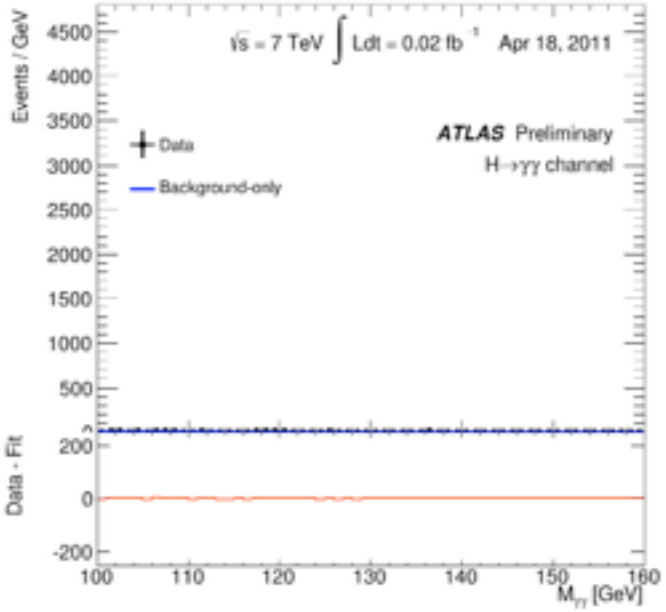
Supersymmetry after Higgs discovery

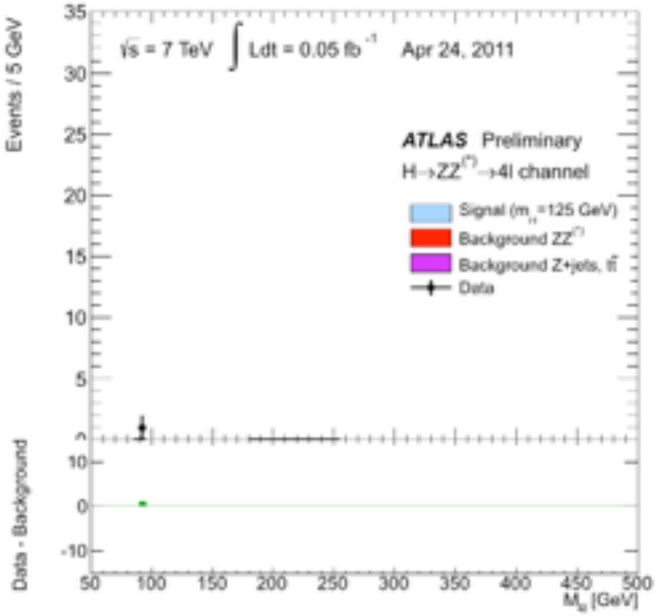
Koichi Hamaguchi (University of Tokyo)

@ Higgs modes in condensed matter and quantum gases, Kyoto, June 23

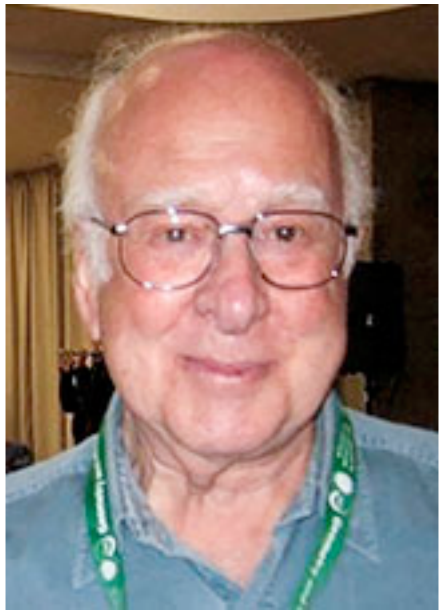
Discovery of the Higgs boson

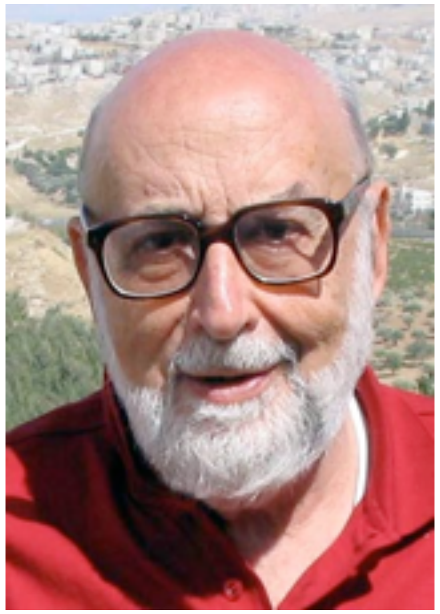
2012. July 4





2013. October 8

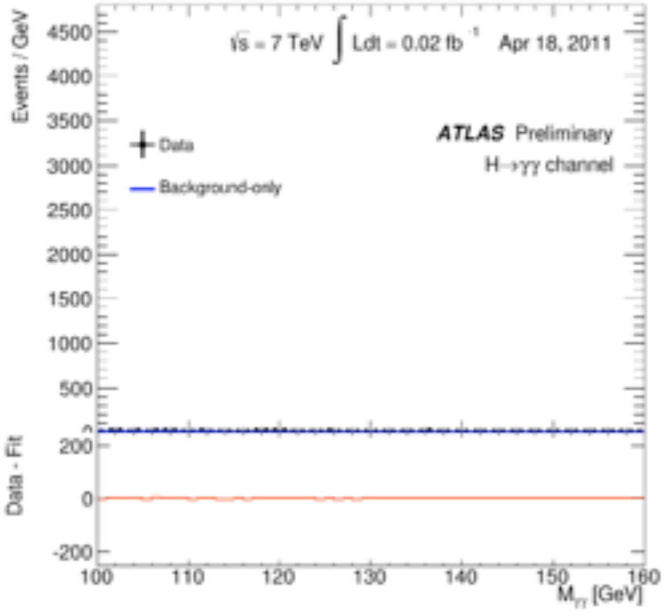


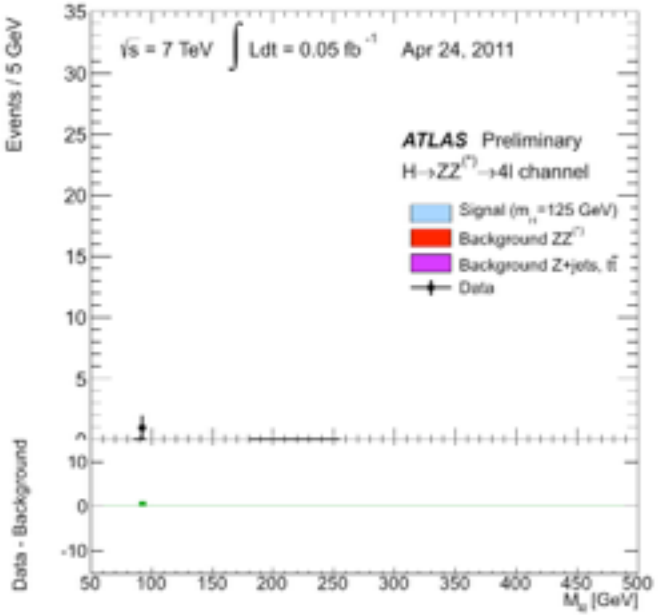


R. Brout (1928-2011)

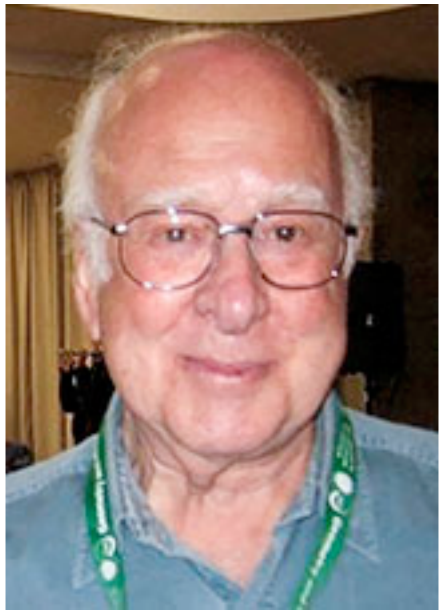
Discovery of the Higgs boson

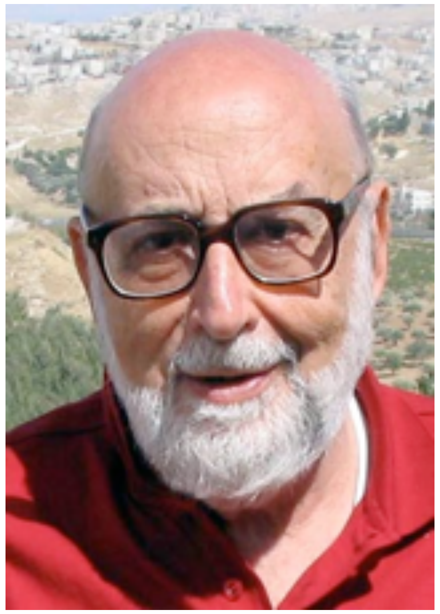
2012. July 4





2013. October 8



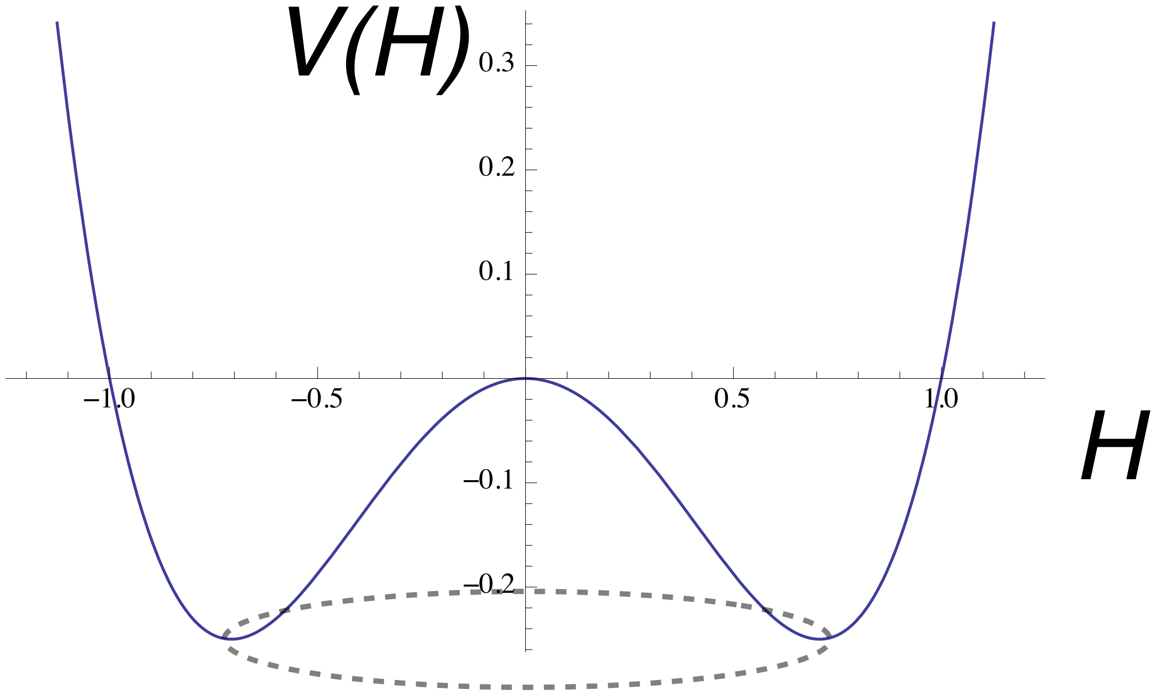


R. Brout (1928-2011)

126 GeV Higgs

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

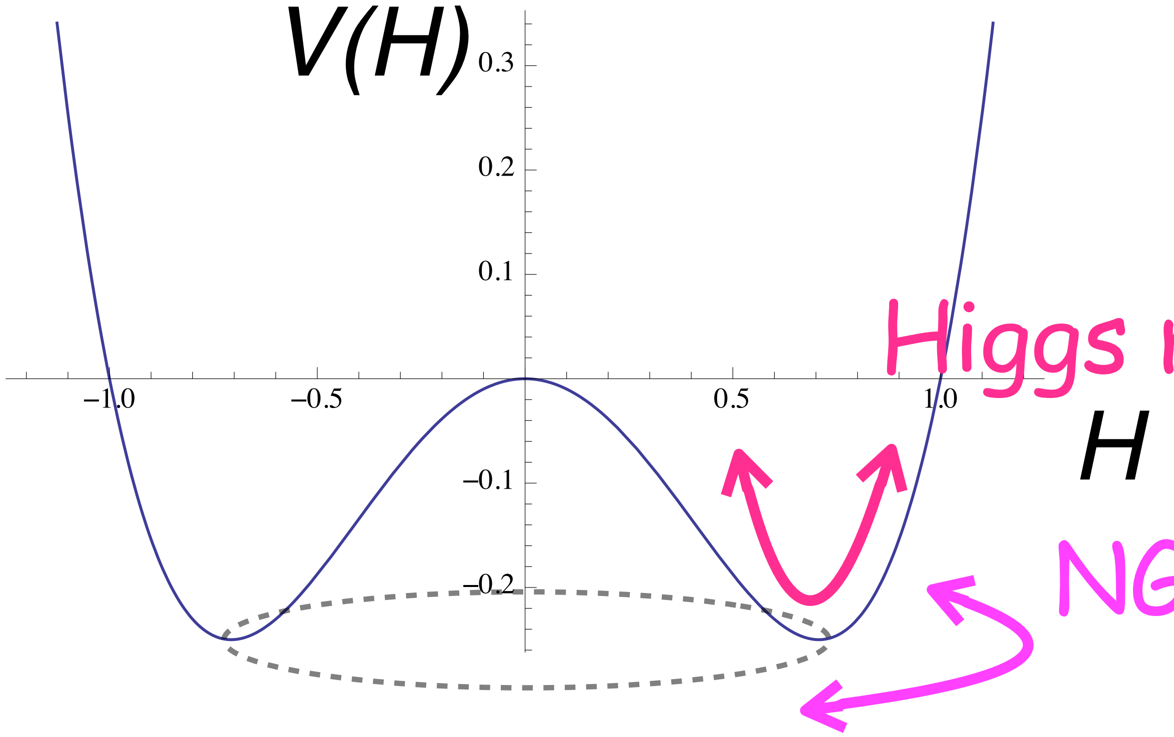
(Note:
- Lorentz inv.
- (3+1)-d
)



126 GeV Higgs

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

(Note:
- Lorentz inv.
- (3+1)-d
)



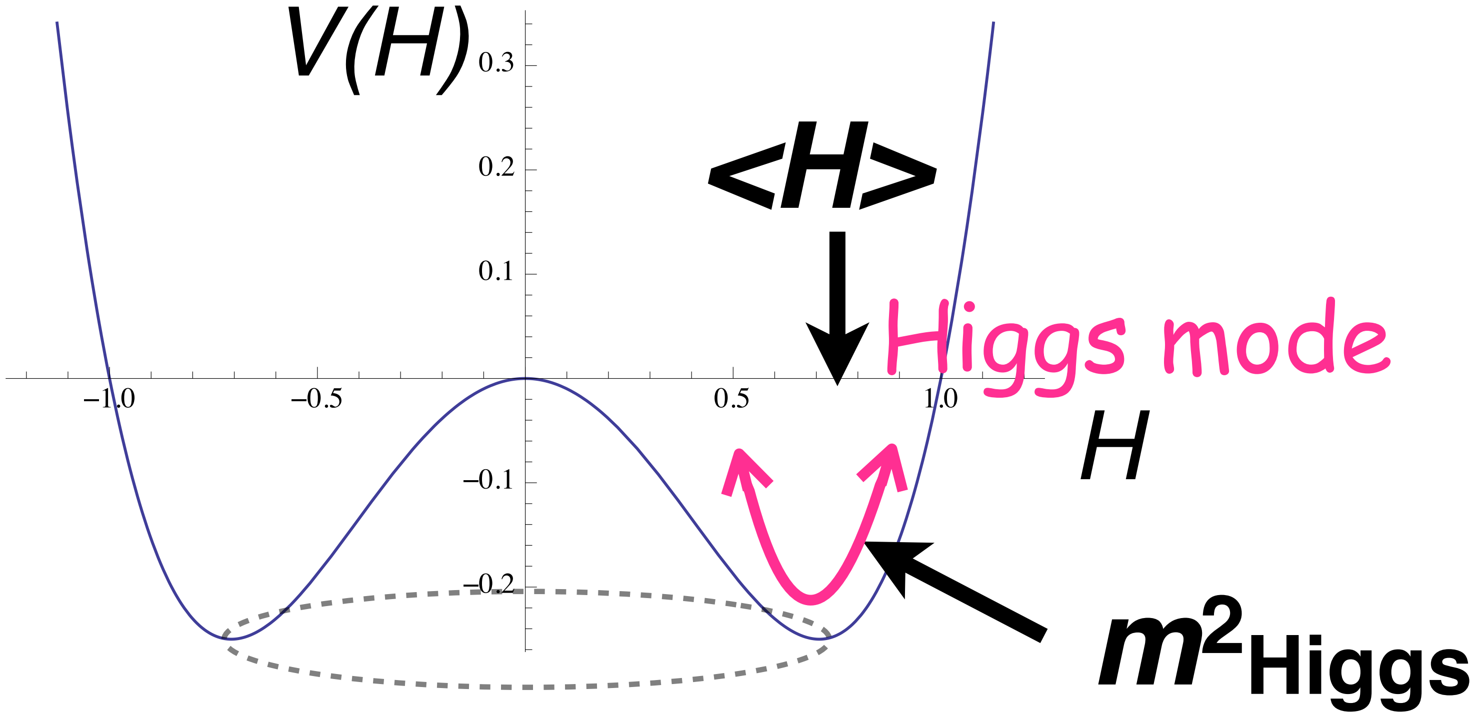
Higgs mode

NG modes (eaten by W and Z bosons)

via Higgs mechanism

126 GeV Higgs

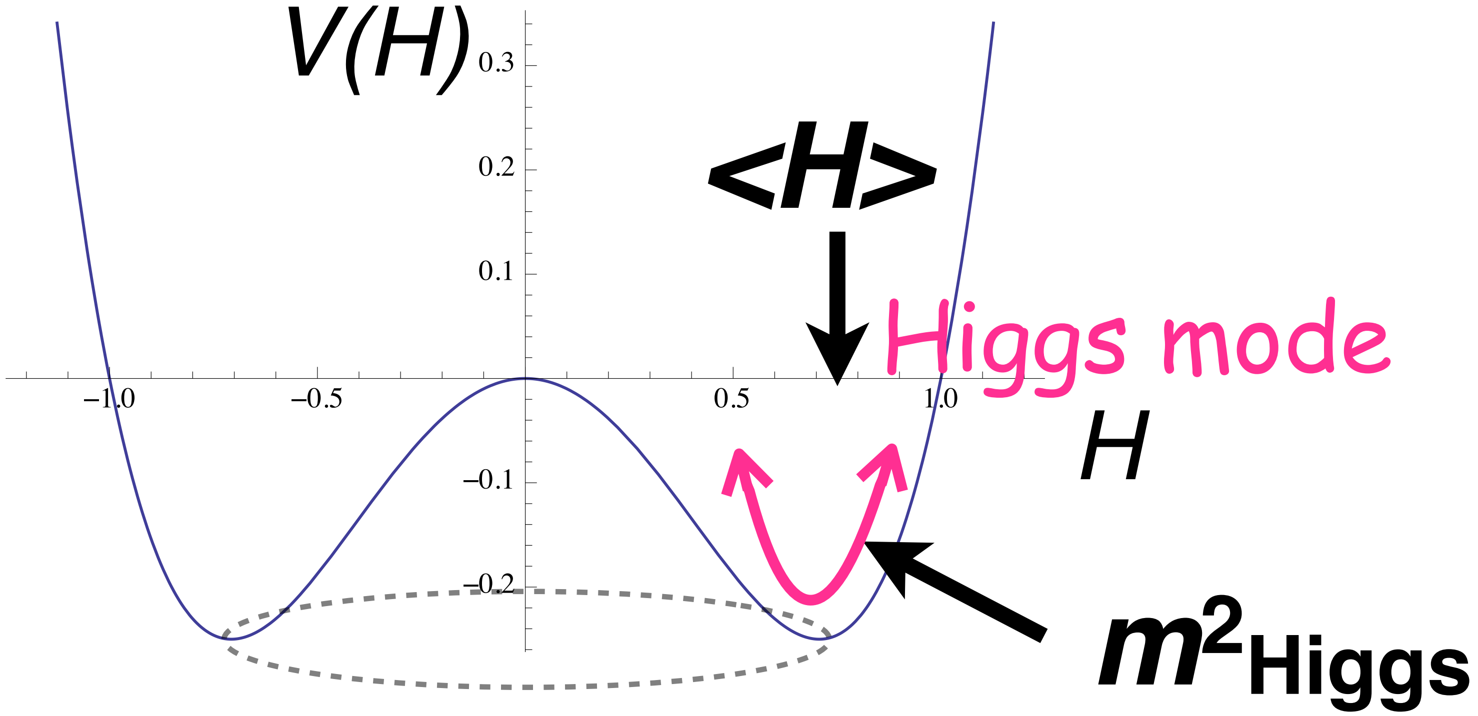
$$V(H) = -m^2(H^\dagger H) + \lambda_{\mathrm{H}}(H^\dagger H)^2$$



126 GeV Higgs

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

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



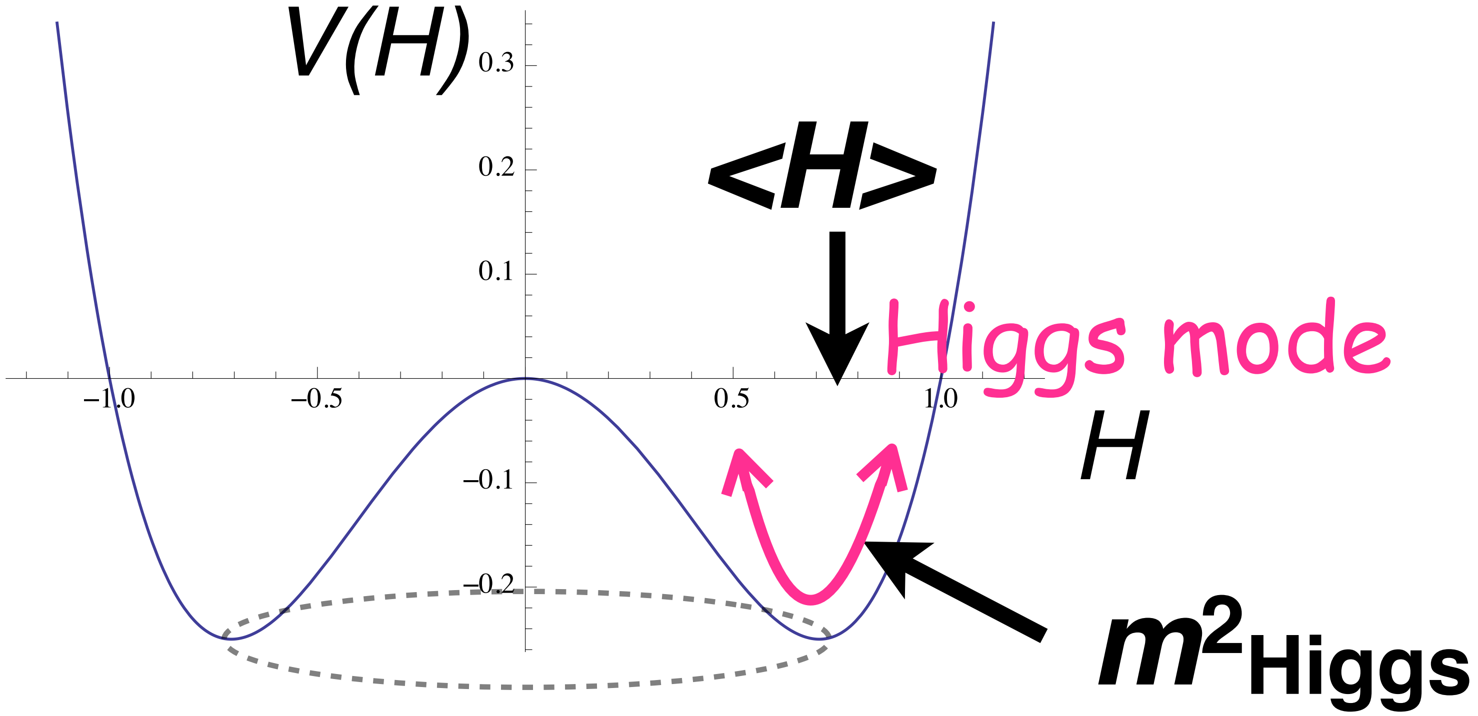
126 GeV Higgs

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

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

Fermi constant

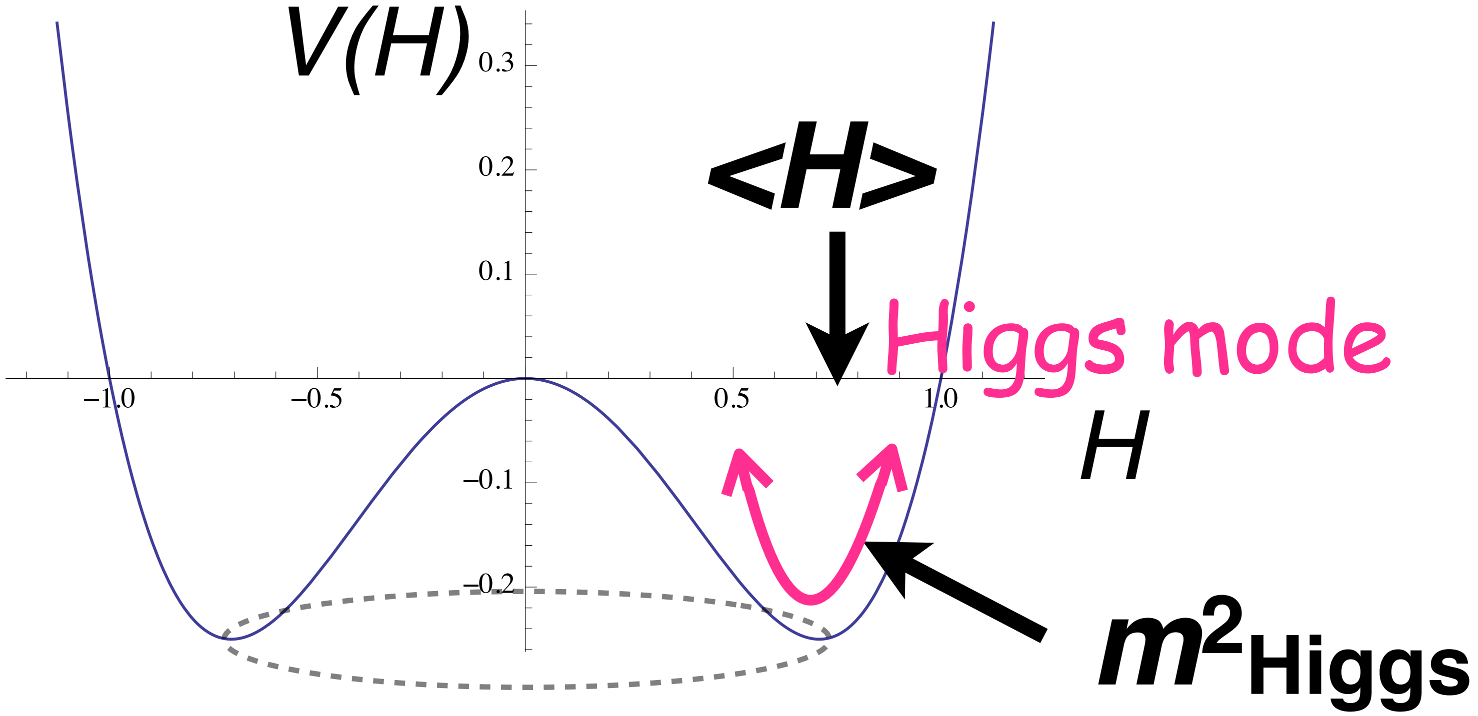
$G_F \simeq 1.17 \times 10^{-5} \mathrm{GeV}^{-2}$



126 GeV Higgs

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

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



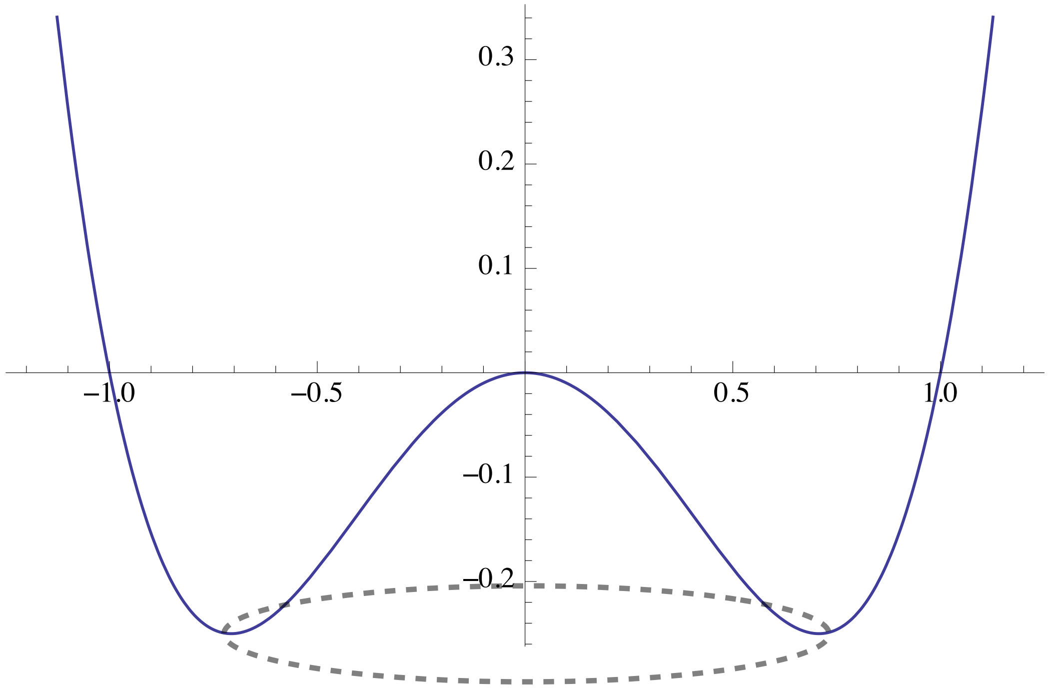
126 GeV Higgs

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

We knew…

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

Now we also know



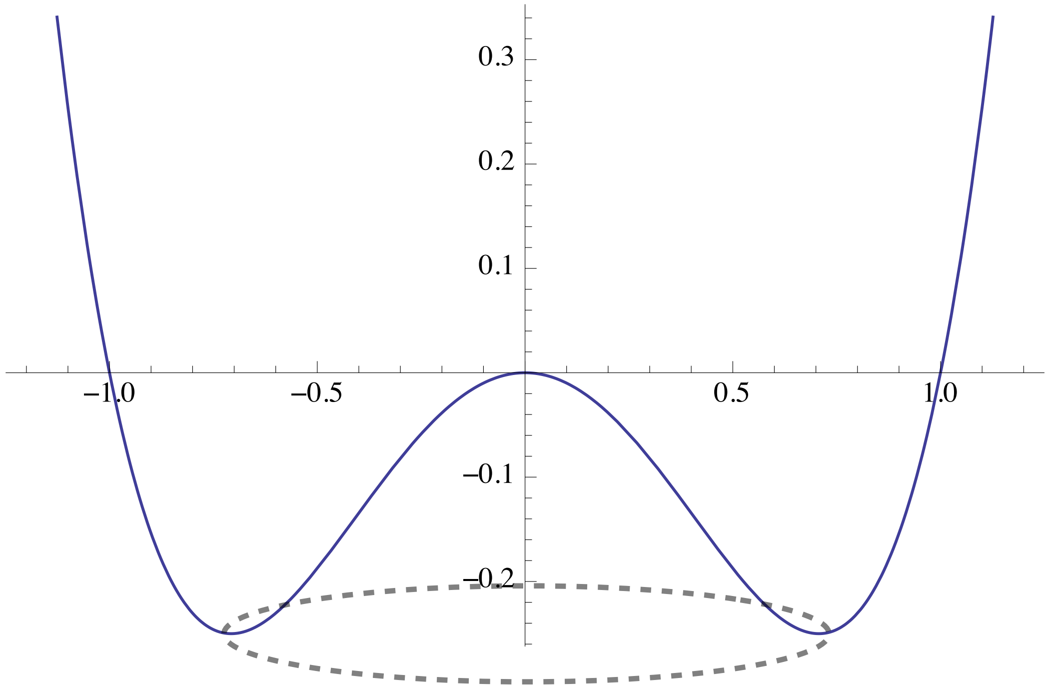
$$\rightarrow \begin{cases} m^2 = \dfrac{m^2_{\mathrm{Higgs}}}{2} \simeq \mathbf{(89\ GeV)^2} \\ \lambda_{\mathrm{H}} = \dfrac{m^2_{\mathrm{Higgs}}}{4\langle H \rangle^2} \simeq \mathbf{0.13} \end{cases}$$

126 GeV Higgs

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

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

completely determined !



