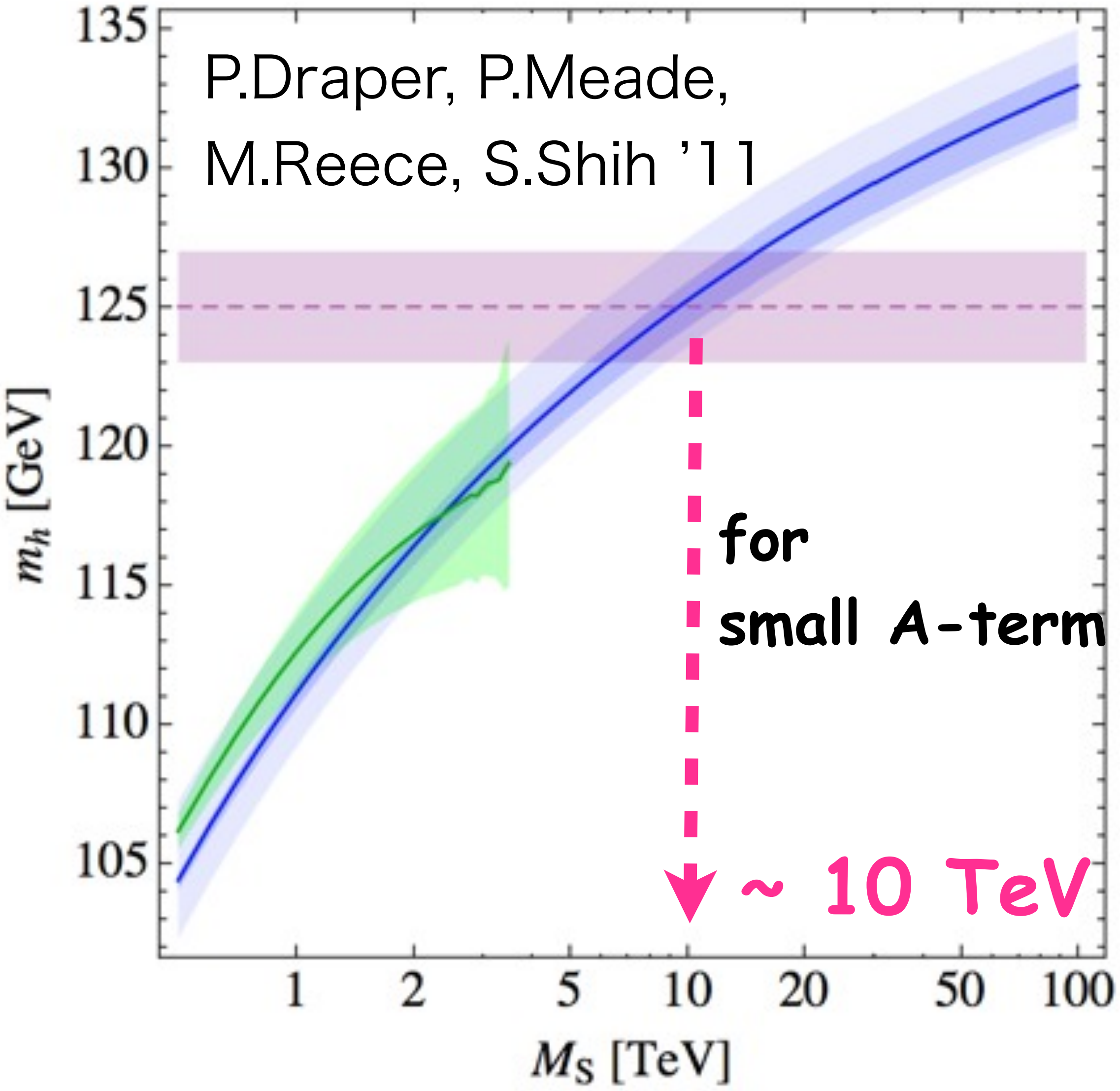
$$\delta\lambda_H^{\mathrm{loop}} = \frac{3y_t^4}{16\pi^2}\left(\log\left(\frac{m_{\mathrm{stop}}^2}{m_t^2}\right) + \alpha^2 - \frac{\alpha^4}{12}\right) + \cdots$$

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

...requires **heavy stop**

and/or **large A-term**

in SUSY...



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

for small A-term

~ 10 TeV

126 GeV Higgs and naturalness

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

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

on the other hand

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

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

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

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...requires **heavy stop**

and/or **large A-term**

126 GeV Higgs and naturalness

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

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

0.13

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

on the other hand

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

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

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

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

large μ -----> fine-tuning.

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

for $|\mu| \simeq 1$ TeV

requires **Light Higgsino** to avoid a fine-tuning.

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

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

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126 GeV Higgs and **naturalness**

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

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

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

on the other hand

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

Moreover,

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

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

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

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

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126 GeV Higgs and naturalness

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small A-term

to avoid a fine-tuning.

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

...requires **heavy stop**

and/or **large A-term**

inconsistent !!

126 GeV Higgs and naturalness

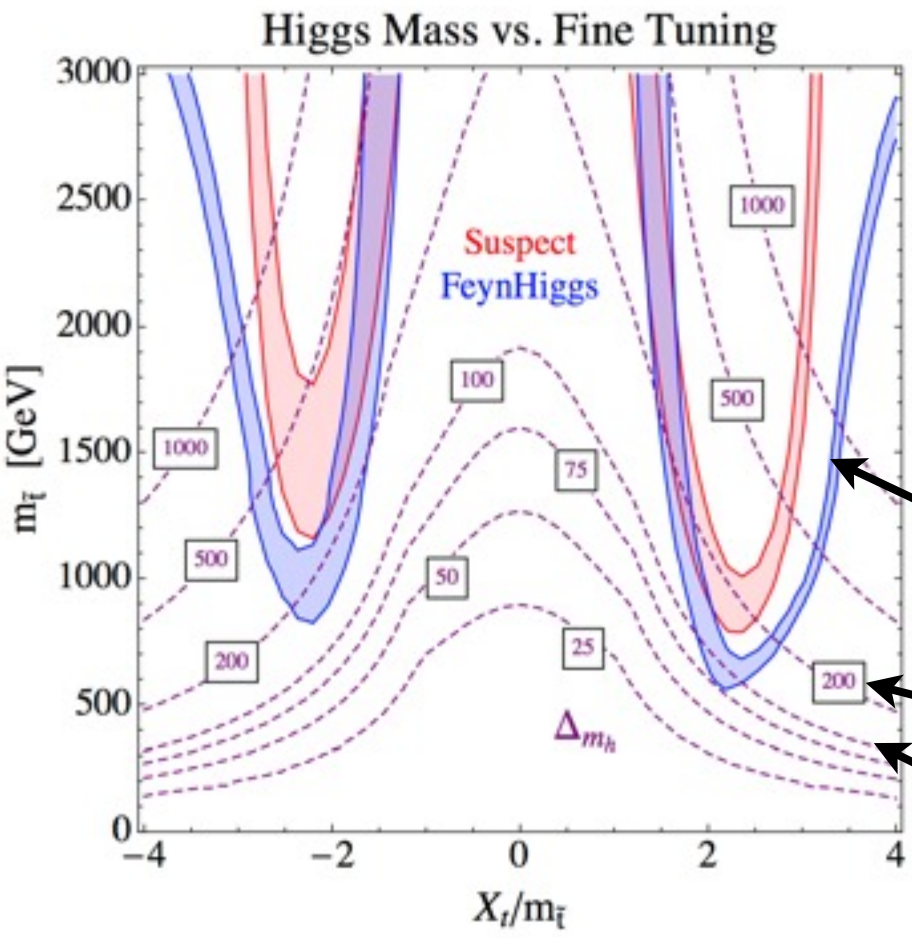
difficult to reconcile within MSSM

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.



mh = 124-126 GeV

fine tuning 0.5 %

fine tuning 1%

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

126 GeV Higgs and naturalness

difficult to reconcile within MSSM

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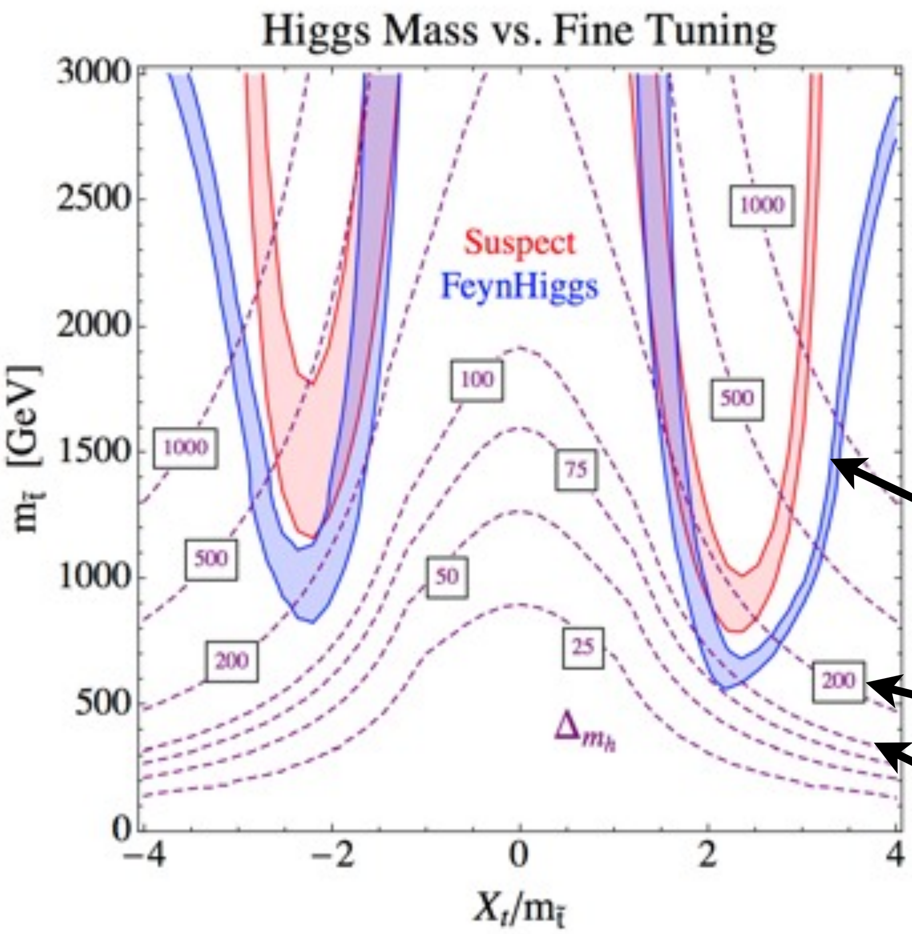

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But see also the next H.Baer's talk. (cf. "Radiatively-driven natural SUSY", Baer, Barger, Huang, Mickelson, Mustafayev, Tata, [1212.2655].)

126 GeV Higgs and naturalness

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implies **Beyond MSSM models.**

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

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

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

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

Model buildings and collider studies of NMSSM with less fine-tuning are interesting and important...

See, e.g.,
L.J.Hall, D.Pinner, J.T.Ruderman, [1112.2703],
G.G.Ross, K.Schmidt-Hoberg, F.Staub [1205.1509], and many related works...

But see also the next H.Baer's talk. (cf. "Radiatively-driven natural SUSY", Baer, Barger, Huang, Mickelson, Mustafayev,Tata, [1212.2655].)

126 GeV Higgs and naturalness

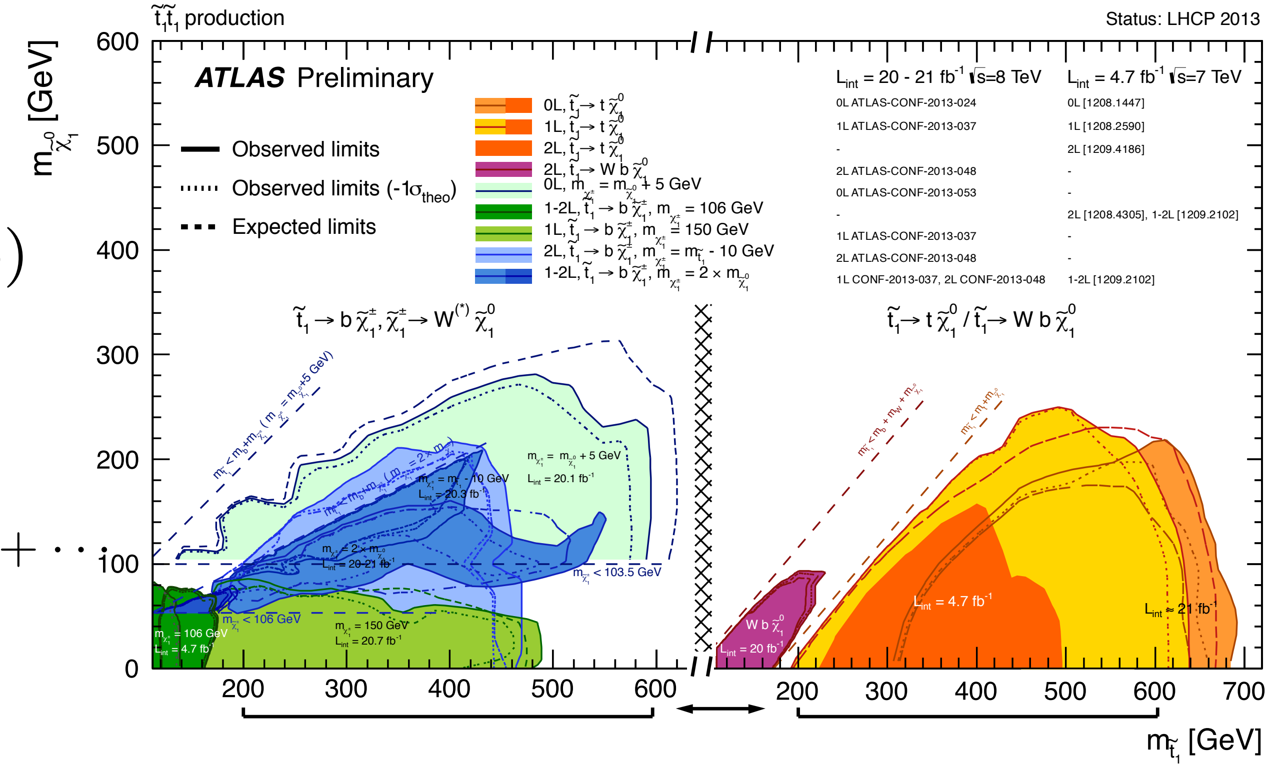
$$V(H) = -\underbrace{m^2}_{(89\ \mathrm{GeV})^2}(H^\dagger H) + \underbrace{\lambda_H}_{0.13}(H^\dagger H)^2$$

e.g., by NMSSM

In any case,...

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

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



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

If discovered, **Higgsino can be further studied at LC.**

126 GeV Higgs and SUSY

Motivations of TeV scale SUSY.....

Today

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.....

Today

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)**

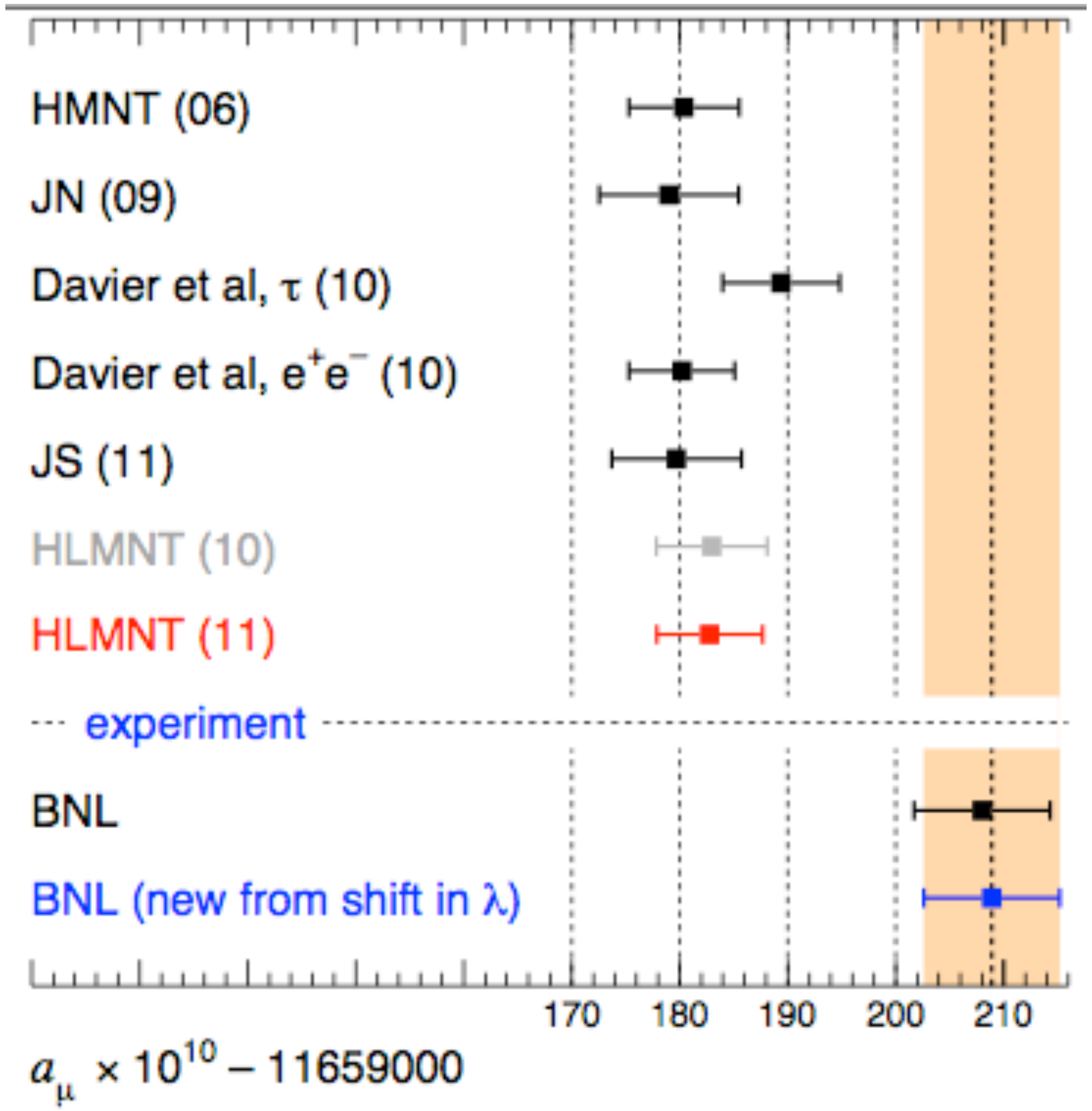
126 GeV Higgs + muon g-2

126 GeV Higgs + muon g-2

muon g-2

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

> 3σ deviation !



