

Higgs Physics and Beyond the Standard Model (mainly SUSY)

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Part 4

Plan

0. Introduction
1. Higgs
2. Beyond the Standard Model
3. SUSY
 - 3.1. motivations
 - 3.2. supersymmetry
 - 3.3. MSSM (minimal SUSY Standard Model)
 - 3.4. MSSM Laqrangian

Let's start from here (again)...

§ 3.3. MSSM

spin			
quark	q	$1/2 \leftrightarrow 0$	squark \tilde{q}
lepton	ℓ	$1/2 \leftrightarrow 0$	slepton $\tilde{\ell}$
Higgs	H_u, H_d	$0 \leftrightarrow 1/2$	higgsino \tilde{h}
gauge bosons		$1 \leftrightarrow 1/2$	gaugino $\tilde{B}, \tilde{W}, \tilde{g}$
	γ, Z, W, g		

MSSM (minimal SUSY Standard Model)

More precisely,...

§ 3.3. MSSM

More precisely,...

	Standard Model	spin	SUSY partner	$(SU(3), SU(2))_{U(1)}$
Q_i	$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} u \\ d \end{pmatrix}_L$	$\frac{1}{2} \longleftrightarrow 0$	$\begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}_L \quad \begin{pmatrix} \tilde{c} \\ \tilde{s} \end{pmatrix}_L \quad \begin{pmatrix} \tilde{t} \\ \tilde{b} \end{pmatrix}_L$	$(3, 2)_{1/6}$
\bar{u}_i	$u_R^\dagger \quad c_R^\dagger \quad t_R^\dagger$		$\tilde{u}_R^* \quad \tilde{c}_R^* \quad \tilde{t}_R^*$	$(\bar{3}, 1)_{-2/3}$
\bar{d}_i	$d_R^\dagger \quad s_R^\dagger \quad b_R^\dagger$		$\tilde{d}_R^* \quad \tilde{s}_R^* \quad \tilde{b}_R^*$	$(\bar{3}, 1)_{1/3}$
L_i	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\frac{1}{2} \longleftrightarrow 0$	$\begin{pmatrix} \tilde{\nu}_e \\ \tilde{e} \end{pmatrix}_L \quad \begin{pmatrix} \tilde{\nu}_\mu \\ \tilde{\mu} \end{pmatrix}_L \quad \begin{pmatrix} \tilde{\nu}_\tau \\ \tilde{\tau} \end{pmatrix}_L$	$(1, 2)_{-1/2}$
\bar{e}_i	$e_R^\dagger \quad \mu_R^\dagger \quad \tau_R^\dagger$		$\tilde{e}_R^* \quad \tilde{\mu}_R^* \quad \tilde{\tau}_R^*$	$(1, 1)_1$
Higgs	$\begin{pmatrix} H_u^+ \\ H_u^0 \\ H_d^0 \\ H_d^- \end{pmatrix}_L$	$0 \longleftrightarrow \frac{1}{2}$	$\begin{pmatrix} \tilde{h}_u^+ \\ \tilde{h}_u^0 \\ \tilde{h}_d^0 \\ \tilde{h}_d^- \end{pmatrix}$	$(1, 2)_{+1/2}$ $(1, 2)_{-1/2}$
gauge	$\gamma \quad B \quad W^0 \quad W^\pm \quad g$	$1 \longleftrightarrow \frac{1}{2}$	$\tilde{B} \quad \widetilde{W^0} \quad \widetilde{W}^\pm \quad \tilde{g}$	$(1, 1)_0$ $(1, 3)_0$ $(8, 1)_0$
	graviton e_μ^a	$2 \longleftrightarrow \frac{3}{2}$		gravitino ψ_μ^α

§ 3.4. MSSM Lagrangian

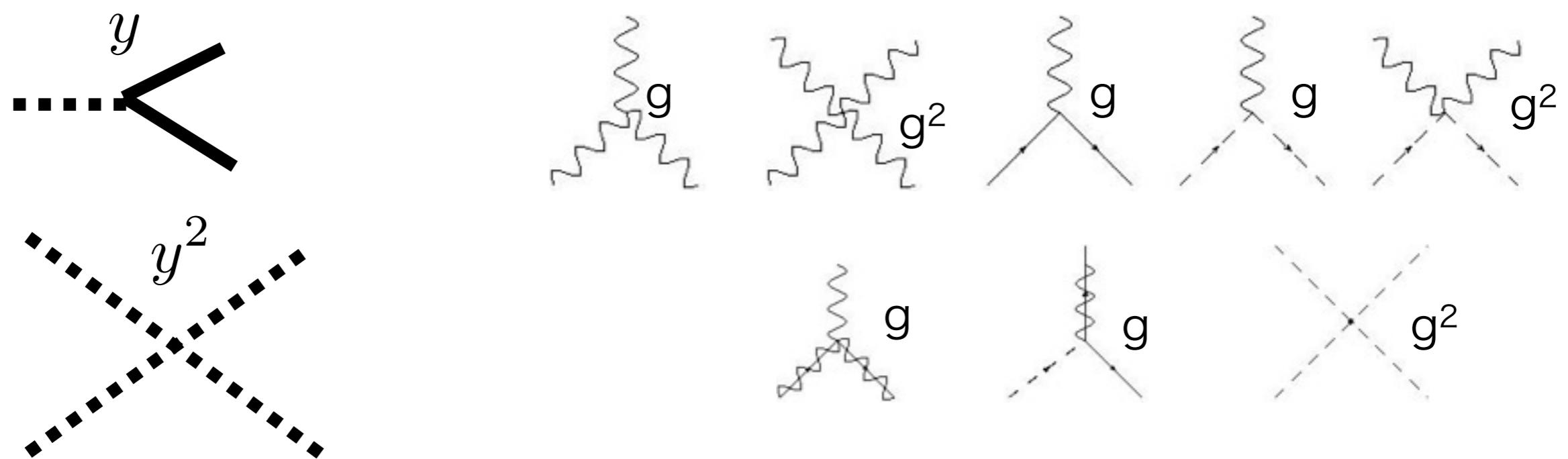
$$\mathcal{L}_{\text{MSSM}} = \mathcal{L}_{\text{SM} \rightarrow \text{SUSY}} + \mathcal{L}_{\text{soft SUSY}}$$

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(i) $\mathcal{L}_{\text{SM} \rightarrow \text{SUSY}}$

$$= \mathcal{L}_{\text{from superpotential}} + \mathcal{L}_{\text{from gauge interactions}}$$



no new free parameter
compared to SM.

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$$W_{\text{MSSM}} = \underbrace{(y_u)_{ij} H_u Q_i u_j^c + (y_d)_{ij} H_d Q_i d_j^c + (y_e)_{ij} H_d Q_i e_i^c}_{\text{corresponding to SM Yukawa}} + \underbrace{\mu H_u H_d}_{\text{"}\mu\text{-term"}}$$

§ 3.4. MSSM Lagrangian

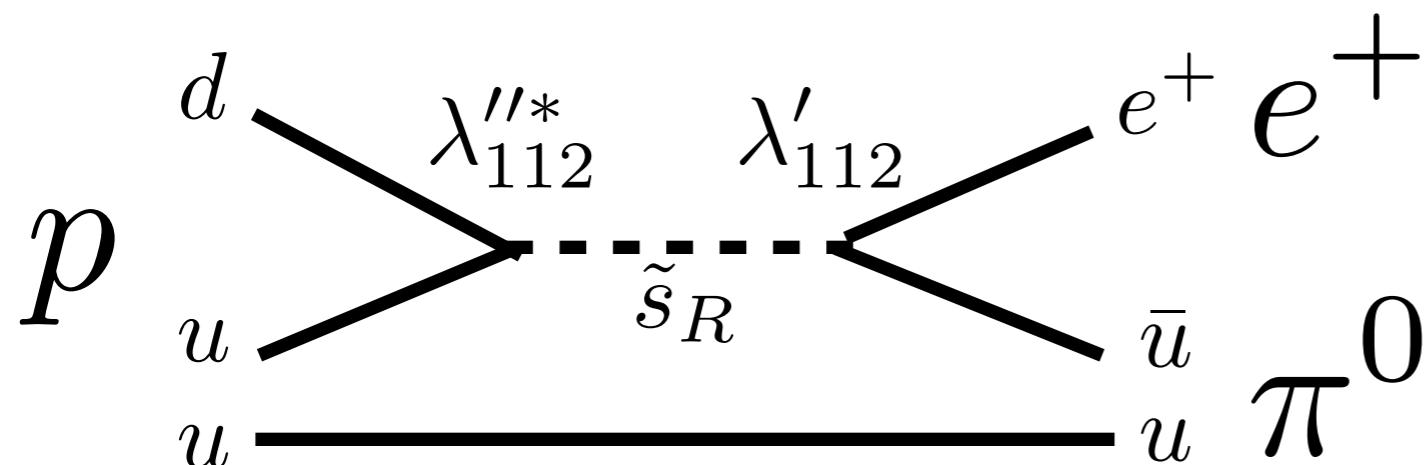
$$W_{\text{MSSM}} = \underbrace{(y_u)_{ij} H_u Q_i u_j^c + (y_d)_{ij} H_d Q_i d_j^c + (y_e)_{ij} H_d Q_i e_i^c}_{\text{corresponding to SM Yukawa}} + \underbrace{\mu H_u H_d}_{\text{"}\mu\text{-term"}}$$

NOTE:

There are other renormalizable terms allowed by gauge invariance.

$$W_{\text{RPV}} = \underbrace{\frac{1}{2} \lambda^{ijk} L_i L_j e_k^c + \lambda'^{ijk} L_i Q_j d_k^c + \mu'_i L_i H_u}_{L\text{-violating}} + \underbrace{\frac{1}{2} \lambda''^{ijk} u_i^c d_j^c d_k^c}_{B\text{-violating}}$$