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

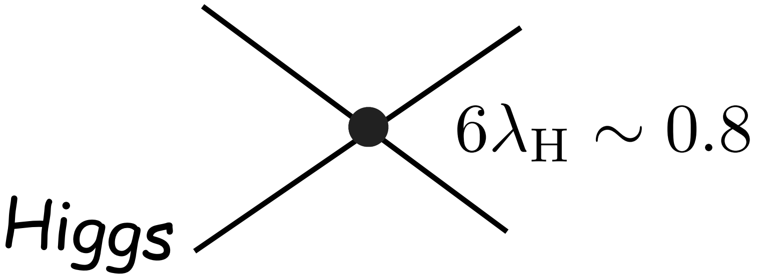
126 GeV Higgs

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

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

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

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



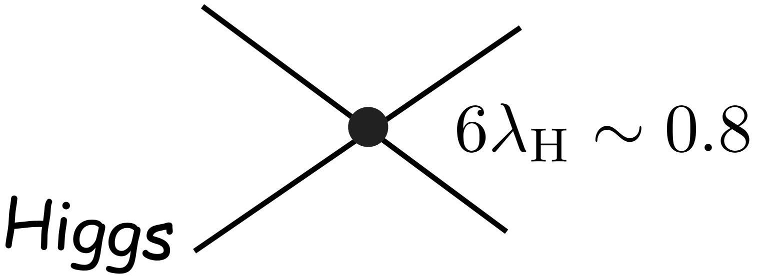
126 GeV Higgs

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

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

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

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



Imlications for BSM (in my opinion.....)

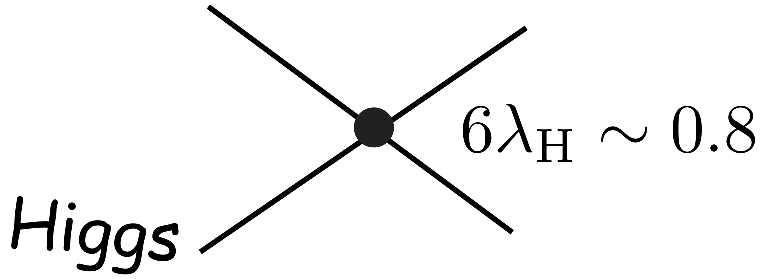
- consistent with the scenario with **heavy right-handed neutrinos** (Seesaw + Leptogenesis)
- consistent with **Supersymmetry**
- can discuss **GUT and coupling unification** in perturbative QFT.

126 GeV Higgs

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

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

It seems... Higgs sector is also described by weakly coupled, perturbative QFT.
(at least no sign of strong interaction etc, so far...)

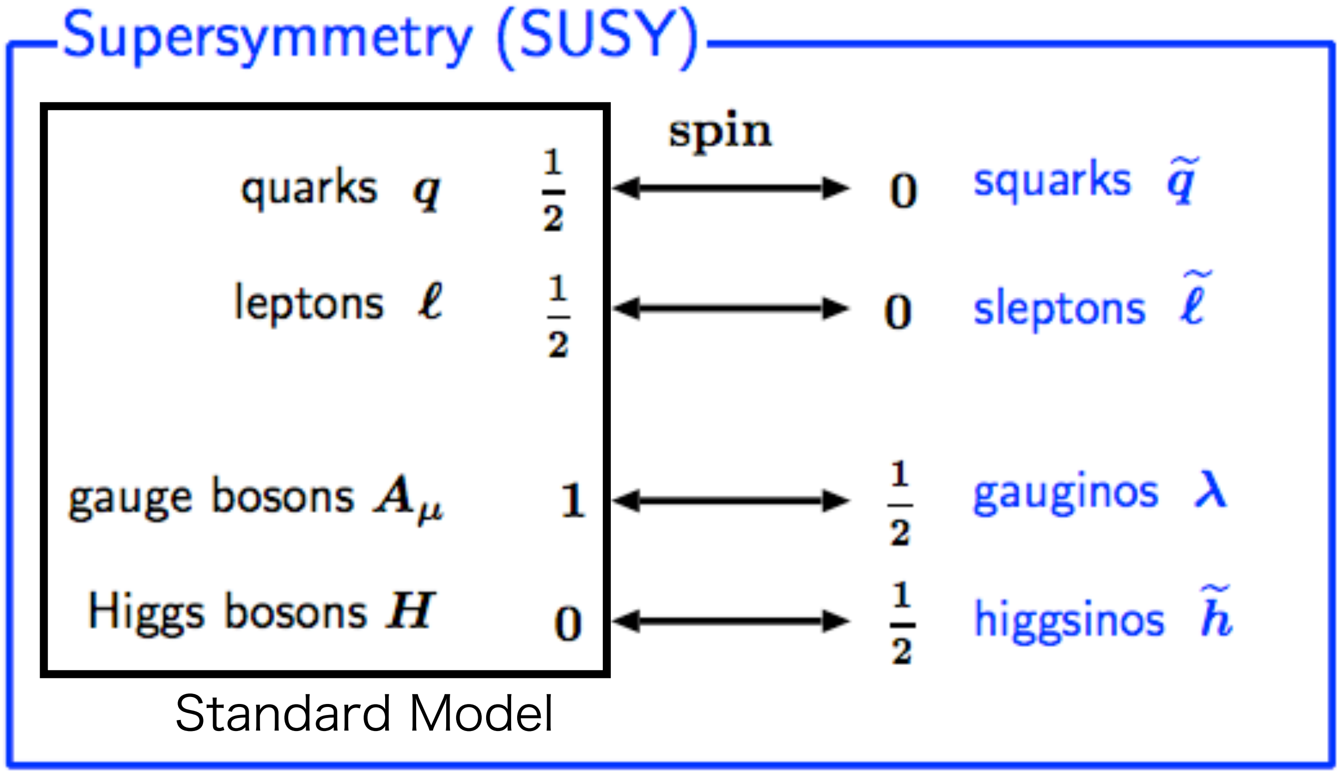


Imlications for BSM (in my opinion.....)

- consistent with the scenario with **heavy right-handed neutrinos** (Seesaw + Leptogenesis)
- consistent with **Supersymmetry**
- can discuss **GUT and coupling unification** in perturbative QFT.

Supersymmetry

boson ⇔ fermion



Supersymmetry (SUSY)

spin

quarks q	$\frac{1}{2}$	⟷	0	squarks $\tilde{q}$
leptons ℓ	$\frac{1}{2}$	⟷	0	sleptons $\tilde{\ell}$
gauge bosons A_μ	1	⟷	$\frac{1}{2}$	gauginos λ
Higgs bosons H	0	⟷	$\frac{1}{2}$	higgsinos $\tilde{h}$

Standard Model

Supersymmetry

boson ⇔ fermion

Supersymmetry (SUSY)

		spin		
quarks q	$\frac{1}{2}$	⟷	0	squarks $\tilde{q}$
leptons ℓ	$\frac{1}{2}$	⟷	0	sleptons $\tilde{\ell}$
gauge bosons A_μ	1	⟷	$\frac{1}{2}$	gauginos λ
Higgs bosons H	0	⟷	$\frac{1}{2}$	higgsinos $\tilde{h}$

Standard Model

naturalness

fine-tuning problem

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

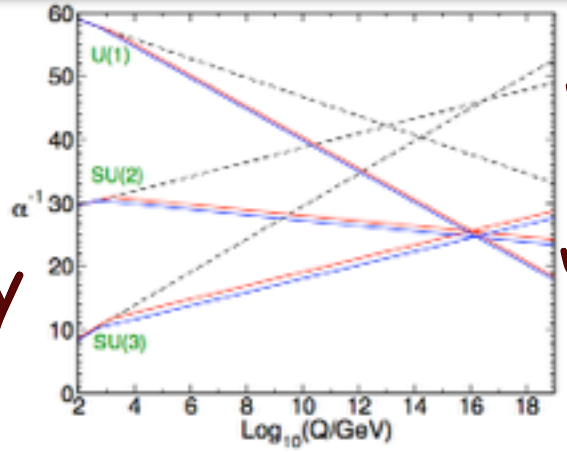
(fine tuning like 1.0000000000000001 - 1)

→ solved by the supersymmetry !

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

coupling unification

Grand Unified Theory



without SUSY

with SUSY

Dark Matter = Lightest SUSY particle

OK, then,....

What's the implications of 126 GeV Higgs for Supersymmetry (SUSY) ??

126 GeV Higgs and SUSY

126 GeV Higgs and SUSY

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

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

in SUSY...

126 GeV Higgs and SUSY

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

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

in SUSY...

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

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

too small...

parameters
in Standard Model
(known)

126 GeV Higgs and SUSY

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

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

0.13

in SUSY...

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

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

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

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

...requires **heavy stop**

and/or **large A-term**

126 GeV Higgs and SUSY

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

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

in SUSY…

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

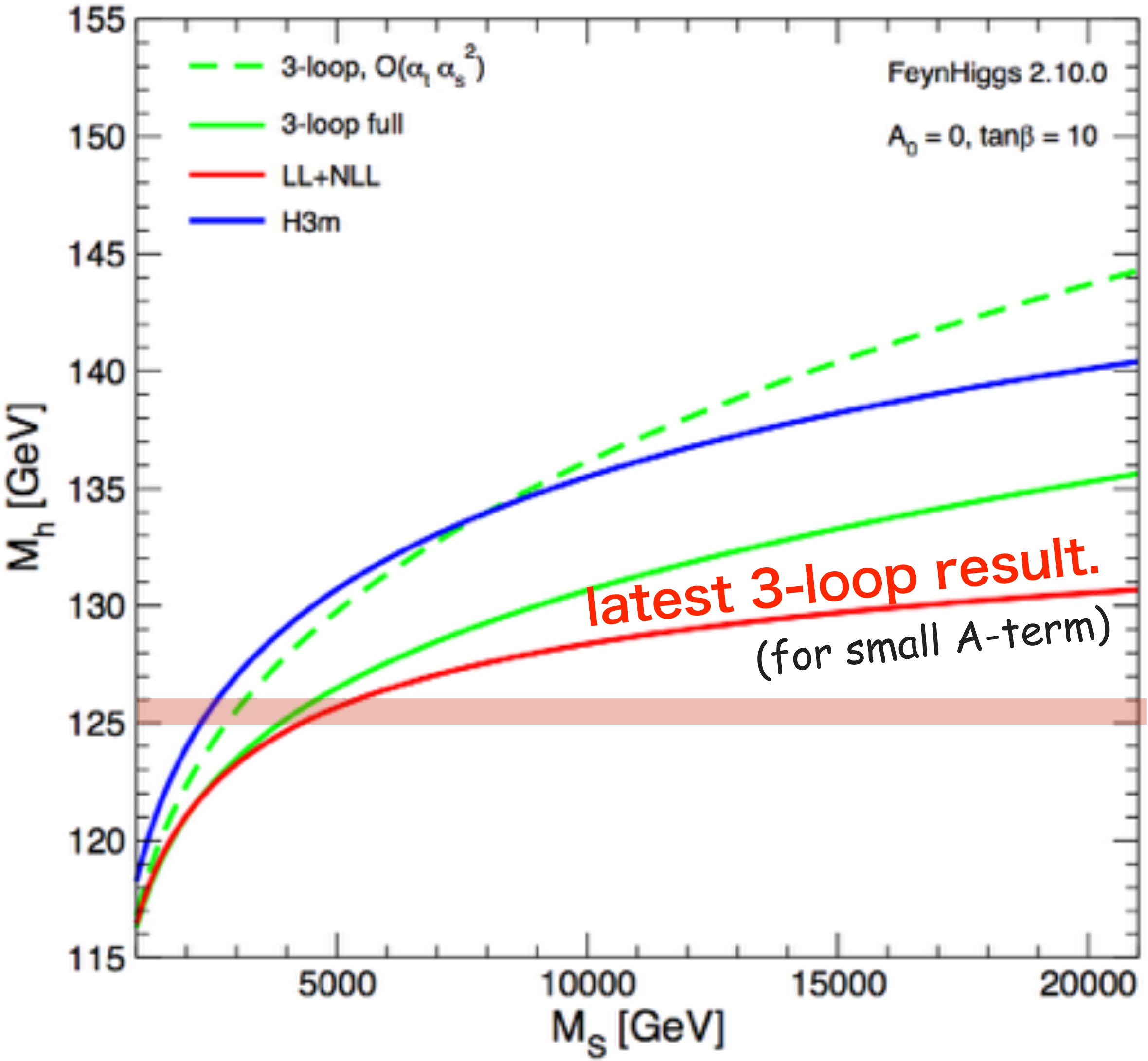
$$\frac{g^2 \cos^2 2\beta}{8\cos^2\theta_W} \simeq 0.069 \cos^2 2\beta$$

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

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

…requires **heavy stop**

and/or **large A-term**



latest 3-loop result.

(for small A-term)

1404.0186 Hahn et.al.

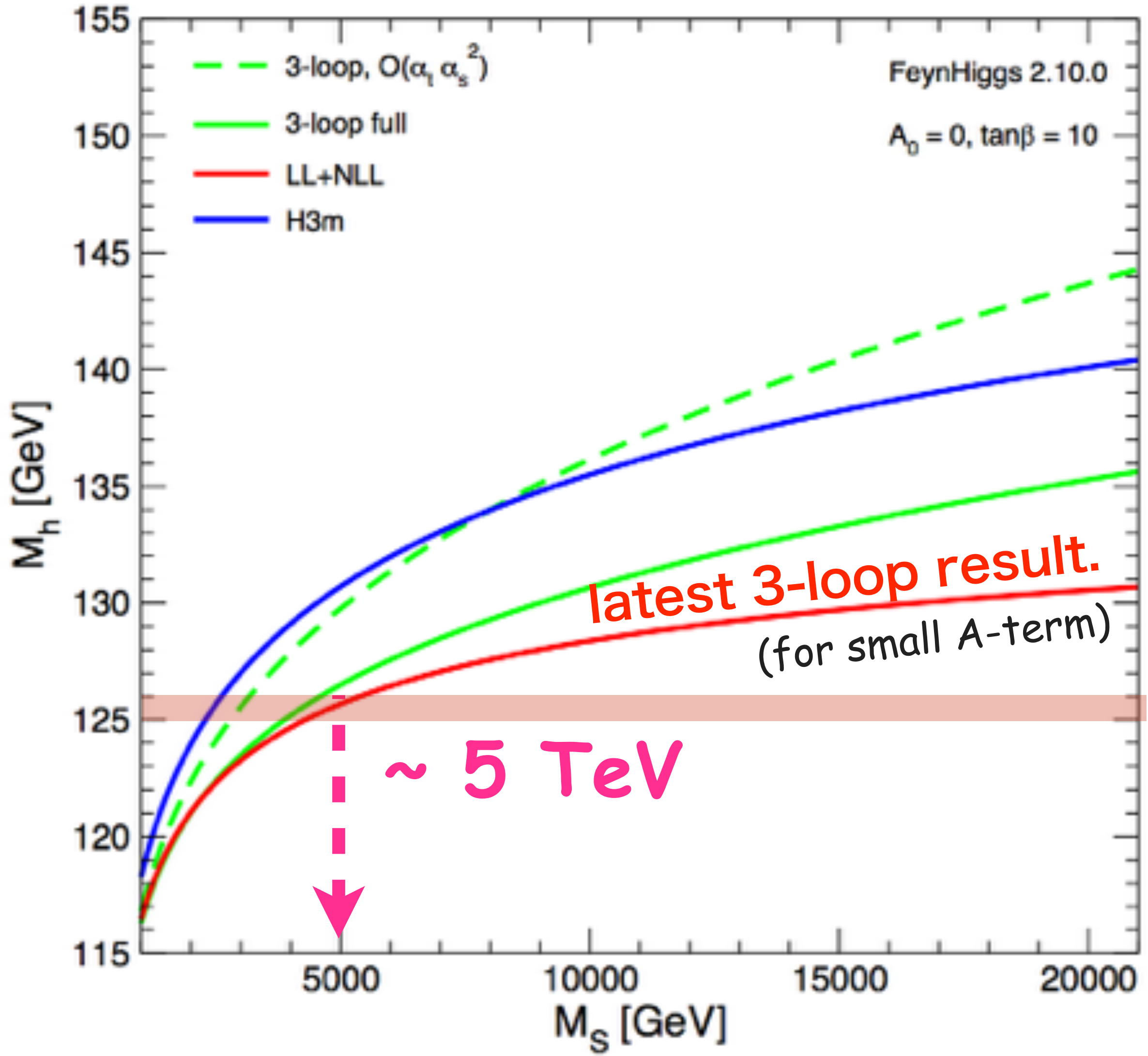
126 GeV Higgs and SUSY

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

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

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

in SUSY...



latest 3-loop result.

(for small A-term)

~ 5 TeV

1404.0186 Hahn et.al.

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

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

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

...requires **heavy stop**

and/or **large A-term**

126 GeV Higgs and SUSY

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

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

on the other hand

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

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

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

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

...requires **heavy stop**

and/or **large A-term**

126 GeV Higgs and SUSY

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

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

0.13

on the other hand

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

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

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

Higgsino mass

soft mass for up-type Higgs

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

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

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

...requires **heavy stop**

and/or **large A-term**

126 GeV Higgs and SUSY

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

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

λ_{H}: $\mathbf{0.13}$

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

on the other hand

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

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

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.

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

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

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

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

126 GeV Higgs and SUSY

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

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

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

on the other hand

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

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.

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

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

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

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

126 GeV Higgs and SUSY

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

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

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,

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

requires **Light stop and**

small A-term

to avoid a fine-tuning.

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

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

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

inconsistent !!

...requires **heavy stop**

and/or **large A-term**

126 GeV Higgs and SUSY

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

(MSSM =Minimal SUSY Standard Model)

126 GeV Higgs and SUSY

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

(MSSM =Minimal SUSY Standard Model)

What does it imply ??

1. No SUSY ?

2. (It's anyway fine-tuned, then....)

Very heavy SUSY ? (10~100 TeV, or even higher...)

3. (still.....)

(0.1-1) TeV SUSY ? (fine-tuned, but less than 2 and 3...)

126 GeV Higgs and SUSY

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

(MSSM =Minimal SUSY Standard Model)

What does it imply ??

1. **No SUSY ?**

2. (It's anyway fine-tuned, then....)
   Very heavy SUSY ? (10~100 TeV, or even higher...)

3. (still.....)
   (0.1-1) TeV SUSY ? (fine-tuned, but less than 2 and 3...)

126 GeV Higgs and SUSY

(It's anyway fine-tuned, then....)

Very heavy SUSY

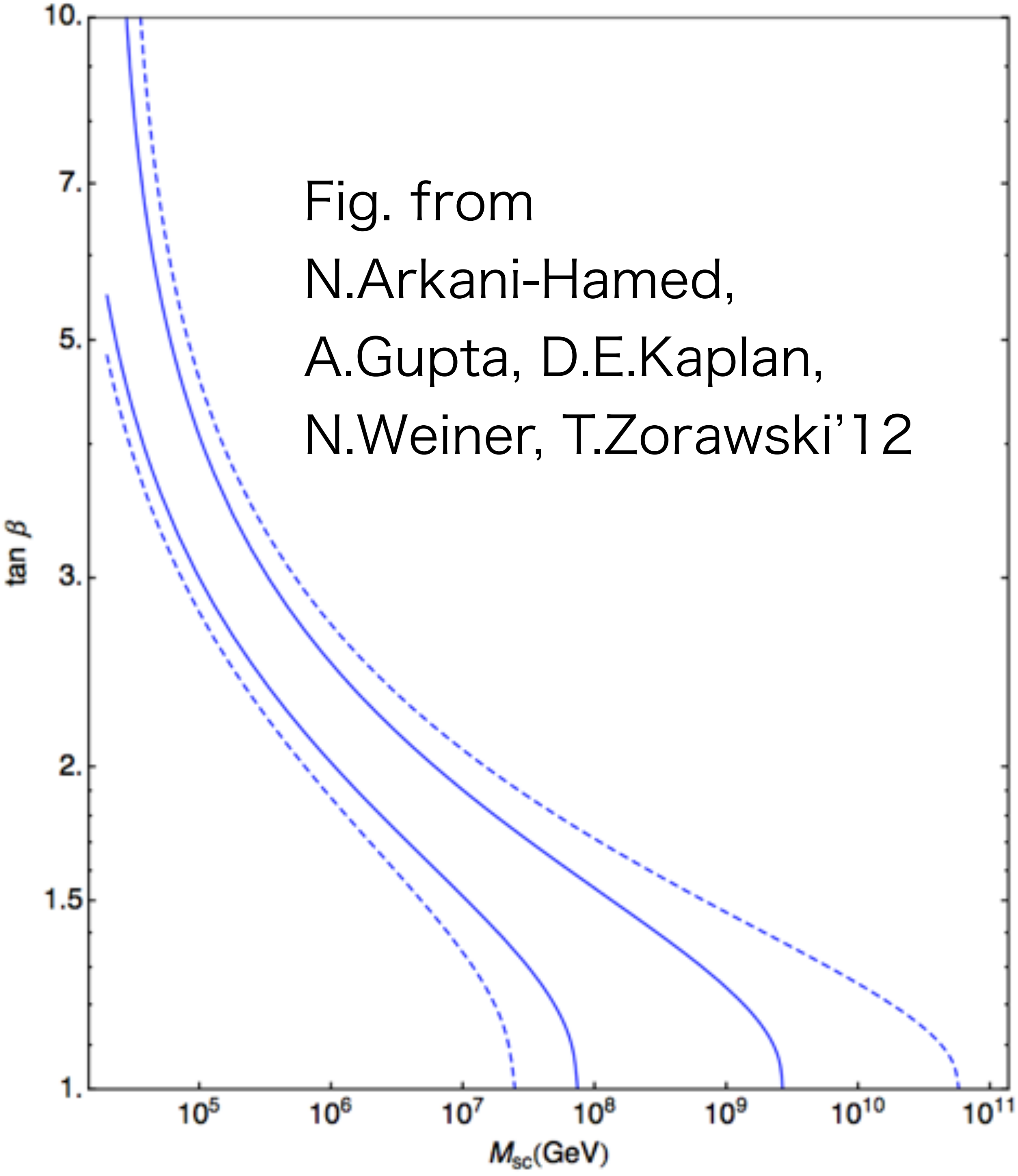
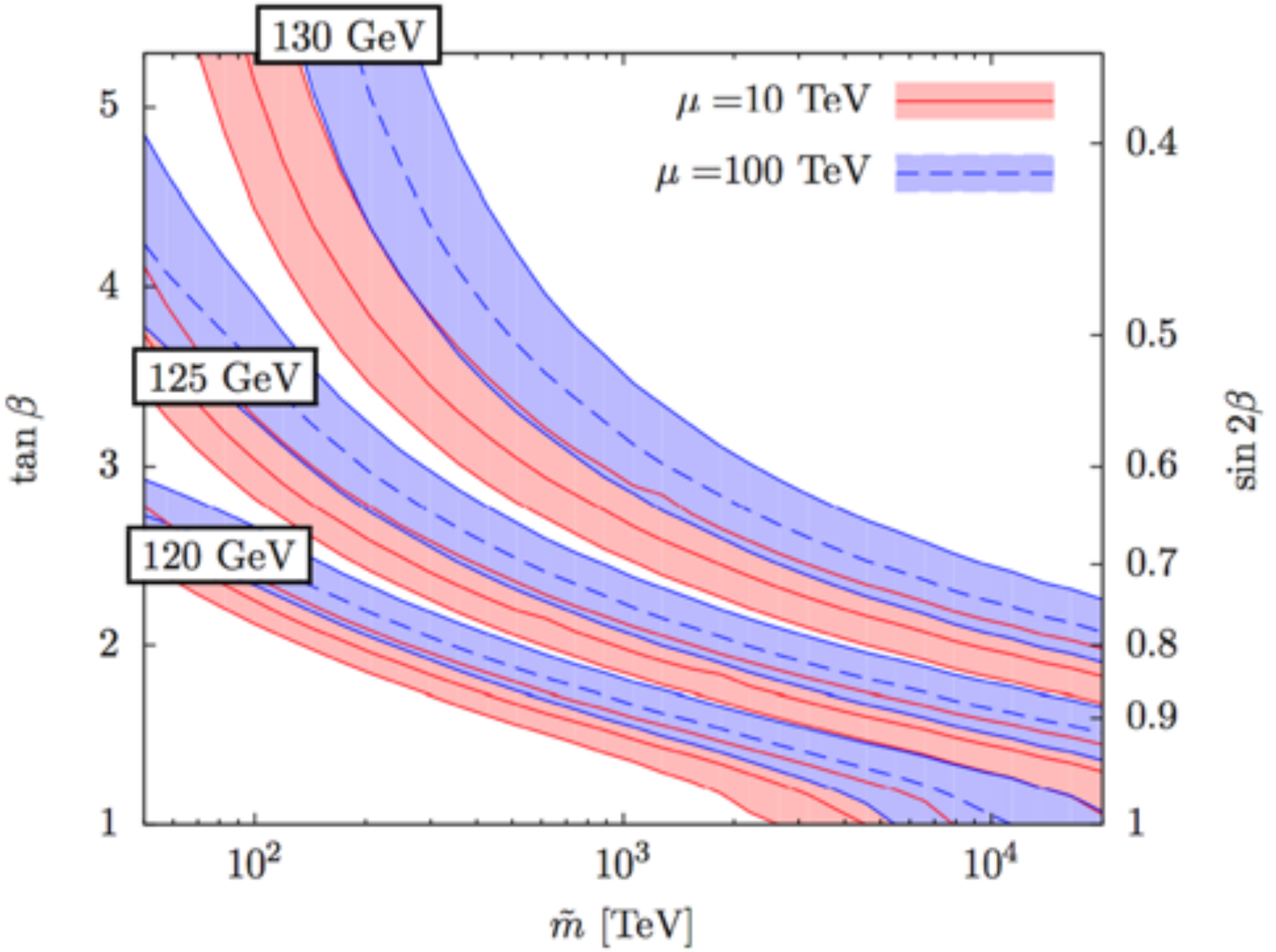
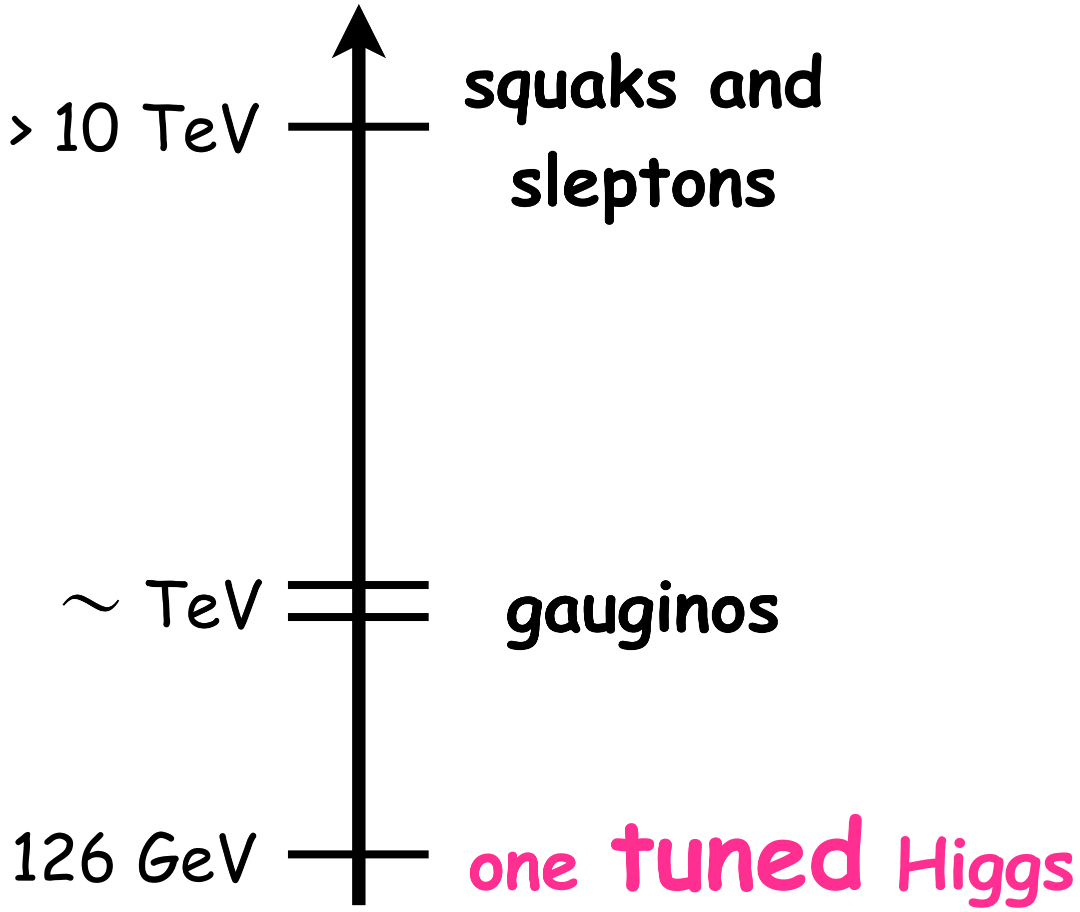


Fig. from N.Arkani-Hamed, A.Gupta, D.E.Kaplan, N.Weiner, T.Zorawski'12

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



126 GeV Higgs and SUSY



> 10 TeV squaks and sleptons

~ TeV gauginos

126 GeV one **tuned** Higgs

(It's anyway fine-tuned, then....)