[Hagiwara, Liao, Martin, Nomura, Teubner, arXiv: 1105.3149. See also references therein!]

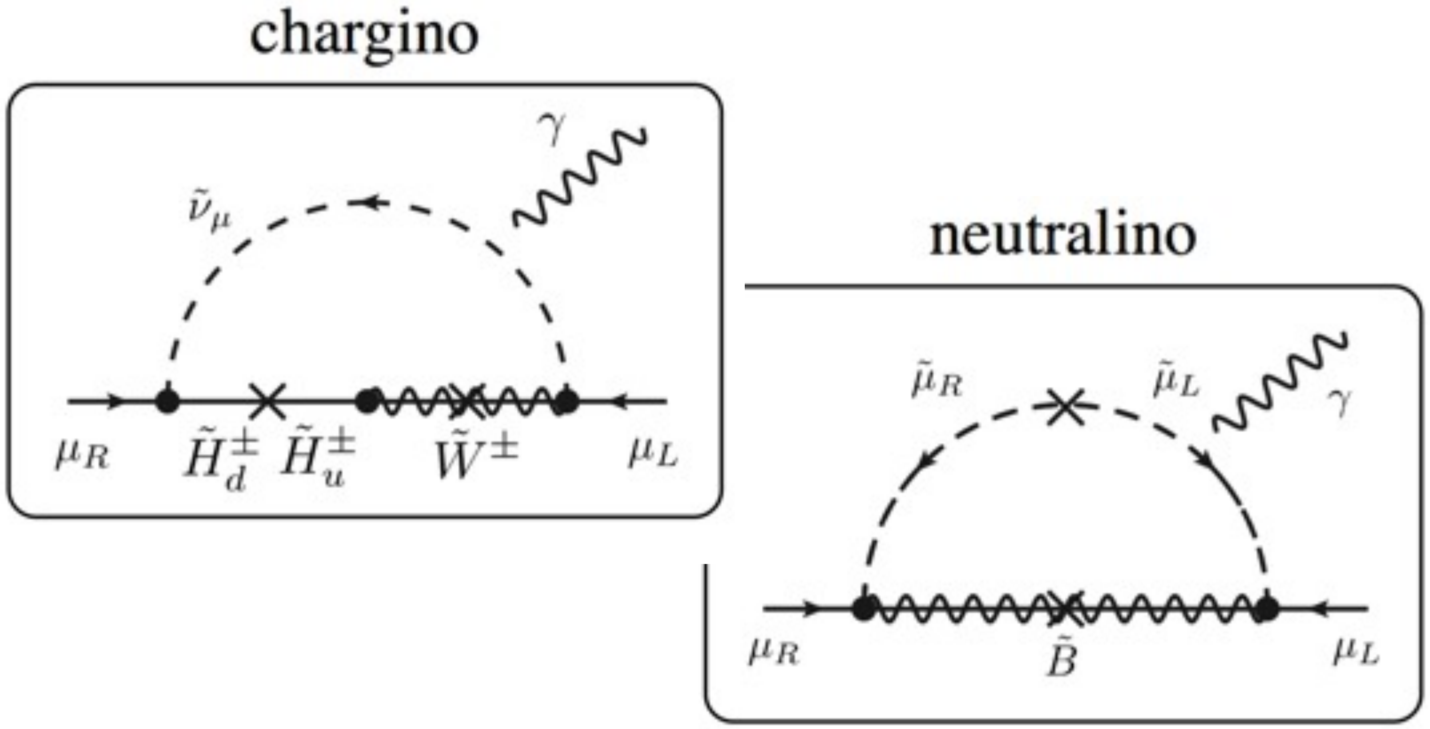
126 GeV Higgs + muon g-2

muon g-2

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

> 3σ deviation !

...can be explained by SUSY.


chargino

neutralino

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

126 GeV Higgs + muon g-2

heavy stop

light smuon/ inos

difficult to reconcile in typical models

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

126 GeV Higgs + muon g-2

heavy stop

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difficult to reconcile in typical models

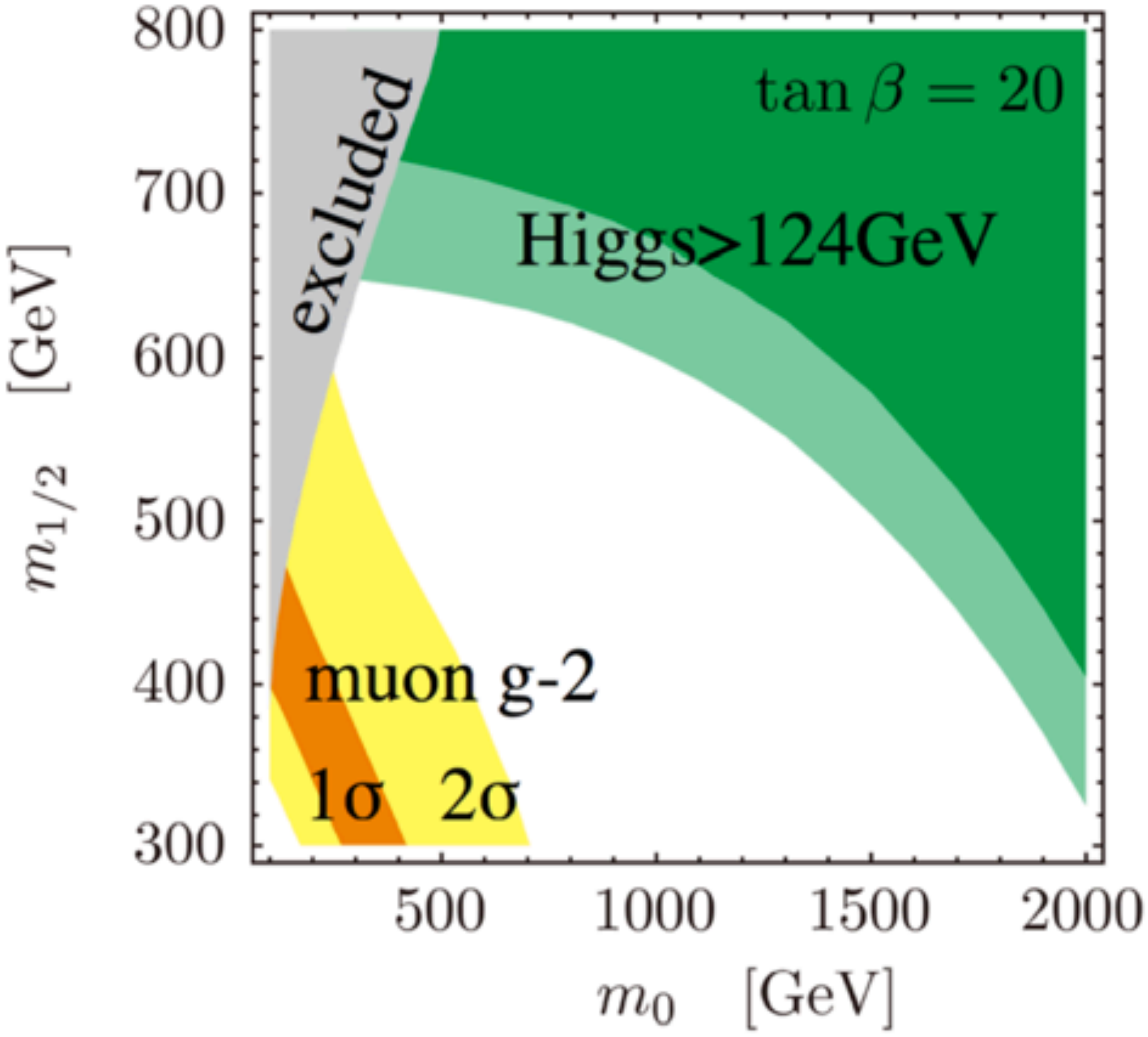
(mSUGRA/GMSB/AMSB/NMSSM (small tanβ) ...)

Example in 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]



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

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 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

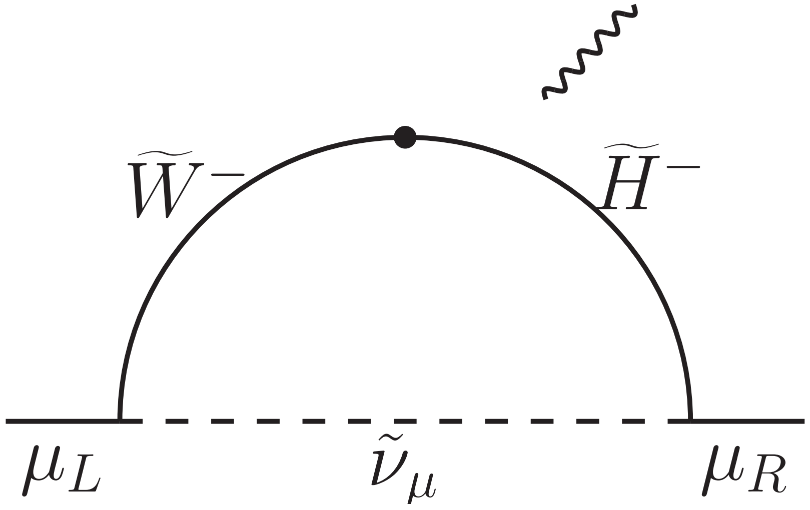
= O(100 GeV)
to explain muon g-2

Can we test it ??

“g-2 motivated” MSSM

two representative parameter regions

Case1



Chargino contribution

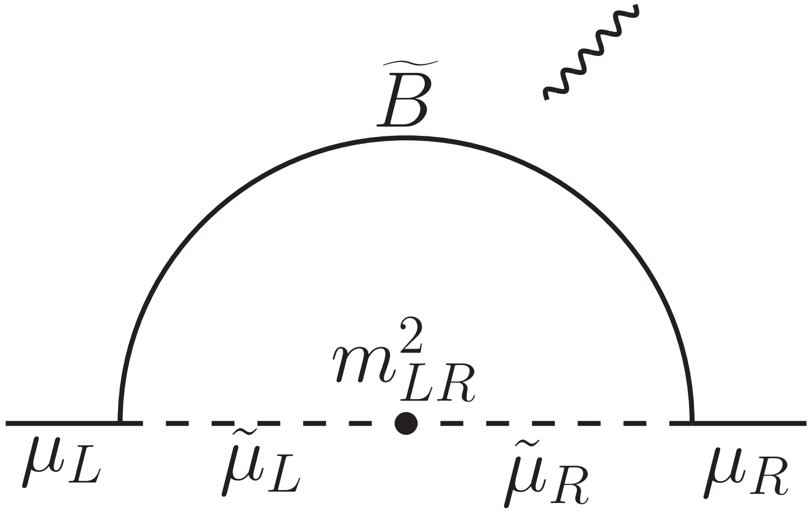
(usually dominant)

enhanced when

Higgsino, Wino, smuon(L)

are light.

Case2



Neutralino contribution

(subdominant)

enhanced when

Bino, smuon(L+R)

are light

(and μ is large).

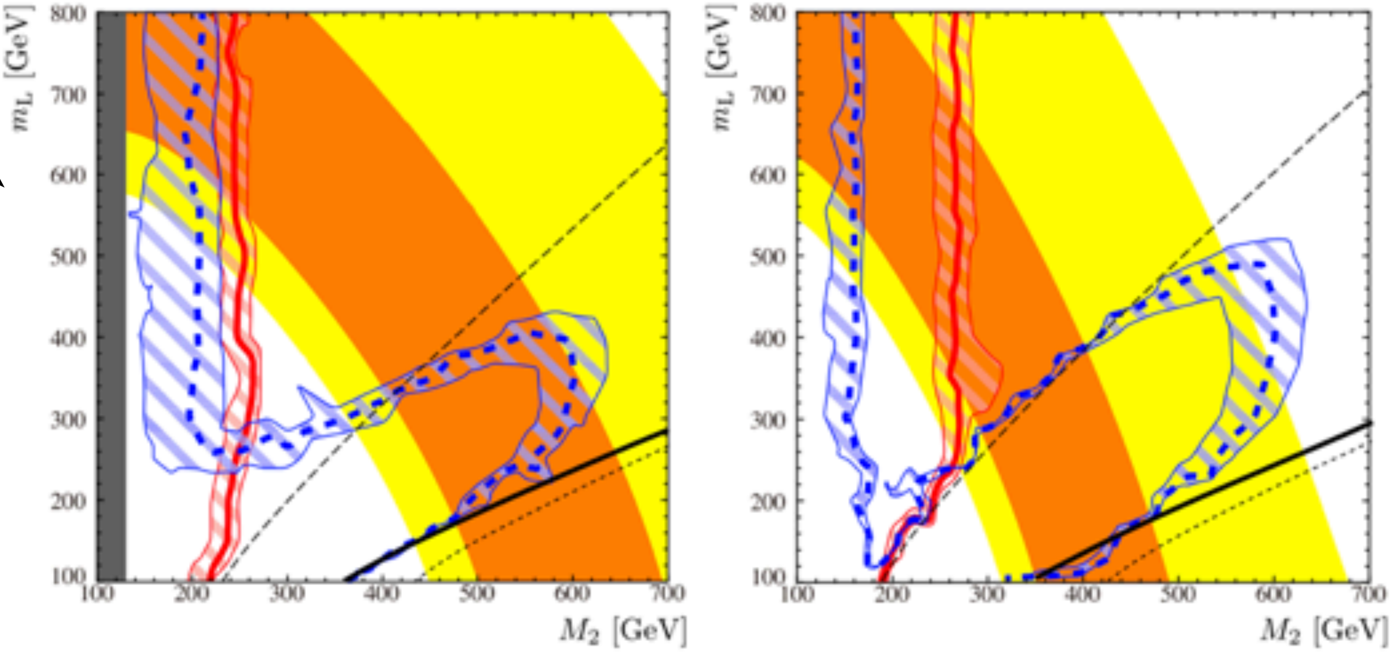
“g-2 motivated” MSSM

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

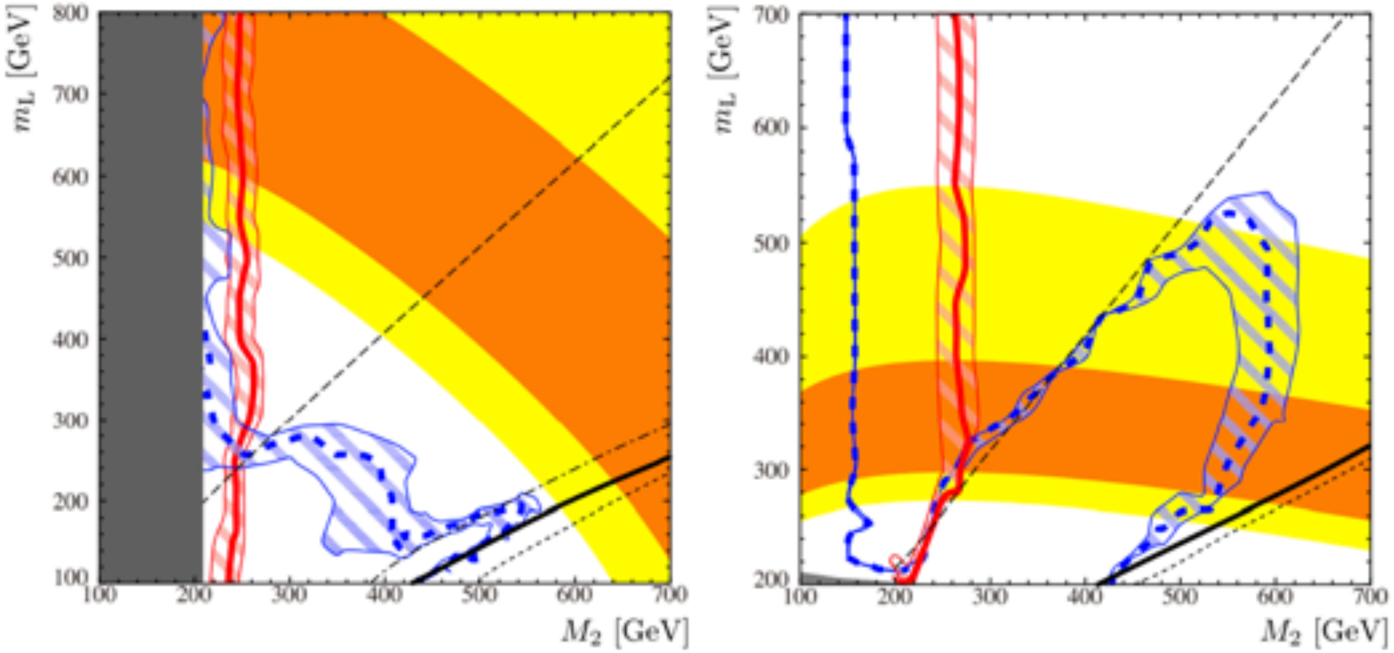
Results

$M_2 = 2M_1$ 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) $\mu = 2\,\mathrm{TeV}$, $m_R = 1.5 m_L$