But they mediate a very rapid proton decay!



exp. bound (super-K)
 $\tau(p \rightarrow e^+ \pi^0) > 1.3 \times 10^{34} \text{ years}$
 $\rightarrow |\lambda'_{11k} \lambda''_{11k}| \lesssim 10^{-29} \left(\frac{m_{\tilde{d}_i}}{1 \text{ TeV}} \right)^2$

§ 3.4. MSSM Lagrangian

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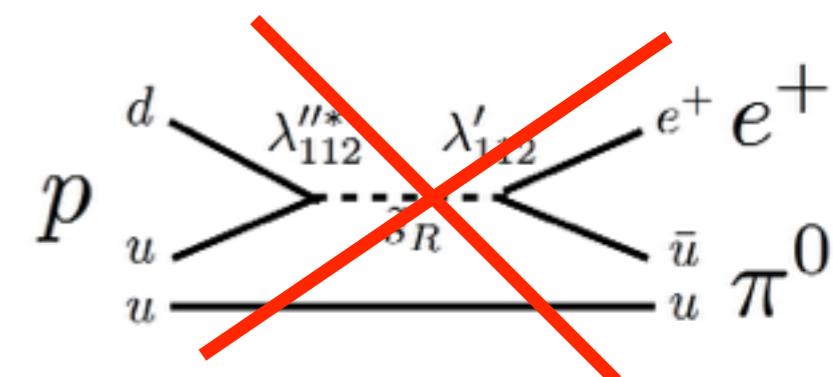
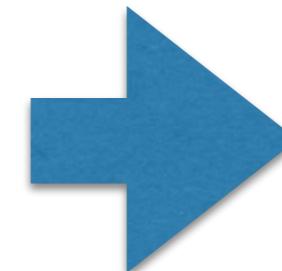
$$W_{\text{RpV}} = \frac{1}{2} \lambda^{ijk} L_i L_j e_k^c + \lambda'^{ijk} L_i Q_j d_k^c + \mu' L_i H_\alpha + \frac{1}{2} \lambda''^{ijk} u_i a_j d_k^c$$

$\underbrace{\hspace{10em}}_{L\text{-violating}}$ $\underbrace{\hspace{10em}}_{B\text{-violating}}$

There is a parity symmetry which forbids W_{RpV} and allows W_{MSSM} .

R-parity

SM particles \rightarrow even (+)
 SUSY particles \rightarrow odd (-)



rapid proton decay
is forbidden.

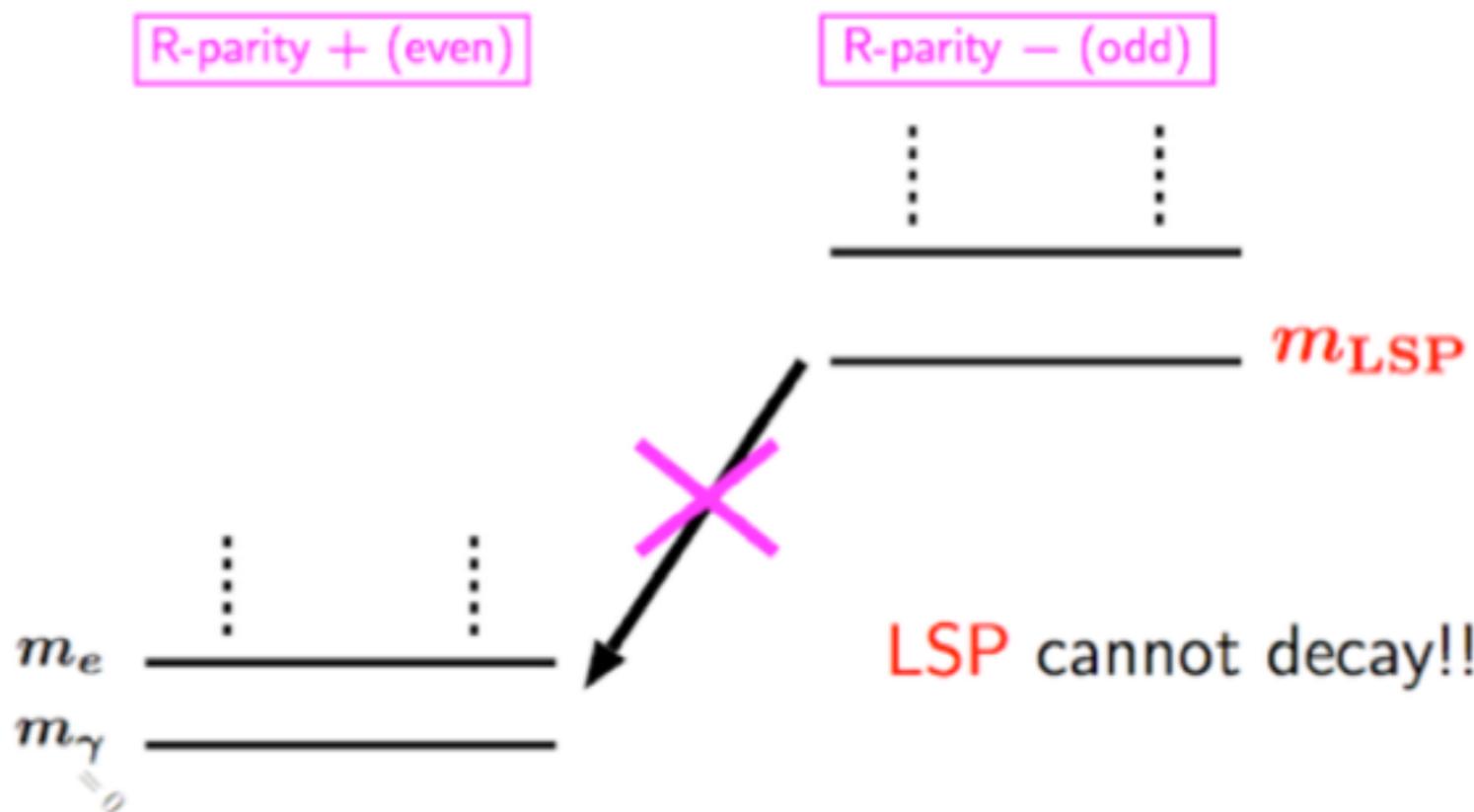
§ 3.4. MSSM Lagrangian

R-parity

SM particles → even (+)

SUSY particles → odd (-)

- Lightest SUSY Particle (LSP) becomes stable.
- Dark Matter candidate!



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R-parity

SM particles → even (+)

SUSY particles → odd (-)

→ Lightest SUSY Particle (LSP) becomes stable.

→ Dark Matter candidate!

$$\text{squarks : } \begin{pmatrix} \widetilde{u}_L \\ \widetilde{d}_L \end{pmatrix}_i \quad \begin{pmatrix} \widetilde{u}_{Ri} \\ \widetilde{d}_{Ri} \end{pmatrix} \quad \text{sleptons : } \begin{pmatrix} \widetilde{\nu}_L \\ \widetilde{e}_L \end{pmatrix}_i \quad \widetilde{e}_{Ri}$$

gauginos and higgsinos : $\widetilde{\chi}_i^0, \quad \widetilde{\chi}_i^\pm, \quad \widetilde{g}$

gravitino : \widetilde{G}

§ 3.4. MSSM Lagrangian

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$$\text{gauginos and higgsinos : } \tilde{\chi}_i^0, \quad \tilde{\chi}_i^\pm, \quad \tilde{g}$$

$$\text{gravitino : } \tilde{G}$$

neutral and color-singlet

§ 3.4. MSSM Lagrangian

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$$\text{sleptons : } \begin{pmatrix} \tilde{\nu}_L \\ \tilde{e}_L \end{pmatrix}_i \quad \tilde{e}_{Ri}$$

$$\text{gauginos and higgsinos : } \tilde{\chi}_i^0, \quad \tilde{\chi}_i^\pm$$

$$\text{gravitino : } \tilde{G}$$

excluded by direct
detection experiments
(cf. Falk, Olive, Srednicki, '94)

neutral and color-singlet

§ 3.4. MSSM Lagrangian

R-parity

SM particles → even (+)

SUSY particles → odd (-)

→ Lightest SUSY Particle (LSP) becomes stable.

→ Dark Matter candidate!

LSP DM candidates within MSSM (+ supergravity):

- **neutralino**
- **gravitino**

👉 Cf. Cosmology Lecture by Prof. Rubakov.