Very heavy SUSY

- consistent with 126 GeV Higgs
- No FCNC/CP problems
- No cosmological gravitino problem
- Coupling Unification is OK
- Dark Matter is also OK

Many many 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 and SUSY

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

(MSSM =Minimal SUSY Standard Model)

What does it imply ??

1. **No SUSY ?**

2. (It's anyway fine-tuned, then....)

   Very heavy SUSY ? (10~100 TeV, or even higher...)

3. (still.....)

   (0.1-1) TeV SUSY ? (fine-tuned, but less than 1 and 2...)

one more motivation for TeV scale SUSY…

muon g-2

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

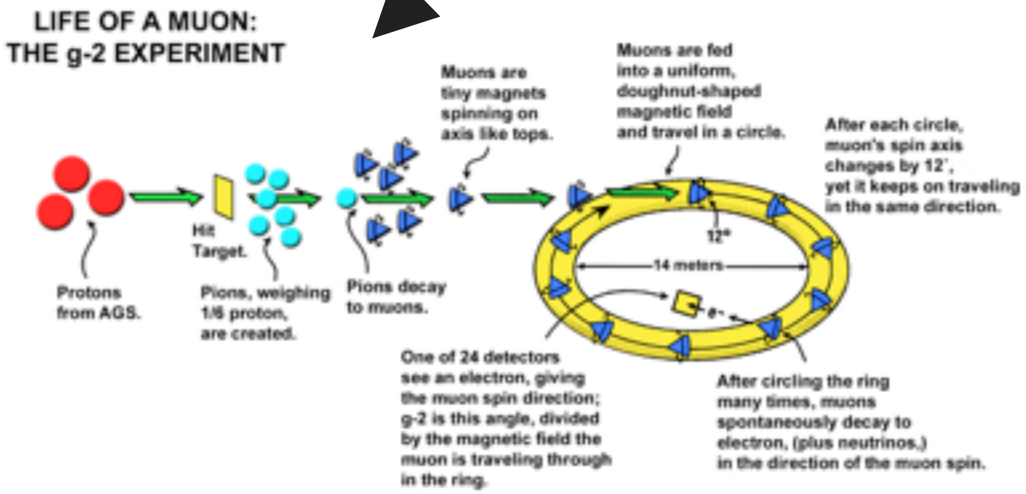
> 3σ deviation !

one more motivation for TeV scale SUSY...

muon g-2

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

> 3σ deviation !



from E821 muon g-2 Home Page

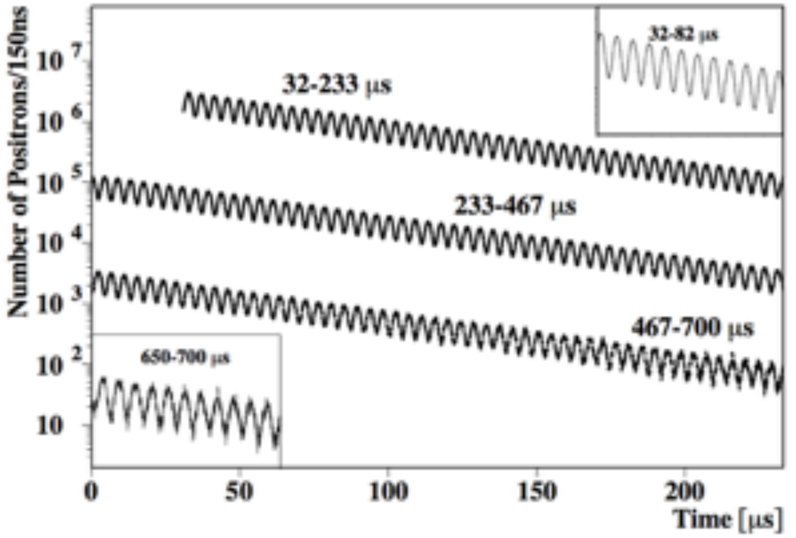
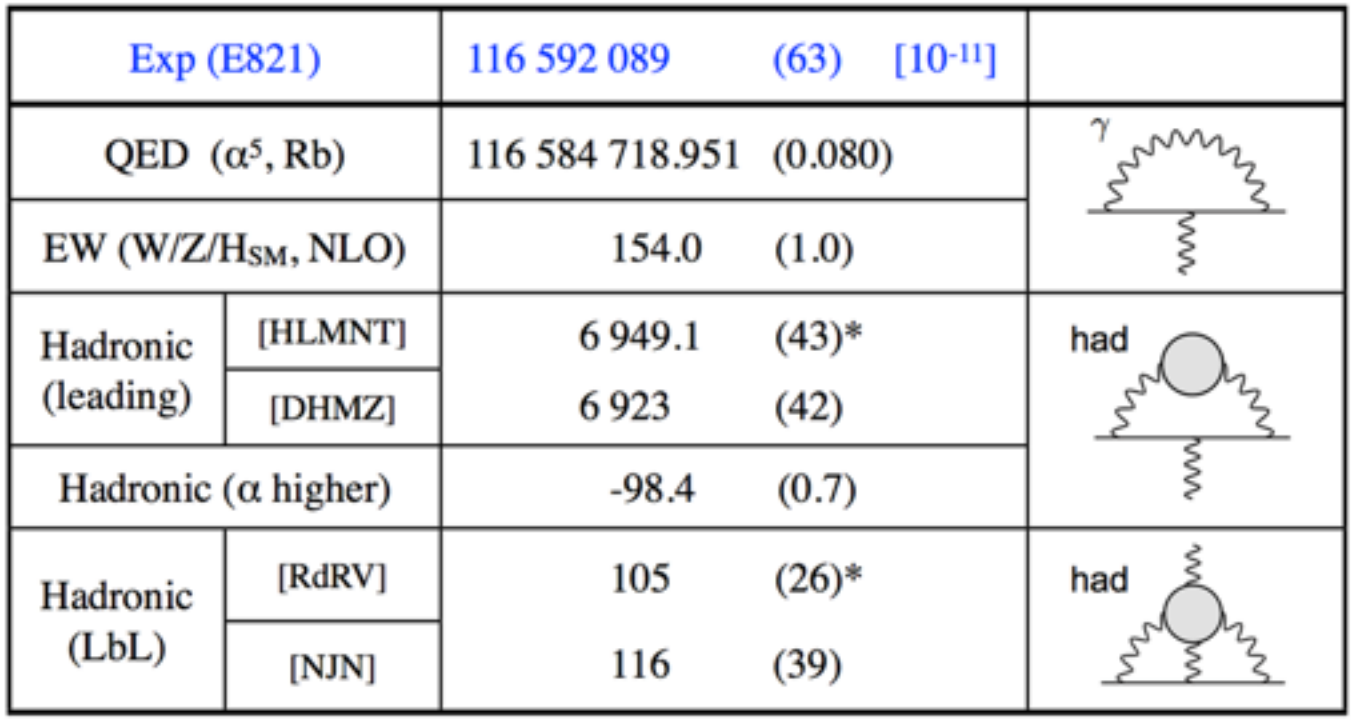


FIG. 3. Positron time spectrum overlaid with the fitted 10 parameter function (χ^2/dof= 3818/3799). The total event sample of 0.95×10^9 e^+ with $E \geq 2.0$ GeV is shown.

from hep-ph/0102017

Standard Model Prediction



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

from Talk by M.Endo
@Hokkaido Winter School 2013

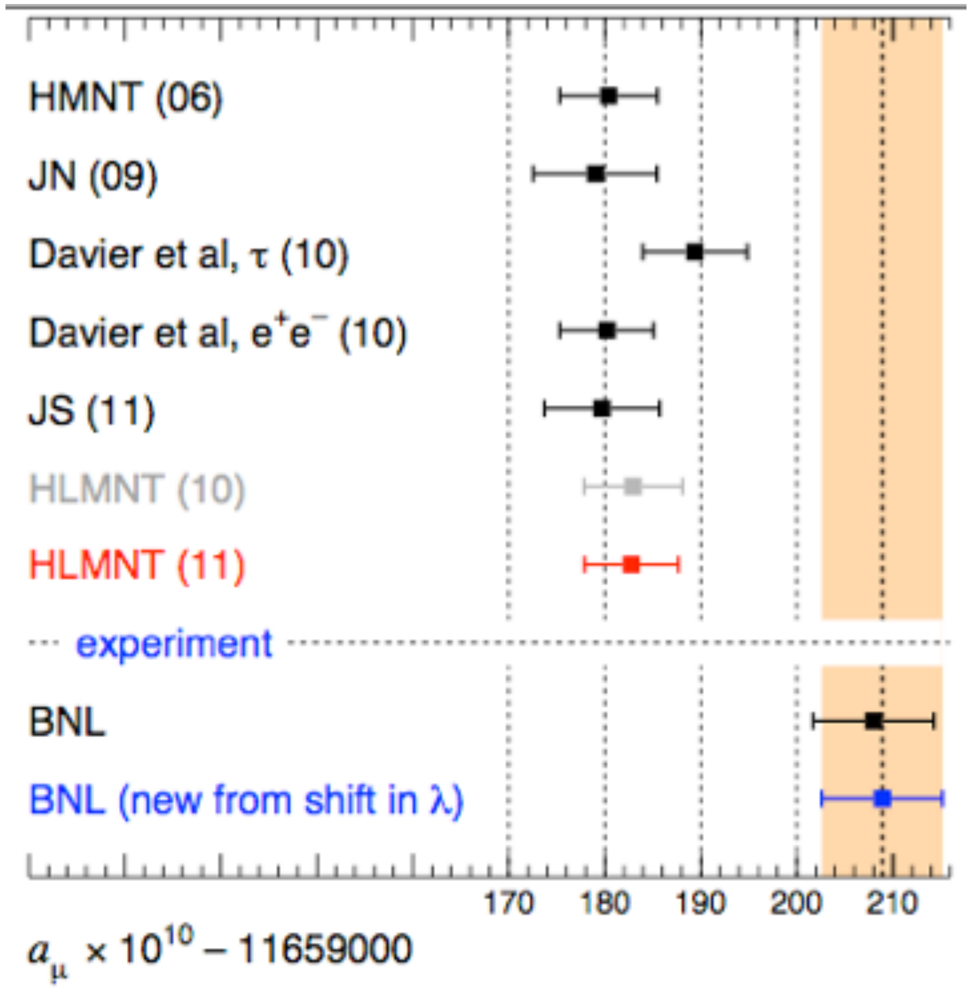
one more motivation for TeV scale SUSY...

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!]



one more motivation for TeV scale SUSY...

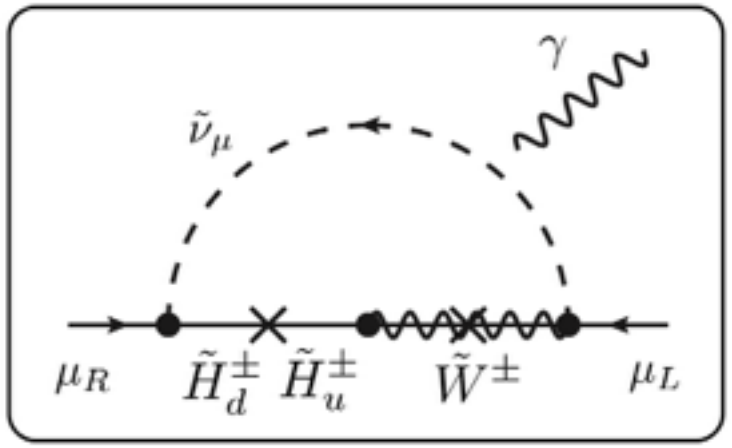
muon g-2

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

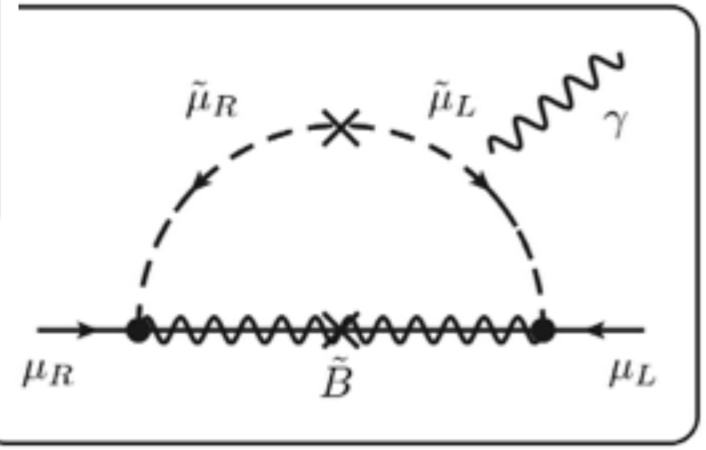
> 3σ deviation !

...can be explained by SUSY.

chargino



neutralino



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

Higgs + SUSY + g-2

heavy stop

light smuon/ inos

difficult to reconcile in typical models

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

Higgs + SUSY + g-2

heavy stop

light smuon/ inos

difficult to reconcile in typical models

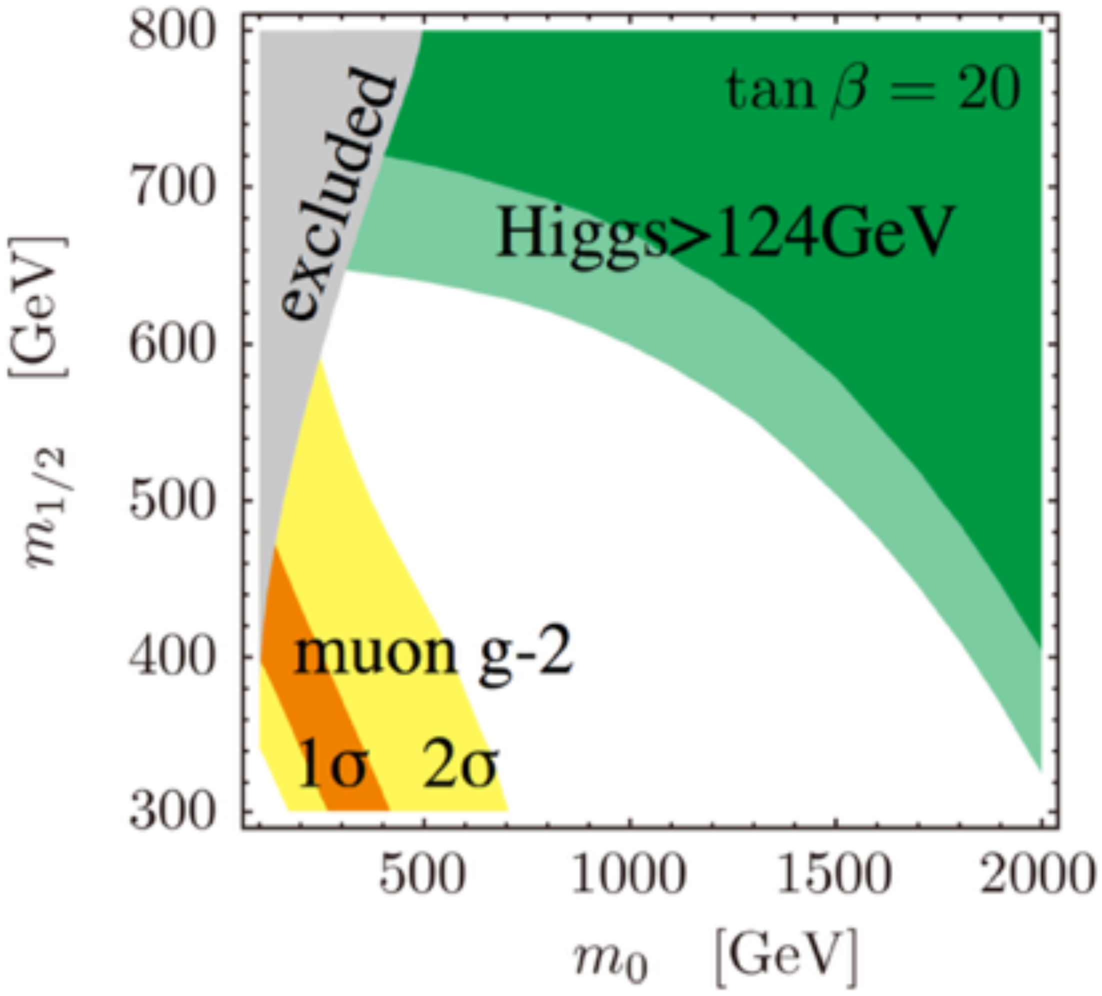
(mSUGRA/GMSB/AMSB/NMSSM (small tanβ) ...)

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]



Higgs + SUSY + g-2

heavy stop

light smuon/ inos

difficult to reconcile in typical models

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

2 approaches

(1) model building

(2) general MSSM

Higgs + SUSY + g-2

heavy stop

light smuon/ inos

difficult to reconcile in typical models

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

2 approaches

(1) model building

[our works]

extra matter

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

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

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

(2) general MSSM

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

M.Endo, KH, T.Kitahara, T.Yoshinaga, arXiv:1309.3065 LHC/ILC+flavor+vacuum

M.Endo, KH, S.Iwamoto, T.Kitahara, T.Moroi, arXiv:1310.4496 ILC

Higgs + SUSY + g-2

heavy stop

light smuon/ inos

difficult to reconcile in typical models

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

2 approaches

(1) model building

[our works]

extra matter

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

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

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

(2) general MSSM

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

M.Endo, KH, T.Kitahara, T.Yoshinaga, arXiv:1309.3065 LHC/ILC+flavor+vacuum

M.Endo, KH, S.Iwamoto, T.Kitahara, T.Moroi, arXiv:1310.4496 ILC

Higgs + SUSY + g-2

"g-2 motivated" MSSM

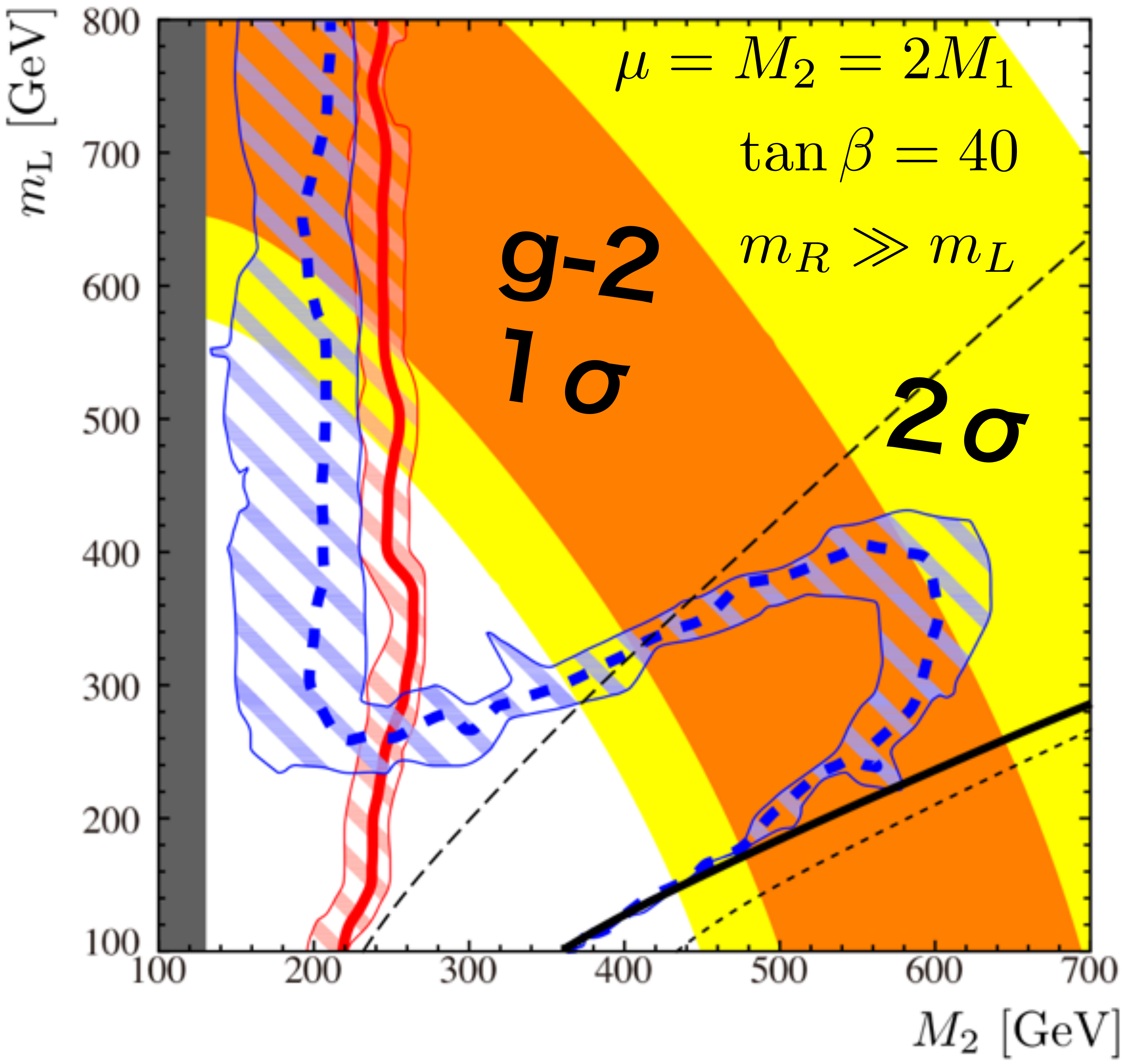
$$m_{\tilde{q}} \gg m_{\tilde{\ell}}, m_{\tilde{\chi}^{\pm}}, m_{\tilde{\chi}^{0}},$$

>> 1 TeV
to explain
Higgs mass

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

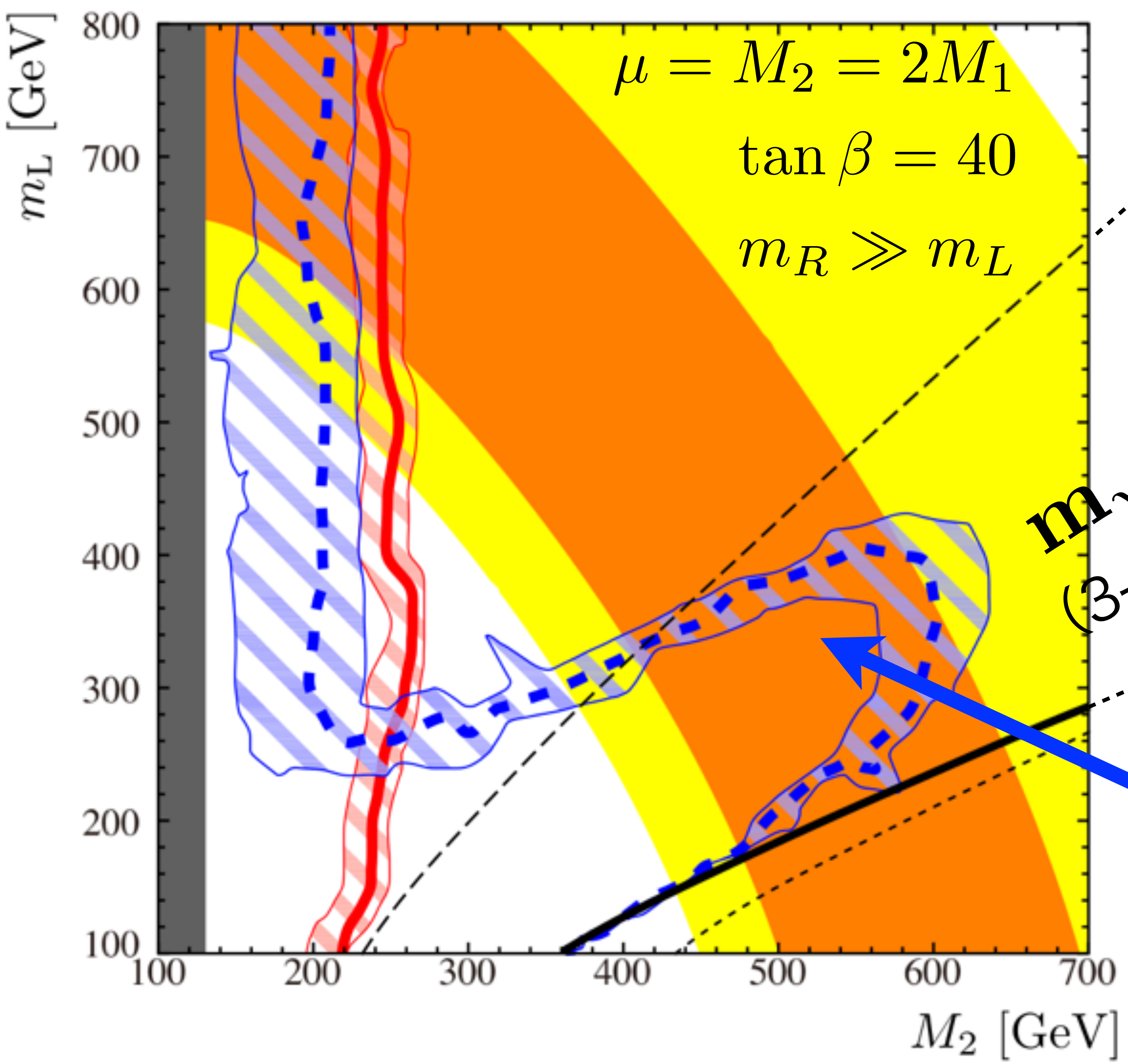
Can we test it ??

muon g-2 vs LHC in SUSY



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

muon g-2 vs LHC in SUSY



8 TeV LHC

$\mathbf{m}_{\chi_2} > \mathbf{m}_{\tilde{\ell}} > \mathbf{m}_{\chi_1}$

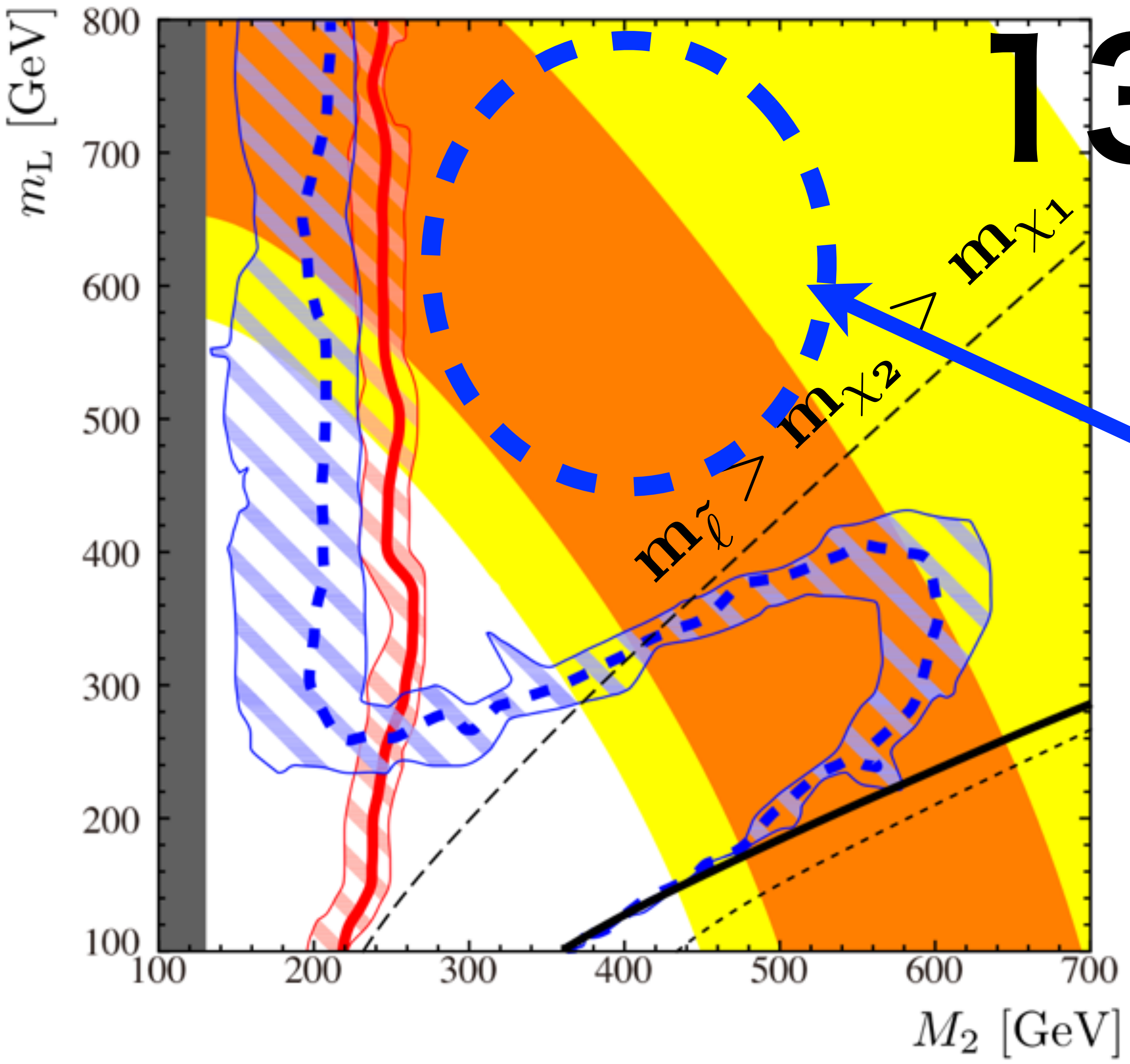
(3-leptons from cascade decay)

already excluded by 3-lepton search.