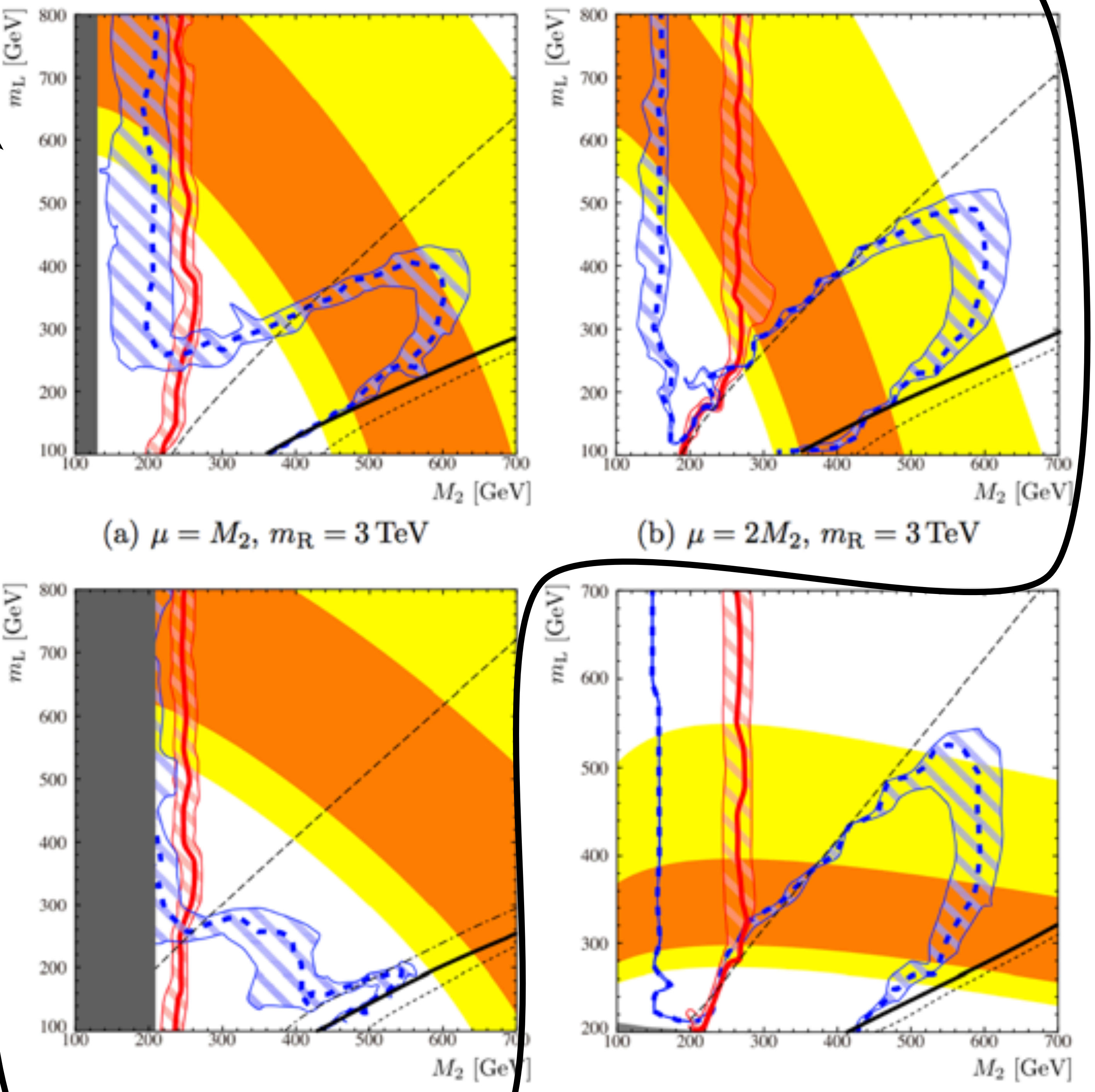
wino mass

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

light

Wino, Higgsino, smuon(L).

slepton_L mass

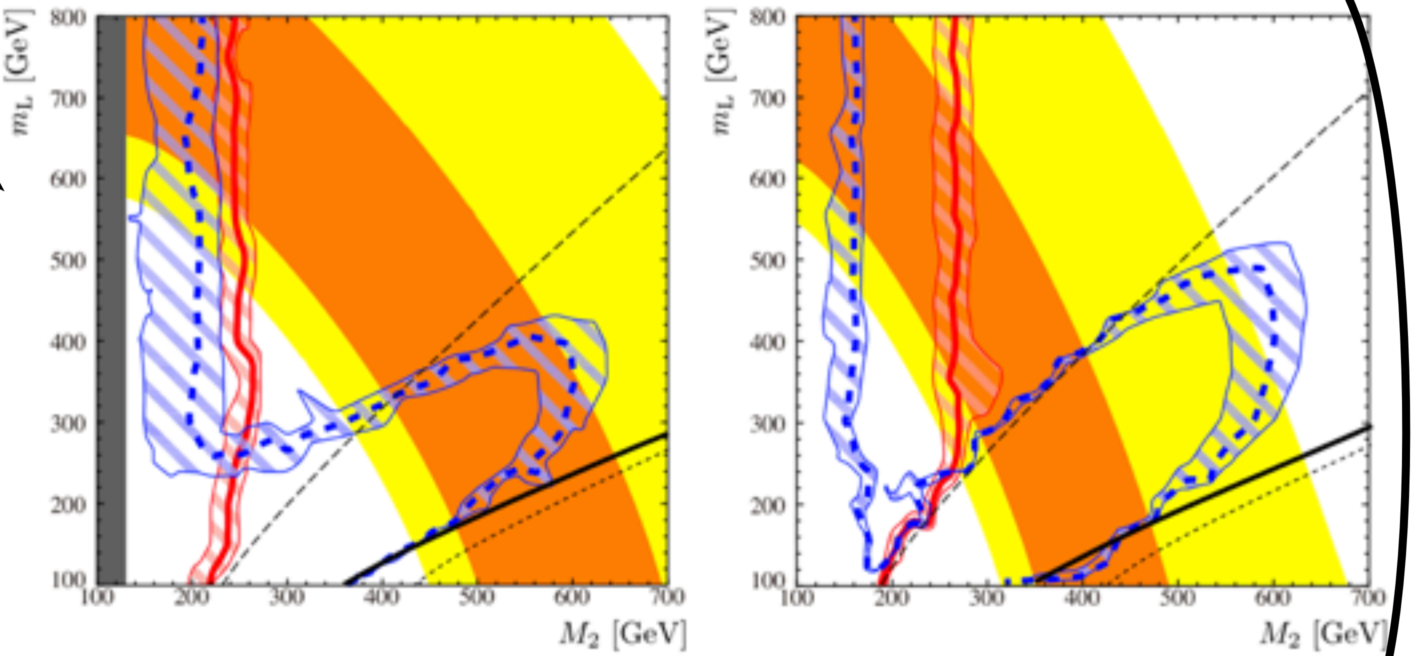
wino mass

“g-2 motivated” MSSM

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

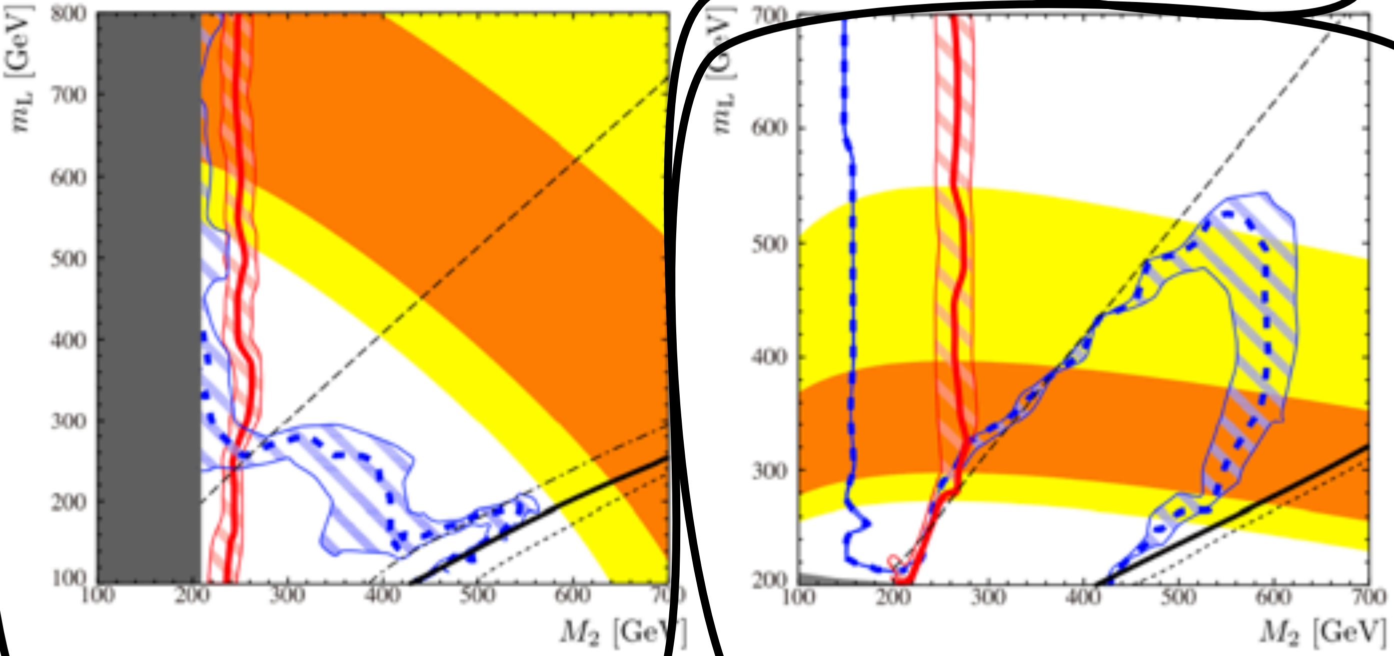
Results

$M_2 = 2M_1$ assumed



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

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



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

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

light
Wino, Higgsino, smuon(L).

light
Bino, smuon(L+R),
+ large μ.

slepton_L mass

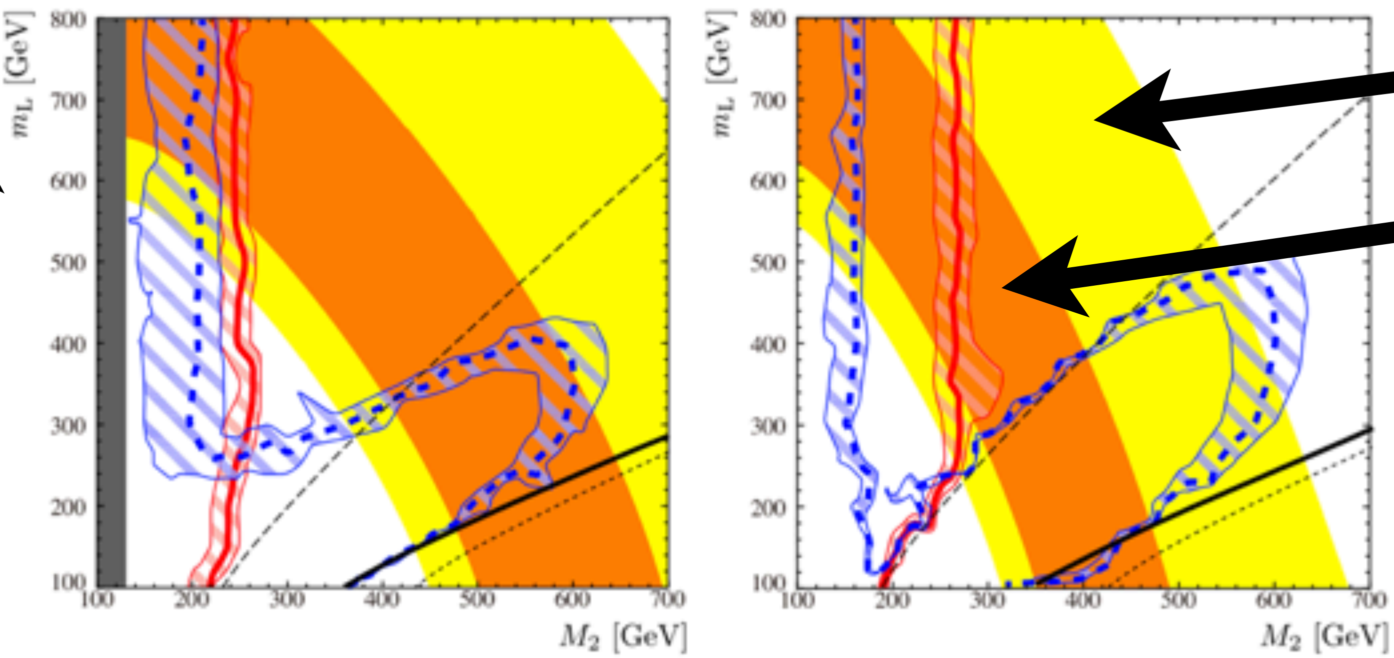
wino mass

“g-2 motivated” MSSM

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

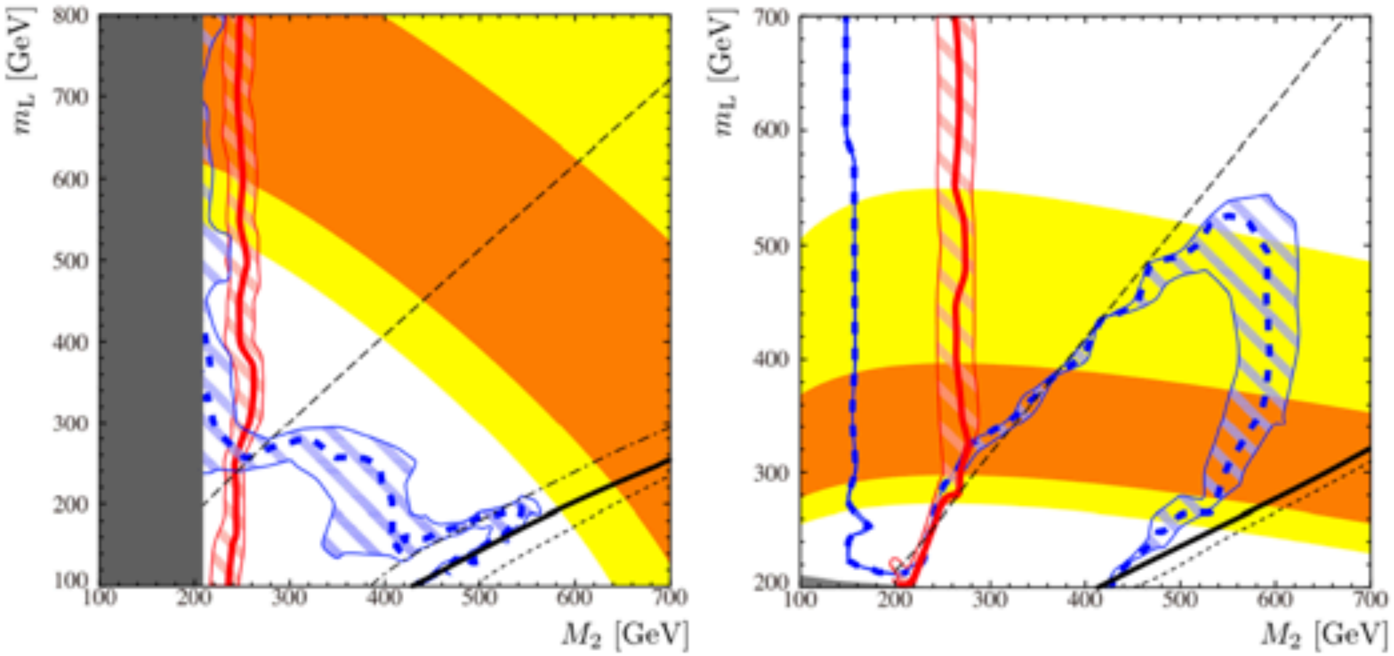
Results

$M_2 = 2M_1$ 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) $\mu = 2\,\mathrm{TeV}$, $m_R = 1.5 m_L$