§ 3.4. MSSM Lagrangian

$$\mathcal{L}_{\text{MSSM}} = \mathcal{L}_{\text{SM} \rightarrow \text{SUSY}} + \mathcal{L}_{\text{soft SUSY}}$$

(ii) $\mathcal{L}_{\text{soft SUSY}}$

Supersymmetry must be
a (spontaneously) broken symmetry

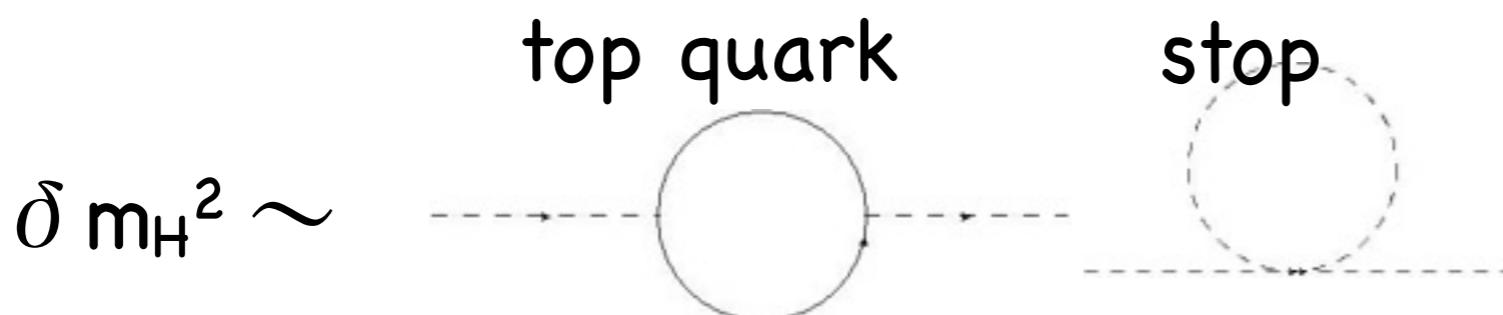
electron ~~selectron (scalar)~~
511 keV \longleftrightarrow 511 keV

§ 3.4. MSSM Lagrangian

$$\mathcal{L}_{\text{MSSM}} = \mathcal{L}_{\text{SM} \rightarrow \text{SUSY}} + \mathcal{L}_{\text{soft SUSY}}$$

(ii) $\mathcal{L}_{\text{soft SUSY}}$

SUSY must be broken only by **parameters with mass dim. > 0.**



hard breaking $y_{\text{top}} \neq y_{\text{stop}}, \longrightarrow \delta m_H^2 \sim (y_{\text{stop}}^2 - y_{\text{top}}^2) \Lambda^2$ 😞

soft breaking $m_{\text{top}} \neq m_{\text{stop}}, \longrightarrow \delta m_H^2 \sim (m_{\text{stop}}^2 - m_{\text{top}}^2) \log \Lambda$ 😐

§ 3.4. MSSM Lagrangian

$$\mathcal{L}_{\text{MSSM}} = \mathcal{L}_{\text{SM} \rightarrow \text{SUSY}} + \mathcal{L}_{\text{soft SUSY}}$$

(ii) $\mathcal{L}_{\text{soft SUSY}}$

SUSY must be broken only by **parameters with mass dim. > 0.**

$$\begin{aligned} \mathcal{L}_{\text{soft}}^{\text{MSSM}} = & -\frac{1}{2} (M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B} + \text{c.c.}) \text{ gaugino masses} \\ & - (\tilde{\bar{u}} \mathbf{a_u} \tilde{Q} H_u - \tilde{\bar{d}} \mathbf{a_d} \tilde{Q} H_d - \tilde{\bar{e}} \mathbf{a_e} \tilde{L} H_d + \text{c.c.}) \text{ A-terms} \\ & - \tilde{Q}^\dagger \mathbf{m_Q^2} \tilde{Q} - \tilde{L}^\dagger \mathbf{m_L^2} \tilde{L} - \tilde{\bar{u}} \mathbf{m_{\bar{u}}^2} \tilde{\bar{u}}^\dagger - \tilde{\bar{d}} \mathbf{m_{\bar{d}}^2} \tilde{\bar{d}}^\dagger - \tilde{\bar{e}} \mathbf{m_{\bar{e}}^2} \tilde{\bar{e}}^\dagger \\ & - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + \text{c.c.}) . \end{aligned}$$

Higgs soft terms

squark and slepton masses
(3x3 matrices.)

§ 3.4. MSSM Lagrangian

$$\mathcal{L}_{\text{MSSM}} = \mathcal{L}_{\text{SM} \rightarrow \text{SUSY}} + \mathcal{L}_{\text{soft SUSY}}$$

(ii) ~~$\mathcal{L}_{\text{soft SUSY}}$~~

$$\begin{aligned} \mathcal{L}_{\text{soft MSSM}} = & -\frac{1}{2} (M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B} + \text{c.c.}) \\ & - (\tilde{\bar{u}} \mathbf{a}_u \tilde{Q} H_u - \tilde{\bar{d}} \mathbf{a}_d \tilde{Q} H_d - \tilde{\bar{e}} \mathbf{a}_e \tilde{L} H_d + \text{c.c.}) \\ & - \tilde{Q}^\dagger m_Q^2 \tilde{Q} - \tilde{L}^\dagger m_L^2 \tilde{L} - \tilde{\bar{u}} m_{\bar{u}}^2 \tilde{\bar{u}}^\dagger - \tilde{\bar{d}} m_{\bar{d}}^2 \tilde{\bar{d}}^\dagger - \tilde{\bar{e}} m_{\bar{e}}^2 \tilde{\bar{e}}^\dagger \\ & - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + \text{c.c.}). \end{aligned}$$

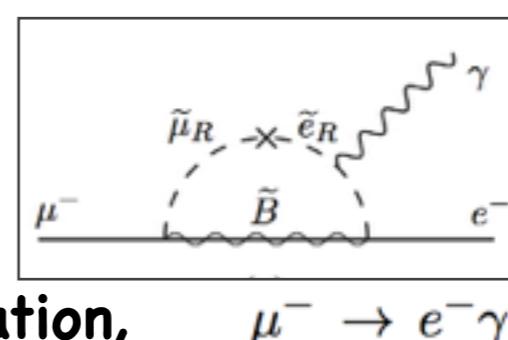
This part contains a variety of interesting SUSY phenomenologies.....

- ▶ SUSY particle masses,
- ▶ Higgs sector (tree level mass, loop corrections...),
- ▶ **Flavor Changing Neutral Current (FCNC) and CP-violation,**
- ▶ SUSY breaking mechanism and its mediations, model-building,
(Gravity mediation, Gauge mediation, Anomaly mediation,...)

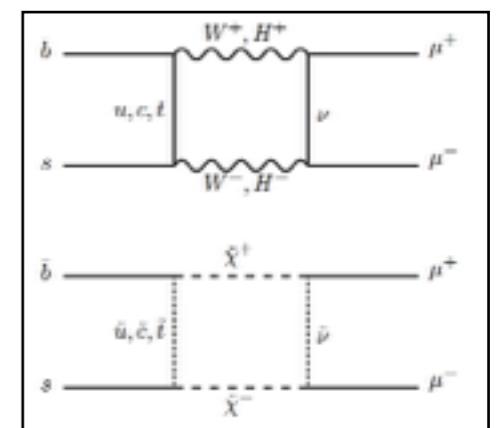
- ▶ **Collider physics,**
- ▶ **Dark Matter**
- ▶

But I skip the details here.

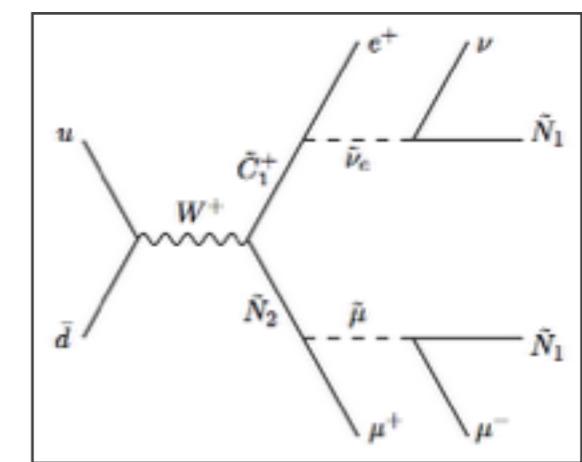
For a review, see,e.g., [hep-ph/9709356](https://arxiv.org/abs/hep-ph/9709356) by S.P.Martin.



$$\mu^- \rightarrow e^- \gamma$$



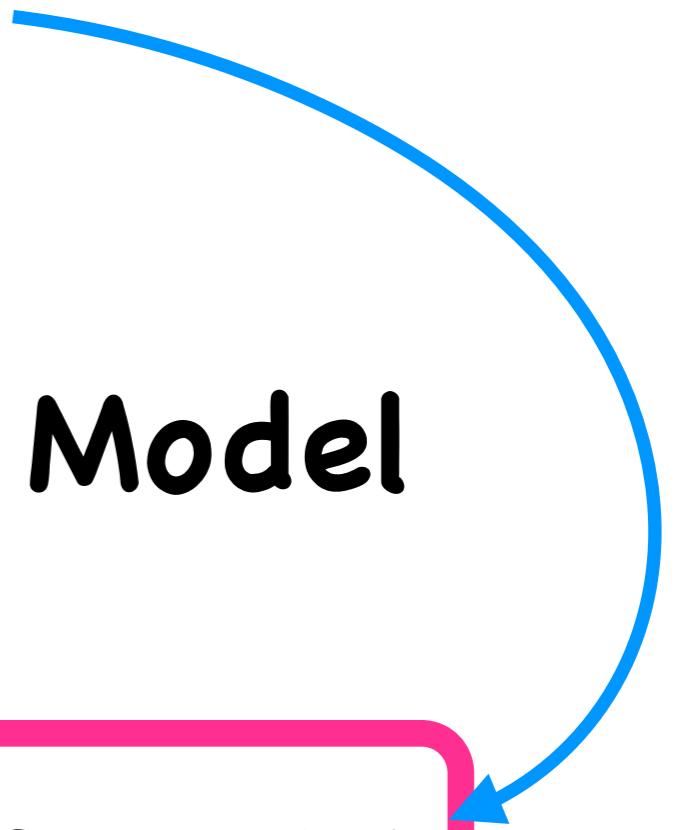
various B-decays



collider signals...