＊ ATLAS $13\mathrm{fb}^{-1}$@8TeV

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

muon g-2 vs LHC in SUSY



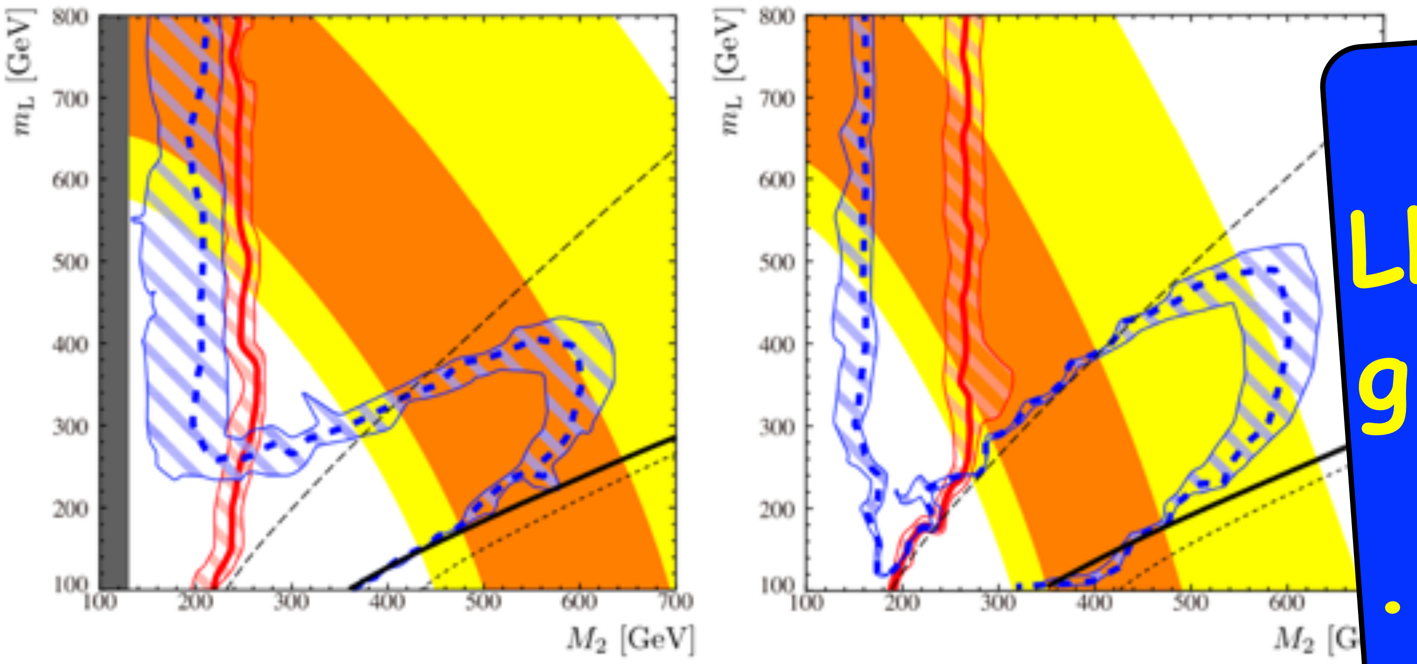
13~14TeV

(2015~)

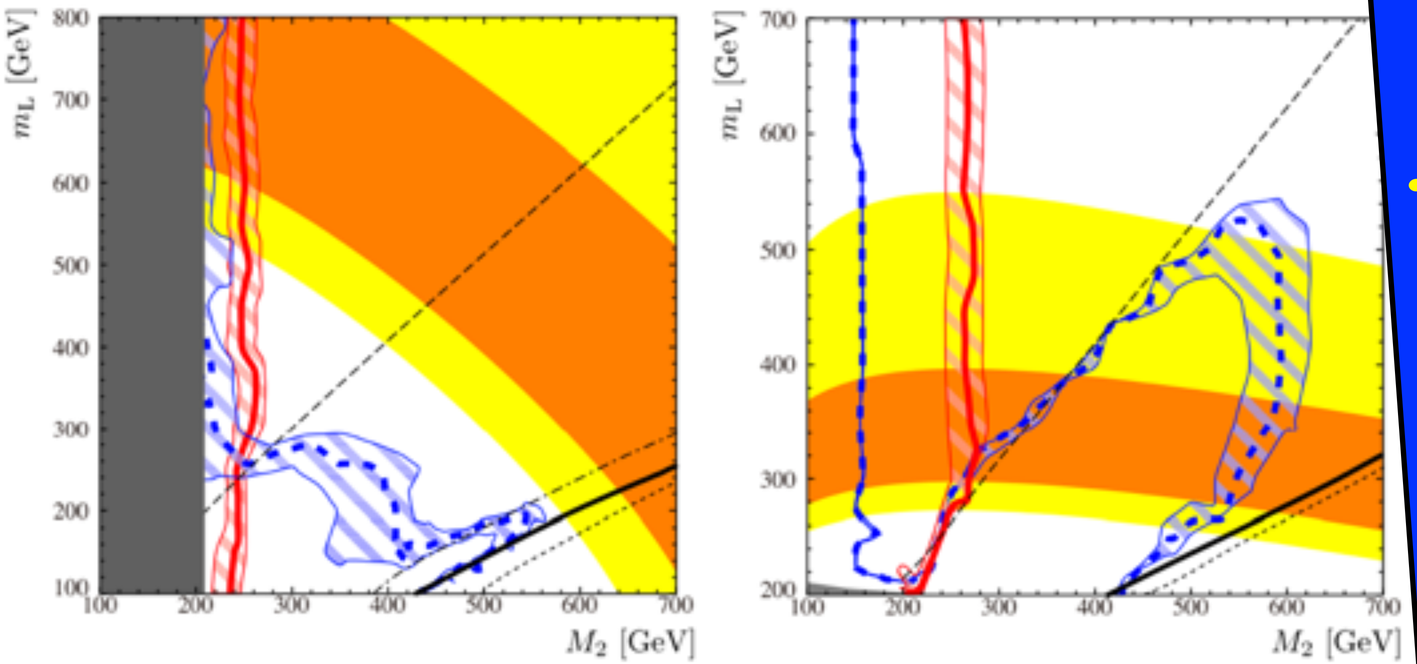
New signals like
$\chi_\mathbf{2} \rightarrow \chi_\mathbf{1} + \mathbf{W/Z/h}$
may cover
this region at 13~14
TeV !

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

muon g-2 vs LHC in SUSY



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

LHC started exclude g-2 motivated regions !

- 13-14 TeV LHC will test more regions.
- If discovered at LHC, --> further test at ILC whether they are really responsible for the g-2.

cf. M.Endo, KH, S.Iwamoto, T.Kitahara, T.Moroi, arXiv:1310.4496

M.Endo, KH, S.Iwamoto, T.Yoshinag
[arXiv:1303.4256]

Summary

- **Higgs mass 126 GeV has a significant impact on SUSY.**
- at least a "little fine-tuning" seems unavoidable.
- It may imply SUSY particles are (much) heavier than TeV scale……

- **muon g-2** $a_\mu^{\rm EXP} - a_\mu^{\rm SM} = (26.1 \pm 8.0) \cdot 10^{-10}$ **> 3σ deviation !** may be a BSM signal.

In SUSY, it can be explained if smuon and chargino/ neutralino are O(100 GeV).

—> tested at 13-14 TeV LHC !

backup

(right-handed neutrino)

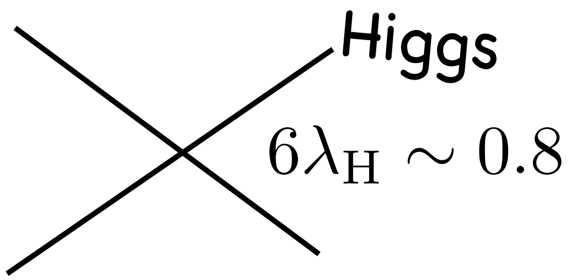
126 GeV Higgs

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

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.

(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

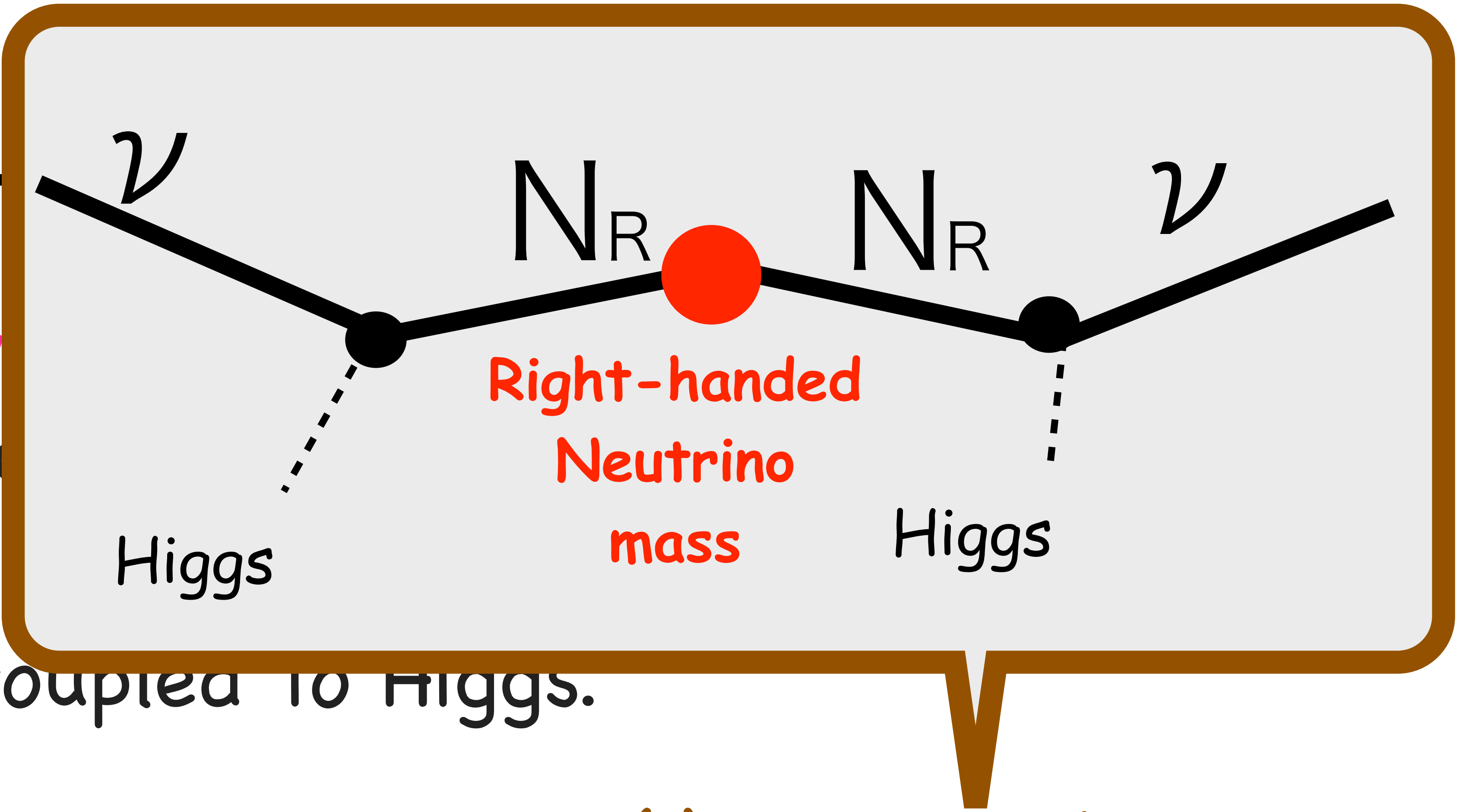
By the way...

perturbative, weakly

is consistent with th

heavy right-hand

which are (weakly) coupled to Higgs.



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

(1) small neutrino masses

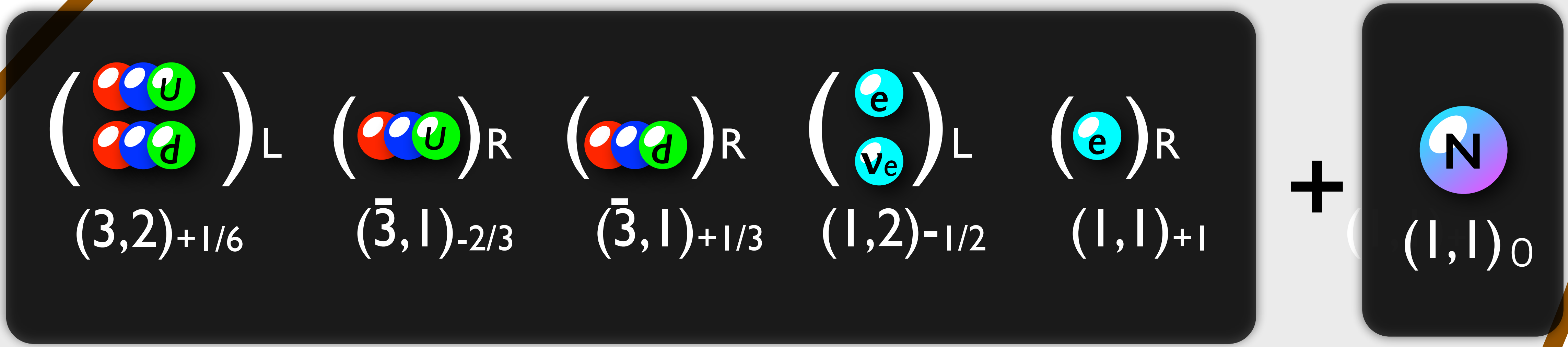
(2) matter unification in 16 of SO(10)

Higgs

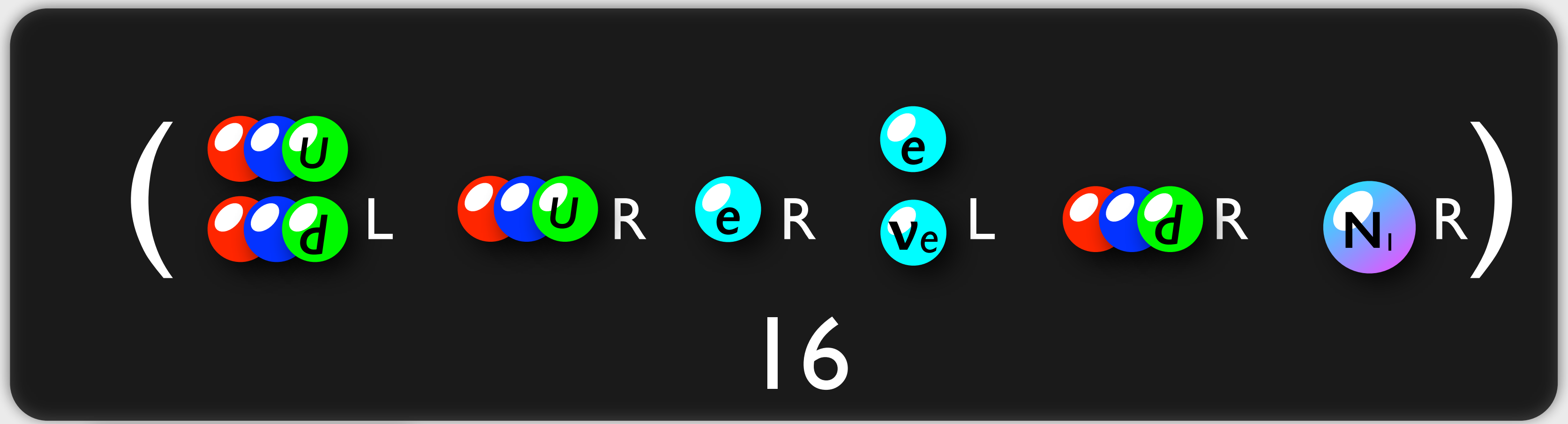
R.H.neutrino

(3) Leptogenesis

... 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)

$h.c.$

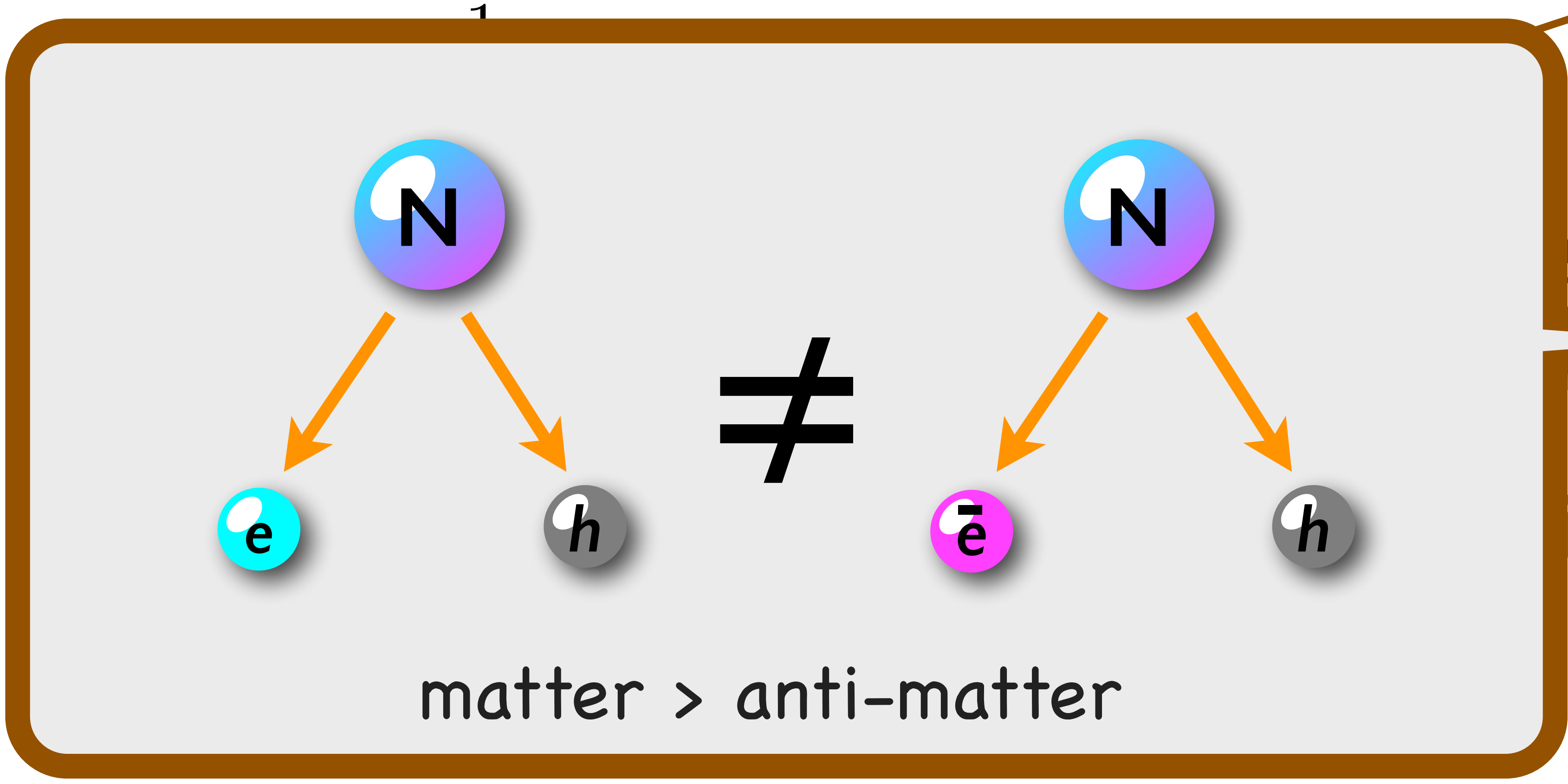
ggs

(3) Leptogenesis

rino

ive Higgs sector

y, > 10^{10} GeV.)



matter > anti-matter

(muon g-2 vs LHC)

muon g-2 vs LHC

model-independent approach

SUSY contributions to g-2

$$\Delta a_\mu(W, \tilde{H}, \tilde{\nu}_\mu) = \frac{\alpha_2}{4\pi}\frac{m_\mu^2}{M_2\mu}\tan\beta \cdot f_C\left(\frac{M_2^2}{m_{\tilde{\nu}}^2}, \frac{\mu^2}{m_{\tilde{\nu}}^2}\right),$$

$$\Delta a_\mu(\tilde{W}, \tilde{H}, \tilde{\mu}_L) = -\frac{\alpha_2}{8\pi}\frac{m_\mu^2}{M_2\mu}\tan\beta \cdot f_N\left(\frac{M_2^2}{m_{\tilde{\mu}_L}^2}, \frac{\mu^2}{m_{\tilde{\mu}_L}^2}\right),$$

$$\Delta a_\mu(\tilde{B}, \tilde{H}, \tilde{\mu}_L) = \frac{\alpha_Y}{8\pi}\frac{m_\mu^2}{M_1\mu}\tan\beta \cdot f_N\left(\frac{M_1^2}{m_{\tilde{\mu}_L}}, \frac{\mu^2}{m_{\tilde{\mu}_L}}\right),$$

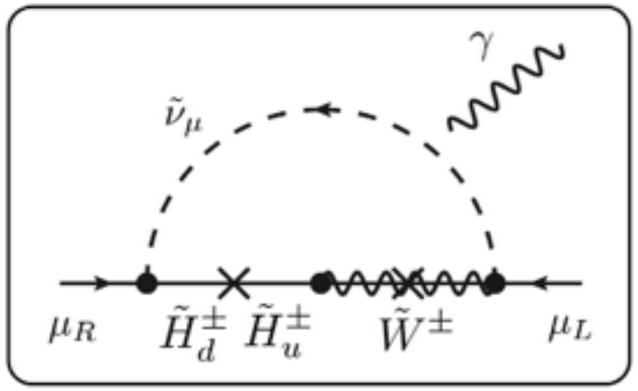
$$\Delta a_\mu(\tilde{B}, \tilde{H}, \tilde{\mu}_R) = -\frac{\alpha_Y}{4\pi}\frac{m_\mu^2}{M_1\mu}\tan\beta \cdot f_N\left(\frac{M_1^2}{m_{\tilde{\mu}_R}^2}, \frac{\mu^2}{m_{\tilde{\mu}_R}^2}\right),$$

$$\Delta a_\mu(\tilde{\mu}_L, \tilde{\mu}_R, \tilde{B}) = \frac{\alpha_Y}{4\pi}\frac{m_\mu^2 M_1\mu}{m_{\tilde{\mu}_L}^2 m_{\tilde{\mu}_R}^2}\tan\beta \cdot f_N\left(\frac{m_{\tilde{\mu}_L}^2}{M_1^2}, \frac{m_{\tilde{\mu}_R}^2}{M_1^2}\right),$$

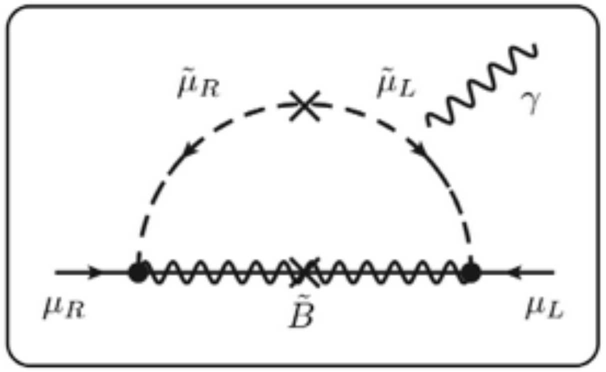
$$f_C(x,y) = xy\left[\frac{5-3(x+y)+xy}{(x-1)^2(y-1)^2} - \frac{2\log x}{(x-y)(x-1)^3} + \frac{2\log y}{(x-y)(y-1)^3}\right],$$

$$f_N(x,y) = xy\left[\frac{-3+x+y+xy}{(x-1)^2(y-1)^2} + \frac{2x\log x}{(x-y)(x-1)^3} - \frac{2y\log y}{(x-y)(y-1)^3}\right].$$

chargino



neutralino



6 parameters

$$M_1, M_2, \mu, m_{\tilde{\mu}_L}, m_{\tilde{\mu}_R}, \tan\beta,$$

difficult to do full-scan
take typical parameter sets

$\tan\beta = 40,$

(A) $M_1 : M_2 : M_3 = 1:2:6,$ or (B) $2M_1 = M_2 \ll M_3,$

$(\mu, m_{\rm R}) = \{(M_2, 3\,{\rm TeV}), (2M_2, 3\,{\rm TeV}), (0.5M_2, 3\,{\rm TeV}), (2\,{\rm TeV}, 1.5m_{\rm L})\}.$

muon g-2 vs LHC

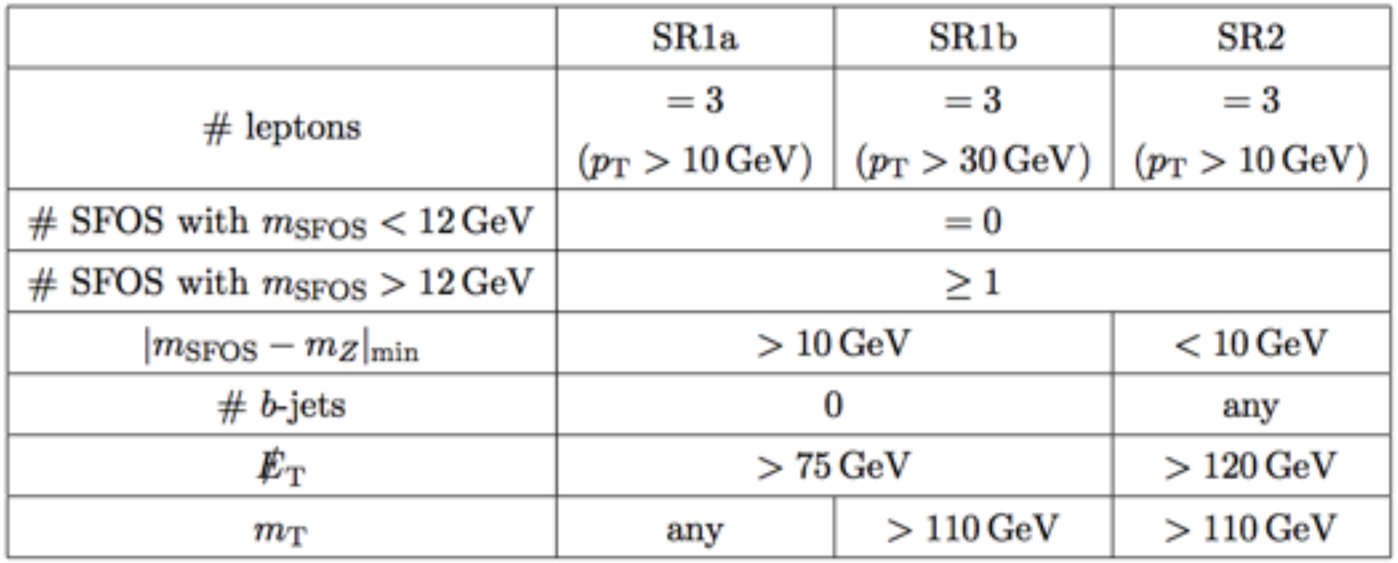
signals from LHC

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

(e.g., $pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$)