muon g-2: 2σ

1σ

slepton_L mass

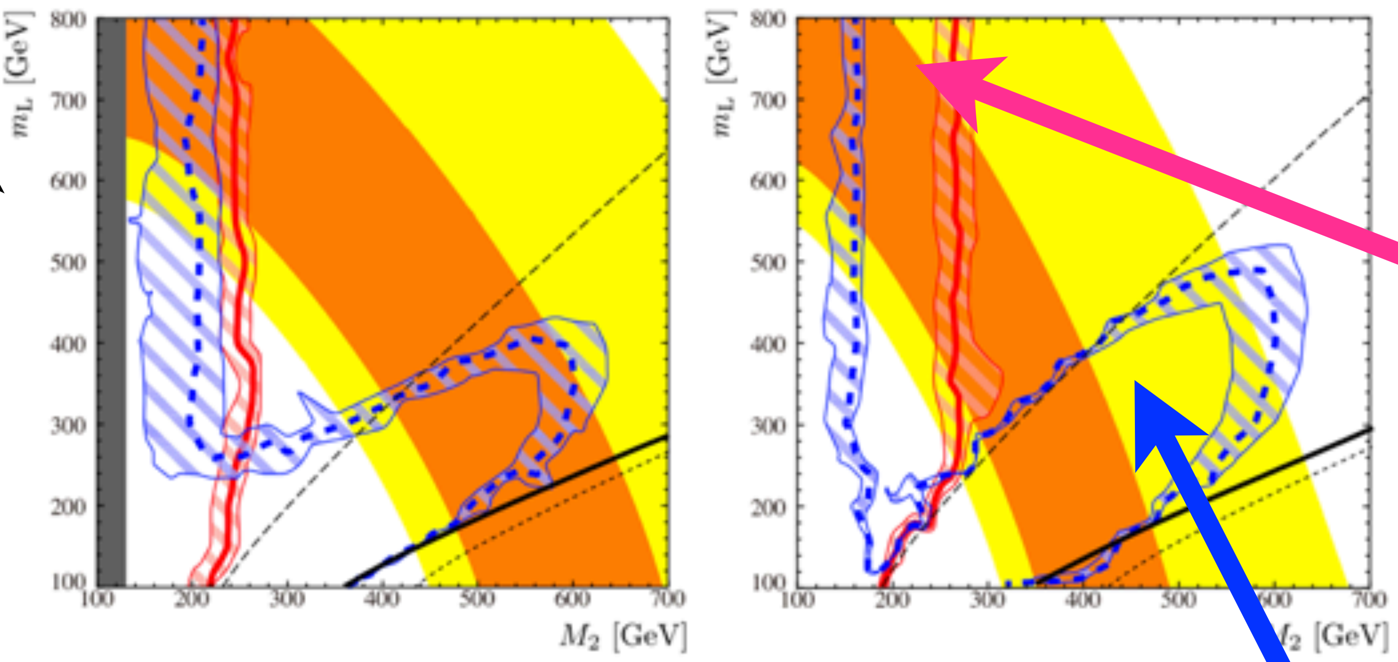
wino mass

“g-2 motivated” MSSM

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

Results

$M_2 = 2M_1$ assumed



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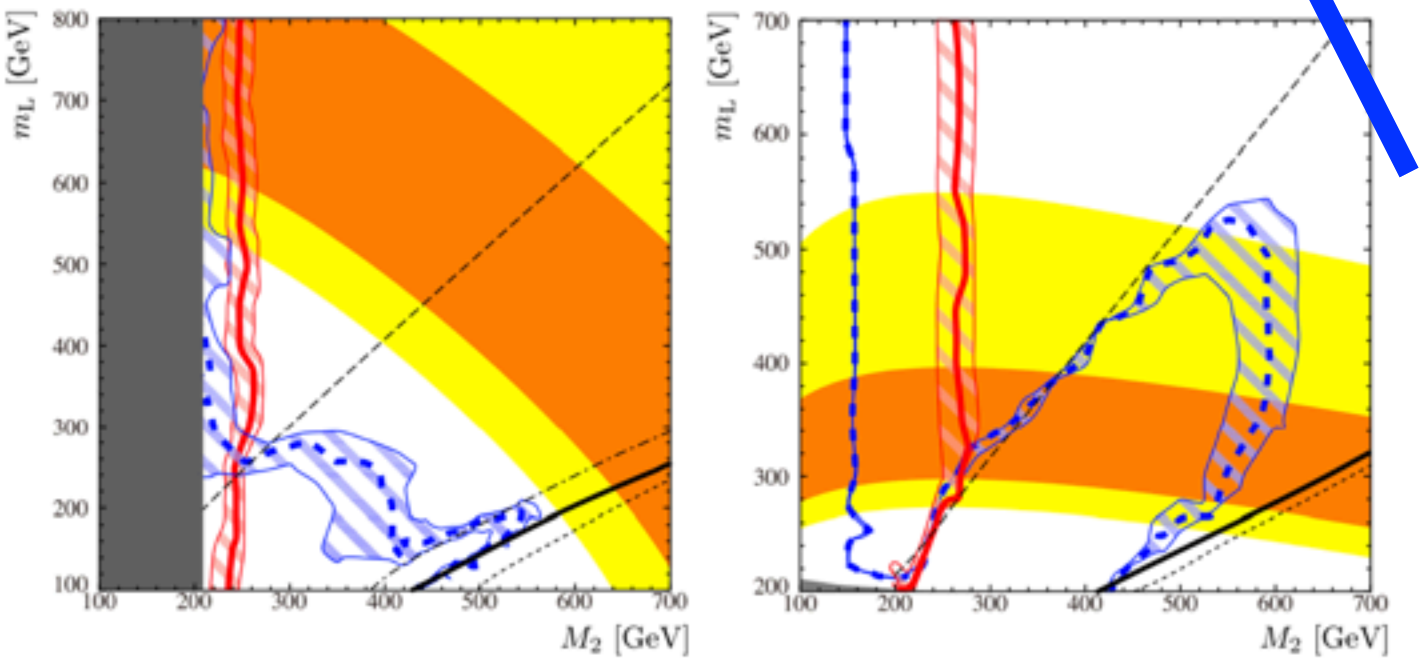


(c) $\mu = M_2/2,\ m_R = 3\,\mathrm{TeV}$

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

slepton_L mass

wino mass

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

this region is excluded by
jets + missing pT search
[ATLAS $5.8\mathrm{fb}^{-1}$@8TeV].

even if gluino is heavy

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

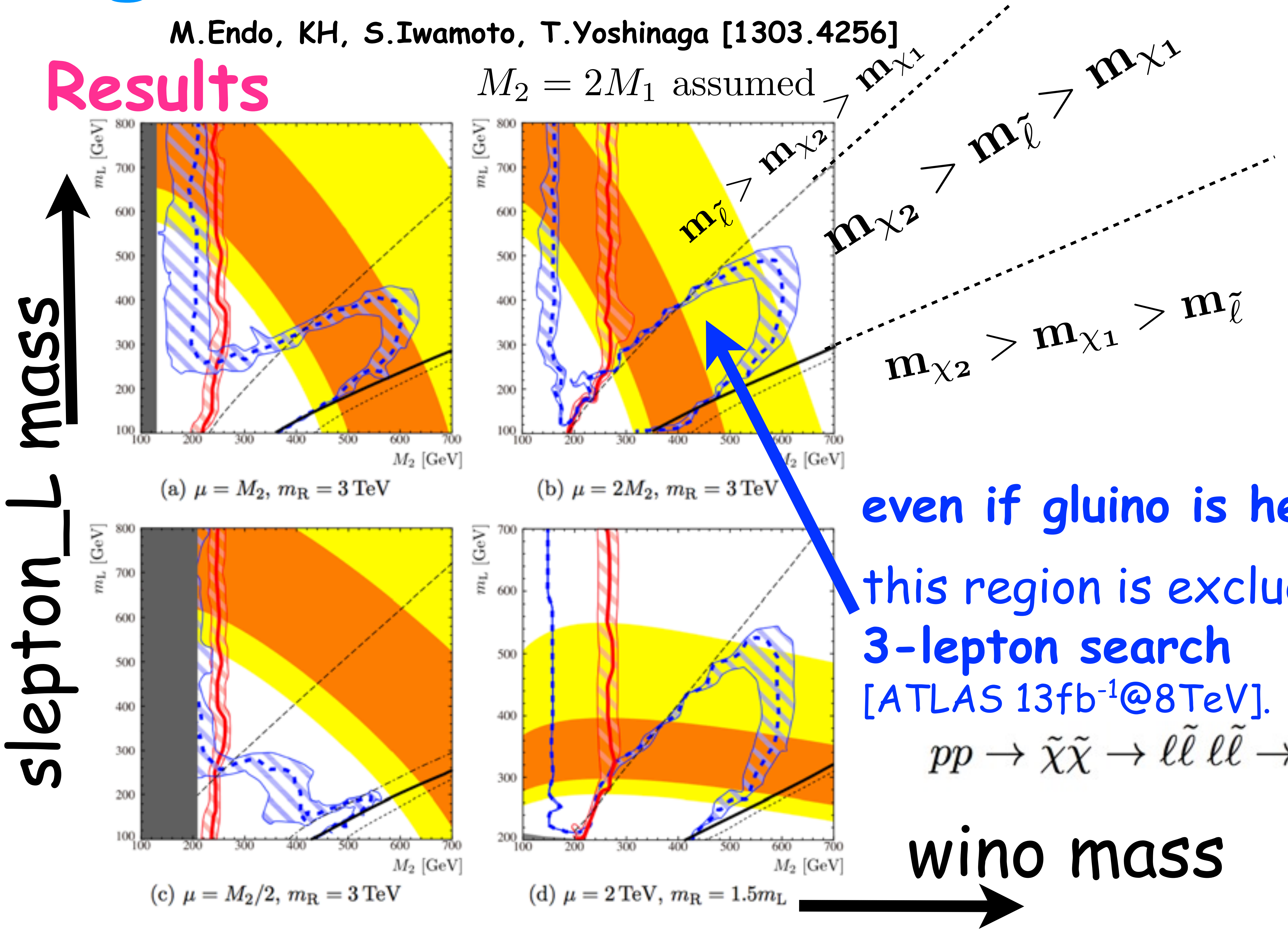
$$pp \to \tilde{\chi}\tilde{\chi} \to \ell\tilde{\ell}\,\ell\tilde{\ell} \to \ell\ell\tilde{\chi}\,\ell\ell\tilde{\chi}$$

“g-2 motivated” MSSM

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

Results

$M_2 = 2M_1$ assumed



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

even if gluino is heavy

this region is excluded by **3-lepton search** [ATLAS 13fb^{-1}@8TeV].

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

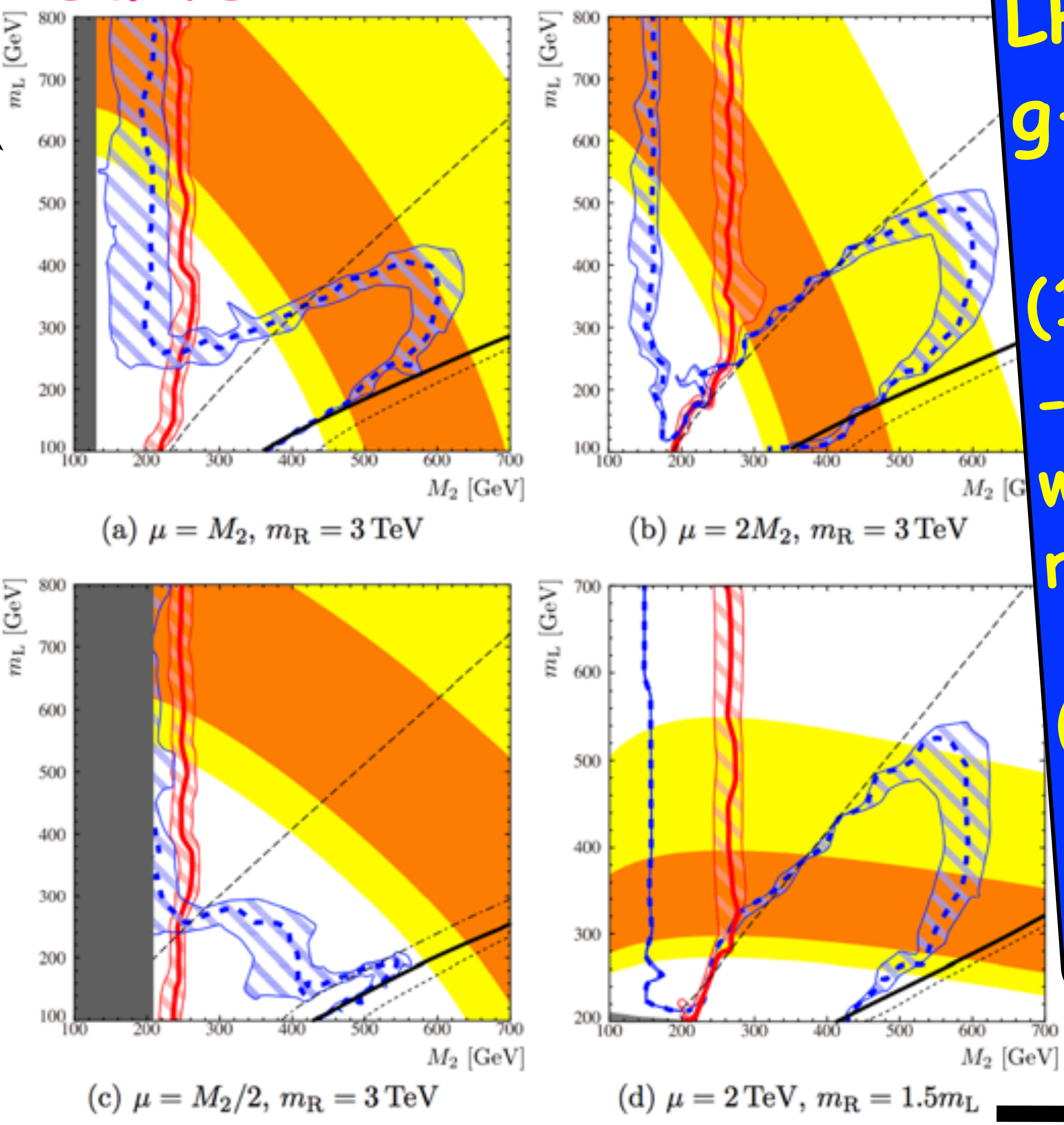
“g-2 motivated” MSSM

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

Results

$M_2 = 2M_1$ assume

slepton_L mass



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

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

wino mass

LHC started exclude g-2 motivated regions !

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

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

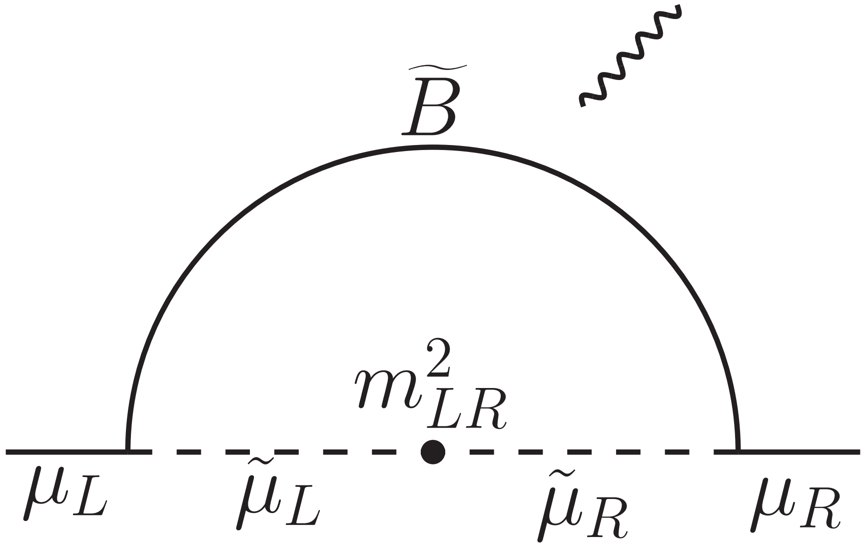
(What is the minimal set of particles that can explain muon g-2 ?)

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)



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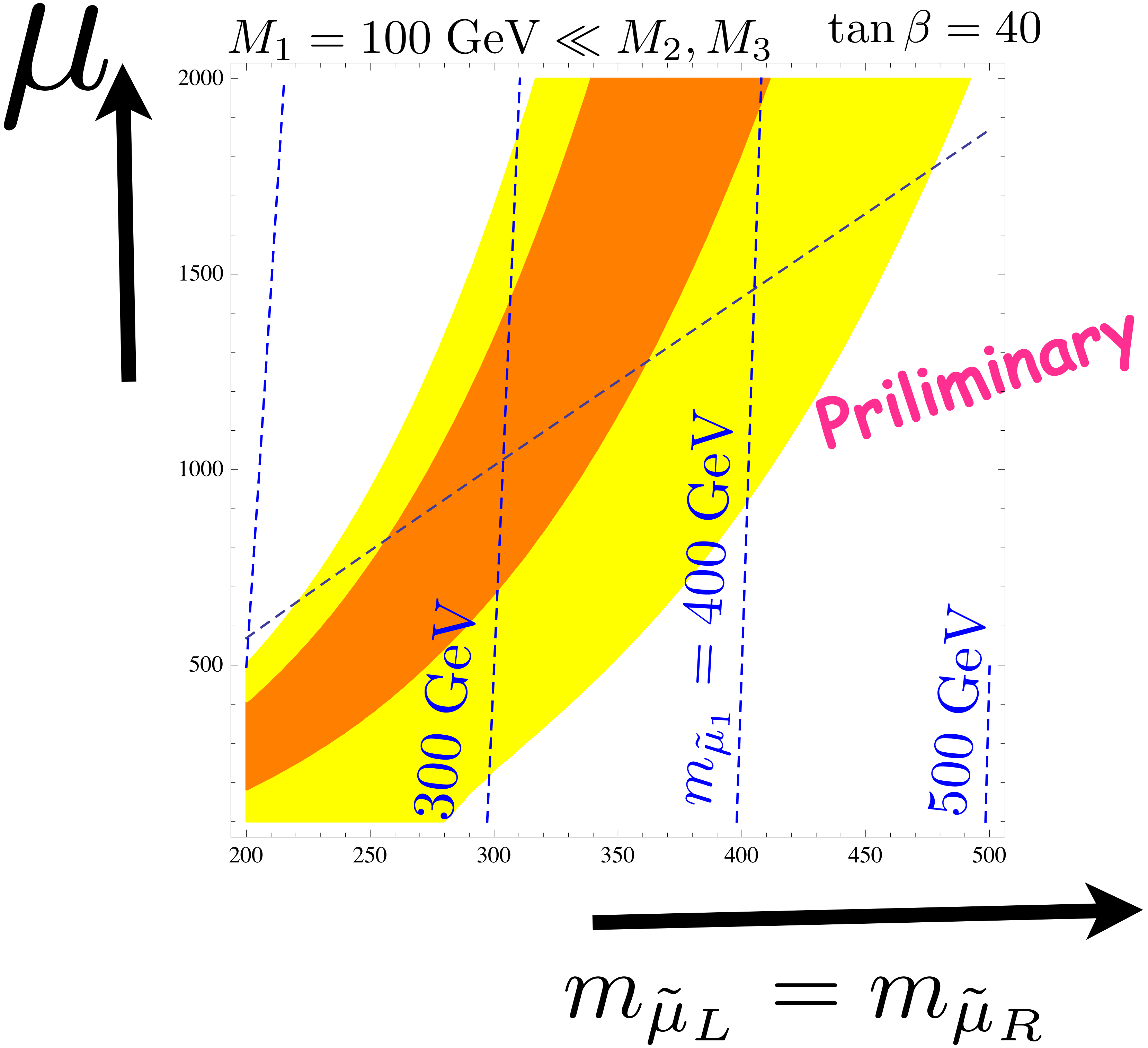