Plan

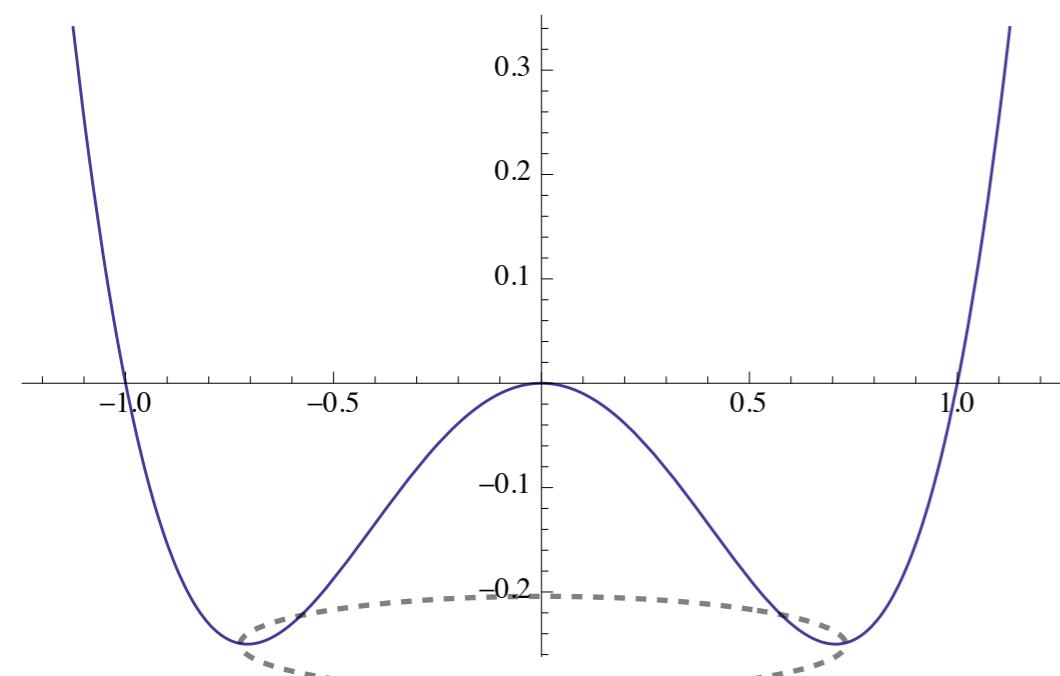
0. Introduction
1. Higgs
2. Beyond the Standard Model
3. SUSY
4. SUSY after Higgs discovery



126 GeV Higgs

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

$$\rightarrow \begin{cases} \langle H \rangle^2 = \frac{m^2}{2 \lambda_H} & \text{we knew...} \\ m_{\text{Higgs}}^2 = 2 m^2 & \text{Now we also know} \end{cases} = \frac{1}{2\sqrt{2} G_F} \simeq (174 \text{ GeV})^2$$

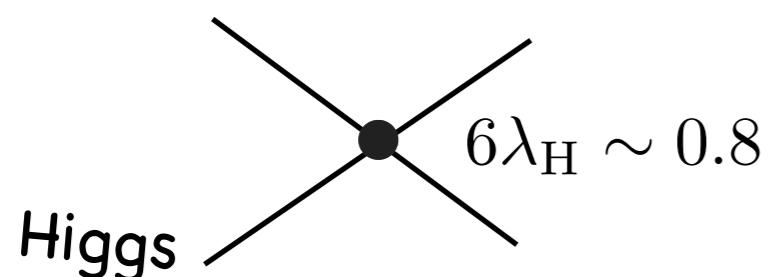


$$\rightarrow \begin{cases} m^2 = \frac{m_{\text{Higgs}}^2}{2} \simeq (89 \text{ GeV})^2 \\ \lambda_H = \frac{m_{\text{Higgs}}^2}{4\langle H \rangle^2} \simeq 0.13 \end{cases}$$

126 GeV Higgs

$$V(H) = -m^2(H^\dagger H) + \lambda_H (H^\dagger H)^2$$
$$(89 \text{ GeV})^2 \quad \underline{\textcolor{red}{0.13}}$$

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



Implications for BSM

(in my opinion....)

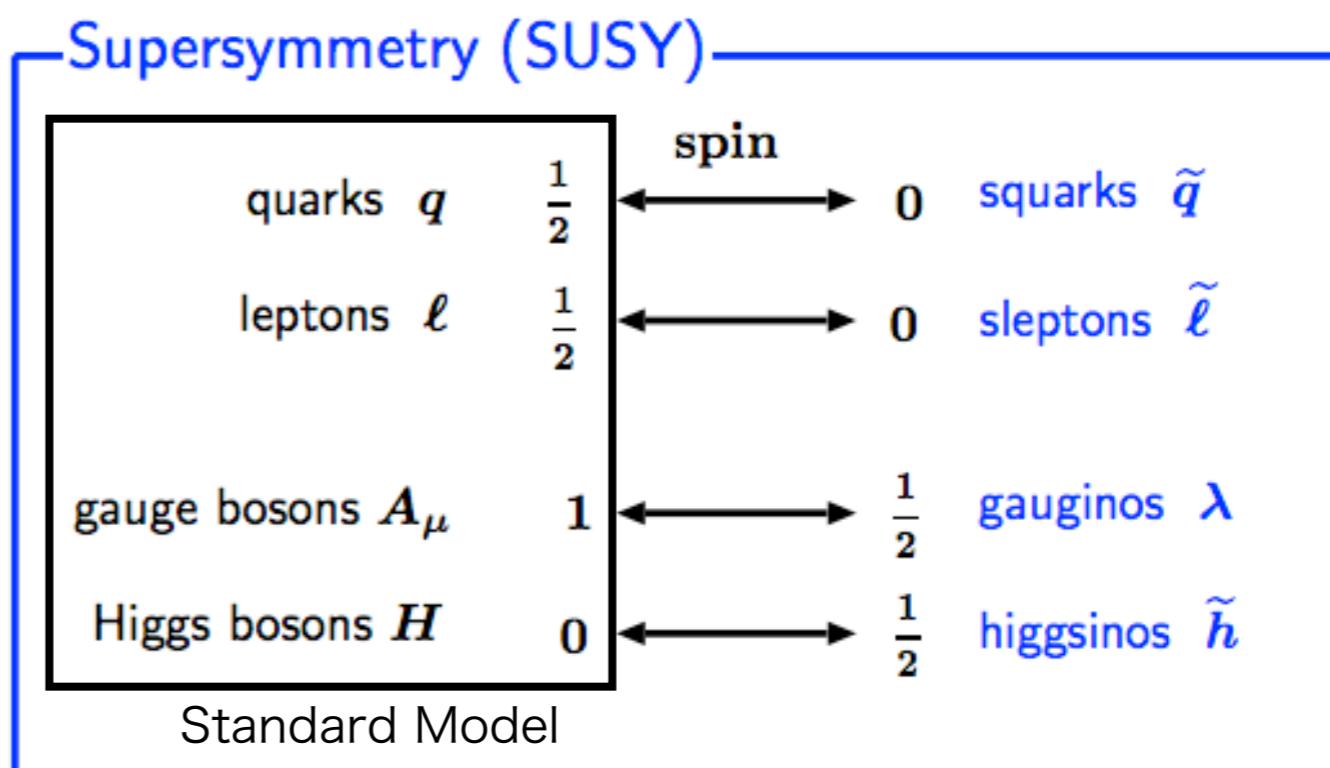
This is compatible with....

- ▶ **GUT and coupling unification** in perturbative QFT. ↗ §2
- ▶ **heavy right-handed neutrinos** (Seesaw + Leptogenesis)
↗ §2 and Neutrino Lecture by Prof. Xing.
- ▶ **Supersymmetry** ↗ §3



Supersymmetry

boson \Leftrightarrow fermion



naturalness

fine-tuning problem

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

(fine tuning like $1.0000000000000001 - 1$)

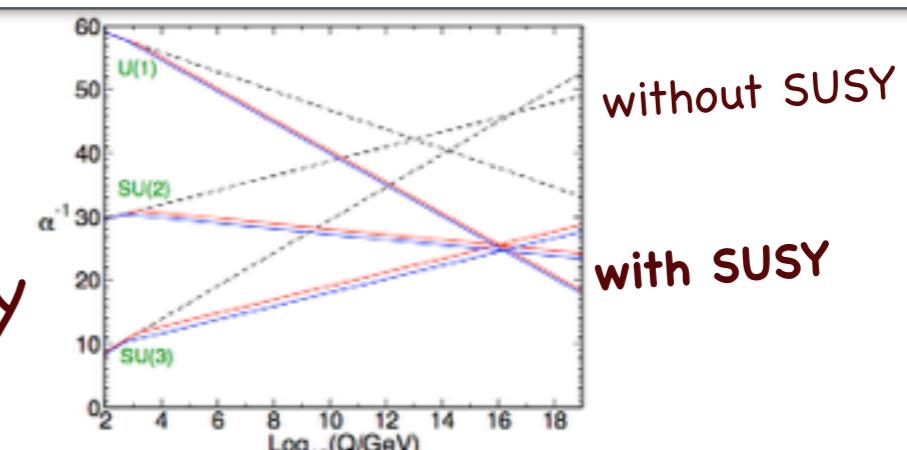
→ solved by the supersymmetry !

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

fermion **boson**

coupling unification

Grand Unified Theory



Dark Matter = Lightest SUSY particle

OK, then,....

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

126 GeV Higgs and SUSY

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

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

in SUSY...

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

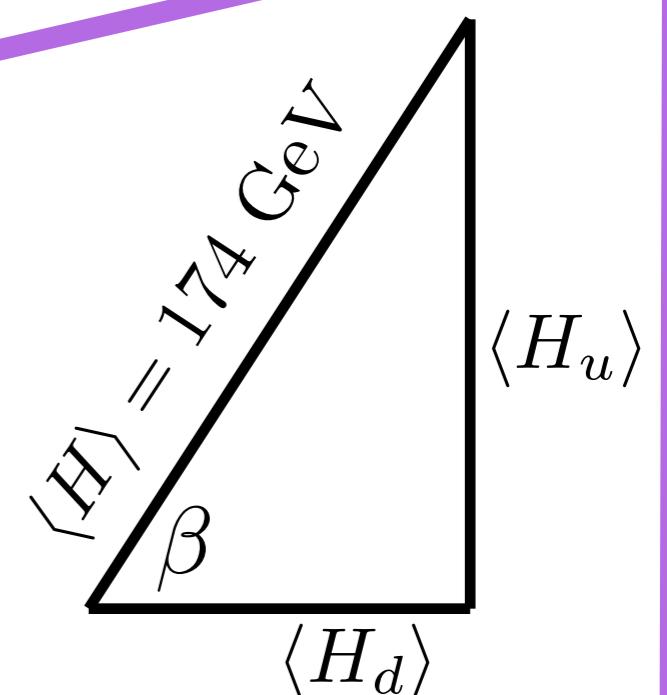
$$\frac{g^2 \cos^2 2\beta}{8 \cos^2 \theta_W} \simeq 0.069 \cos^2 2\beta$$

parameters
in Standard Model
(known)

too small...