3 lepton + missing

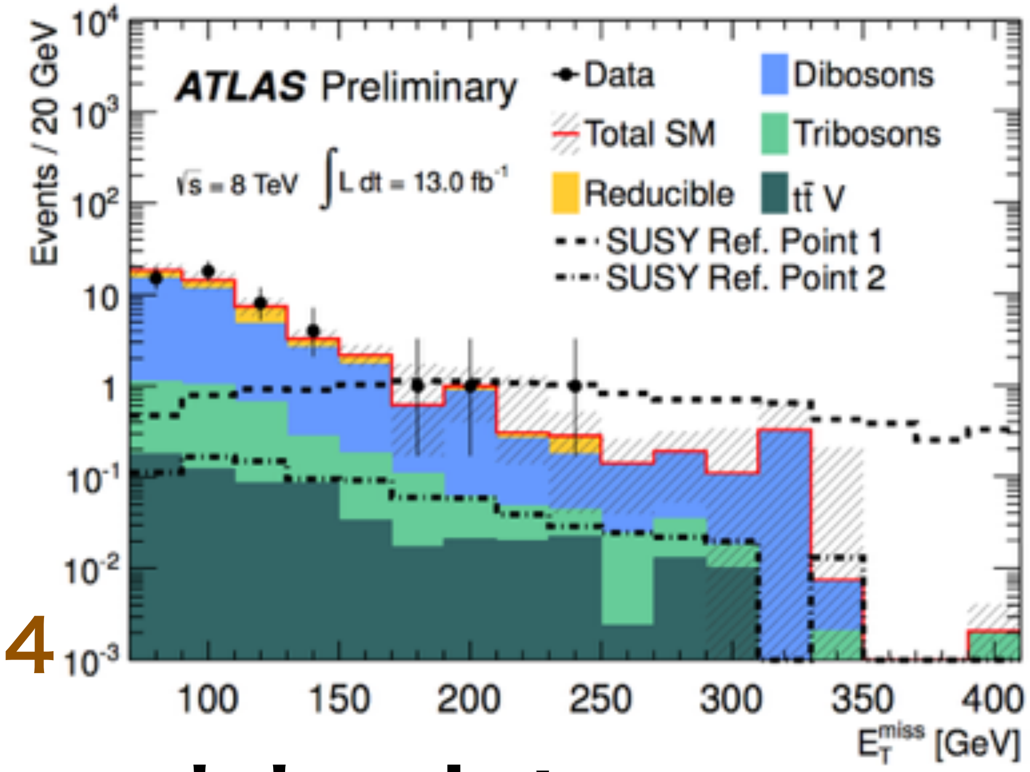
cuts used at ATLAS



	SR1a	SR1b	SR2
# leptons	$= 3$ ($p_T > 10\,\mathrm{GeV}$)	$= 3$ ($p_T > 30\,\mathrm{GeV}$)	$= 3$ ($p_T > 10\,\mathrm{GeV}$)
# SFOS with $m_{\mathrm{SFOS}} < 12\,\mathrm{GeV}$	$= 0$		
# SFOS with $m_{\mathrm{SFOS}} > 12\,\mathrm{GeV}$	≥ 1		
$\lvert m_{\mathrm{SFOS}} - m_Z \rvert_{\mathrm{min}}$	$> 10\,\mathrm{GeV}$		$< 10\,\mathrm{GeV}$
# b-jets	0		any
$\not{E}_T$	$> 75\,\mathrm{GeV}$		$> 120\,\mathrm{GeV}$
m_T	any	$> 110\,\mathrm{GeV}$	$> 110\,\mathrm{GeV}$

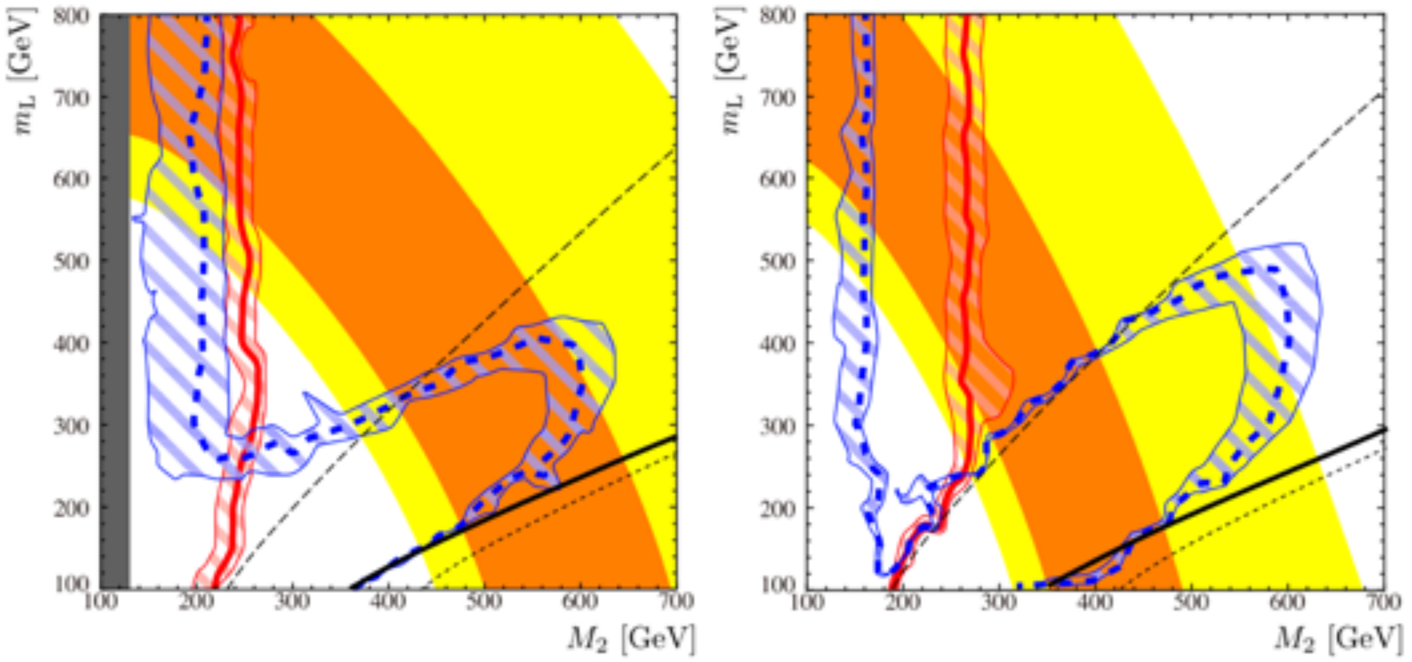
from ATLAS-CONF-2012-154

events at ATLAS



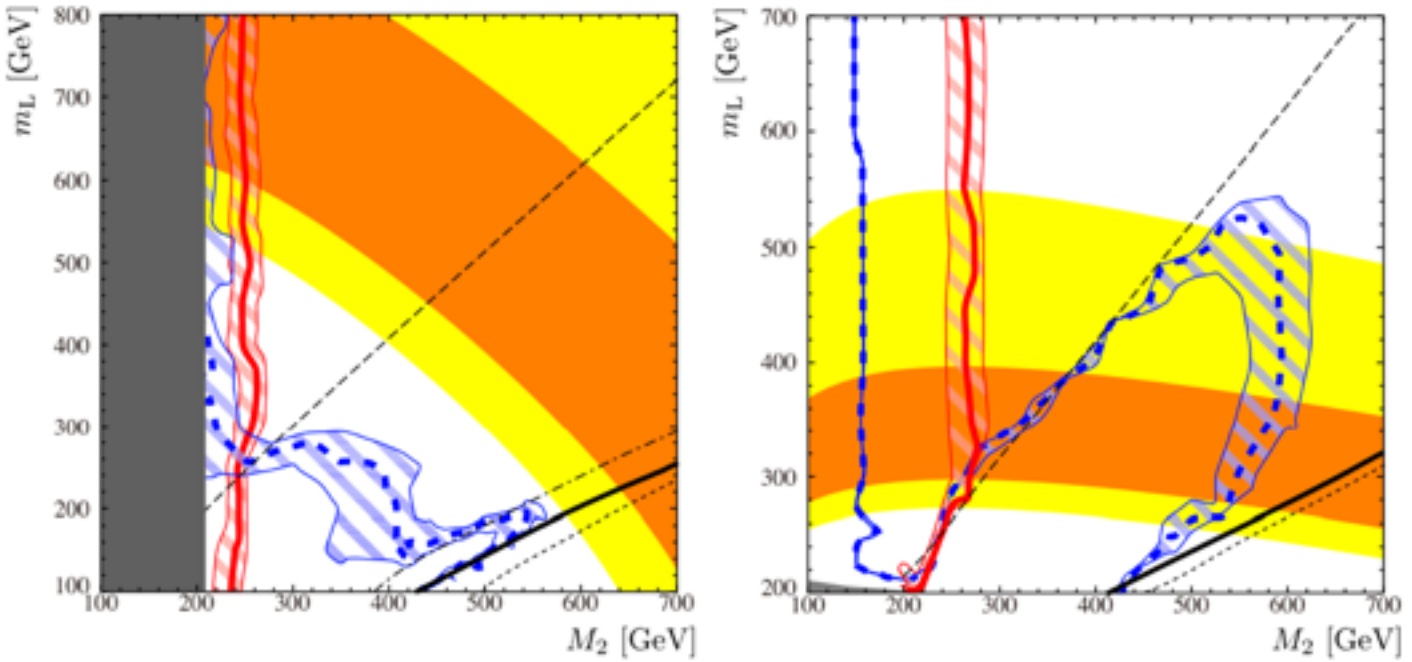
We did a fast simulation at our model points and compared it with experimental results.

muon g-2 vs LHC in SUSY



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

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

(muon g-2: a model)

Higgs + SUSY + g-2

heavy stop

light smuon/ inos

difficult to reconcile in typical models

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

2 approaches

(1) model building

[our works]

extra matter

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

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

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

(2) general MSSM

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

M.Endo, KH, T.Kitahara, T.Yoshinaga, arXiv:1309.3065 LHC/ILC+flavor+vacuum

M.Endo, KH, S.Iwamoto, T.Kitahara, T.Moroi, arXiv:1310.4496 ILC

Higgs + SUSY + g-2

heavy stop

light smuon/ inos

difficult to reconcile in typical models

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

2 approaches

(1) model building

[our works]

extra matter

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

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

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

(2) general MSSM

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

M.Endo, KH, T.Kitahara, T.Yoshinaga, arXiv:1309.3065 LHC/ILC+flavor+vacuum

M.Endo, KH, S.Iwamoto, T.Kitahara, T.Moroi, arXiv:1310.4496 ILC

126 GeV Higgs + muon g-2

MSSM + vector-like matter

Idea:

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

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

$$\begin{aligned}\delta m^2_{\rm Higgs} &\propto \lambda_{\rm H}\ (\simeq 0.13)\\ &= \lambda_{\rm H}^{(\rm tree)} + \delta\lambda_{\rm H}^{(\rm loop)} \longleftarrow \delta\lambda_{\rm H}^{(\rm loop)} \propto Y_{\rm top}^4 \cdot (\text{top, stop-loop})\end{aligned}$$

126 GeV Higgs + muon g-2

MSSM + vector-like matter

Idea:

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

--> Add **new vector-like matters (10+10bar)**
with a Yukawa coupling to Higgs.

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

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

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

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

126 GeV Higgs + muon g-2

Results

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

for "V-GMSB"

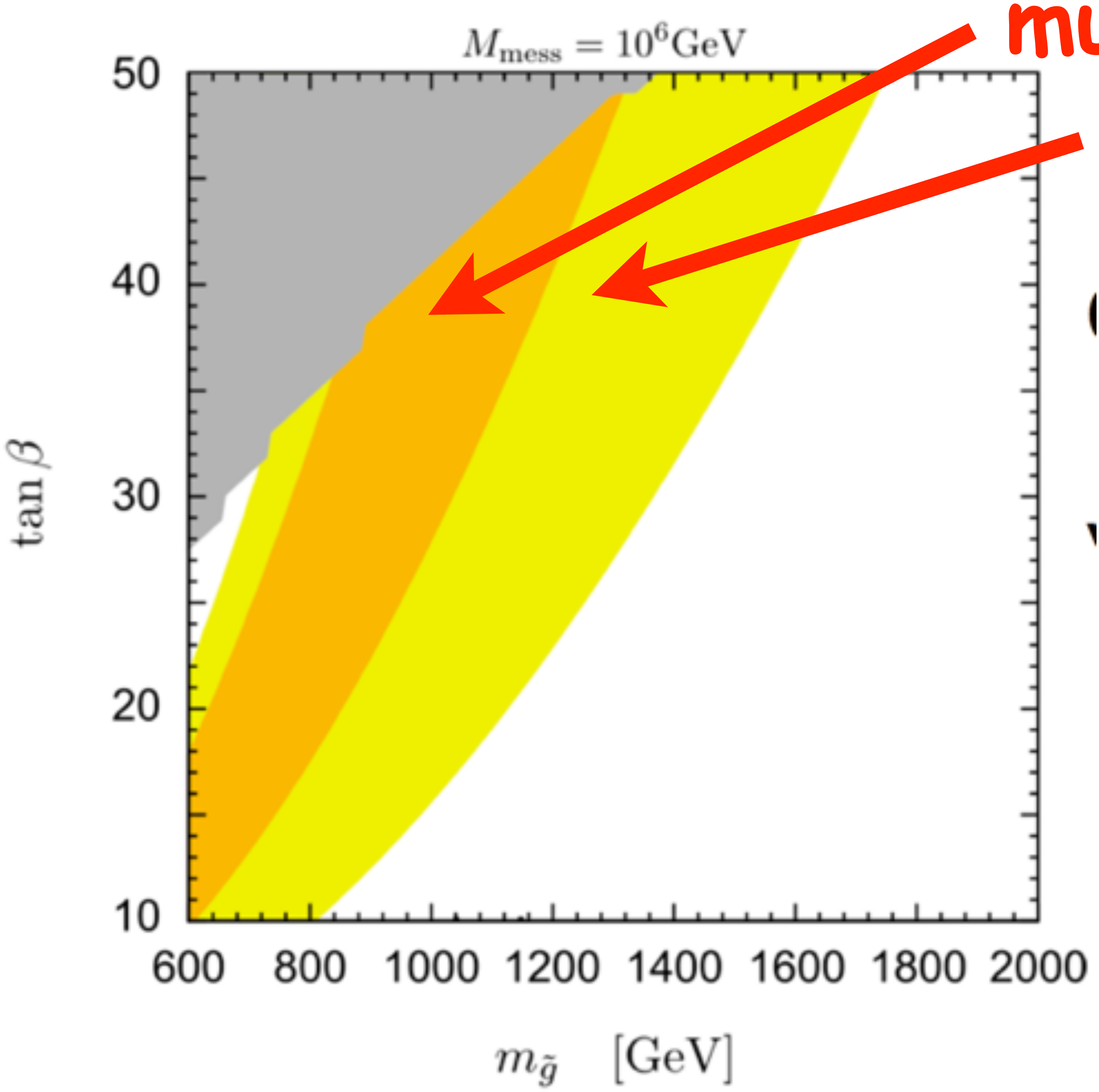
= gauge mediation (GMSB) + vector-like matter

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)

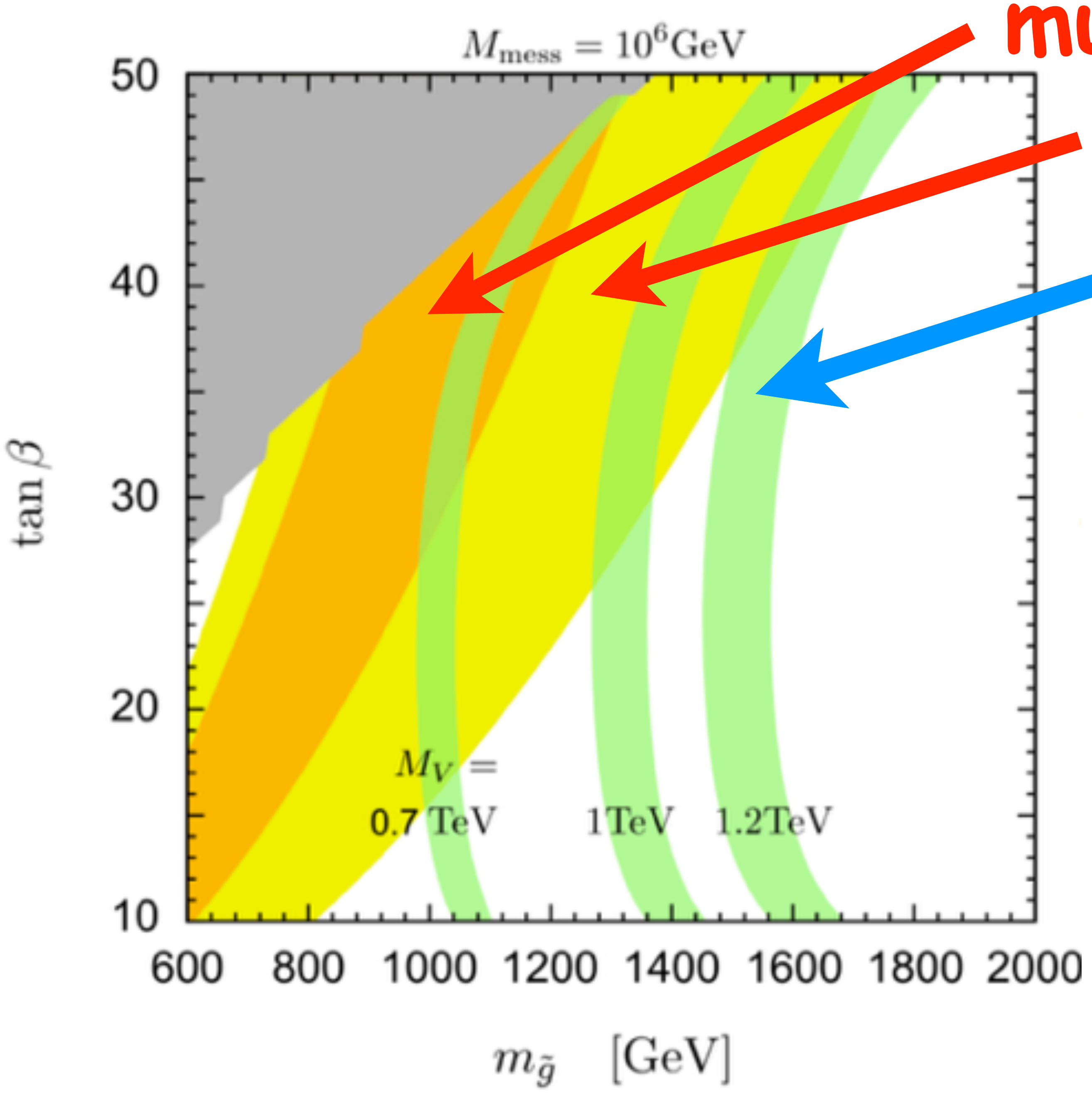
(2σ)

126 GeV Higgs + muon g-2

Results

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

for "V-GMSB"



muon g-2 explained (1σ)

(2σ)

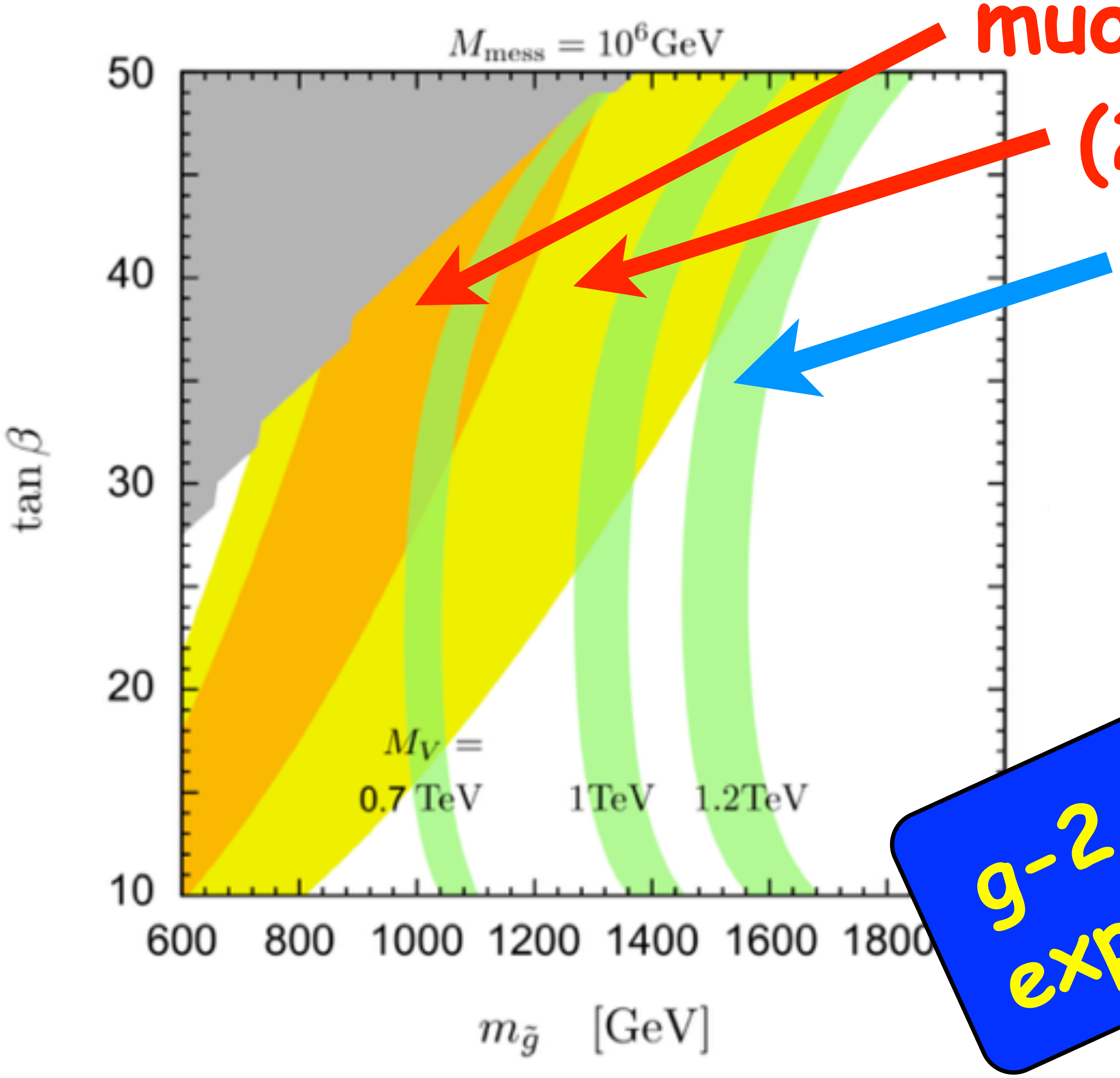
Higgs mass
125-126 GeV

126 GeV Higgs + muon g-2

Results

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

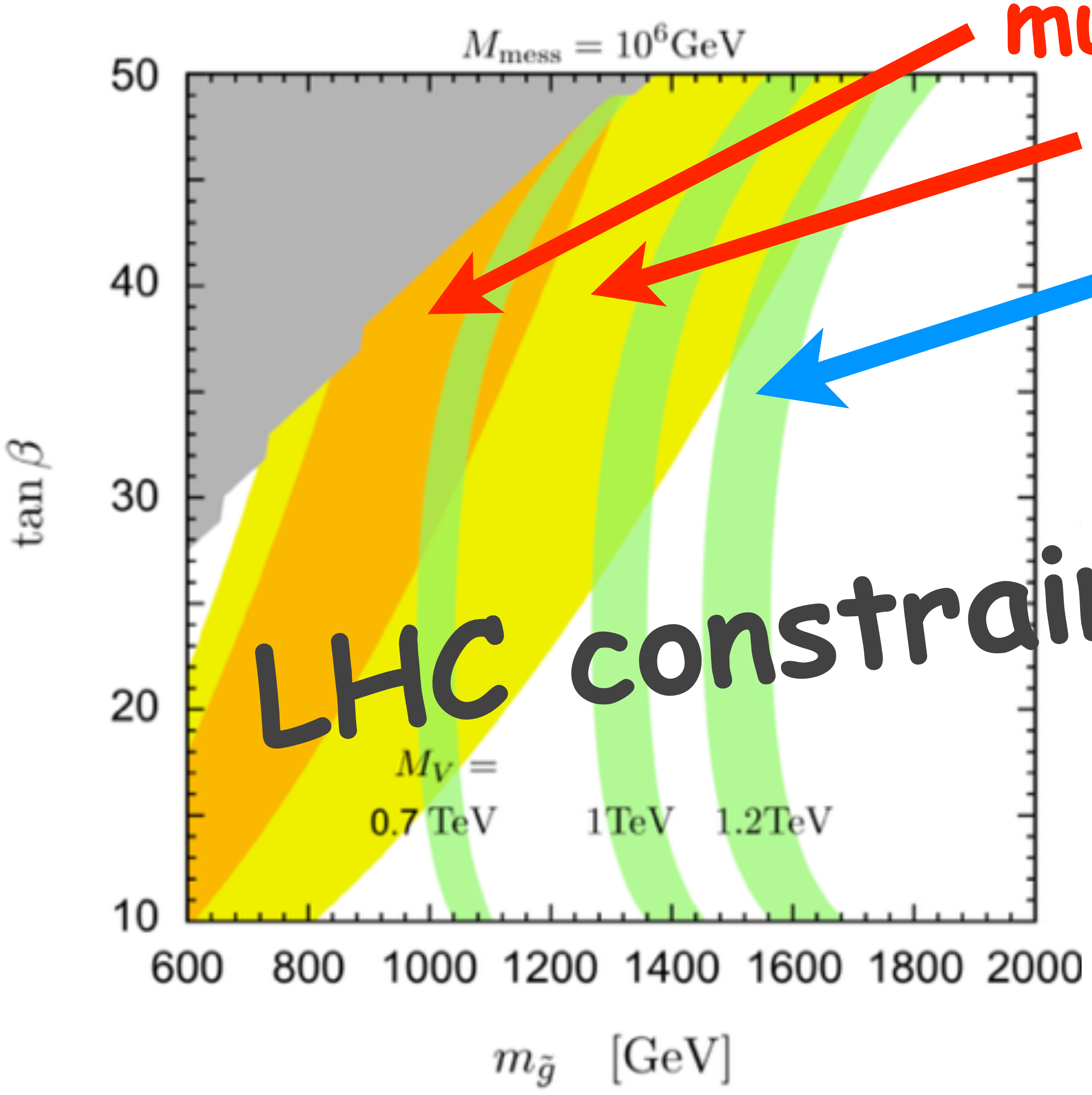
g-2 and Higgs mass are explained simultaneously!

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

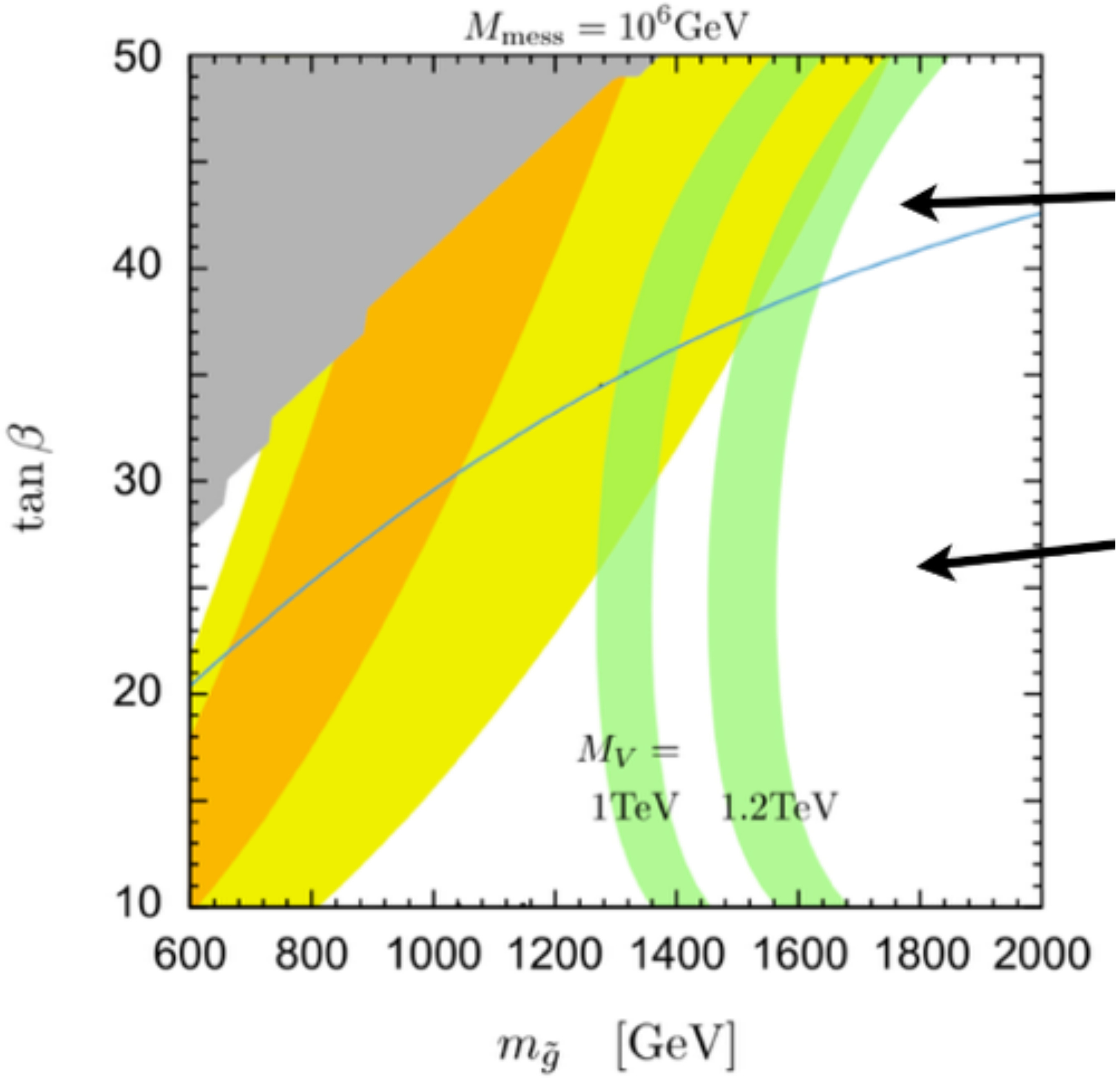
LHC constraints ?