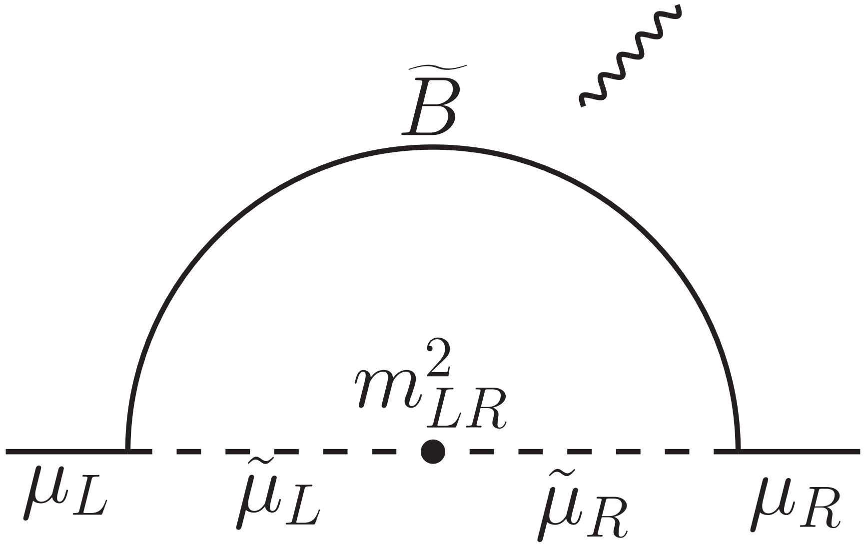

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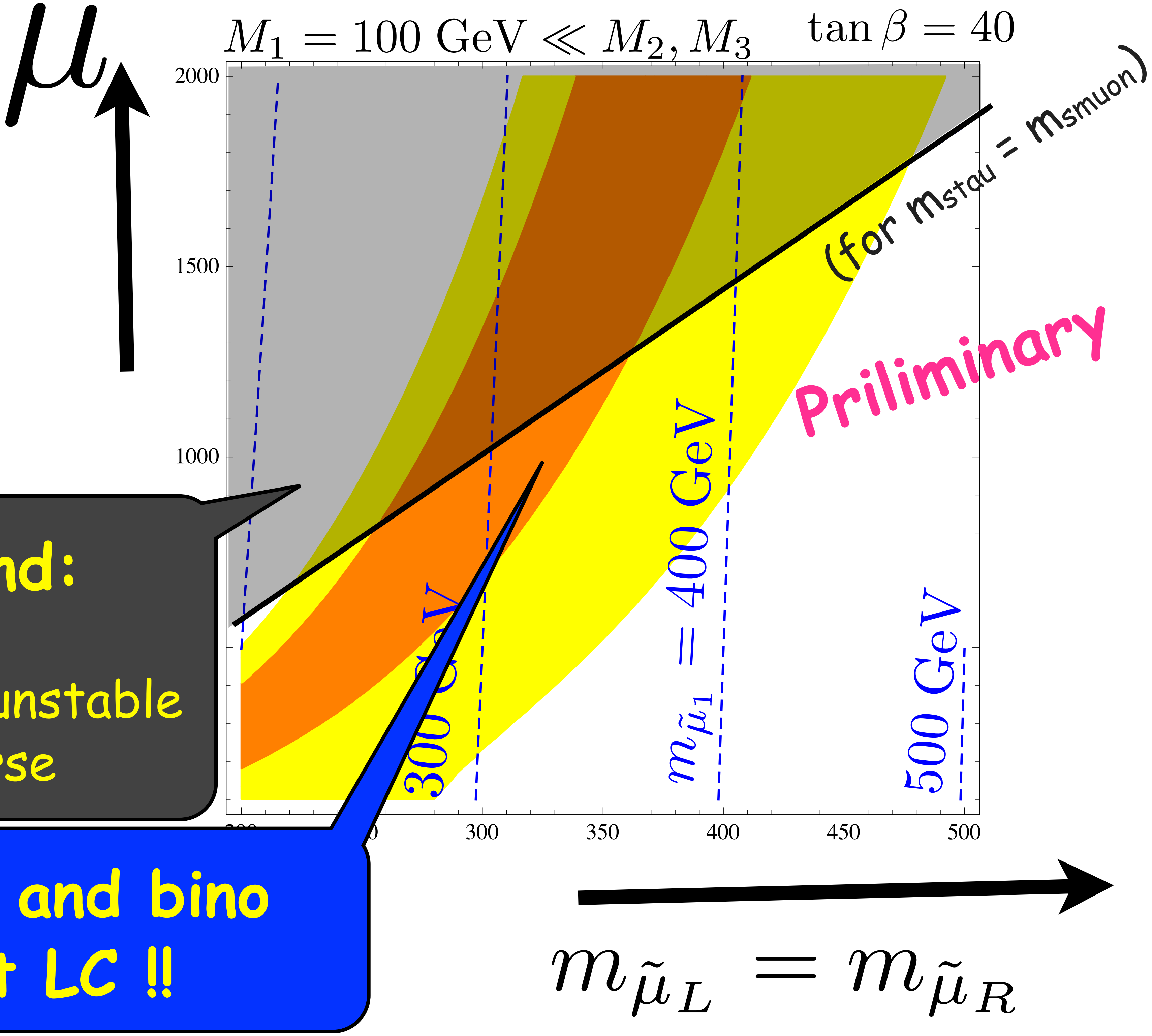

Vacuum stability bound:

(too large μ

--> slepton-Higgs potential unstable

--> Lifetime < Age of Universe

O(100 GeV) slepton and bino

... can be tested at LC !!

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

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(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

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126 GeV Higgs + muon g-2

MSSM + vector-like matter

Idea:

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

$$W = Y_{\rm top}\, Q_3 U_3 Hu$$

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

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

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]

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

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

126 GeV Higgs + muon g-2

Results

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

for "V-GMSB"

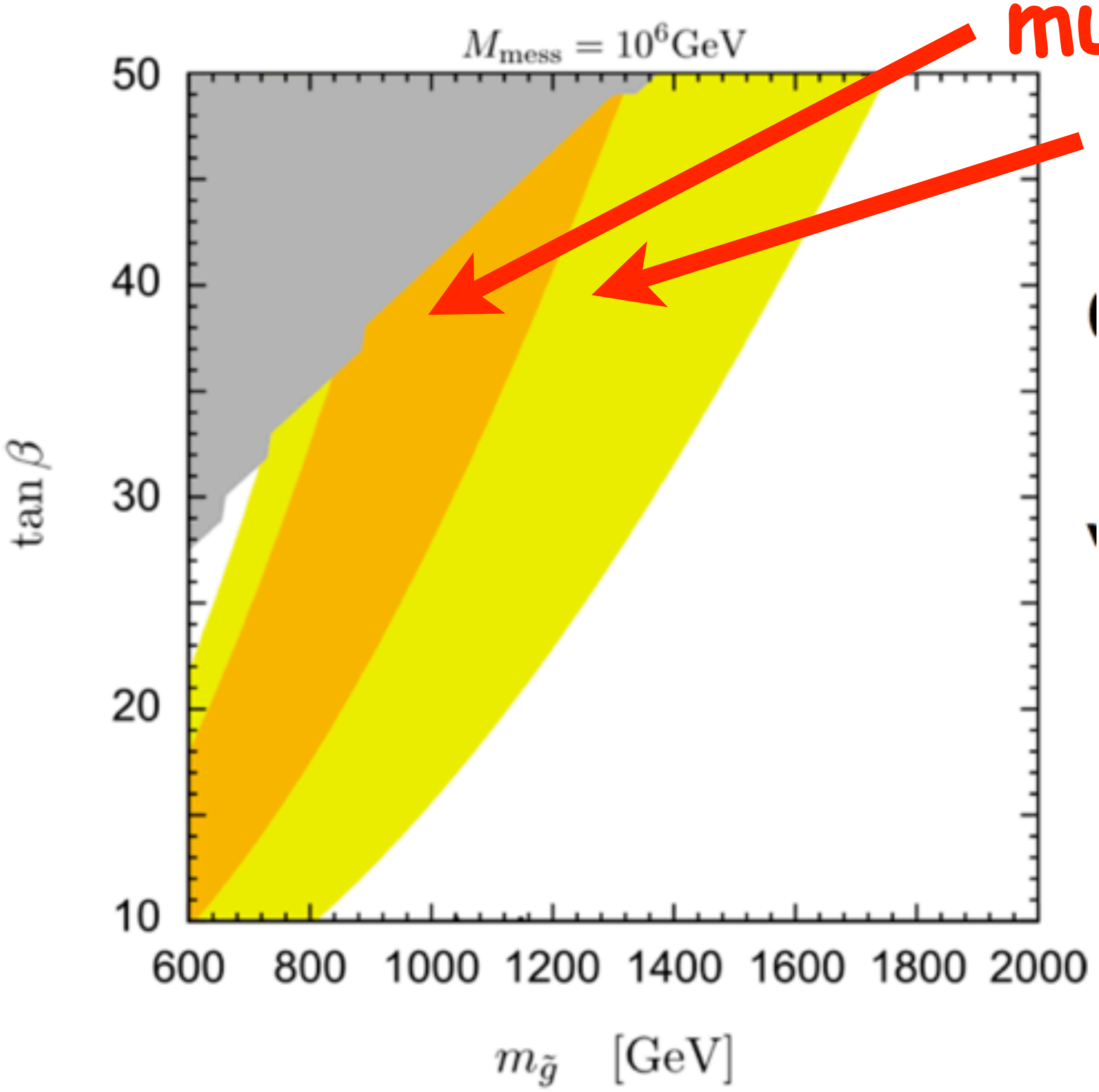
= gauge mediation (GMSB) + vector-like matter

126 GeV Higgs + muon g-2

Results

for "V-GMSB"

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



muon g-2 explained (1σ)

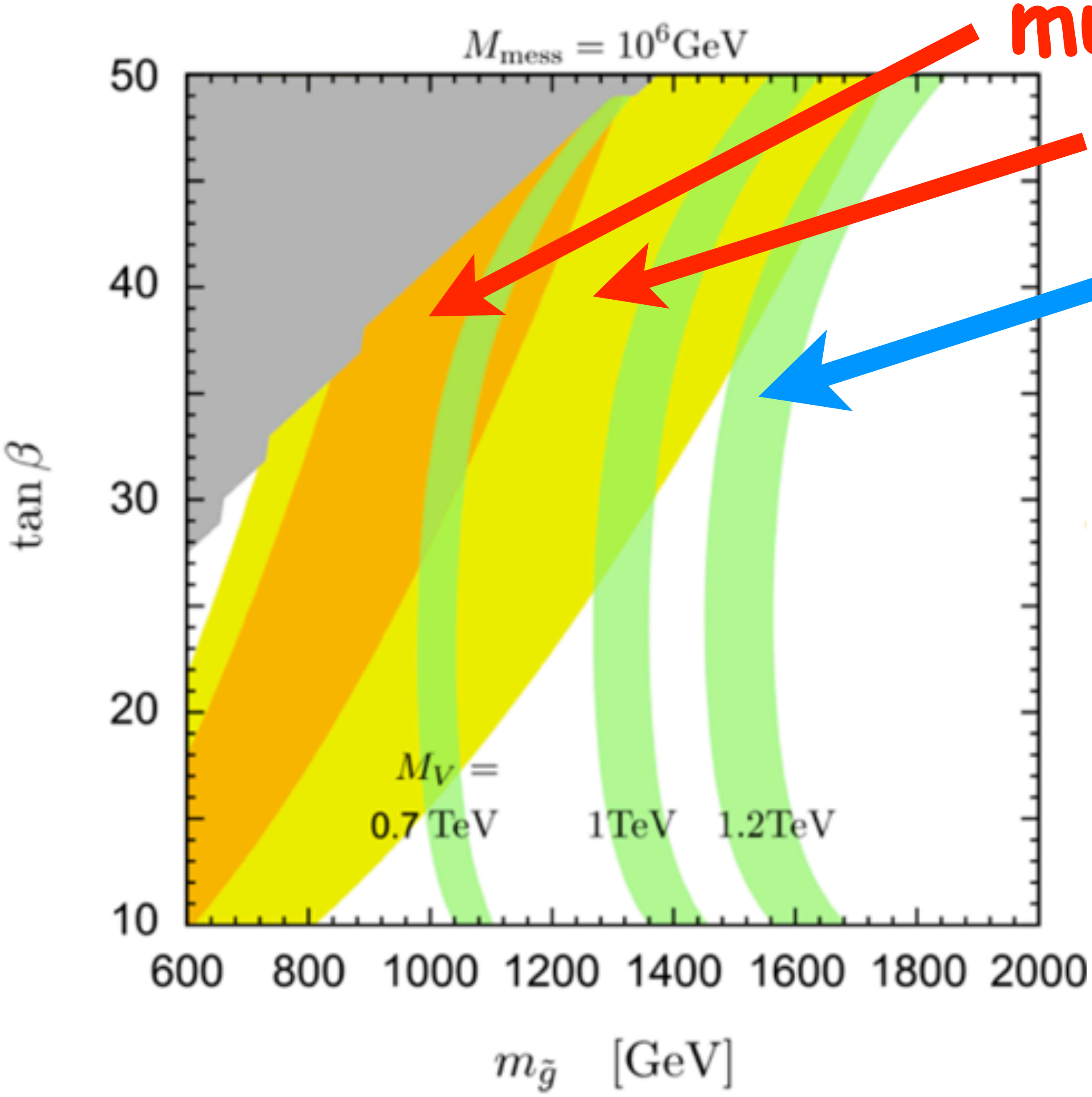
(2σ)

126 GeV Higgs + muon g-2

Results

for "V-GMSB"

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



muon g-2 explained (1σ)

(2σ)

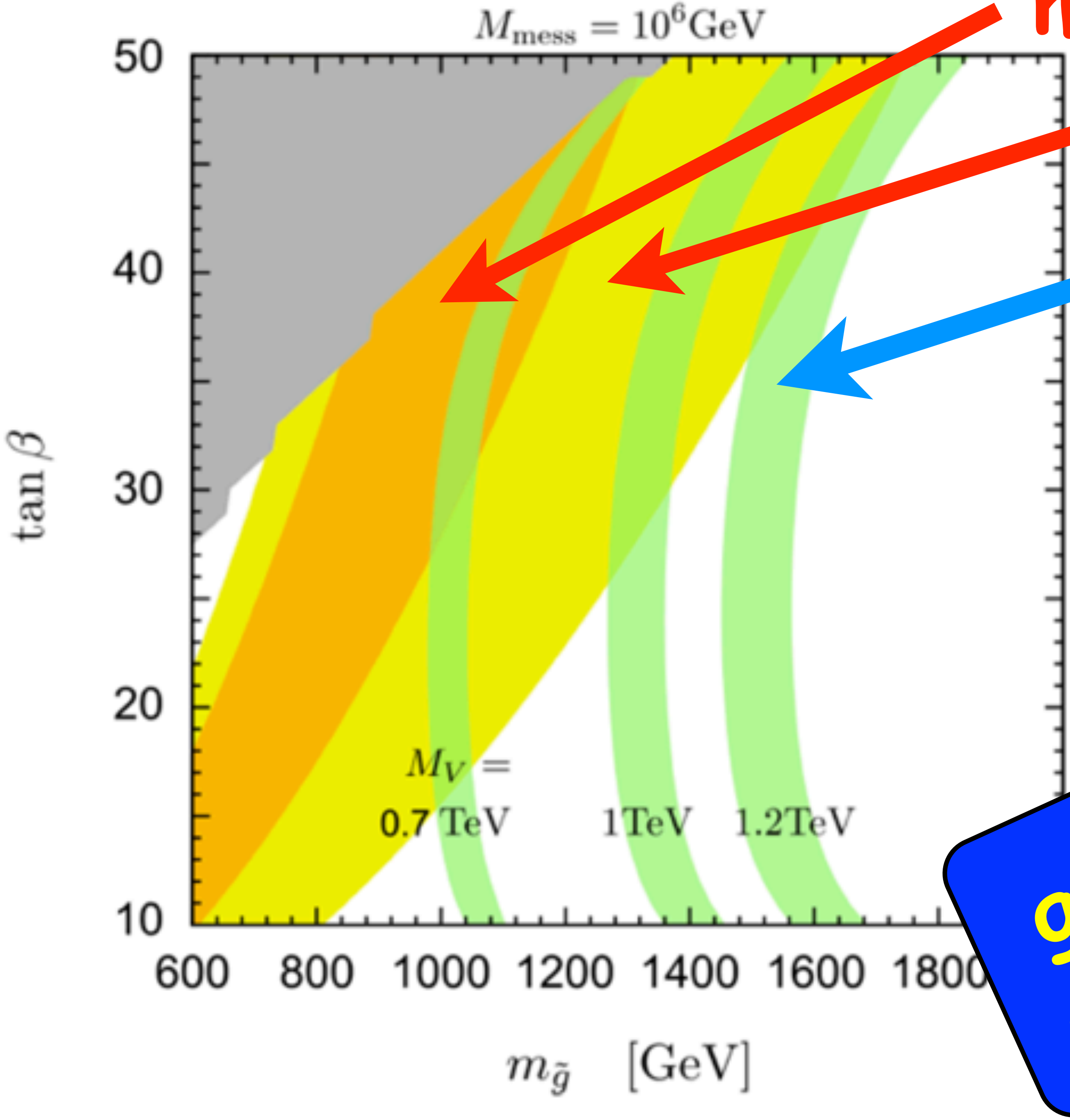
Higgs mass 125-126 GeV

126 GeV Higgs + muon g-2

Results

for "V-GMSB"

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



muon g-2 explained (1σ)

(2σ)

Higgs mass
125-126 GeV

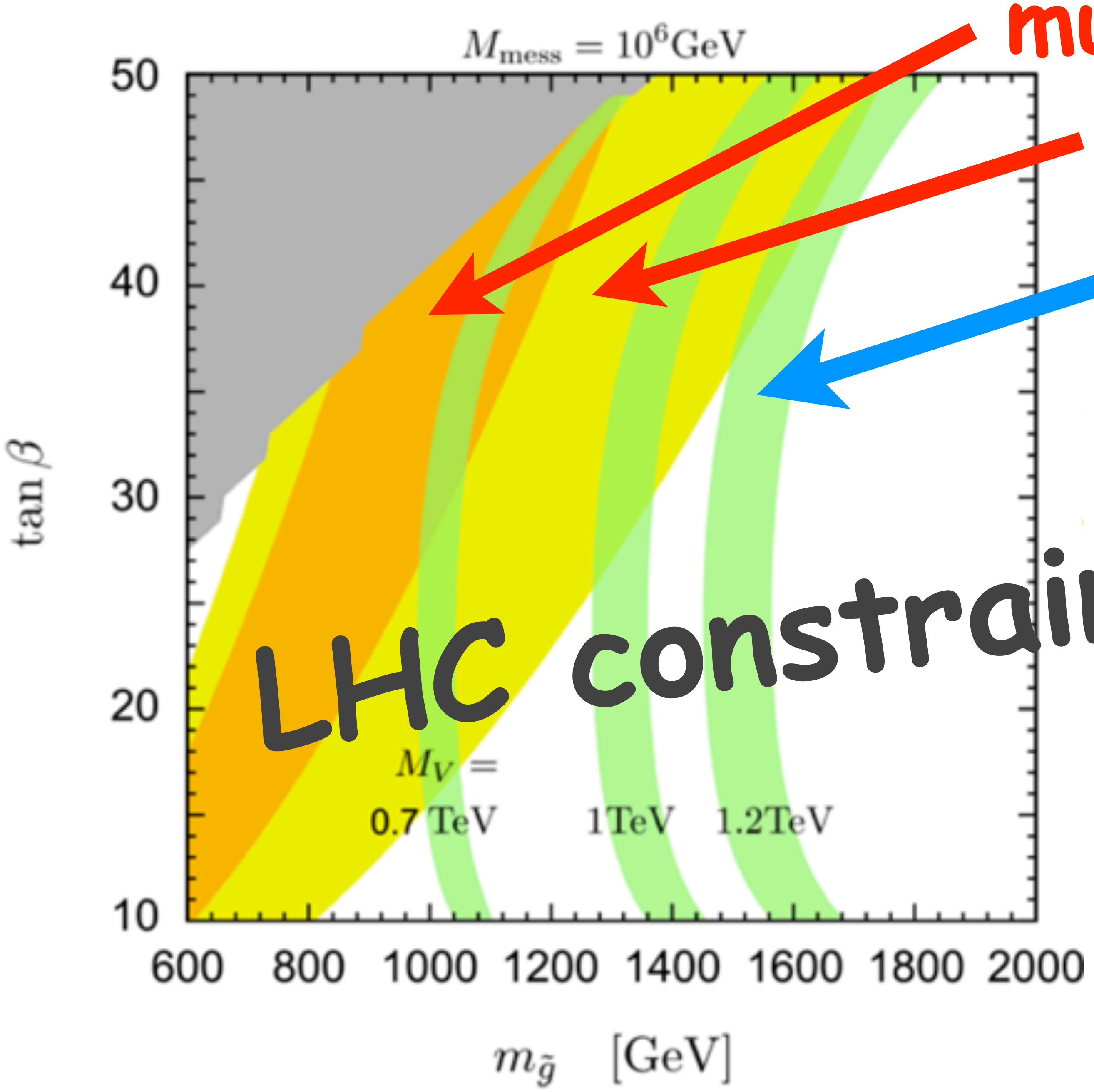
g-2 and Higgs mass are explained simultaneously!