What is $\beta??$

$$\tan \beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}$$



126 GeV Higgs and SUSY

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

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

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

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

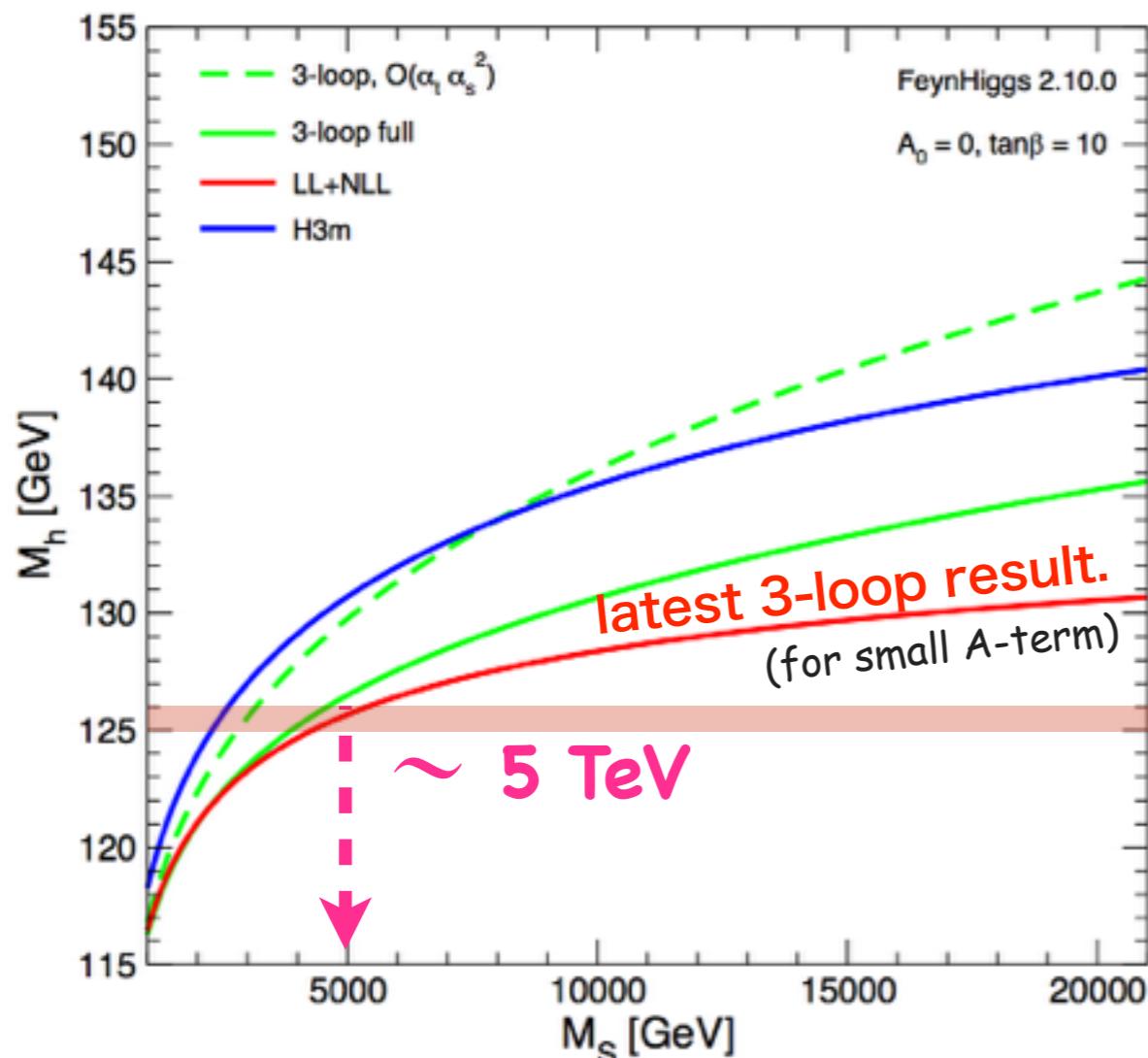
...requires **heavy stop**
and/or **large A-term**

126 GeV Higgs and SUSY

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

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126 GeV Higgs and SUSY

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

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

0.13

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

on the other hand

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

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

Higgsino mass

soft mass for
up-type Higgs

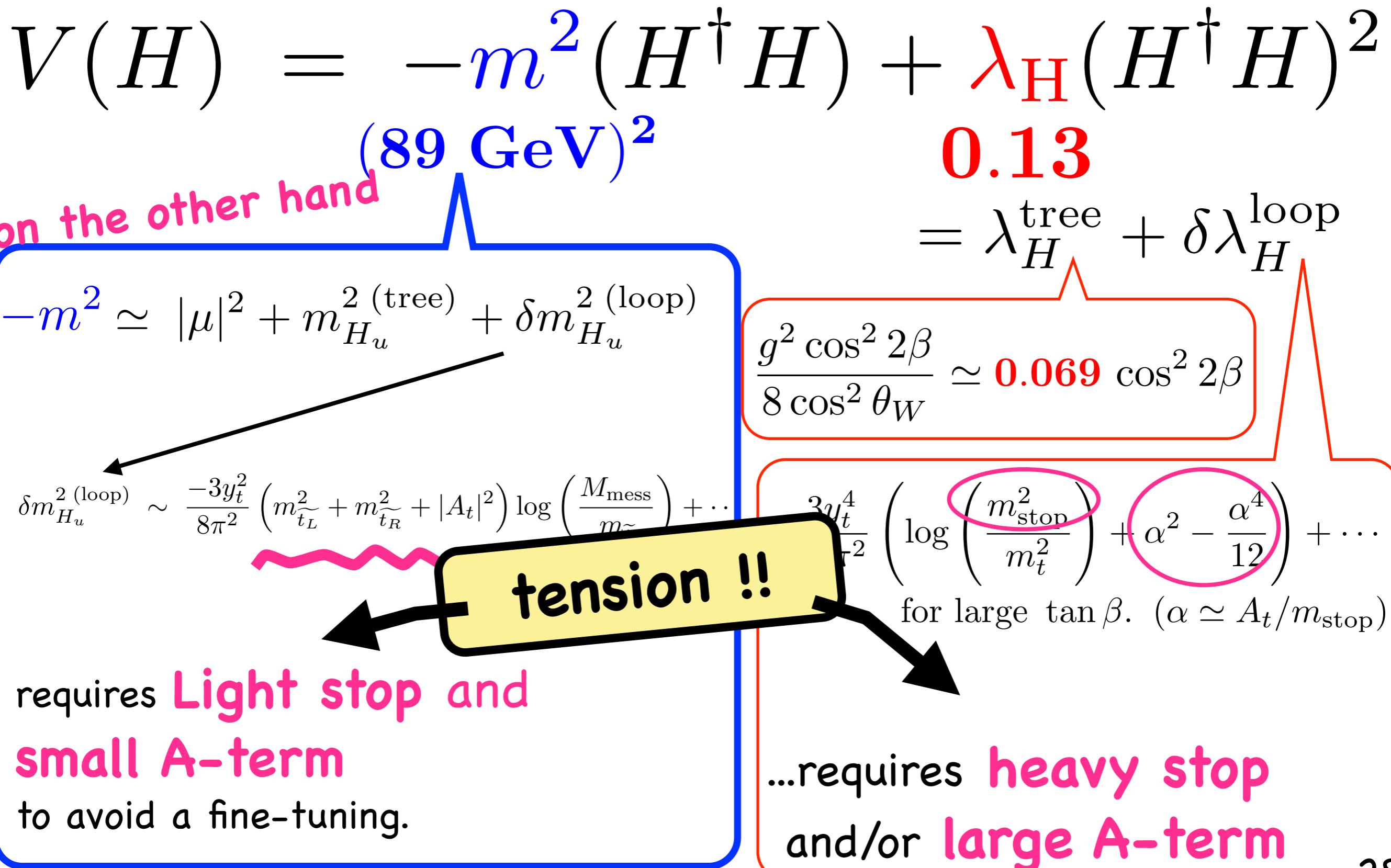
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...requires **heavy stop**
and/or **large A-term**

126 GeV Higgs and SUSY



126 GeV Higgs and SUSY

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

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



126 GeV Higgs and SUSY



What happens to
neutralino Dark Matter after Higgs discovery?

126 GeV Higgs and SUSY

- ▶ What happens to neutralino Dark Matter after Higgs discovery?
- ▶ Still OK... and SUSY particles may be seen at LHC.

As an example..., benchmark model points in CMSSM/mSUGRA shown in 1305.2914, Cohen Wacker

"Stau coannihilation"

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

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

within 13-14 TeV
LHC reach

gluino
squark
stop

neutralino DM

Higgs

correct
DM density

fine-tuning
< 0.1 %

126 GeV Higgs and SUSY

- ▶ What happens to neutralino Dark Matter after Higgs discovery?
- ▶ Still OK... and SUSY particles may be seen at LHC,
..... or may not be seen.