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

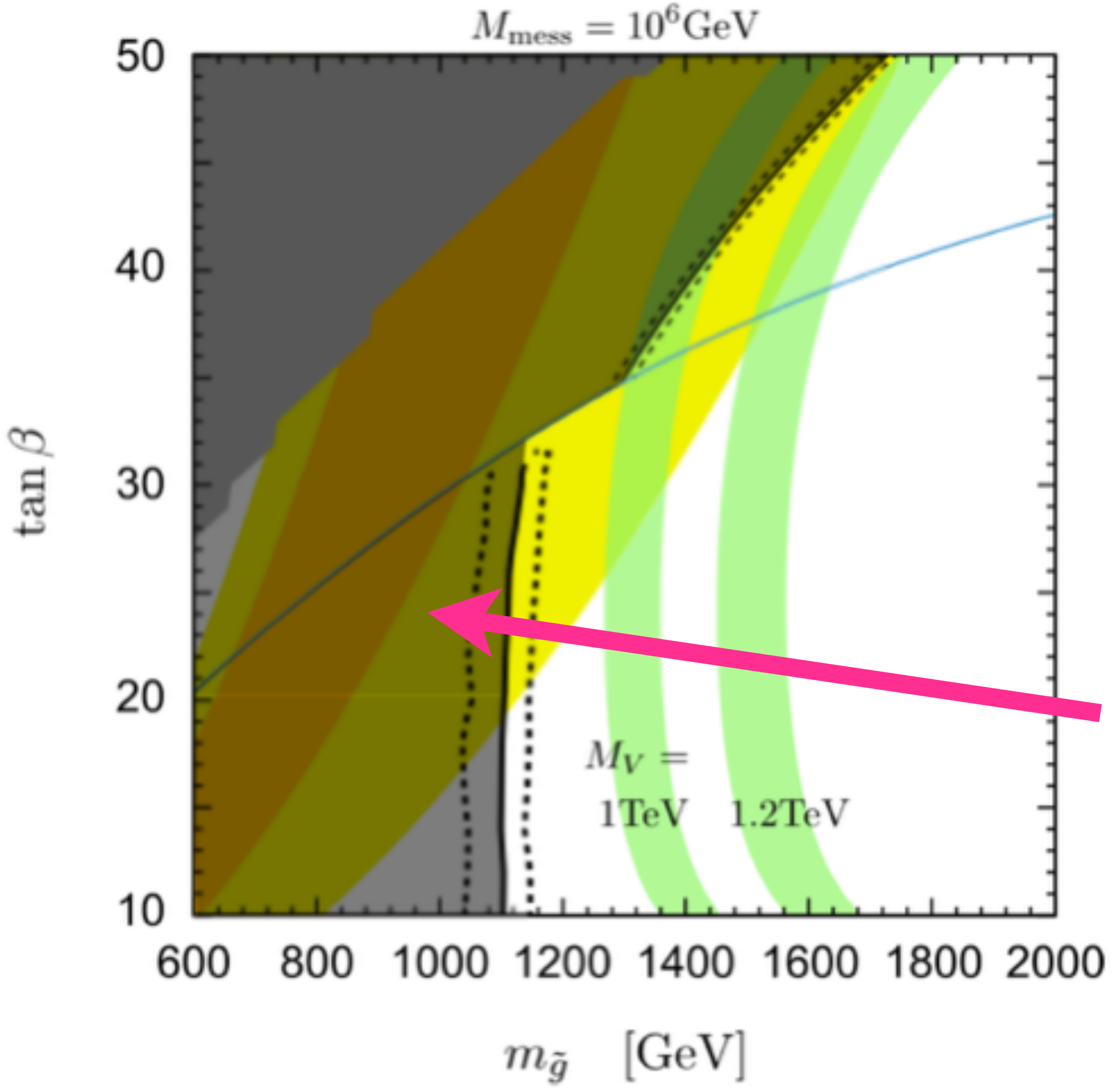
= jets + missing energy

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

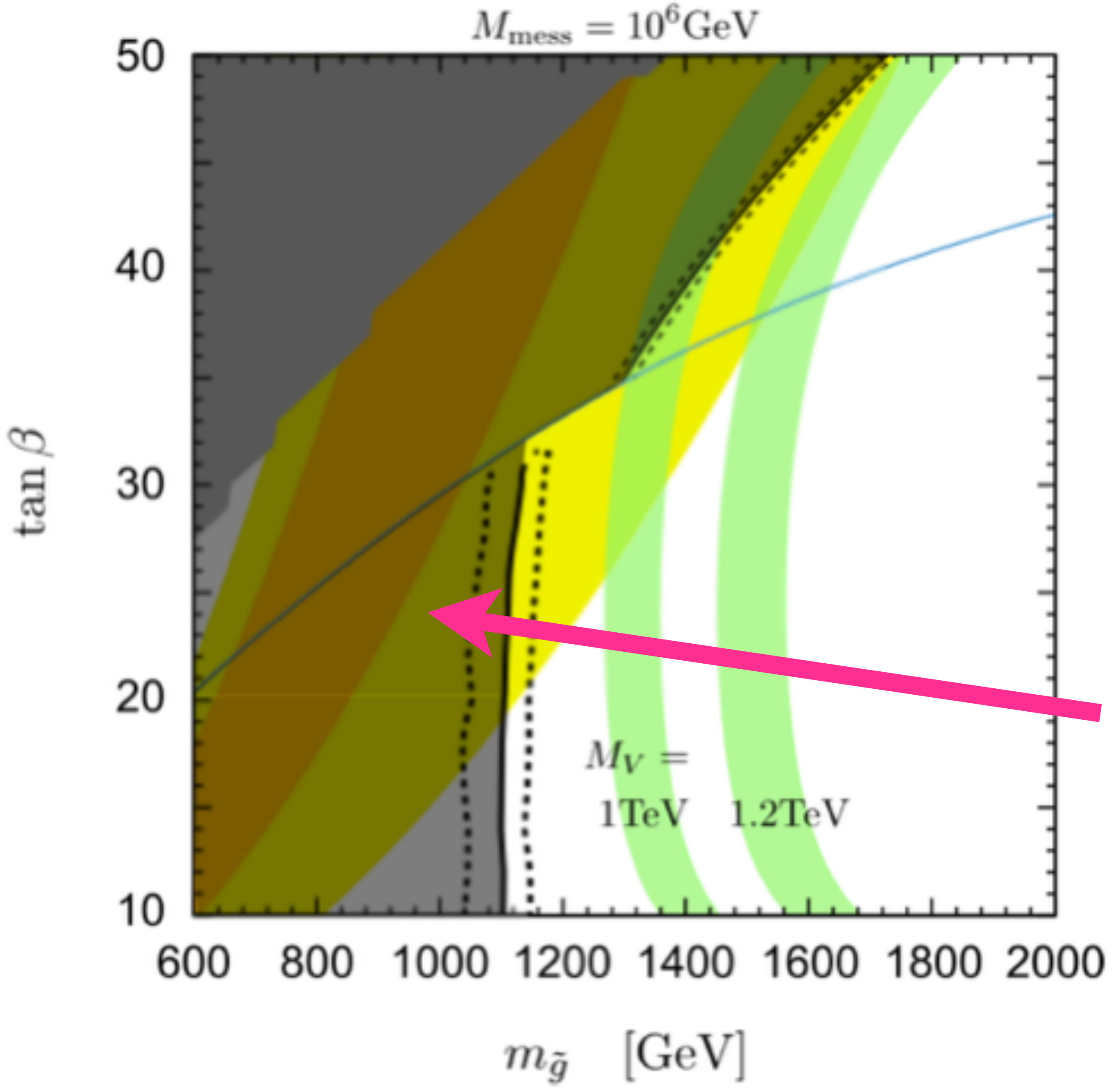
126 GeV Higgs + muon g-2

Results

for "V-GMSB"

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

New LHC results were reported after our analysis.



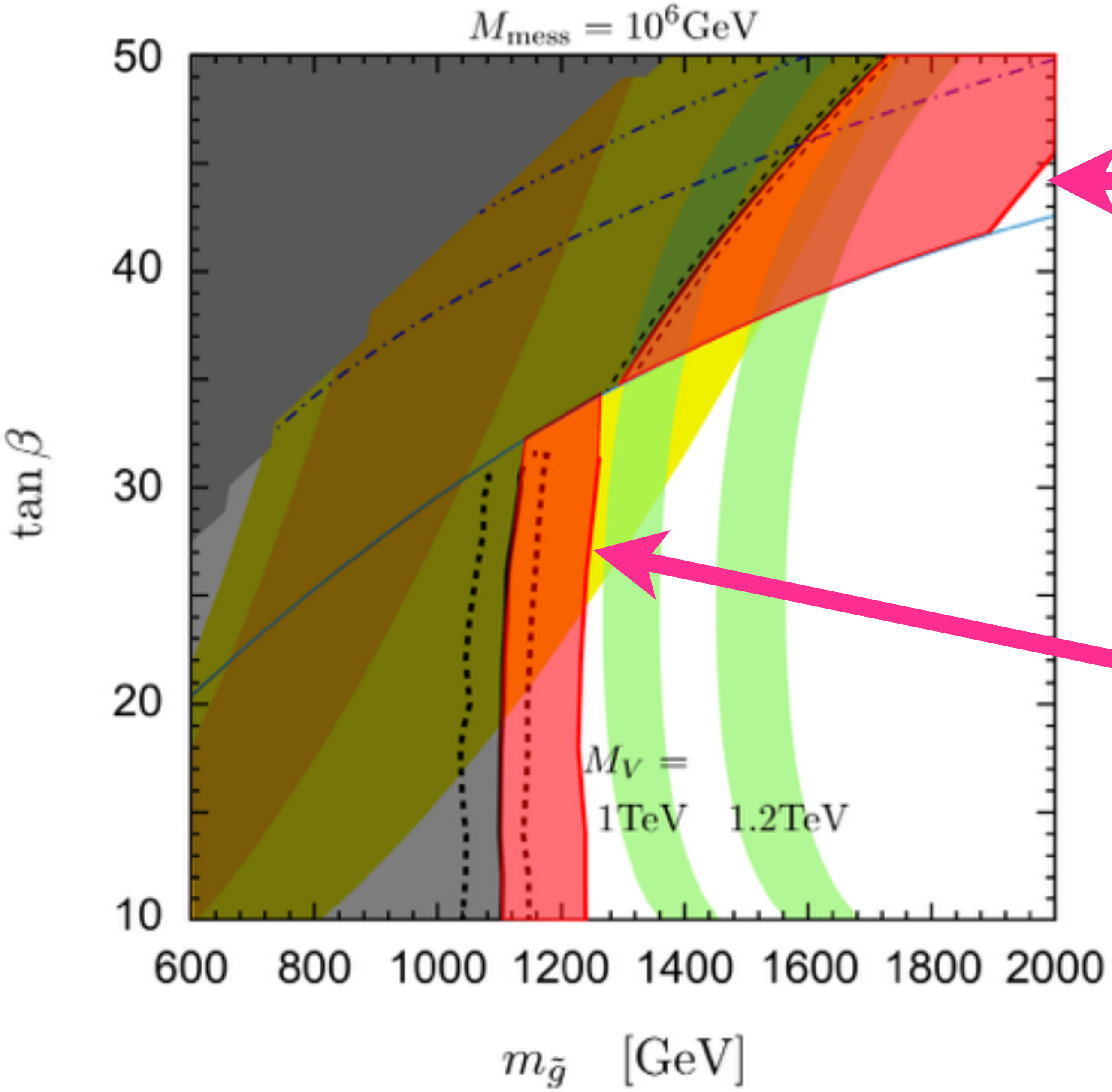
already excluded

[* 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"



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]

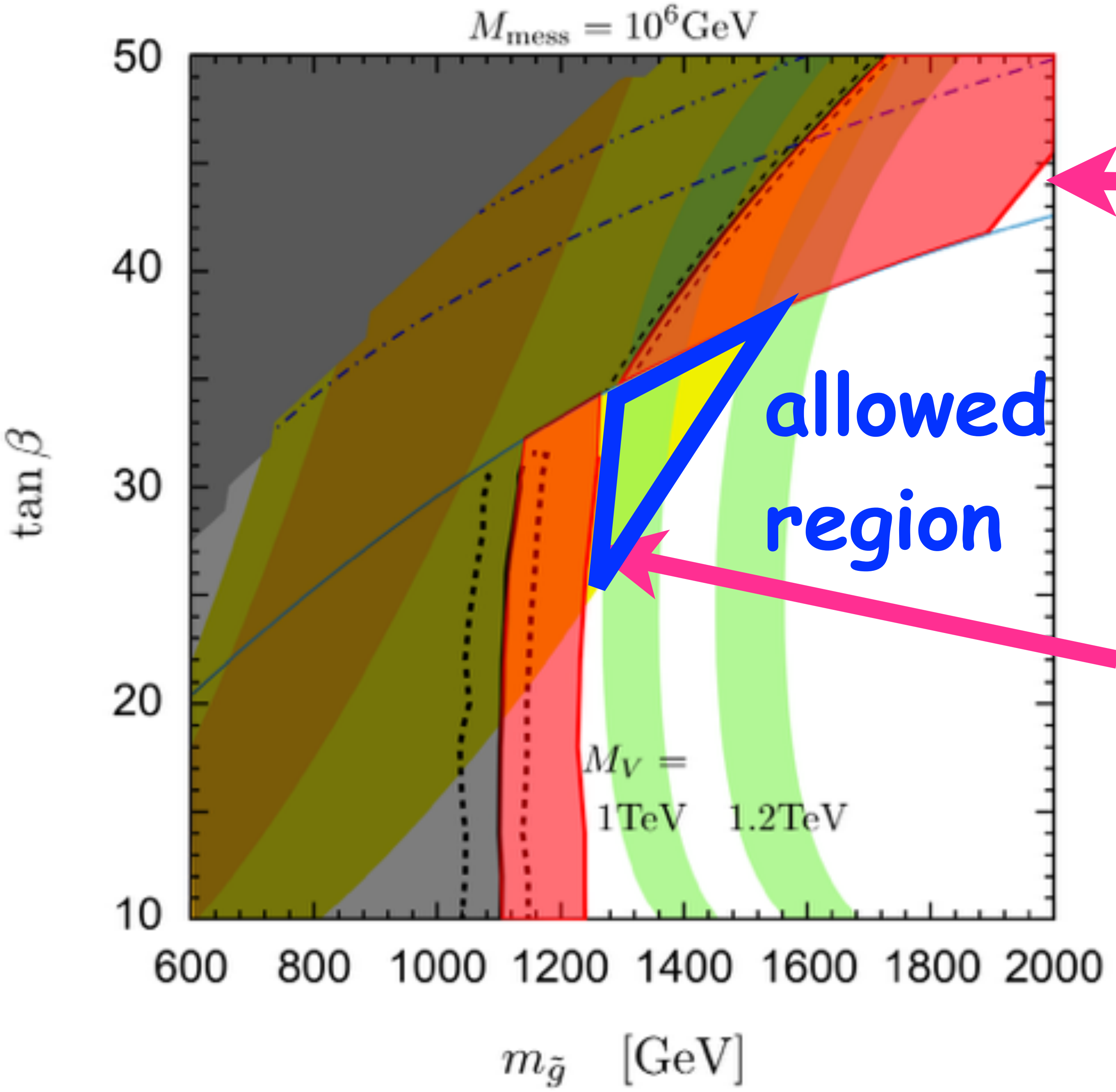
New analysis: thanks to **Kazuya Ishikawa**.

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**.

(muon g-2: ILC test)

muon g-2 vs ILC

Can we reconstruct the SUSY contributions to the muon g-2 by using ILC data ?

Assume one specific (optimistic) model point

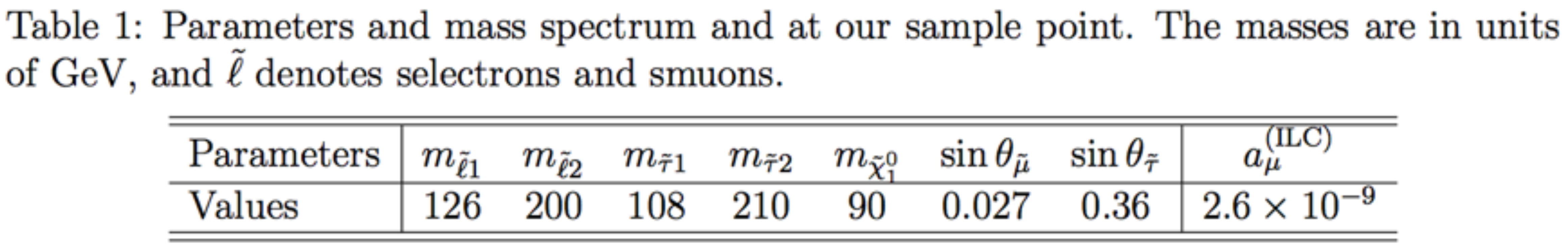
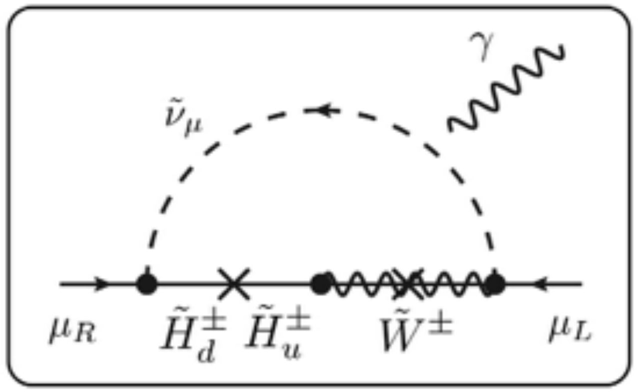


Table 1: Parameters and mass spectrum and at our sample point. The masses are in units of GeV, and $\tilde{\ell}$ denotes selectrons and smuons.

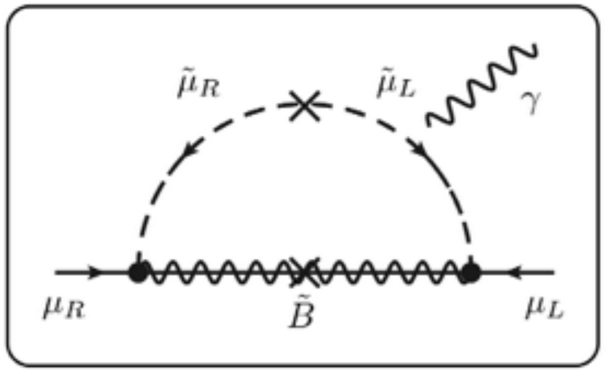
Parameters	$m_{\tilde{\ell}1}$	$m_{\tilde{\ell}2}$	$m_{\tilde{\tau}1}$	$m_{\tilde{\tau}2}$	$m_{\tilde{\chi}_1^0}$	$\sin\theta_{\tilde{\mu}}$	$\sin\theta_{\tilde{\tau}}$	$a_\mu^{(\mathrm{ILC})}$
Values	126	200	108	210	90	0.027	0.36	2.6×10^{-9}

chargino



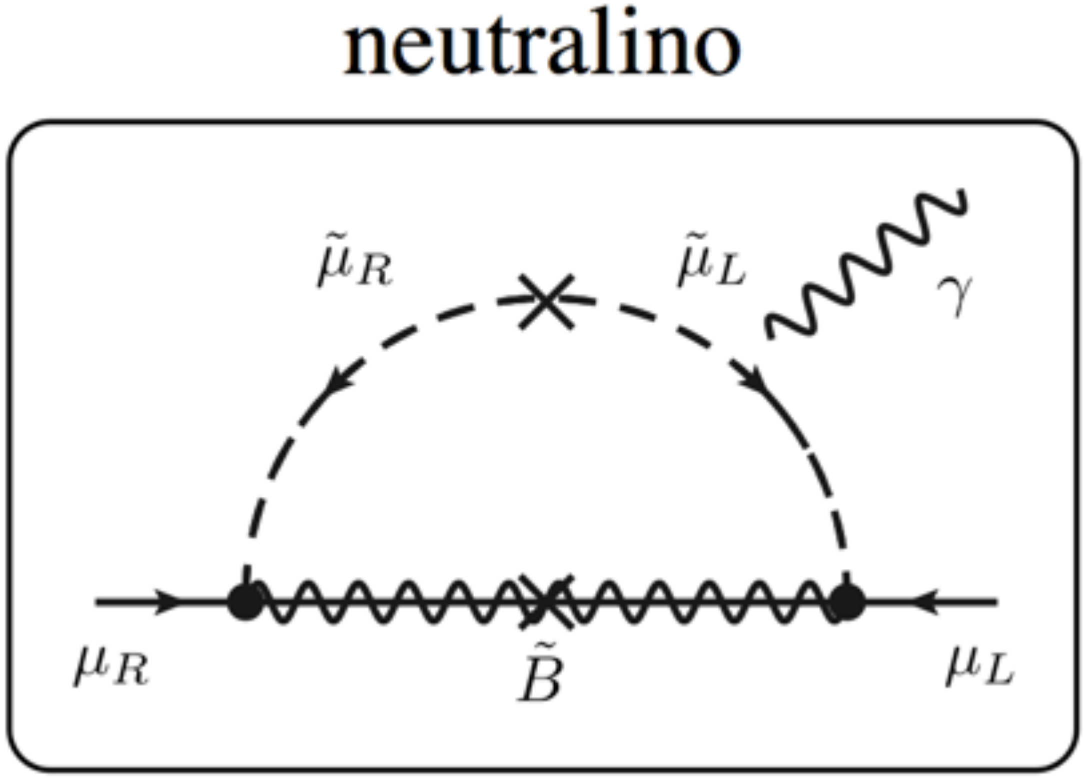
<<

neutralino



this one dominates

muon g-2 vs ILC



Can we reconstruct the contribution of this loop-diagram by using ILC measurements?

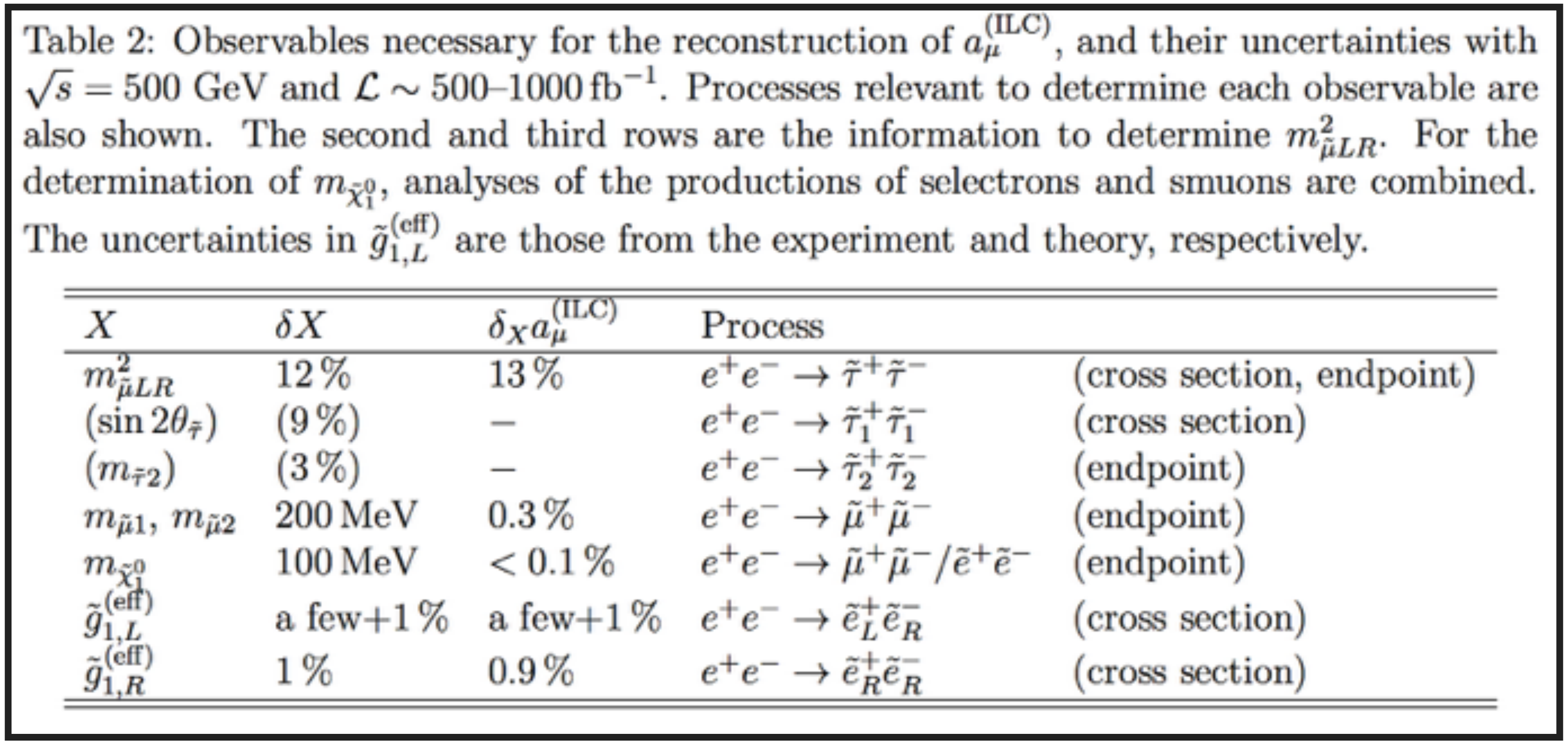
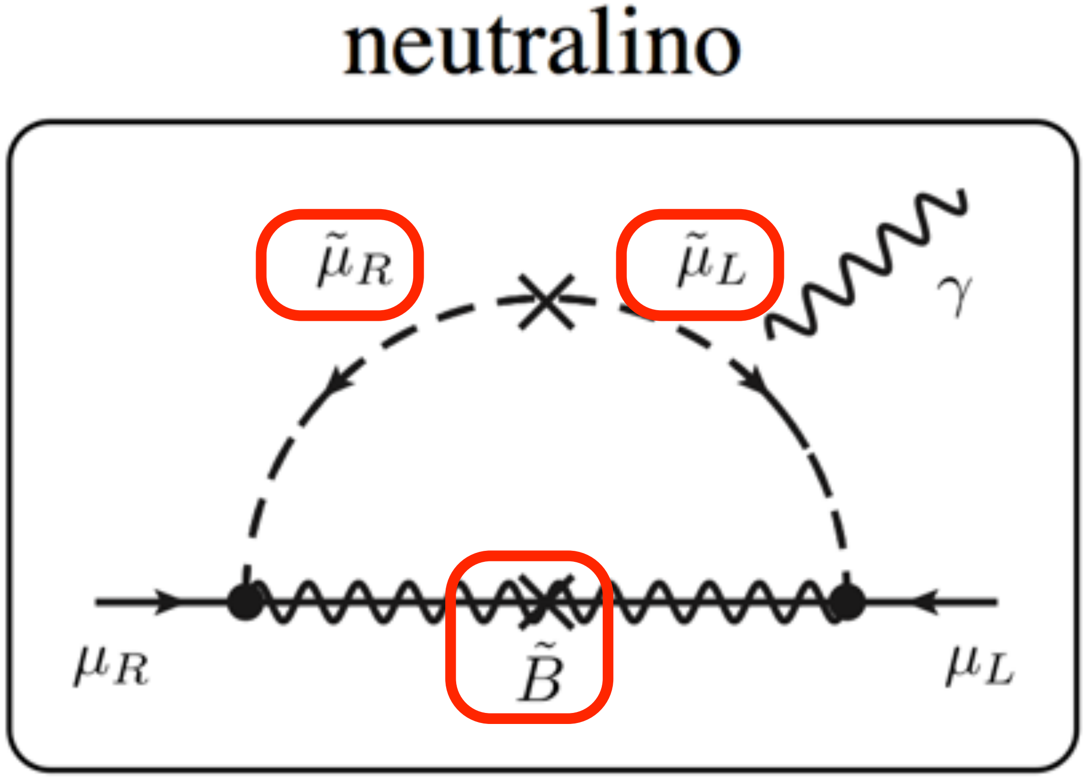


Table 2: Observables necessary for the reconstruction of $a_\mu^{(\mathrm{ILC})}$, and their uncertainties with $\sqrt{s} = 500$ GeV and $\mathcal{L} \sim 500$–$1000\,\mathrm{fb}^{-1}$. Processes relevant to determine each observable are also shown. The second and third rows are the information to determine $m^2_{\tilde{\mu}LR}$. For the determination of $m_{\tilde{\chi}^0_1}$, analyses of the productions of selectrons and smuons are combined. The uncertainties in $\tilde{g}^{(\mathrm{eff})}_{1,L}$ are those from the experiment and theory, respectively.