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

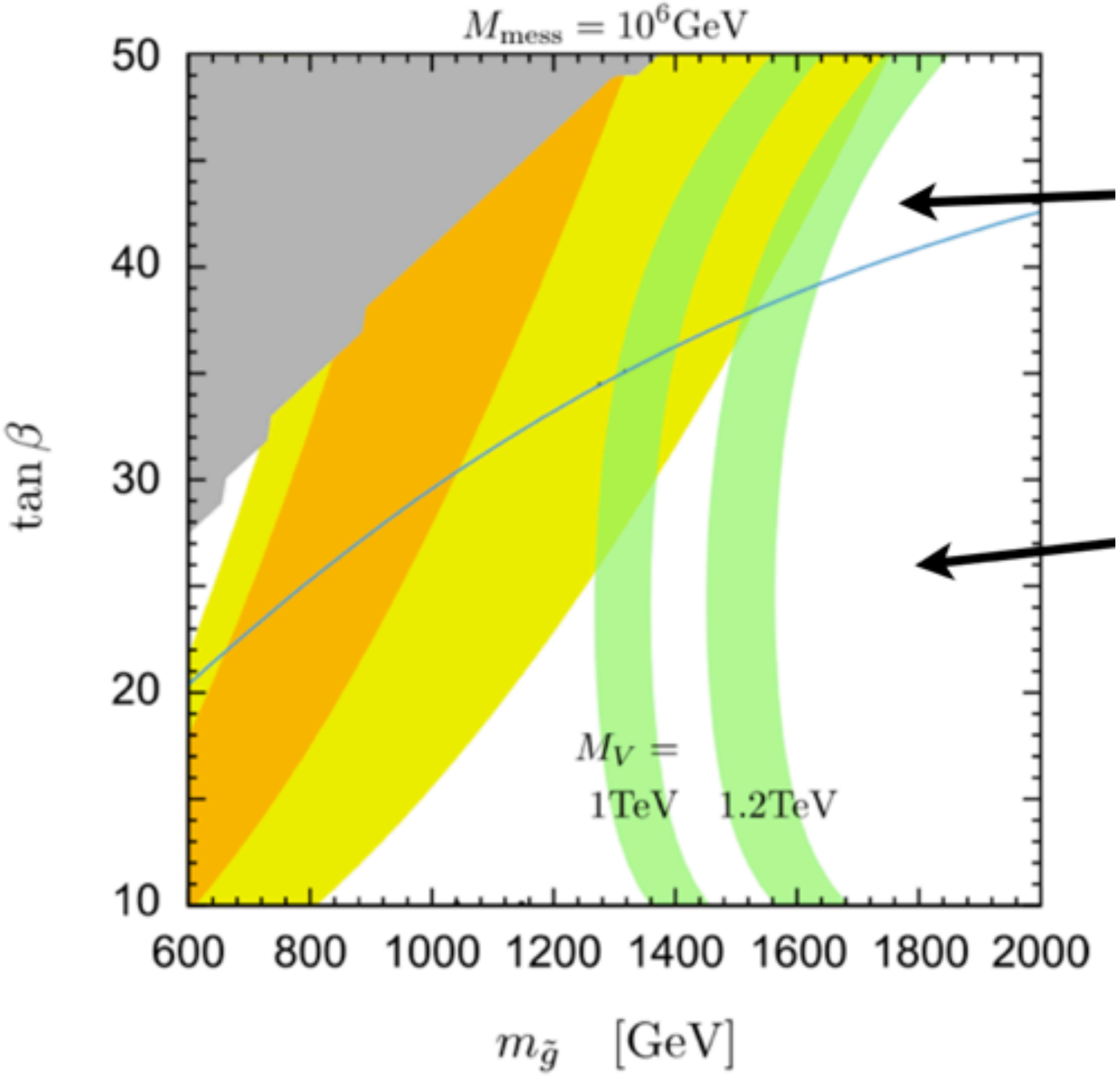
LHC constraints ?

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

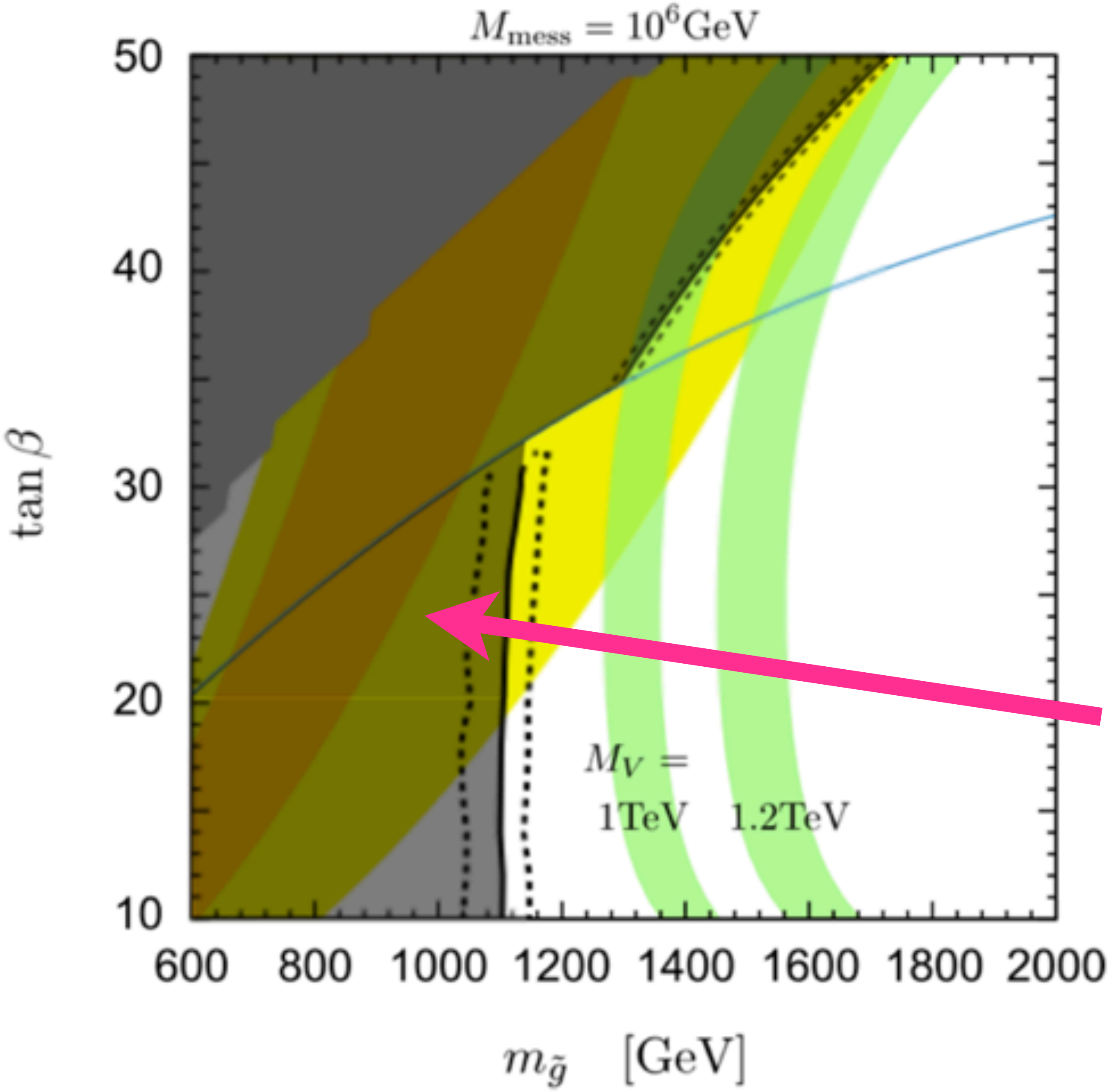
= **jets + missing energy**

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.]

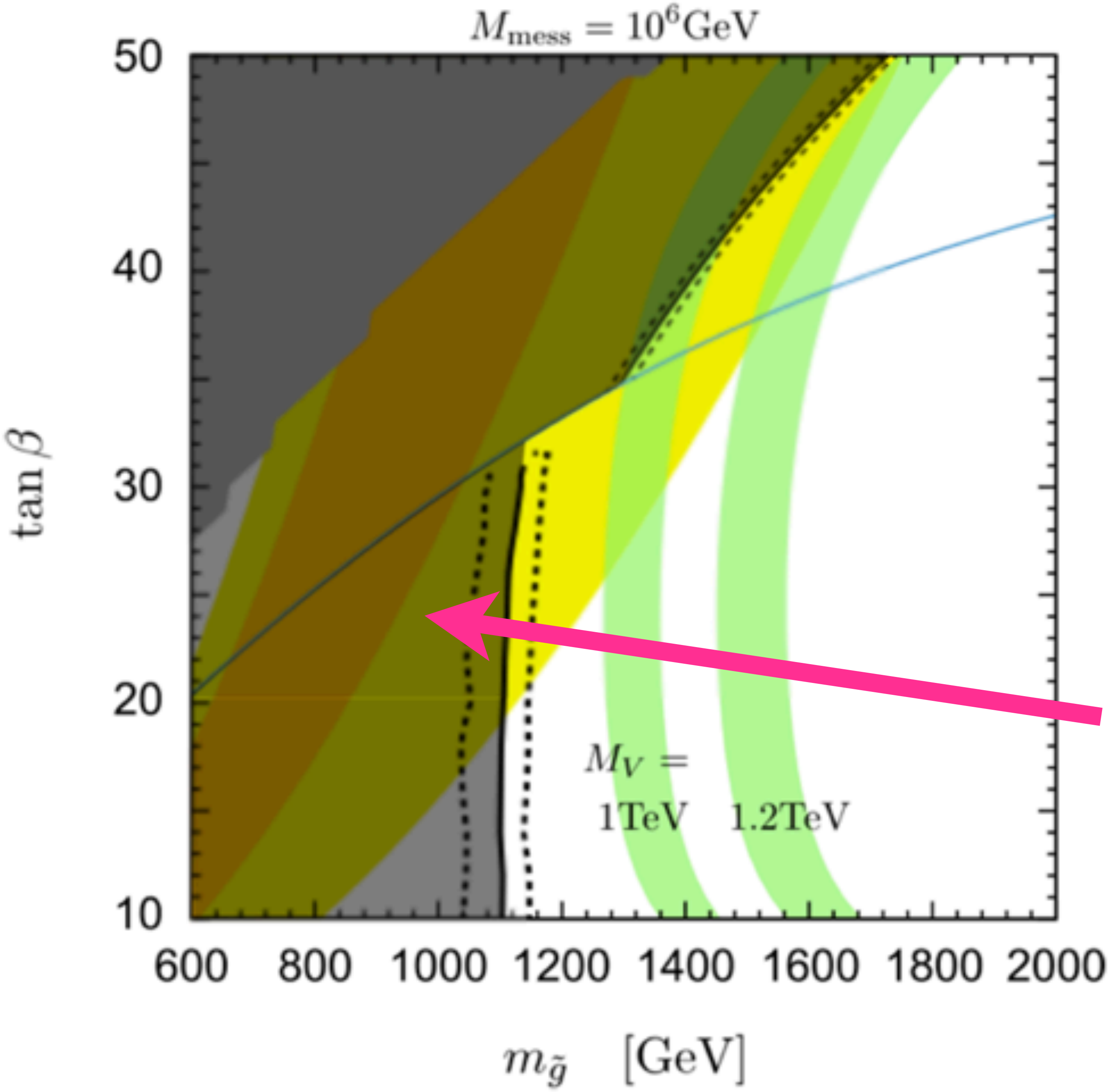
126 GeV Higgs + muon g-2

Results

for "V-GMSB"

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

New LHC results were reported after our analysis.



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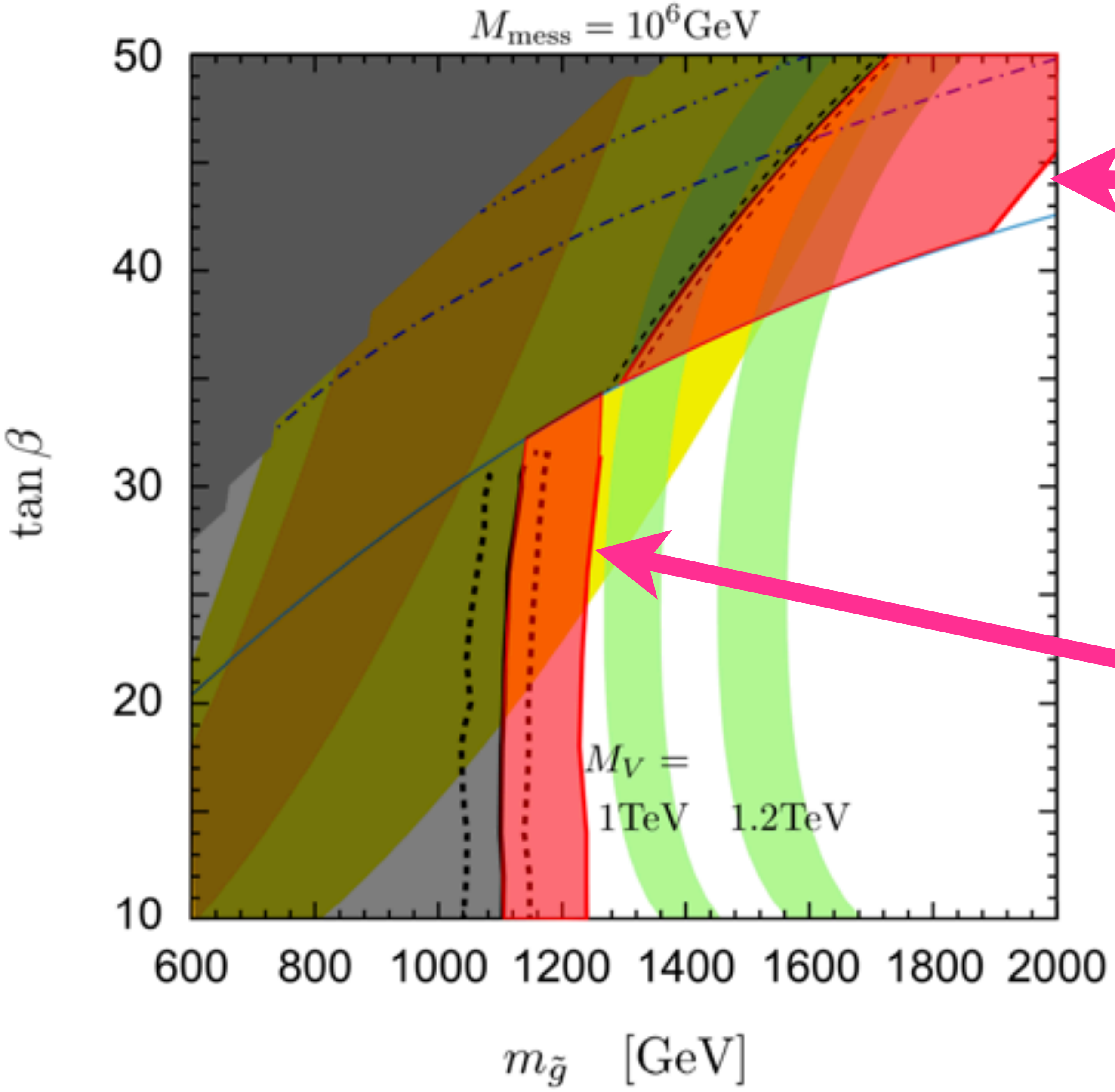
for jets + missing
and CMS result ($5.0 {\rm fb}^{-1}$@7TeV)
for long-lived charged particle.]

126 GeV Higgs + muon g-2

Results

for "V-GMSB"

Now...



stau NLSP region is completely excluded.

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

neutralino NLSP region is still allowed.