As an example..., benchmark model points in CMSSM/mSUGRA shown in 1305.2914, Cohen Wacker

"Well tempered"
pure Higssino limit

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

gluino
squark
stop

outside the
13 TeV LHC reach

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

neutralino DM

Higgs

correct
DM density

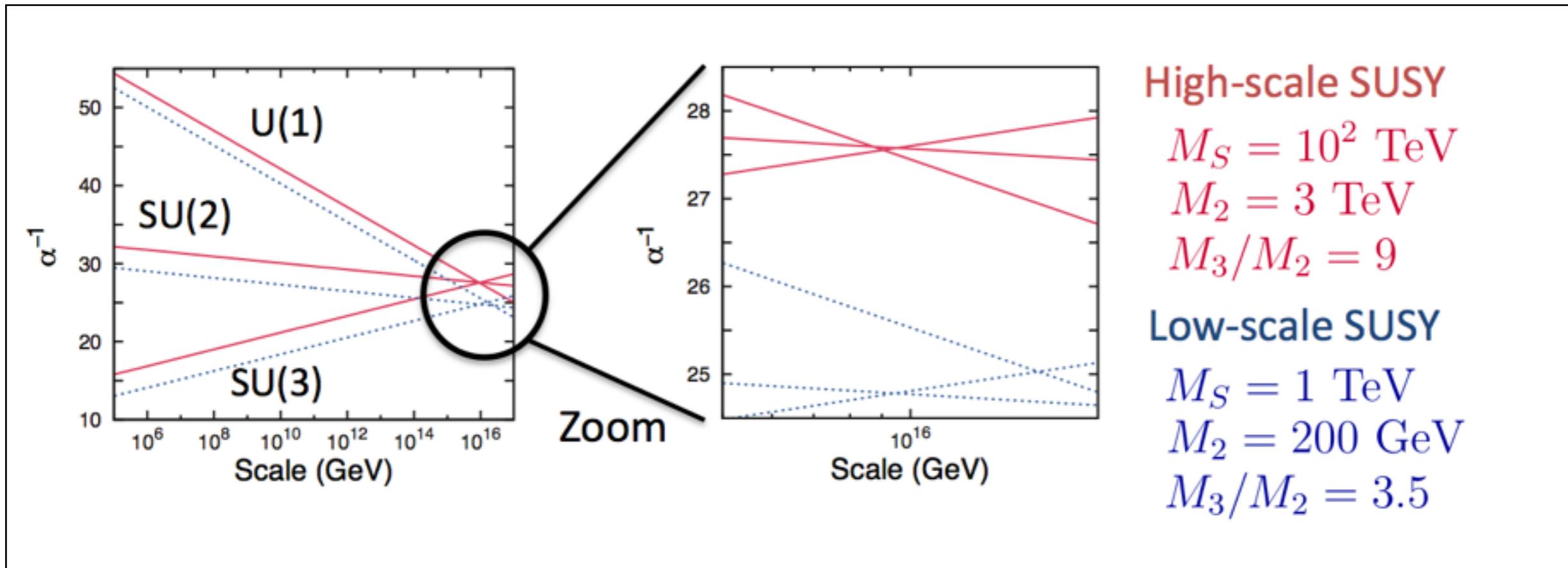
fine-tuning
< 0.01%

126 GeV Higgs and SUSY

► What happens to
coupling unification after Higgs discovery?

126 GeV Higgs and SUSY

- ▶ What happens to coupling unification after Higgs discovery?
- ▶ No problem.
O(10-100) TeV SUSY can make it even better.....



[talk given by N.Nagata at YITP workshop 2013
Hisano,Kuwahara,Nagata'13, Hisano,Kobayashi,Kuwahara,Nagata'13]

126 GeV Higgs and SUSY

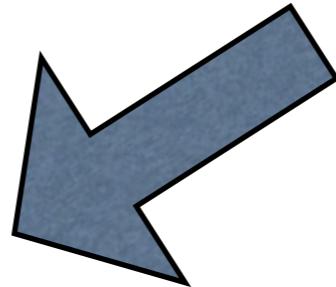
Fine-tuning worse than 1% seems unavoidable in MSSM.

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

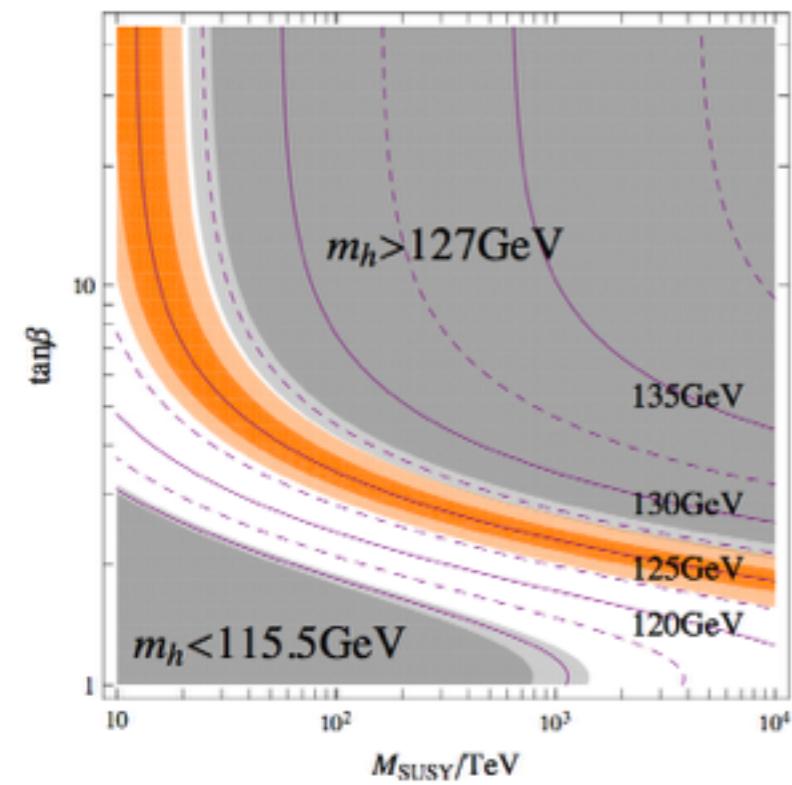
126 GeV Higgs and SUSY

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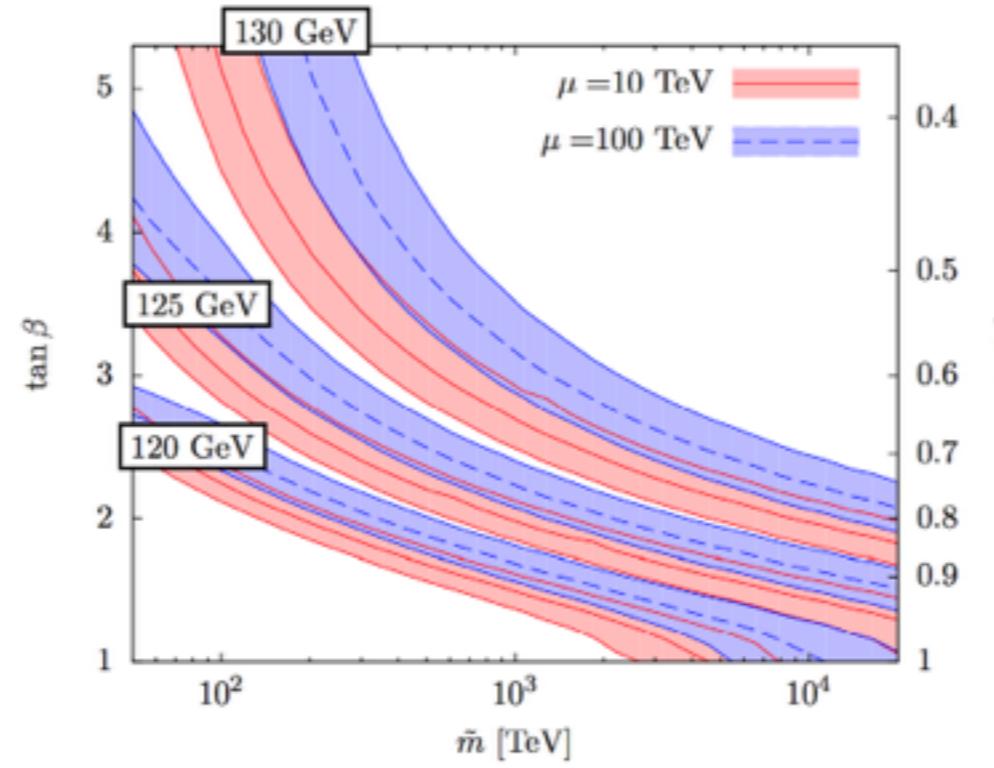
Very heavy SUSY

$$\begin{aligned}
 m_H^2 &= 4\lambda_H \langle H \rangle^2 \\
 \rightarrow \lambda_H &\simeq 0.13 \\
 &= \underbrace{\lambda_H^{\text{tree}}}_{0.07 \cos^2 2\beta} + \underbrace{\delta\lambda_H^{\text{loop}}}_{\sim \log(m_{\text{stop}}^2)}
 \end{aligned}$$