X	δX	$\delta_X a_\mu^{(\mathrm{ILC})}$	Process	
$m^2_{\tilde{\mu}LR}$	12 %	13 %	$e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$	(cross section, endpoint)
$(\sin 2\theta_{\tilde{\tau}})$	(9 %)	–	$e^+e^- \to \tilde{\tau}^+_1\tilde{\tau}^-_1$	(cross section)
$(m_{\tilde{\tau}2})$	(3 %)	–	$e^+e^- \to \tilde{\tau}^+_2\tilde{\tau}^-_2$	(endpoint)
$m_{\tilde{\mu}1}$, $m_{\tilde{\mu}2}$	200 MeV	0.3 %	$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$	(endpoint)
$m_{\tilde{\chi}^0_1}$	100 MeV	$< 0.1\,\%$	$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-/\tilde{e}^+\tilde{e}^-$	(endpoint)
$\tilde{g}^{(\mathrm{eff})}_{1,L}$	a few+1 %	a few+1 %	$e^+e^- \to \tilde{e}^+_L\tilde{e}^-_R$	(cross section)
$\tilde{g}^{(\mathrm{eff})}_{1,R}$	1 %	0.9 %	$e^+e^- \to \tilde{e}^+_R\tilde{e}^-_R$	(cross section)

M.Endo, KH, S.Iwamoto, T.Kitahara, T.Moroi arXiv:1310.4496

muon g-2 vs ILC



Can we reconstruct the contribution of this loop-diagram by using ILC measurements?

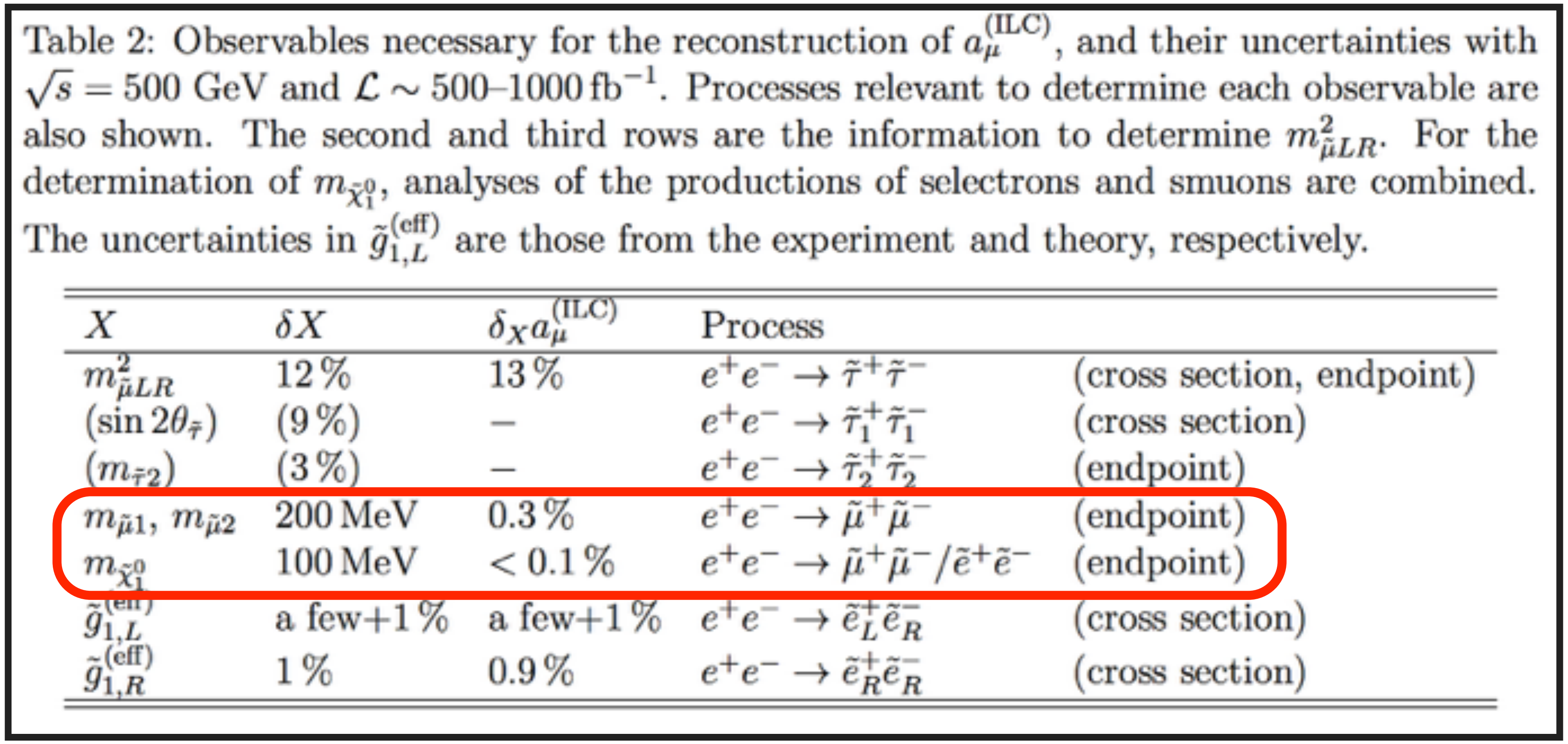


Table 2: Observables necessary for the reconstruction of $a_\mu^{(\mathrm{ILC})}$, and their uncertainties with $\sqrt{s} = 500$ GeV and $\mathcal{L} \sim 500$–$1000\,\mathrm{fb}^{-1}$. Processes relevant to determine each observable are also shown. The second and third rows are the information to determine $m^2_{\tilde{\mu}LR}$. For the determination of $m_{\tilde{\chi}^0_1}$, analyses of the productions of selectrons and smuons are combined. The uncertainties in $\tilde{g}^{(\mathrm{eff})}_{1,L}$ are those from the experiment and theory, respectively.

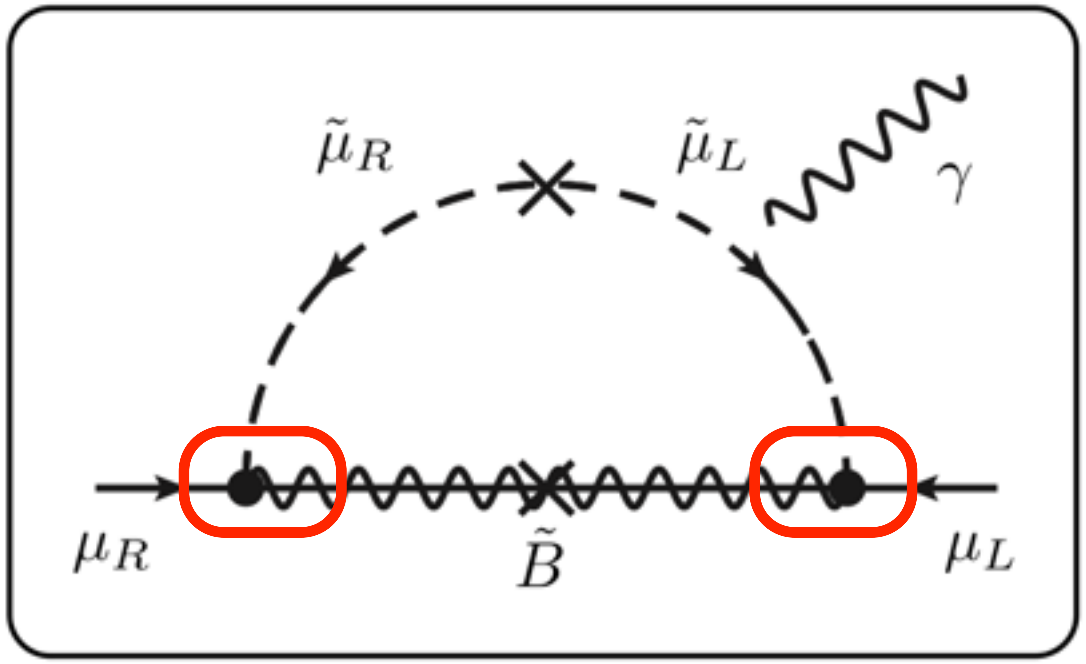
X	δX	$\delta_X a_\mu^{(\mathrm{ILC})}$	Process	
$m^2_{\tilde{\mu}LR}$	12 %	13 %	$e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$	(cross section, endpoint)
$(\sin 2\theta_{\tilde{\tau}})$	(9 %)	–	$e^+e^- \to \tilde{\tau}_1^+\tilde{\tau}_1^-$	(cross section)
$(m_{\tilde{\tau}2})$	(3 %)	–	$e^+e^- \to \tilde{\tau}_2^+\tilde{\tau}_2^-$	(endpoint)
$m_{\tilde{\mu}1}$, $m_{\tilde{\mu}2}$	200 MeV	0.3 %	$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$	(endpoint)
$m_{\tilde{\chi}^0_1}$	100 MeV	< 0.1 %	$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-/\tilde{e}^+\tilde{e}^-$	(endpoint)
$\tilde{g}^{(\mathrm{eff})}_{1,L}$	a few+1 %	a few+1 %	$e^+e^- \to \tilde{e}^+_L\tilde{e}^-_R$	(cross section)
$\tilde{g}^{(\mathrm{eff})}_{1,R}$	1 %	0.9 %	$e^+e^- \to \tilde{e}^+_R\tilde{e}^-_R$	(cross section)

particle masses

M.Endo, KH, S.Iwamoto, T.Kitahara, T.Moroi arXiv:1310.4496

muon g-2 vs ILC

neutralino



Can we reconstruct the contribution of this loop-diagram by using ILC measurements?

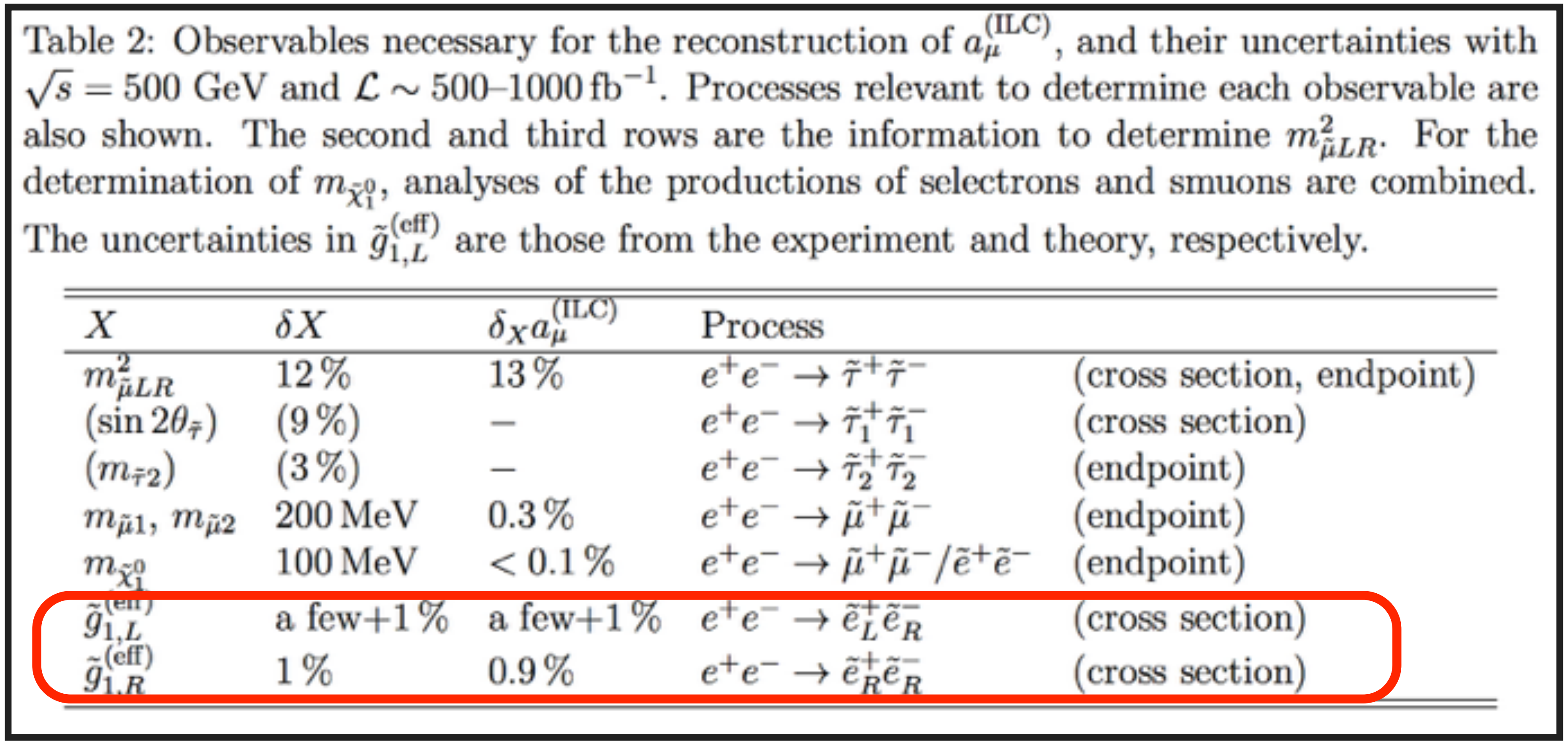
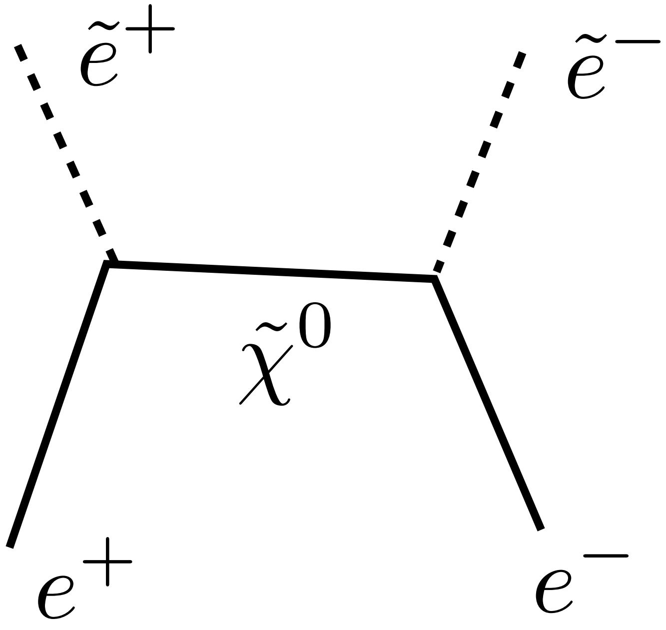


Table 2: Observables necessary for the reconstruction of $a_\mu^{(\mathrm{ILC})}$, and their uncertainties with $\sqrt{s} = 500$ GeV and $\mathcal{L} \sim 500$–$1000\,\mathrm{fb}^{-1}$. Processes relevant to determine each observable are also shown. The second and third rows are the information to determine $m^2_{\tilde{\mu}LR}$. For the determination of $m_{\tilde{\chi}^0_1}$, analyses of the productions of selectrons and smuons are combined. The uncertainties in $\tilde{g}^{(\mathrm{eff})}_{1,L}$ are those from the experiment and theory, respectively.

X	δX	$\delta_X a_\mu^{(\mathrm{ILC})}$	Process	
$m^2_{\tilde{\mu}LR}$	12 %	13 %	$e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$	(cross section, endpoint)
$(\sin 2\theta_{\tilde{\tau}})$	(9 %)	–	$e^+e^- \to \tilde{\tau}^+_1\tilde{\tau}^-_1$	(cross section)
$(m_{\tilde{\tau}2})$	(3 %)	–	$e^+e^- \to \tilde{\tau}^+_2\tilde{\tau}^-_2$	(endpoint)
$m_{\tilde{\mu}1}$, $m_{\tilde{\mu}2}$	200 MeV	0.3 %	$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$	(endpoint)
$m_{\tilde{\chi}^0_1}$	100 MeV	< 0.1 %	$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-/\tilde{e}^+\tilde{e}^-$	(endpoint)
$\tilde{g}^{(\mathrm{eff})}_{1,L}$	a few+1 %	a few+1 %	$e^+e^- \to \tilde{e}^+_L\tilde{e}^-_R$	(cross section)
$\tilde{g}^{(\mathrm{eff})}_{1,R}$	1 %	0.9 %	$e^+e^- \to \tilde{e}^+_R\tilde{e}^-_R$	(cross section)

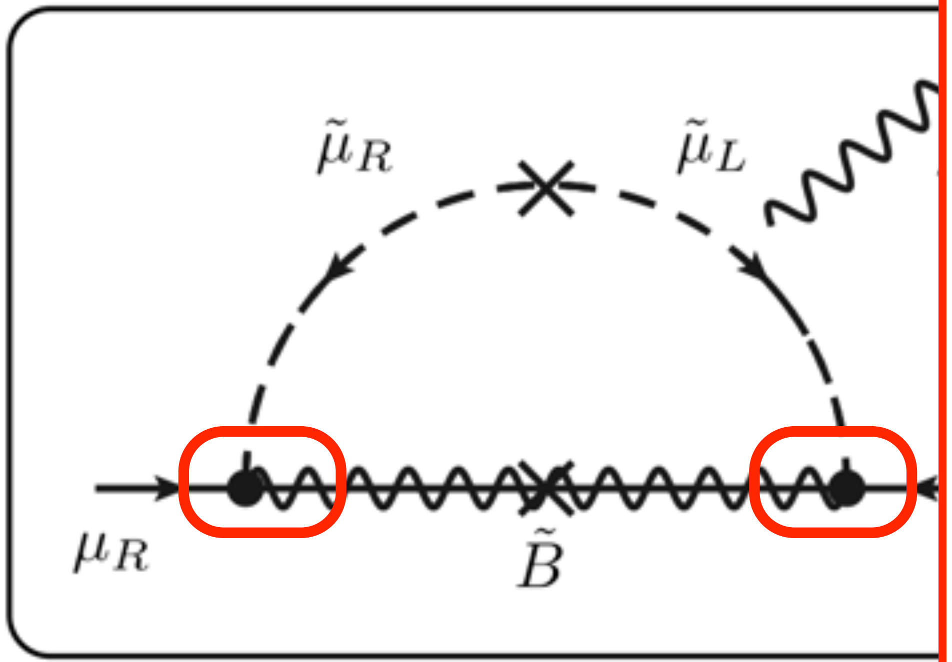
couplings



M.Endo, KH, S.Iwamoto, T.Kitahara, T.Moroi arXiv:1310.4496

muon g-2 vs ILC

neutralino



comment:

$$\tilde g^{(\rm eff)}_{1,L} \equiv \tilde g_{Y,L}(U_{\chi^0})_{1\tilde B} + \tilde g_2 (U_{\chi^0})_{1\tilde W},$$

$$\tilde g^{(\rm eff)}_{1,R} \equiv \tilde g_{Y,R}(U_{\chi^0})_{1\tilde B}.$$

$$\tilde g_{Y,L}(Q) \simeq g_Y(Q)\left[1+\frac{1}{4\pi}\left(4\alpha_Y \ln\frac{M_{\rm soft}}{Q} - \frac{1}{6}\alpha_Y\ln\frac{M_{\tilde H}}{Q} + \frac{9}{4}\alpha_2 \ln\frac{M_{\tilde W}}{Q}\right)\right],$$

$$\tilde g_{Y,R}(Q) \simeq g_Y(Q)\left[1+\frac{1}{4\pi}\left(4\alpha_Y\ln\frac{M_{\rm soft}}{Q} - \frac{1}{6}\alpha_Y \ln\frac{M_{\tilde H}}{Q}\right)\right],$$

If heavy SUSY particles decouple,
gaugino coupling ≠ gauge coupling
-----> but directly measurable.

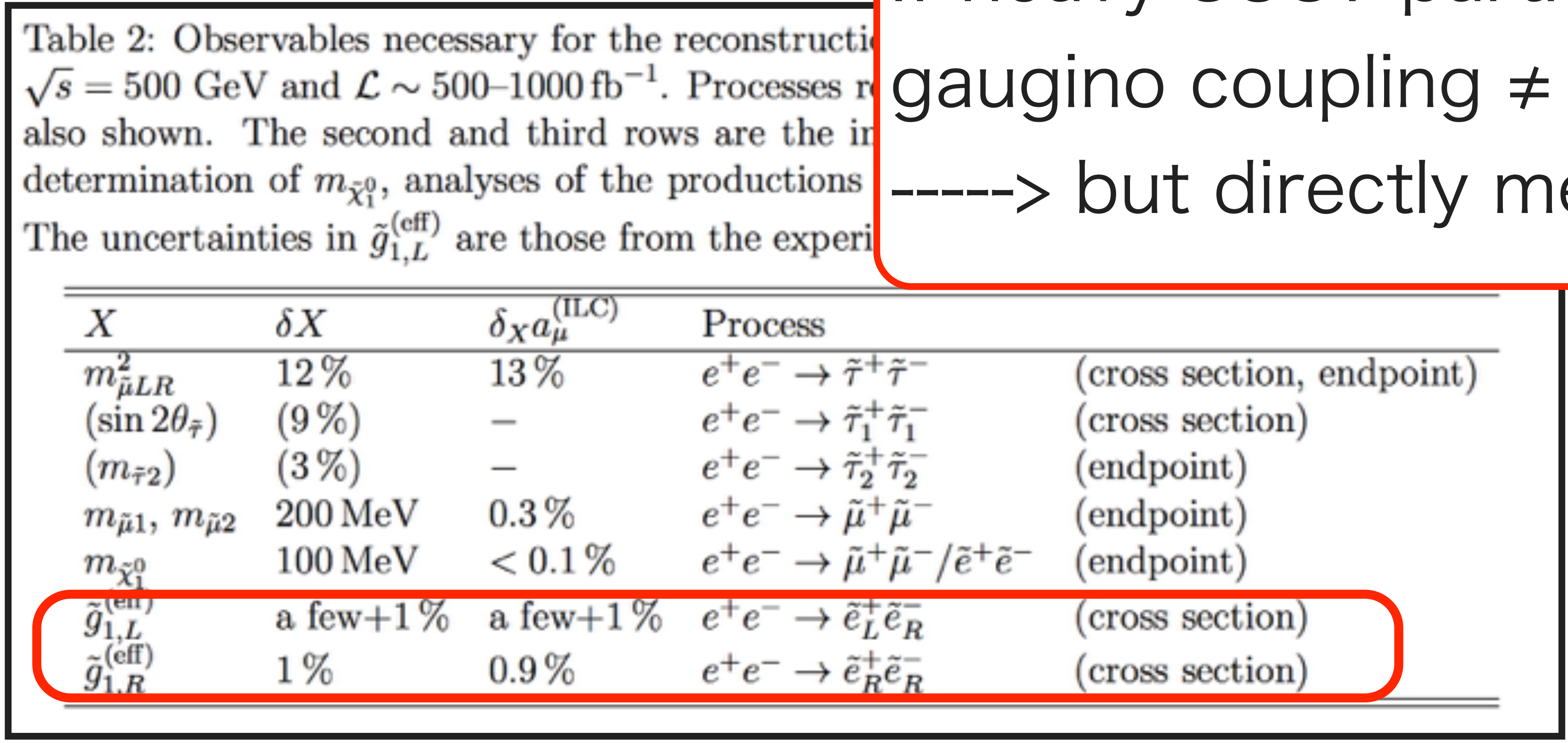
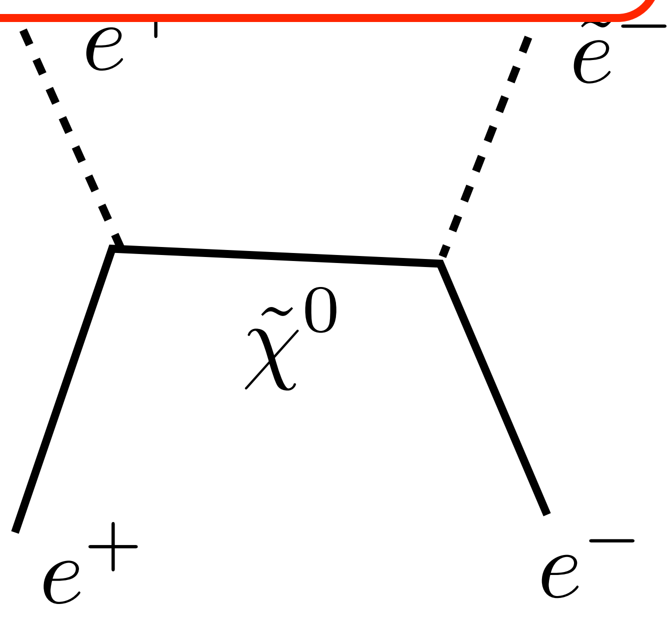


Table 2: Observables necessary for the reconstructi
$\sqrt{s} = 500$ GeV and $\mathcal{L} \sim 500$–$1000\ \mathrm{fb}^{-1}$. Processes r
also shown. The second and third rows are the in
determination of $m_{\tilde\chi^0_1}$, analyses of the productions
The uncertainties in $\tilde g^{(\rm eff)}_{1,L}$ are those from the experi

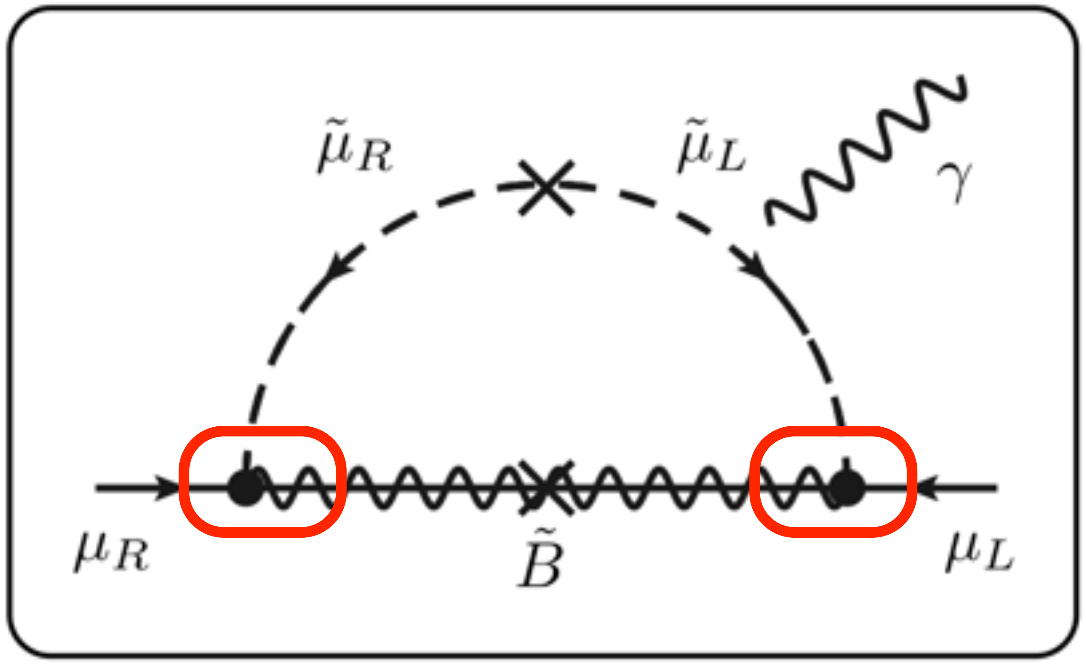
X	δX	$\delta_X a_\mu^{(\rm ILC)}$	Process	
$m^2_{\tilde\mu LR}$	12 %	13 %	$e^+e^- \to \tilde\tau^+\tilde\tau^-$	(cross section, endpoint)
$(\sin 2\theta_{\tilde\tau})$	(9 %)	–	$e^+e^- \to \tilde\tau_1^+\tilde\tau_1^-$	(cross section)
$(m_{\tilde\tau 2})$	(3 %)	–	$e^+e^- \to \tilde\tau_2^+\tilde\tau_2^-$	(endpoint)
$m_{\tilde\mu 1}$, $m_{\tilde\mu 2}$	200 MeV	0.3 %	$e^+e^- \to \tilde\mu^+\tilde\mu^-$	(endpoint)
$m_{\tilde\chi^0_1}$	100 MeV	< 0.1 %	$e^+e^- \to \tilde\mu^+\tilde\mu^-/\tilde e^+\tilde e^-$	(endpoint)
$\tilde g^{(\rm eff)}_{1,L}$	a few+1 %	a few+1 %	$e^+e^- \to \tilde e_L^+\tilde e_R^-$	(cross section)
$\tilde g^{(\rm eff)}_{1,R}$	1 %	0.9 %	$e^+e^- \to \tilde e_R^+\tilde e_R^-$	(cross section)



M.Endo, KH, S.Iwamoto, T.Kitahara, T.Moroi arXiv:1310.4496

muon g-2 vs ILC

neutralino



Can we reconstruct the contribution of this loop-diagram by using ILC measurements?