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

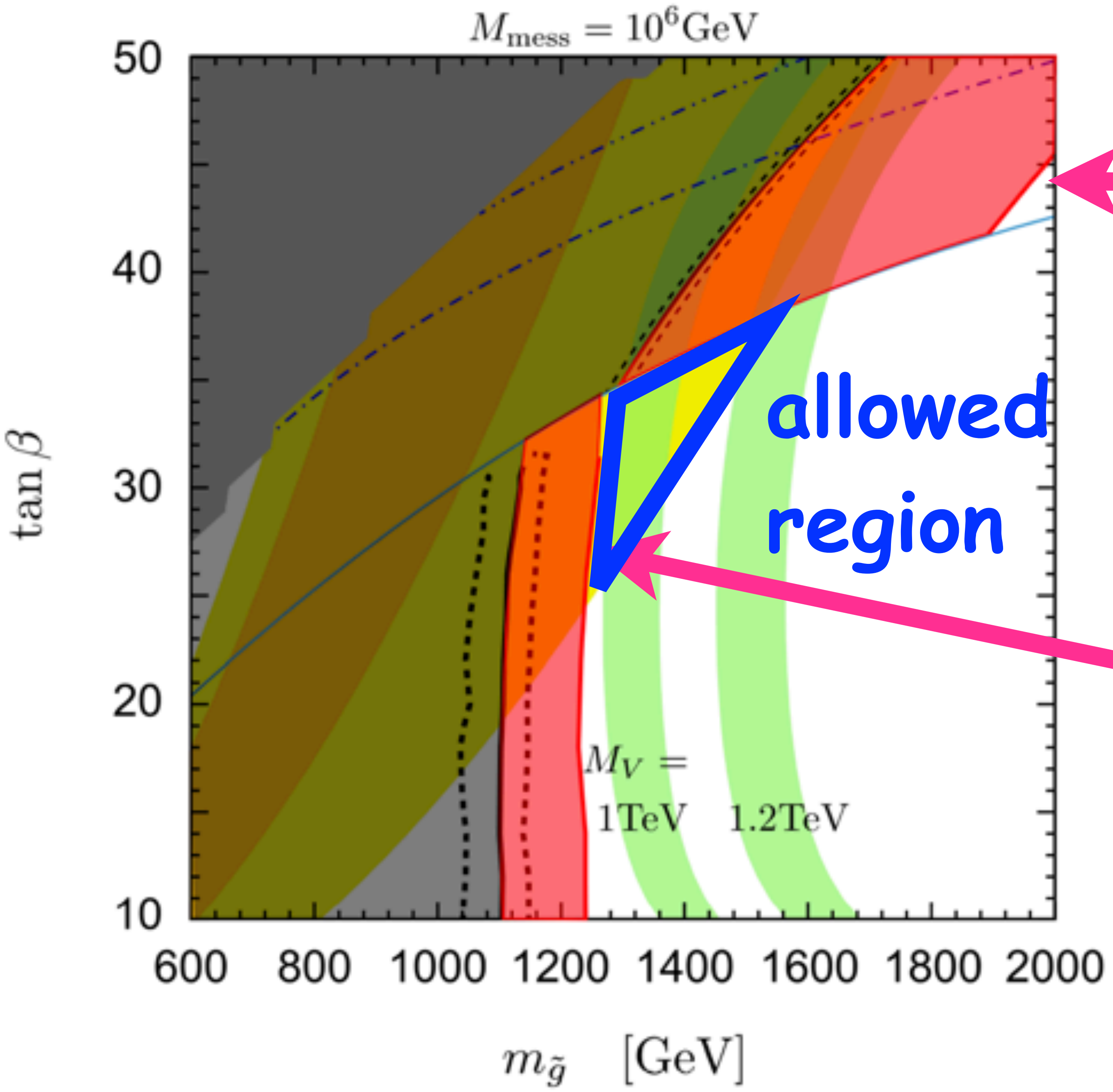
New analysis: thanks to **Kazuya Ishikawa**.

126 GeV Higgs + muon g-2

Results

for "V-GMSB"

Now...



allowed region

stau NLSP region is completely excluded.

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

neutralino NLSP region is still allowed.

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

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

SUMMARY

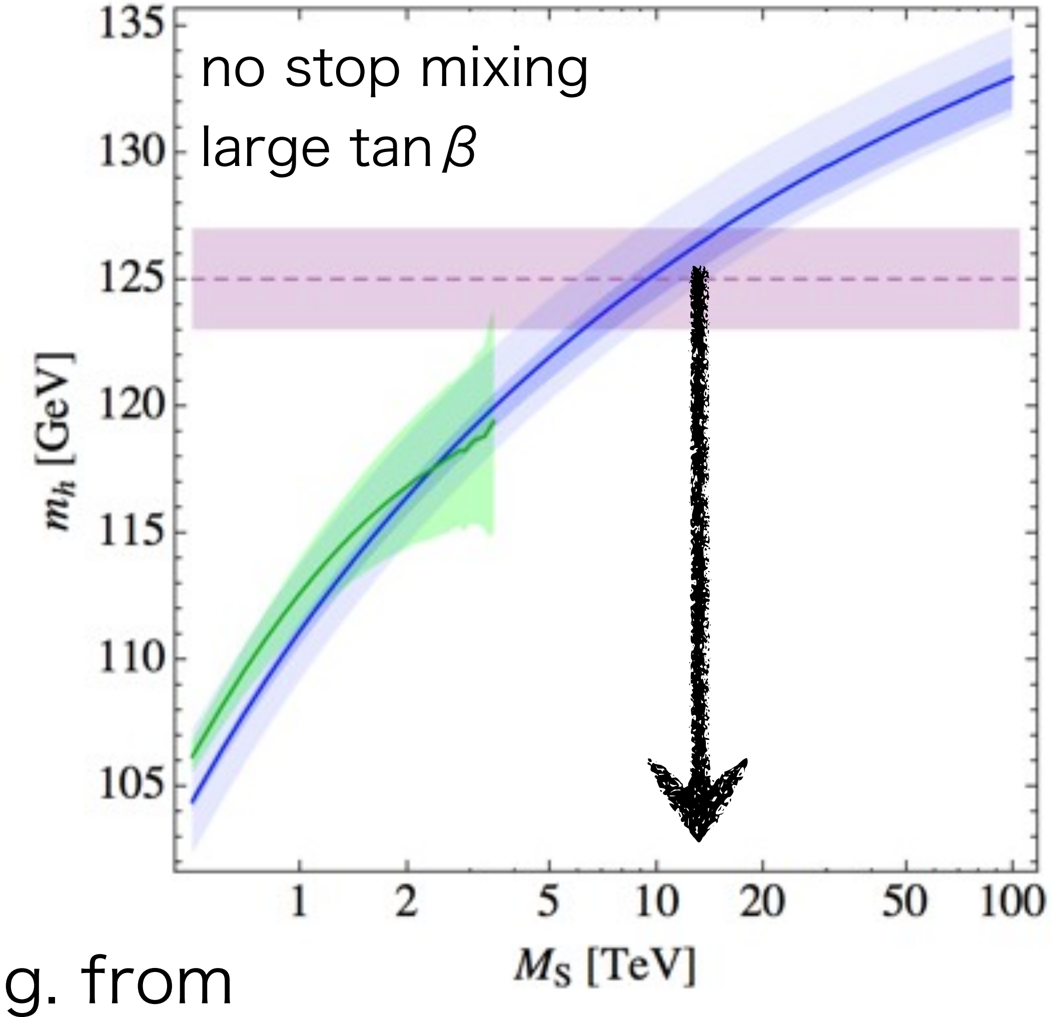
SUSY < O(TeV) after Higgs discovery

<table>
<tr><th>motivations</th><th>model</th><th>LHC/LC signal</th></tr>
<tr><td>126 GeV Higgs
+ naturalness</td><td>implies
beyond MSSM
(e.g. NMSSM)</td><td>light stop and light Higgsino.</td></tr>
<tr><td>126 GeV Higgs
+ muon g-2
($>3\sigma$!!)</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/LC.
(2) example: "V-GMSB"
--> barely alive. tested soon.</td></tr>
<tr><td>126 GeV Higgs
+ Dark Matter</td><td colspan="2">* No problem in simple models (e.g., mSUGRA).</td></tr>
<tr><td>126 GeV Higgs
+ coupling unification</td><td colspan="2">* O(TeV) gauginos/Higgsinos are sufficient (split/spread SUSY).
AMS-02 result on anti-proton will be important.</td></tr>
</table>

- backup

126 GeV Higgs and SUSY

simplest possibility: heavy SUSY

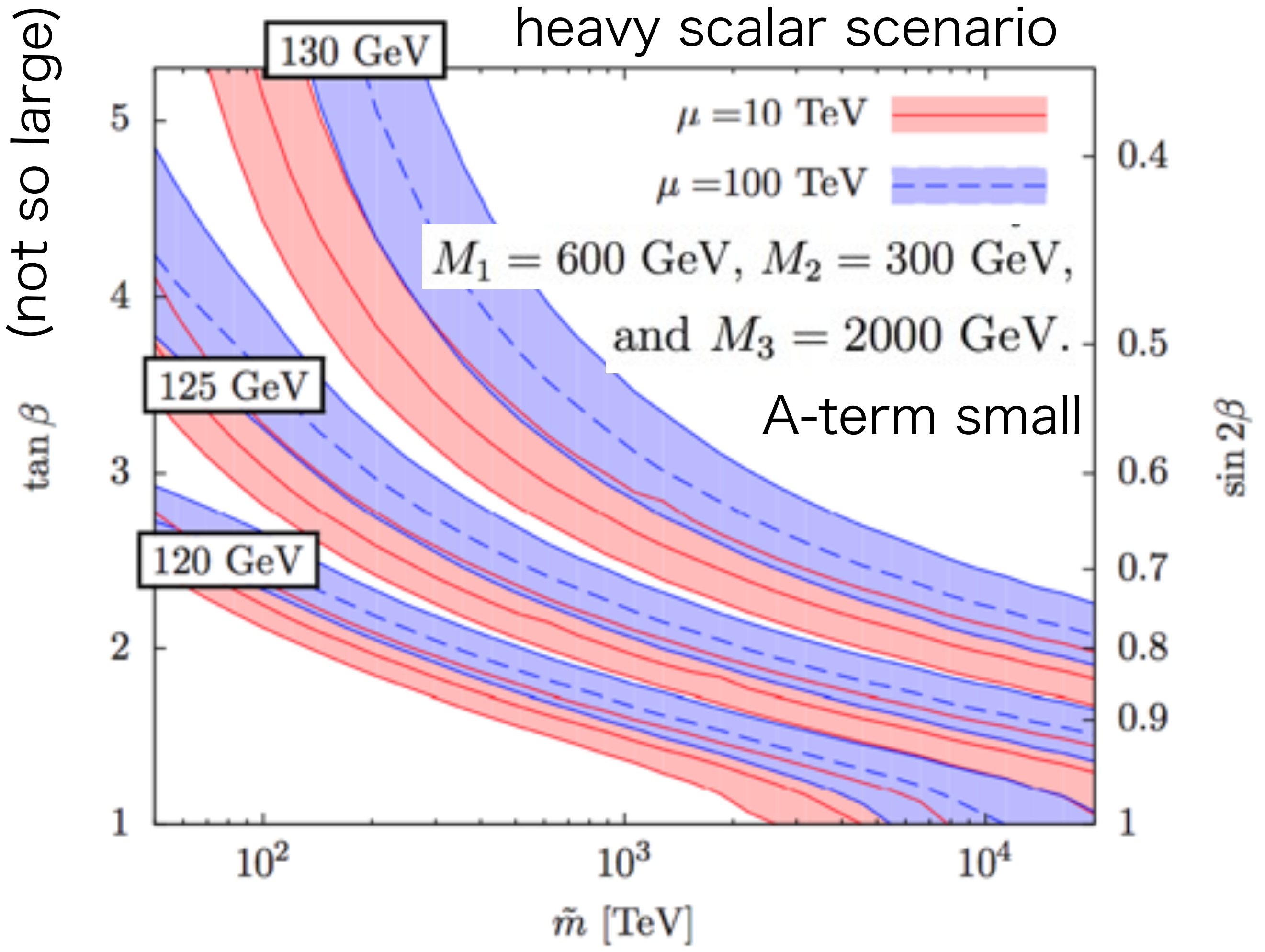


no stop mixing

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

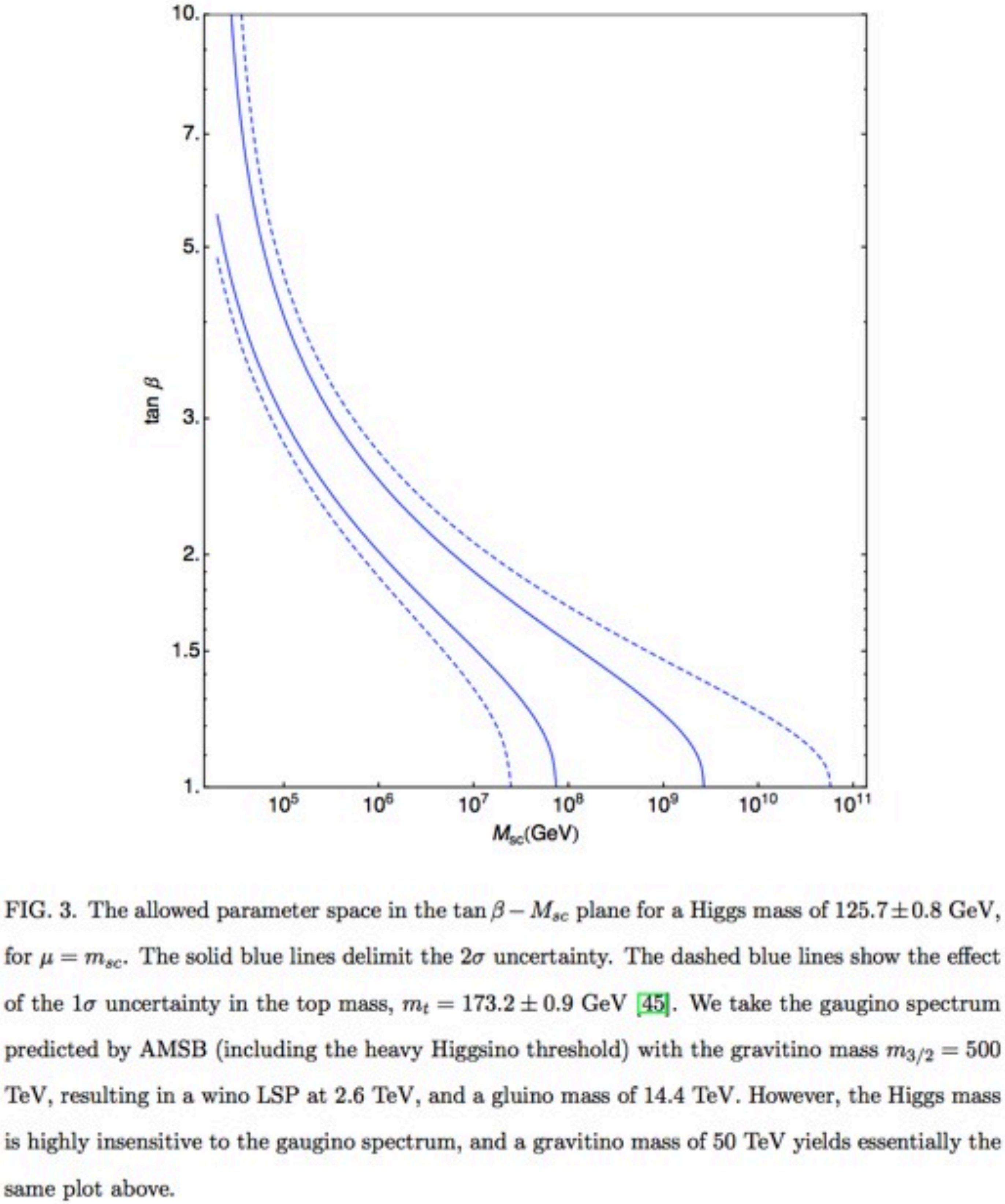
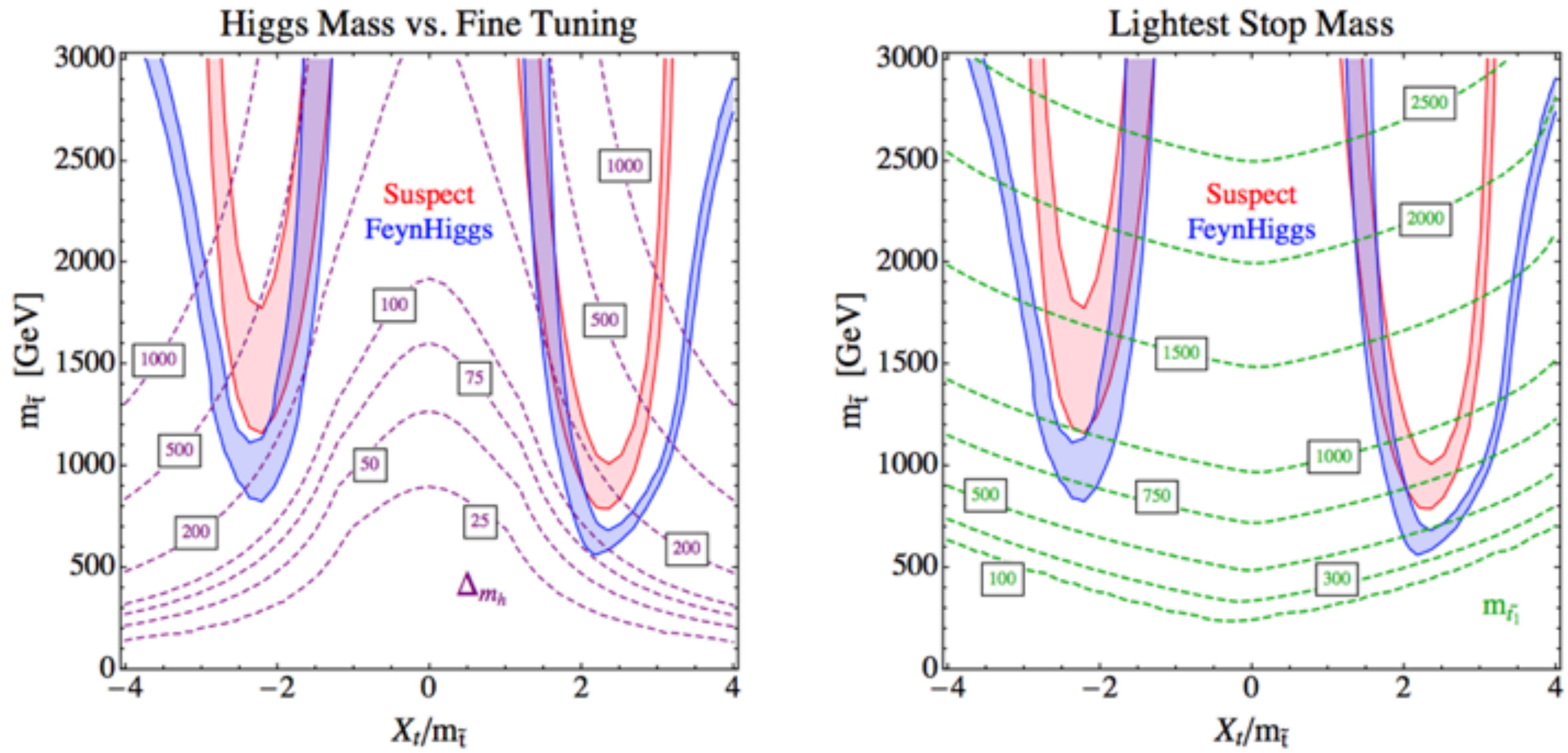


FIG. 3. The allowed parameter space in the $\tan\beta - M_{sc}$ plane for a Higgs mass of 125.7 ± 0.8 GeV, for $\mu = m_{sc}$. The solid blue lines delimit the 2σ uncertainty. The dashed blue lines show the effect of the 1σ uncertainty in the top mass, $m_t = 173.2 \pm 0.9$ GeV [45]. We take the gaugino 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.