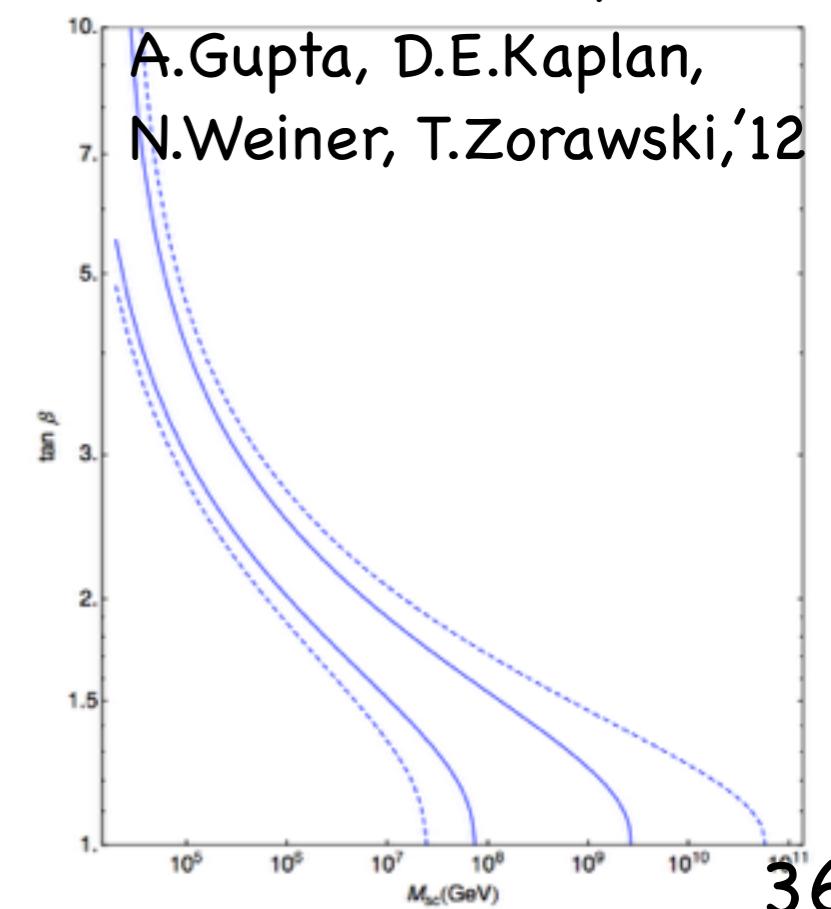
Ibe, Matsumoto,
Yanagida '12



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



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

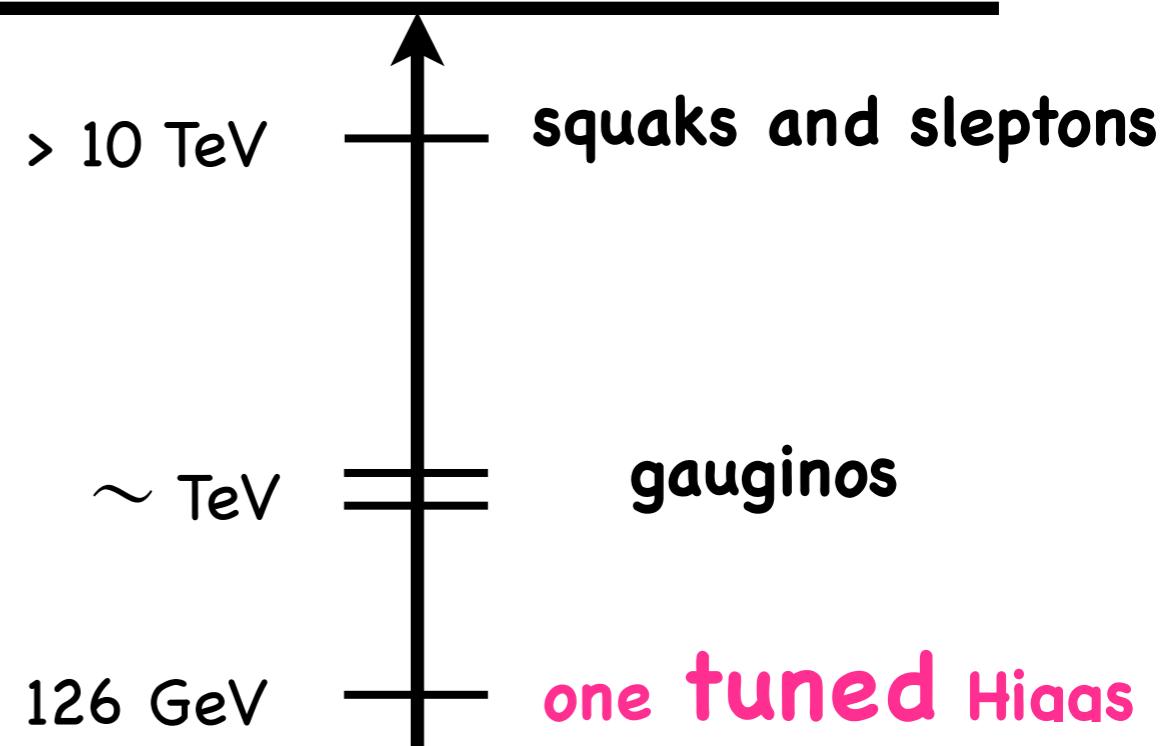


126 GeV Higgs and SUSY

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

Very heavy SUSY

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



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

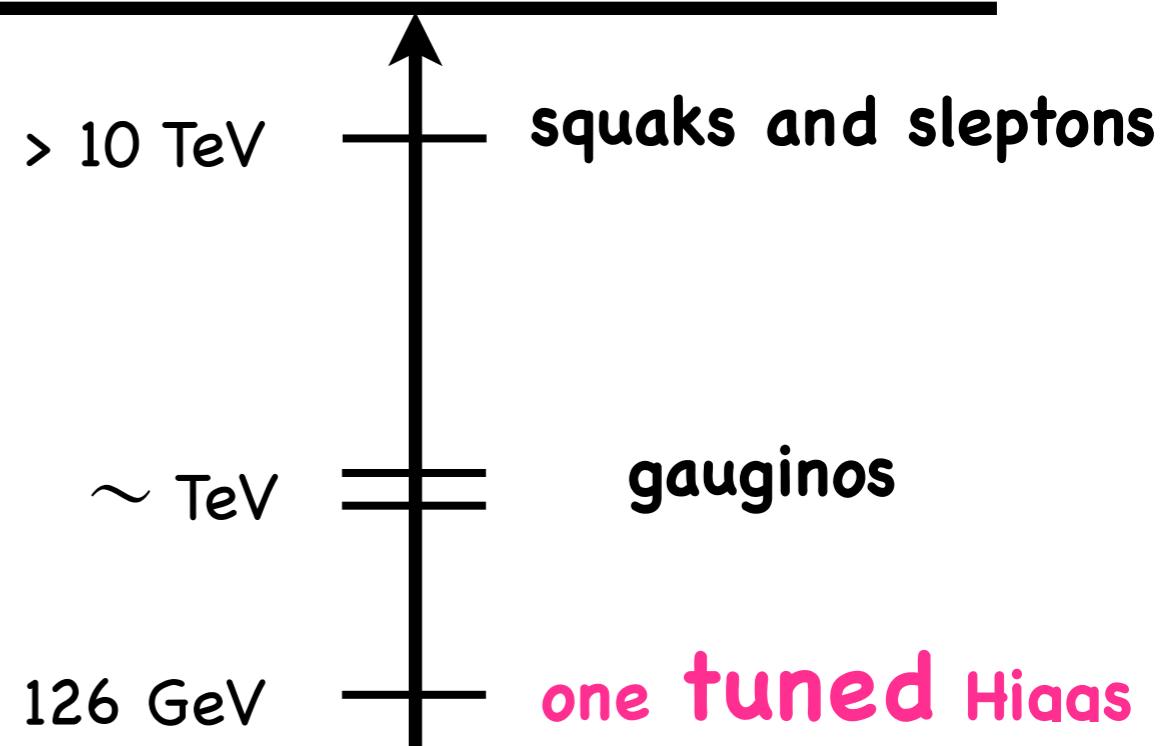
Ibe,Yanagida'11, Ibe,Matsumoto,Yanagida'12,
Bhattacherjee,Feldstein,Ibe,Matsumoto,Yanagida'12,
Hall,Nomura'11, Hall,Nomura,Shirai'12,
Giudice,Strumia'11, Arvanitaki,Craig,Dimopoulos,Villadoro'12
Arkani-Hamed,Gupta,Kaplan,Weiner,Zorawski'12, Ibanez,Valenzuela'13,
Jeong,Shimosuka,Yamaguchi'11, Hisano,Ishiwata,Nagata'12, 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