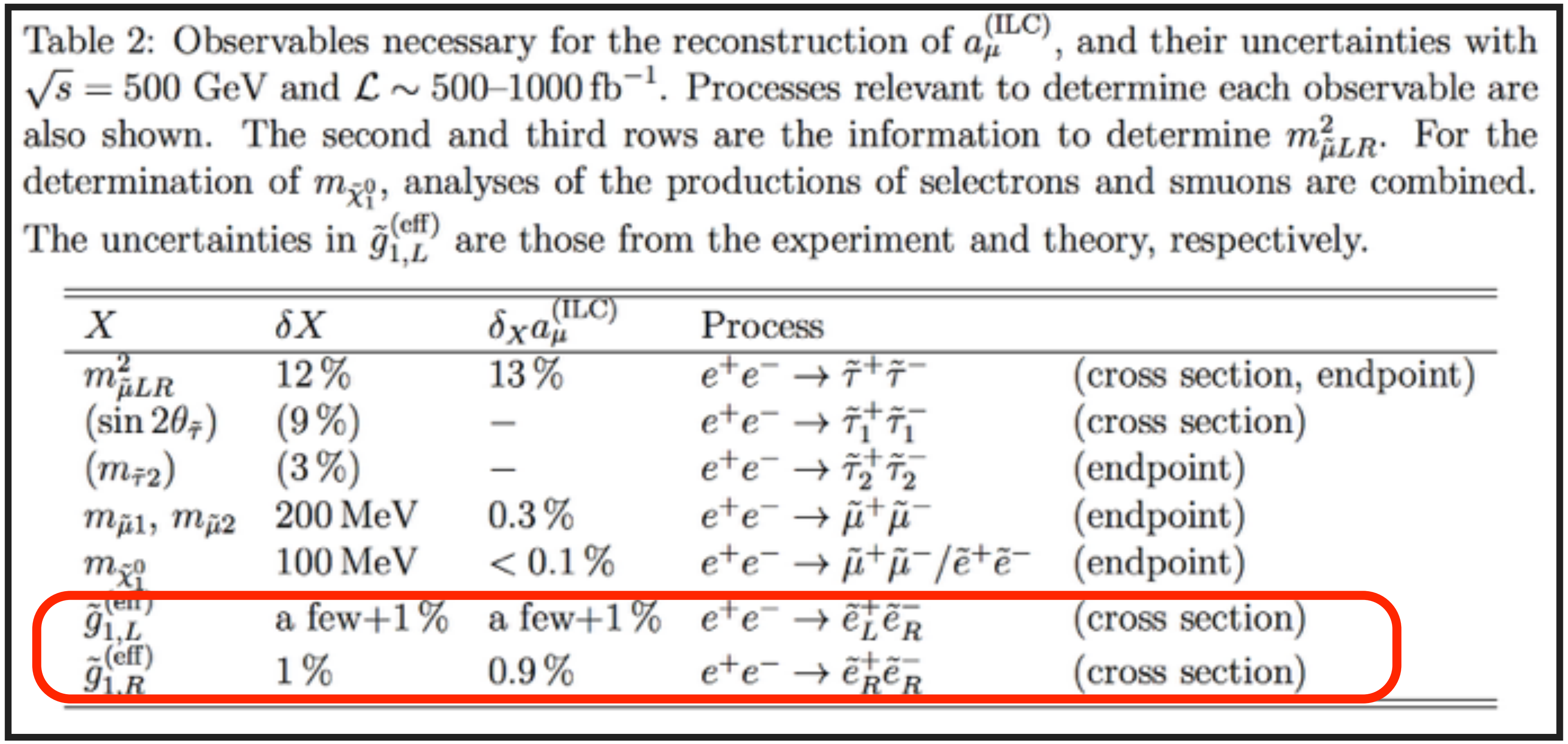
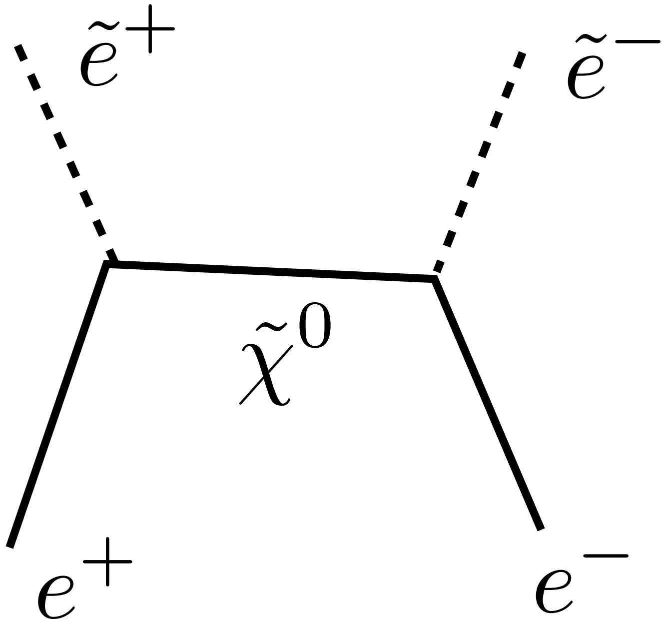


Table 2: Observables necessary for the reconstruction of $a_\mu^{(\mathrm{ILC})}$, and their uncertainties with $\sqrt{s} = 500$ GeV and $\mathcal{L} \sim 500$–$1000\,\mathrm{fb}^{-1}$. Processes relevant to determine each observable are also shown. The second and third rows are the information to determine $m^2_{\tilde{\mu}LR}$. For the determination of $m_{\tilde{\chi}^0_1}$, analyses of the productions of selectrons and smuons are combined. The uncertainties in $\tilde{g}^{(\mathrm{eff})}_{1,L}$ are those from the experiment and theory, respectively.

X	δX	$\delta_X a_\mu^{(\mathrm{ILC})}$	Process	
$m^2_{\tilde{\mu}LR}$	12 %	13 %	$e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$	(cross section, endpoint)
$(\sin 2\theta_{\tilde{\tau}})$	(9 %)	–	$e^+e^- \to \tilde{\tau}_1^+\tilde{\tau}_1^-$	(cross section)
$(m_{\tilde{\tau}2})$	(3 %)	–	$e^+e^- \to \tilde{\tau}_2^+\tilde{\tau}_2^-$	(endpoint)
$m_{\tilde{\mu}1}$, $m_{\tilde{\mu}2}$	200 MeV	0.3 %	$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$	(endpoint)
$m_{\tilde{\chi}^0_1}$	100 MeV	< 0.1 %	$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^- / \tilde{e}^+\tilde{e}^-$	(endpoint)
$\tilde{g}^{(\mathrm{eff})}_{1,L}$	a few+1 %	a few+1 %	$e^+e^- \to \tilde{e}^+_L\tilde{e}^-_R$	(cross section)
$\tilde{g}^{(\mathrm{eff})}_{1,R}$	1 %	0.9 %	$e^+e^- \to \tilde{e}^+_R\tilde{e}^-_R$	(cross section)

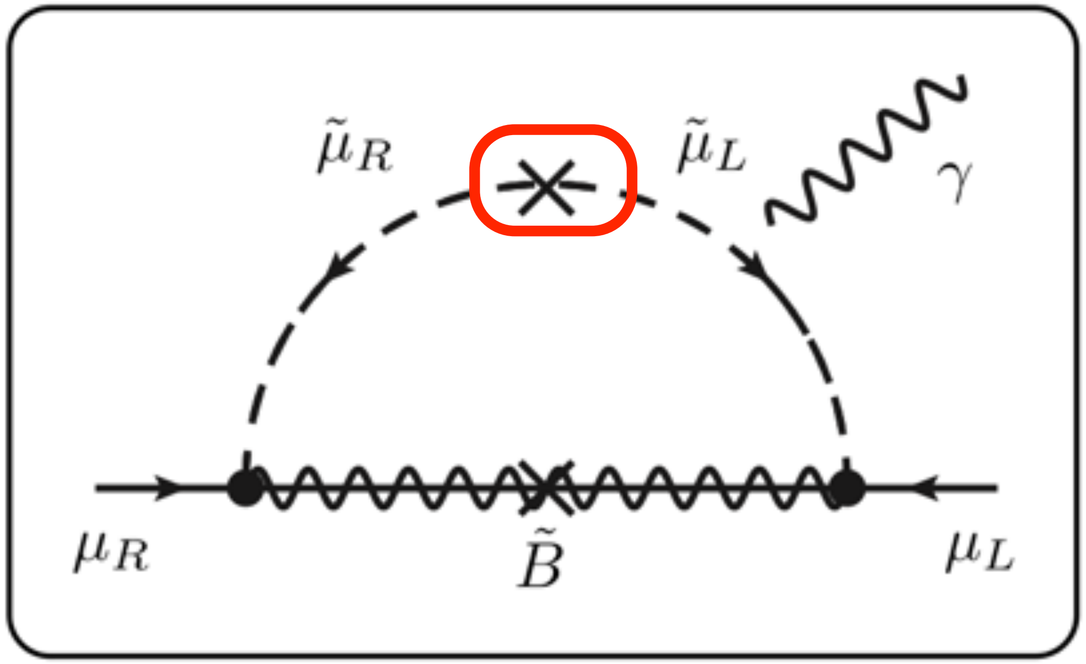
couplings



M.Endo, KH, S.Iwamoto, T.Kitahara, T.Moroi arXiv:1310.4496

muon g-2 vs ILC

neutralino



Can we reconstruct the contribution of this loop-diagram by using ILC measurements?

mixing can also be reconstructed

$$m^2_{\tilde{\mu}LR} = \frac{m_\mu}{m_\tau} m^2_{\tilde{\tau}LR}.$$

$$m^2_{\tilde{\ell}LR} = \frac{1}{2}(m^2_{\tilde{\ell}1} - m^2_{\tilde{\ell}2}) \sin 2\theta_{\tilde{\ell}}.$$

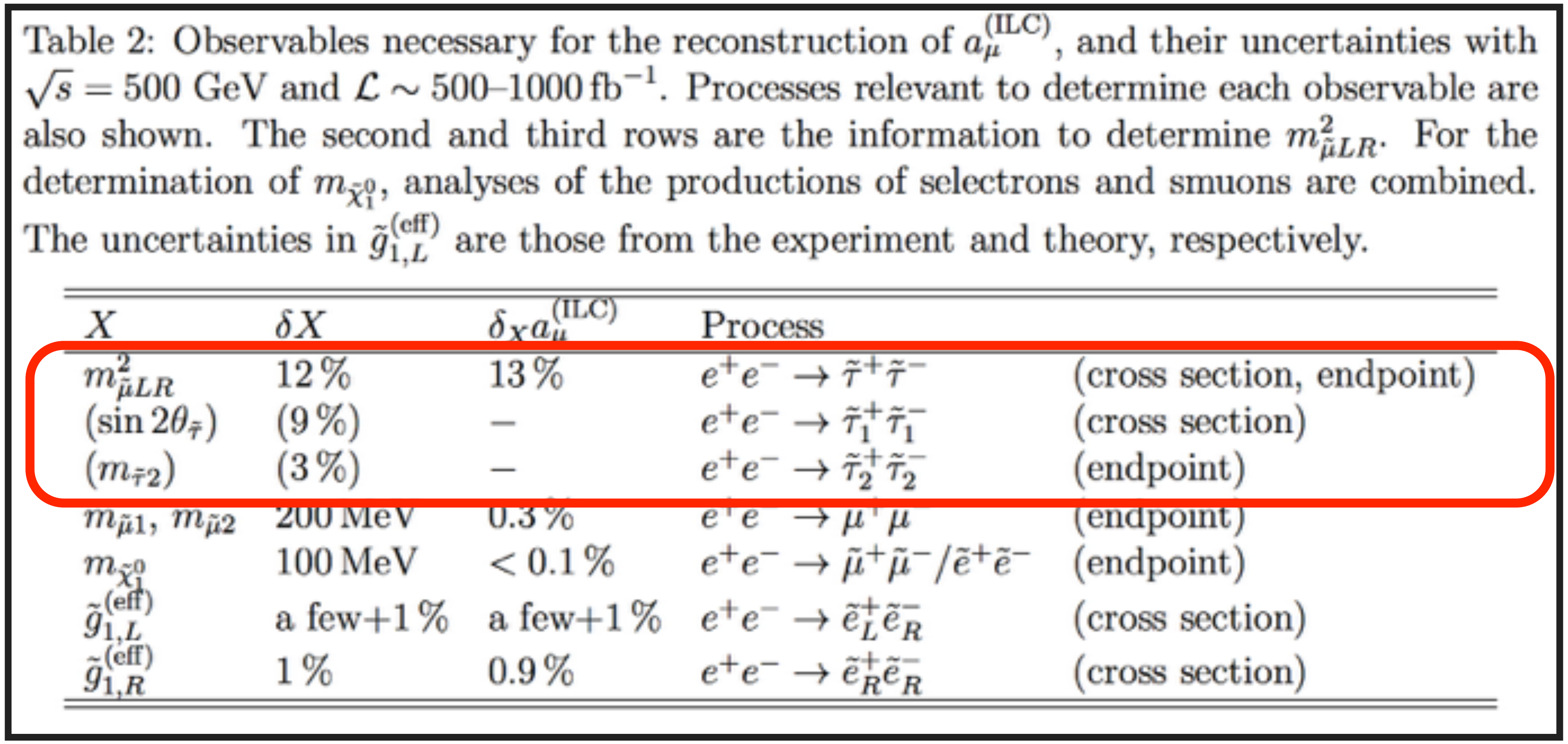


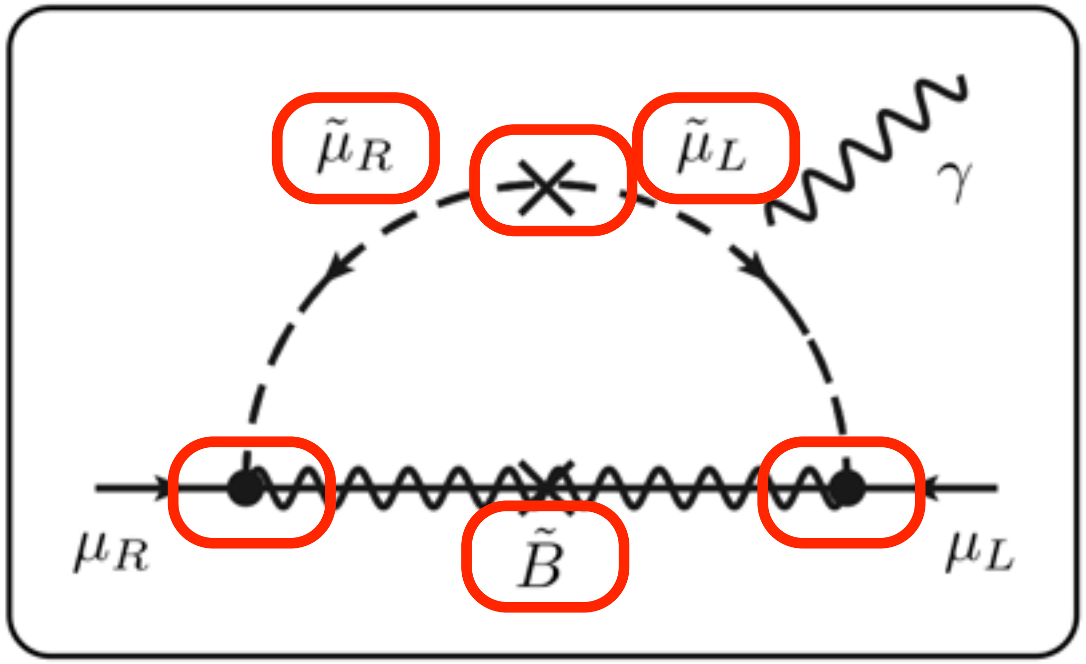
Table 2: Observables necessary for the reconstruction of $a_\mu^{(\mathrm{ILC})}$, and their uncertainties with $\sqrt{s} = 500$ GeV and $\mathcal{L} \sim 500$–$1000\ \mathrm{fb}^{-1}$. Processes relevant to determine each observable are also shown. The second and third rows are the information to determine $m^2_{\tilde{\mu}LR}$. For the determination of $m_{\tilde{\chi}^0_1}$, analyses of the productions of selectrons and smuons are combined. The uncertainties in $\tilde{g}^{(\mathrm{eff})}_{1,L}$ are those from the experiment and theory, respectively.

X	δX	$\delta_X a_\mu^{(\mathrm{ILC})}$	Process	
$m^2_{\tilde{\mu}LR}$	12 %	13 %	$e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$	(cross section, endpoint)
$(\sin 2\theta_{\tilde{\tau}})$	(9 %)	–	$e^+e^- \to \tilde{\tau}_1^+\tilde{\tau}_1^-$	(cross section)
$(m_{\tilde{\tau}2})$	(3 %)	–	$e^+e^- \to \tilde{\tau}_2^+\tilde{\tau}_2^-$	(endpoint)
$m_{\tilde{\mu}1}$, $m_{\tilde{\mu}2}$	200 MeV	0.3 %	$e^+e^- \to \mu^+\mu^-$	(endpoint)
$m_{\tilde{\chi}^0_1}$	100 MeV	< 0.1 %	$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-/\tilde{e}^+\tilde{e}^-$	(endpoint)
$\tilde{g}^{(\mathrm{eff})}_{1,L}$	a few+1 %	a few+1 %	$e^+e^- \to \tilde{e}_L^+\tilde{e}_R^-$	(cross section)
$\tilde{g}^{(\mathrm{eff})}_{1,R}$	1 %	0.9 %	$e^+e^- \to \tilde{e}_R^+\tilde{e}_R^-$	(cross section)

M.Endo, KH, S.Iwamoto, T.Kitahara, T.Moroi arXiv:1310.4496

muon g-2 vs ILC

neutralino



Can we reconstruct the contribution of this loop-diagram by using ILC measurements?

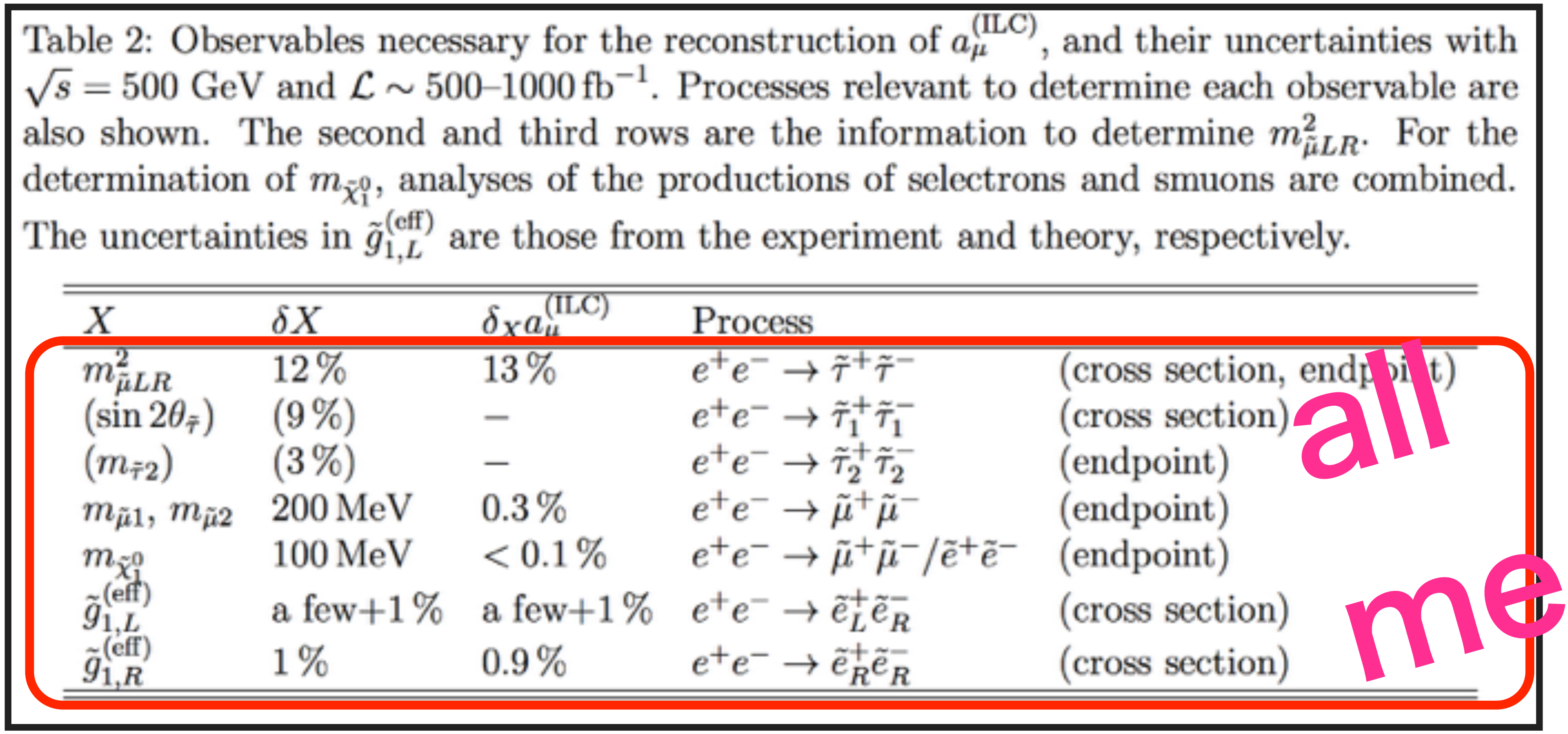


Table 2: Observables necessary for the reconstruction of $a_\mu^{(\mathrm{ILC})}$, and their uncertainties with $\sqrt{s} = 500$ GeV and $\mathcal{L} \sim 500$–$1000\,\mathrm{fb}^{-1}$. Processes relevant to determine each observable are also shown. The second and third rows are the information to determine $m^2_{\tilde{\mu}LR}$. For the determination of $m_{\tilde{\chi}^0_1}$, analyses of the productions of selectrons and smuons are combined. The uncertainties in $\tilde{g}^{(\mathrm{eff})}_{1,L}$ are those from the experiment and theory, respectively.

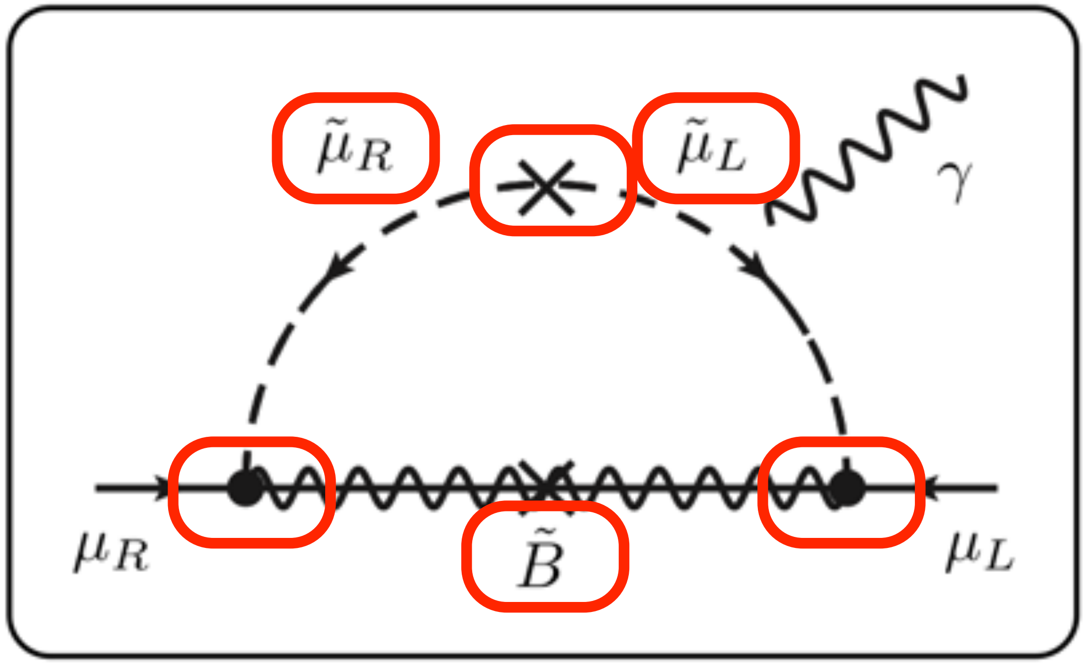
X	δX	$\delta_X a_\mu^{(\mathrm{ILC})}$	Process	
$m^2_{\tilde{\mu}LR}$	12 %	13 %	$e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$	(cross section, endpoint)
$(\sin 2\theta_{\tilde{\tau}})$	(9 %)	–	$e^+e^- \to \tilde{\tau}_1^+\tilde{\tau}_1^-$	(cross section)
$(m_{\tilde{\tau}2})$	(3 %)	–	$e^+e^- \to \tilde{\tau}_2^+\tilde{\tau}_2^-$	(endpoint)
$m_{\tilde{\mu}1}$, $m_{\tilde{\mu}2}$	200 MeV	0.3 %	$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$	(endpoint)
$m_{\tilde{\chi}^0_1}$	100 MeV	< 0.1 %	$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-/\tilde{e}^+\tilde{e}^-$	(endpoint)
$\tilde{g}^{(\mathrm{eff})}_{1,L}$	a few+1 %	a few+1 %	$e^+e^- \to \tilde{e}_L^+\tilde{e}_R^-$	(cross section)
$\tilde{g}^{(\mathrm{eff})}_{1,R}$	1 %	0.9 %	$e^+e^- \to \tilde{e}_R^+\tilde{e}_R^-$	(cross section)

all measurable!

M.Endo, KH, S.Iwamoto, T.Kitahara, T.Moroi arXiv:1310.4496

muon g-2 vs ILC

neutralino



Can we reconstruct the contribution of this loop-diagram by using ILC measurements?

at this model point,

$$\delta a_\mu^{(\mathrm{ILC})} / a_\mu^{(\mathrm{ILC})} = 13\,\%,$$

with $\sqrt{s} = 500\,\mathrm{GeV},\ \mathcal{L} \sim 500\mathrm{fb}^{-1}$

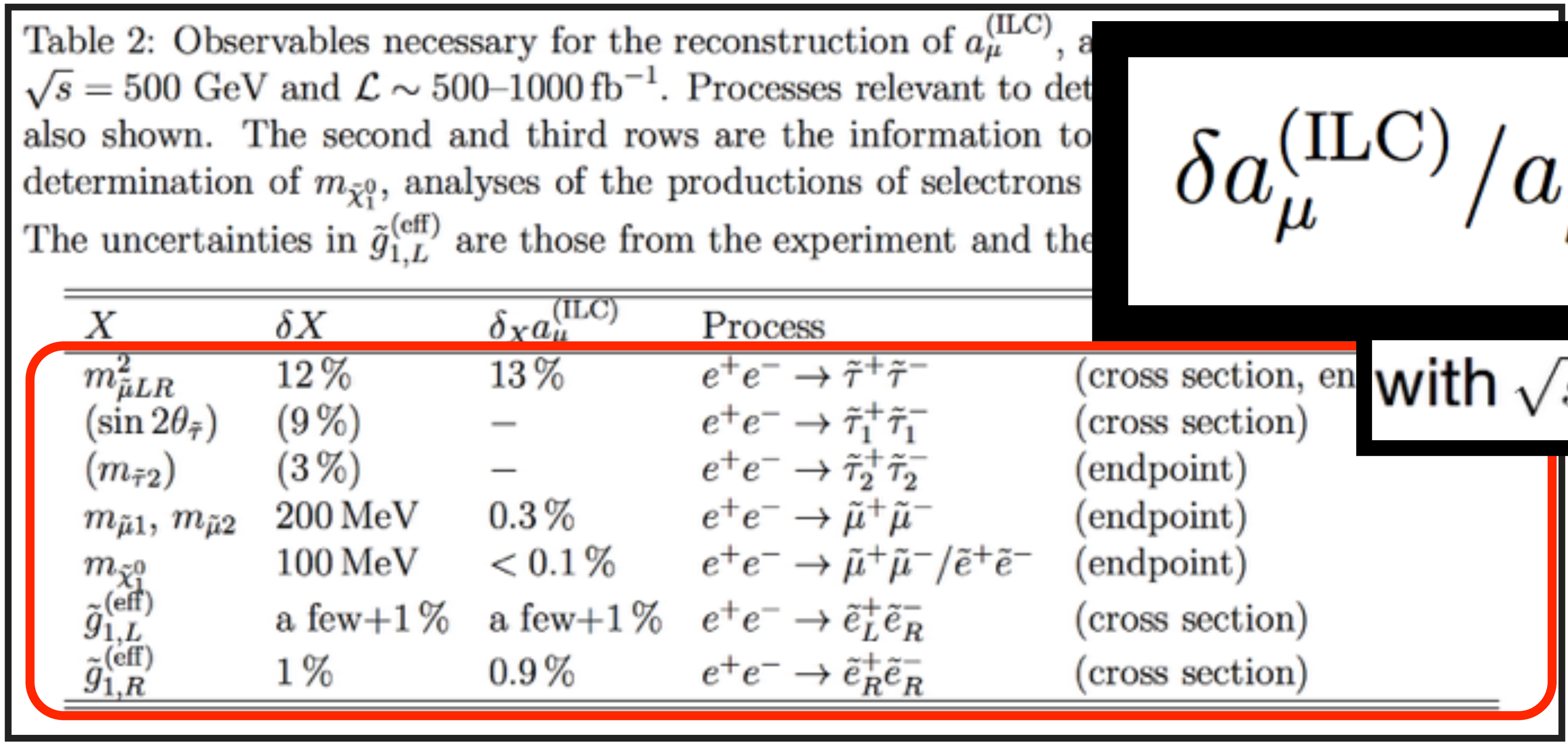


Table 2: Observables necessary for the reconstruction of $a_\mu^{(\mathrm{ILC})}$, a
$\sqrt{s} = 500$ GeV and $\mathcal{L} \sim 500$–$1000\,\mathrm{fb}^{-1}$. Processes relevant to det
also shown. The second and third rows are the information to
determination of $m_{\tilde{\chi}_1^0}$, analyses of the productions of selectrons
The uncertainties in $\tilde{g}_{1,L}^{(\mathrm{eff})}$ are those from the experiment and the

X	δX	$\delta_X a_\mu^{(\mathrm{ILC})}$	Process	
$m^2_{\tilde{\mu}LR}$	$12\,\%$	$13\,\%$	$e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$	(cross section, en
$(\sin 2\theta_{\tilde{\tau}})$	$(9\,\%)$	–	$e^+e^- \to \tilde{\tau}_1^+\tilde{\tau}_1^-$	(cross section)
$(m_{\tilde{\tau}2})$	$(3\,\%)$	–	$e^+e^- \to \tilde{\tau}_2^+\tilde{\tau}_2^-$	(endpoint)
$m_{\tilde{\mu}1}$, $m_{\tilde{\mu}2}$	200 MeV	$0.3\,\%$	$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$	(endpoint)
$m_{\tilde{\chi}_1^0}$	100 MeV	$< 0.1\,\%$	$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-/\tilde{e}^+\tilde{e}^-$	(endpoint)
$\tilde{g}_{1,L}^{(\mathrm{eff})}$	a few+1 %	a few+1 %	$e^+e^- \to \tilde{e}_L^+\tilde{e}_R^-$	(cross section)
$\tilde{g}_{1,R}^{(\mathrm{eff})}$	$1\,\%$	$0.9\,\%$	$e^+e^- \to \tilde{e}_R^+\tilde{e}_R^-$	(cross section)

M.Endo, KH, S.Iwamoto, T.Kitahara, T.Moroi arXiv:1310.4496