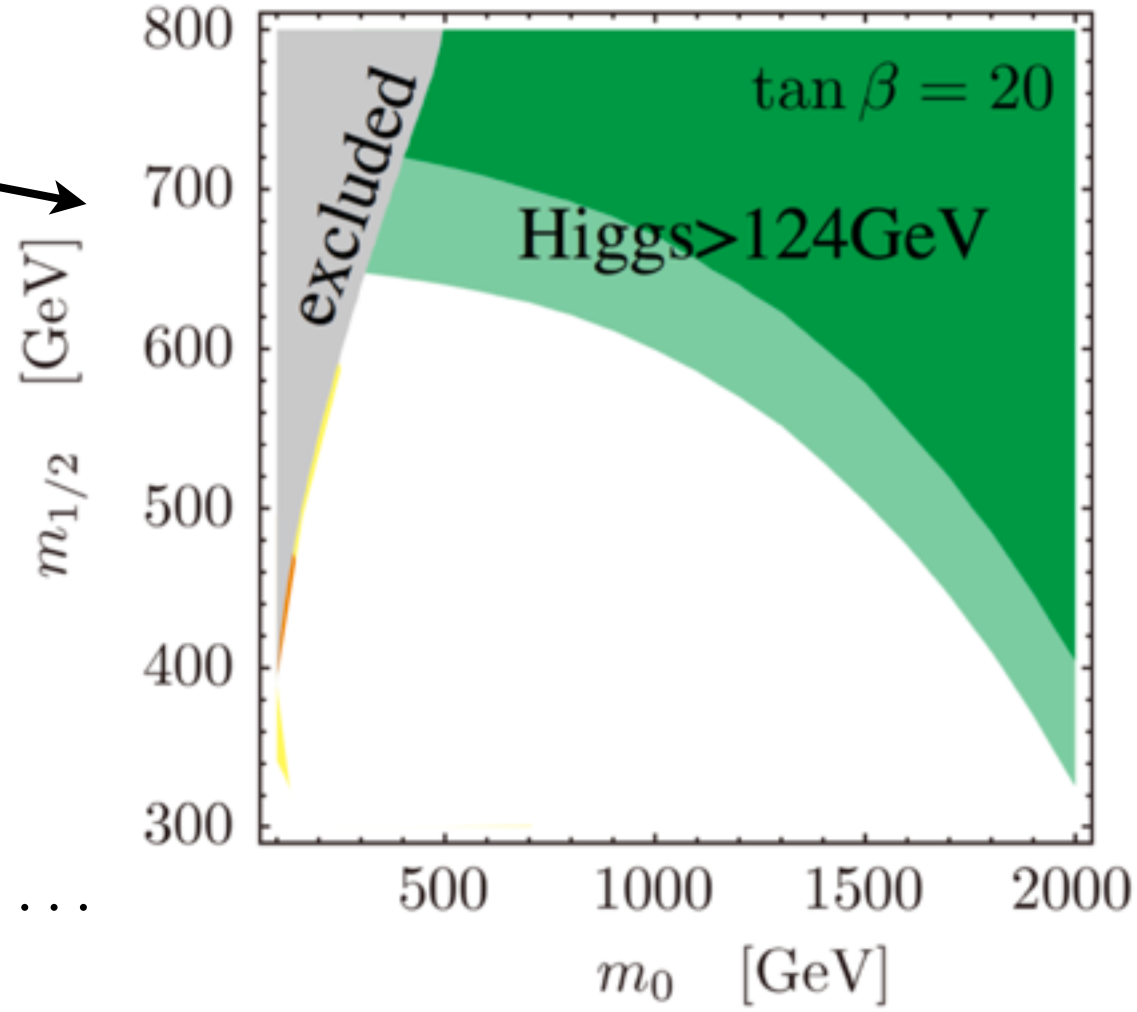
$$\Delta_{m_h} = \max_i \left| \frac{\partial \ln m_h^2}{\partial \ln p_i} \right| ,$$

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

126 GeV Higgs and naturalness

difficult to reconcile within MSSM

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



$$\delta m^2_{\rm Higgs} \propto \lambda_{\rm H}$$

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

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

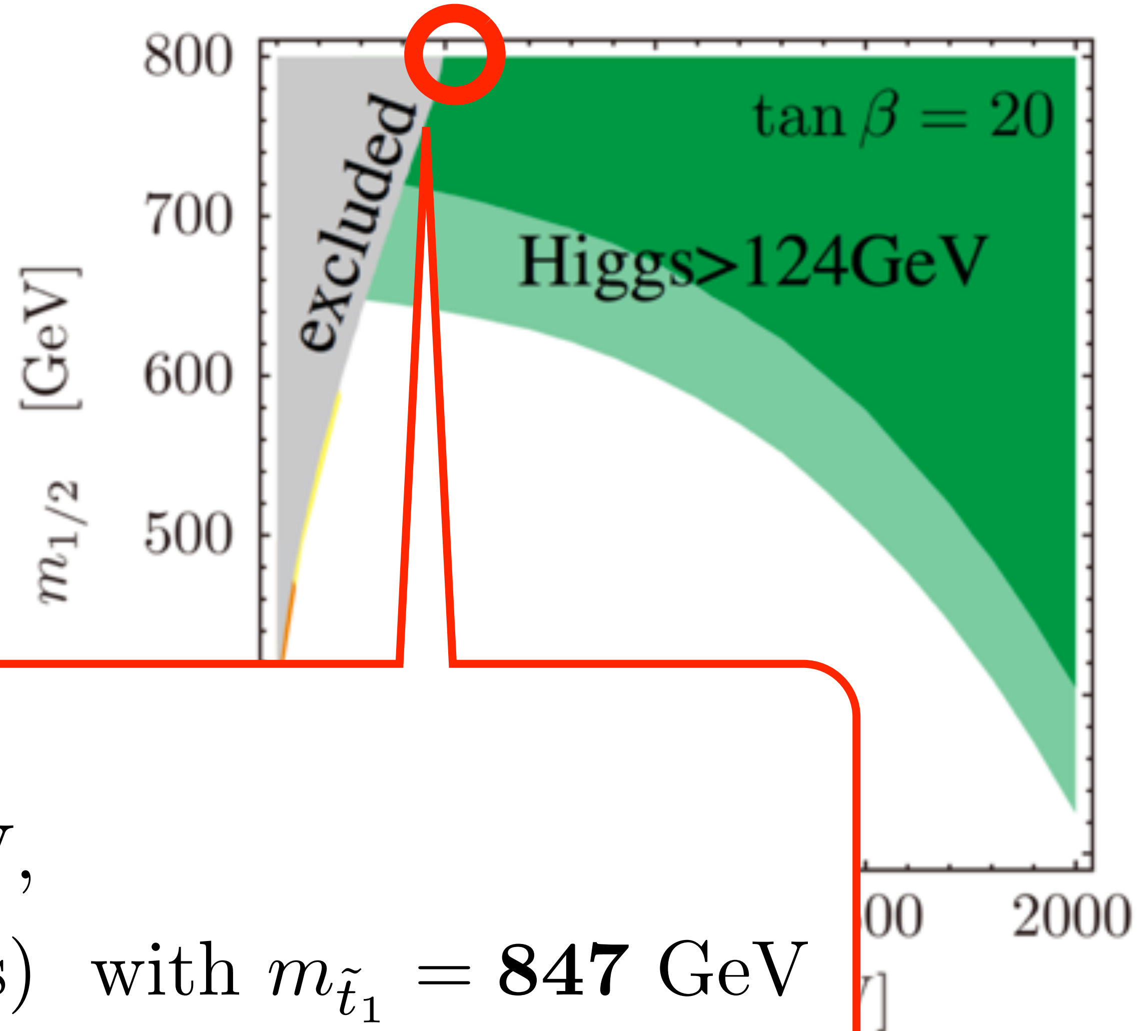
[See M.Endo, KH, S.Iwamoto, K.Nakayama, N.Yokozaki '11]

126 GeV Higgs and naturalness

difficult to reconcile within MSSM

example: mSUGRA
126 GeV Higgs can be consistent
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,

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

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

A-term,
otoi Endo)
ozaki '11]

126

difficul

requir

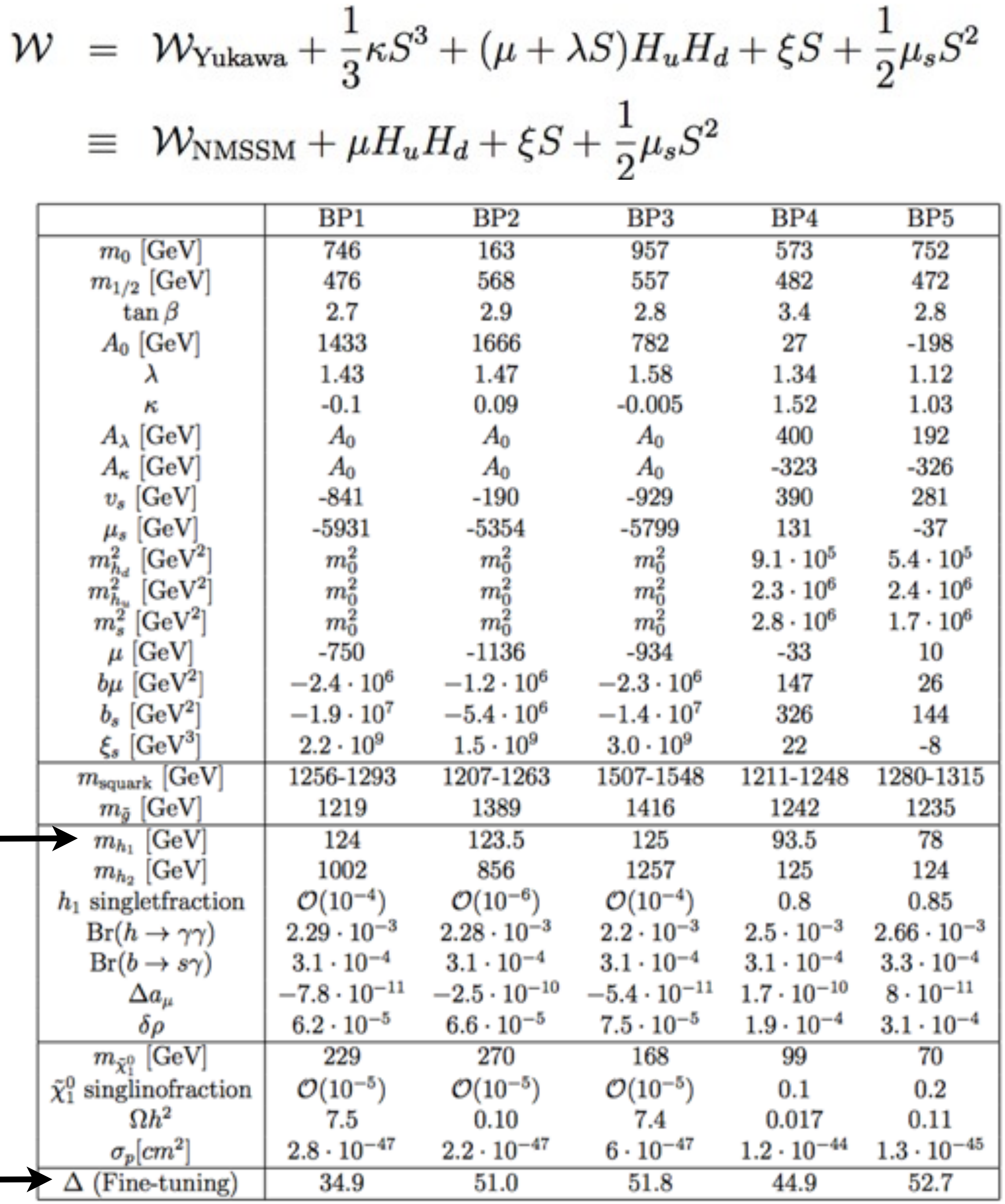
example

can realize

Any concrete model, perturbative up to GUT ??

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	$-7.8 \cdot 10^{-11}$	$-2.5 \cdot 10^{-10}$	$-5.4 \cdot 10^{-11}$	$1.7 \cdot 10^{-10}$	$8 \cdot 10^{-11}$
$\delta\rho$	$6.2 \cdot 10^{-5}$	$6.6 \cdot 10^{-5}$	$7.5 \cdot 10^{-5}$	$1.9 \cdot 10^{-4}$	$3.1 \cdot 10^{-4}$
$m_{\tilde{\chi}_1^0}$ [GeV]	229	270	168	99	70
$\tilde{\chi}_1^0$ 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 →

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

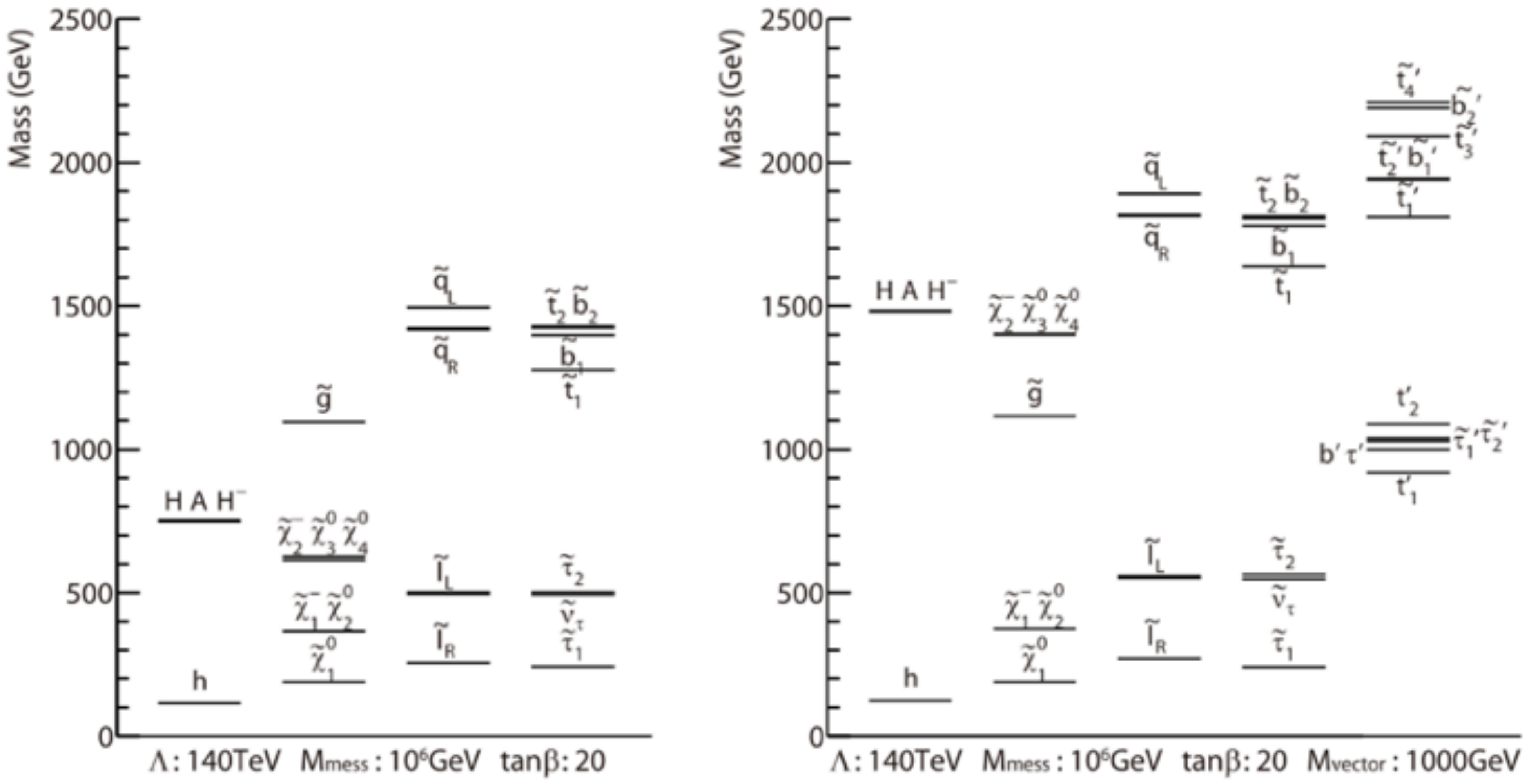


Figure 1: The mass spectra of the GMSB model (left) and the V-GMSB model (right). The GMSB parameters are $(\Lambda, M_{\text{mess}}, \tan\beta, N_{\text{mess}}) = (140\,\text{TeV}, 10^6\,\text{GeV}, 20, 1)$ in both cases. The SUSY-invariant mass of vectorlike fields are set as $M_{Q'} = M_{U'} = M_{E'} = 1\,\text{TeV}$ for the V-GMSB model. The masses of vectorlike fermions (scalars) are labelled by τ', b', and $t'_{1,2}$ $(\tilde{\tau}'_{1,2}, \tilde{b}'_{1,2}$, and $\tilde{t}'_{1,2,3,4})$, respectively.

(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)