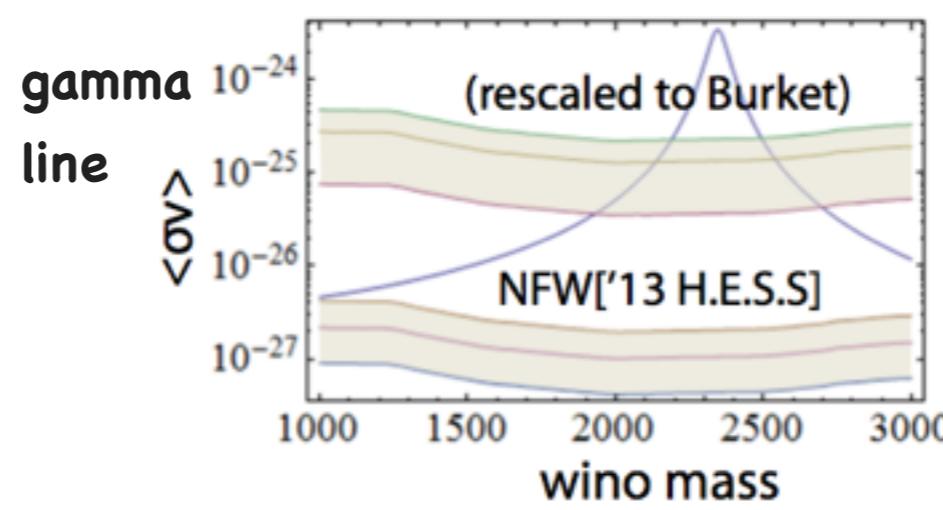
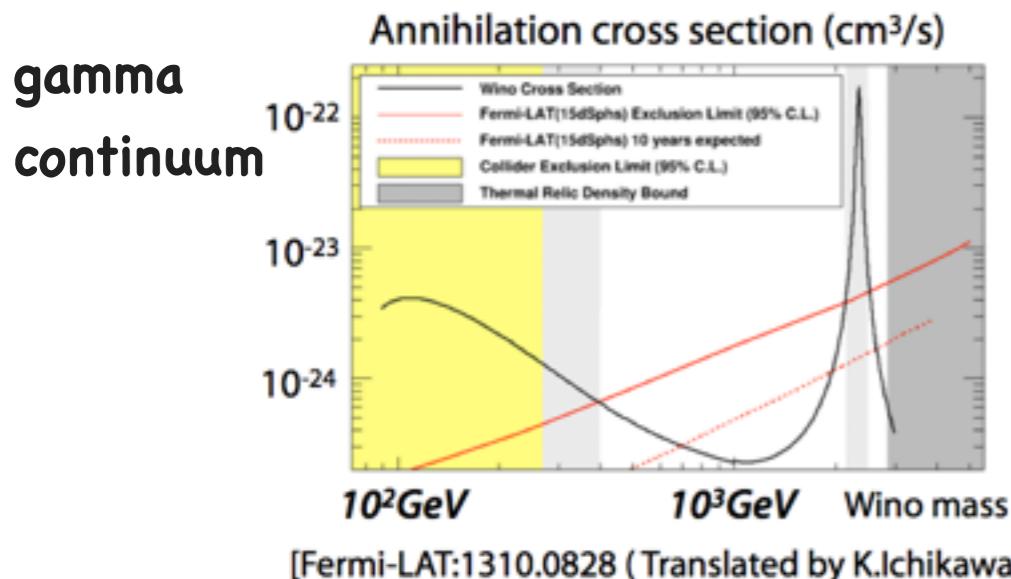
(It's anyway fine-tuned, then....)

Very heavy SUSY

Typical DM = Wino DM
(AMSB)



- ▶ if thermal relic,... 2.7 TeV
(>> LHC reach) (Hisano,Matsumoto,Nagai,Saito,Senami'07)
- ▶ if non-thermal, it can be lighter.
- ▶ indirect DM signal expected !



[Figure by S.Matsumoto]

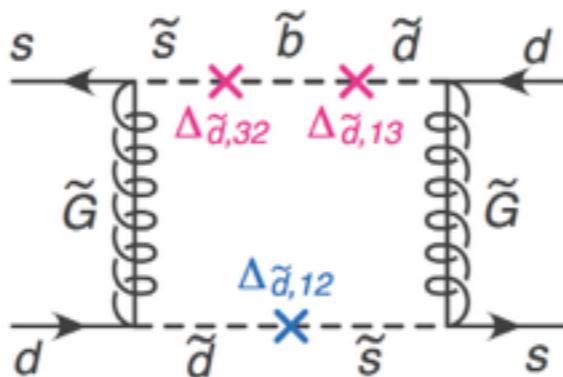
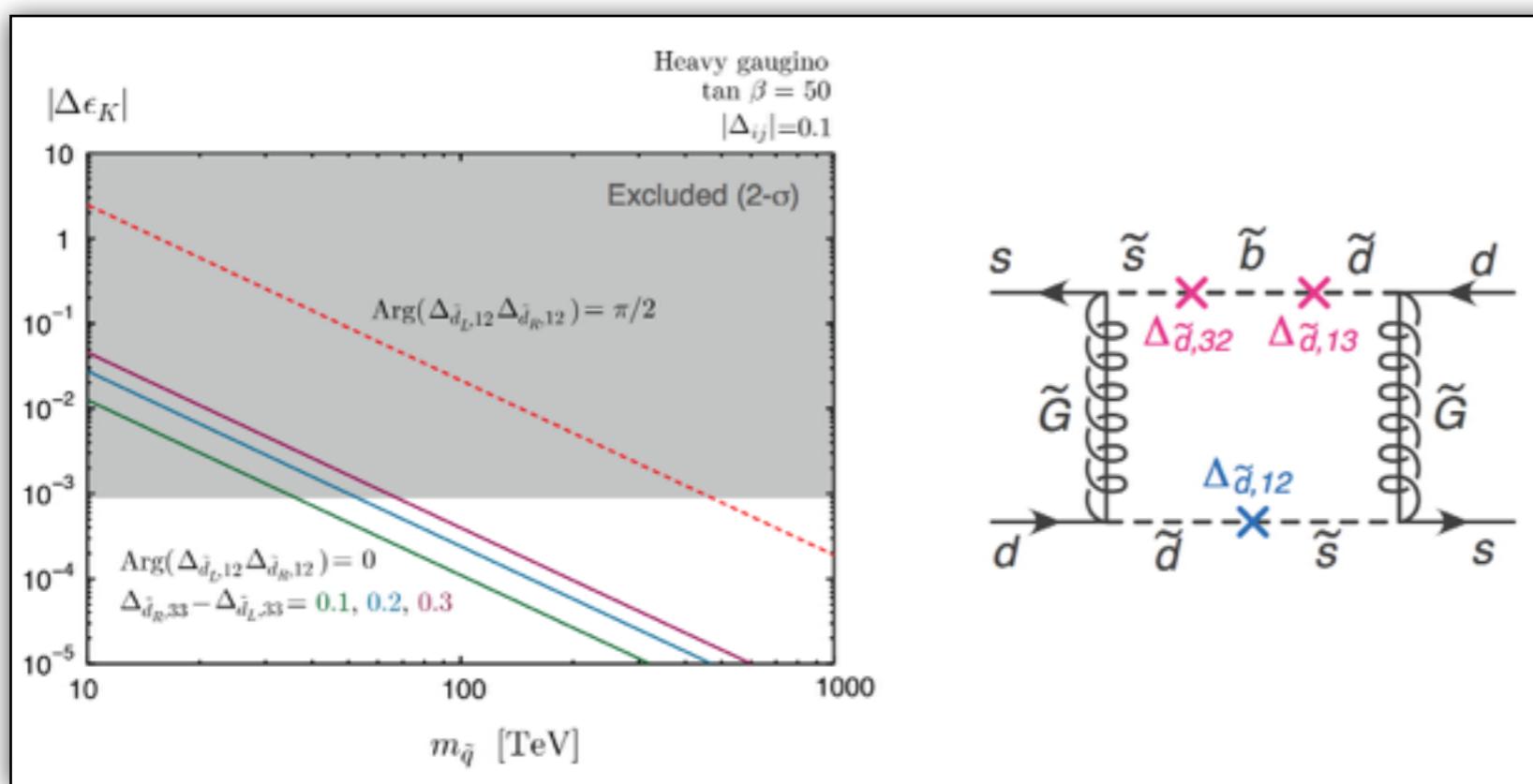
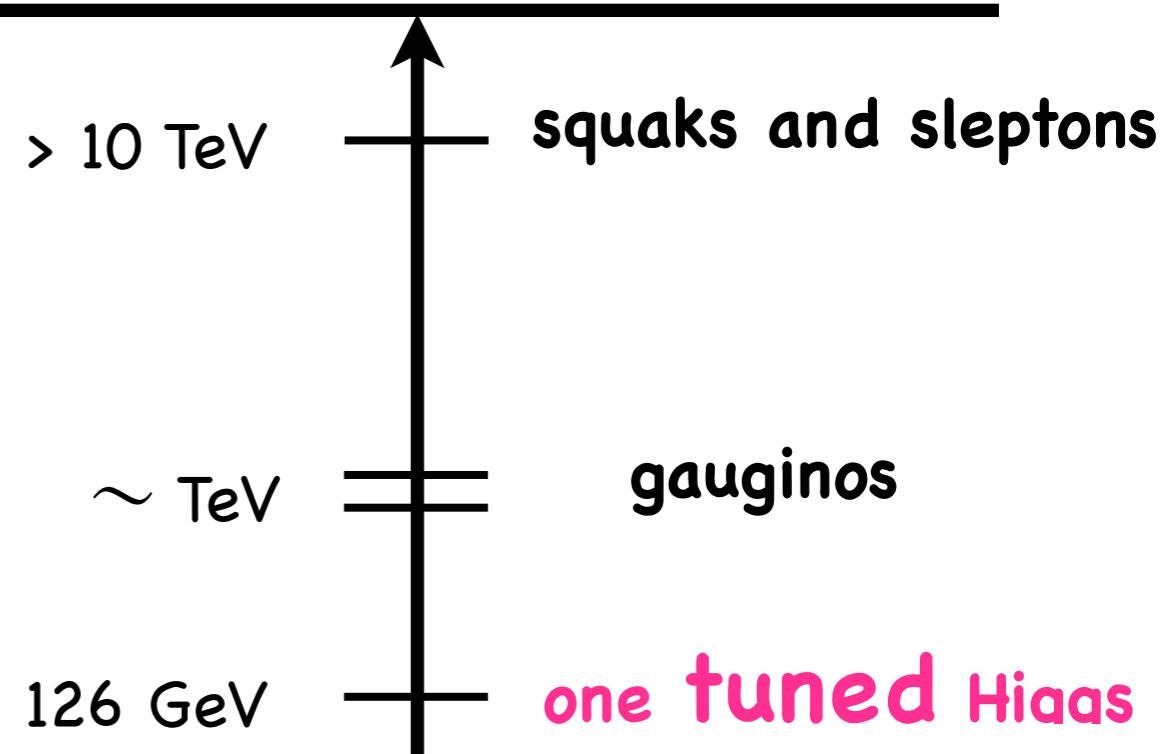
Figures from talk by
M.Ibe at KIAS workshop,
October 2014.

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Very heavy SUSY

**Flavor Physics
can probe it !**



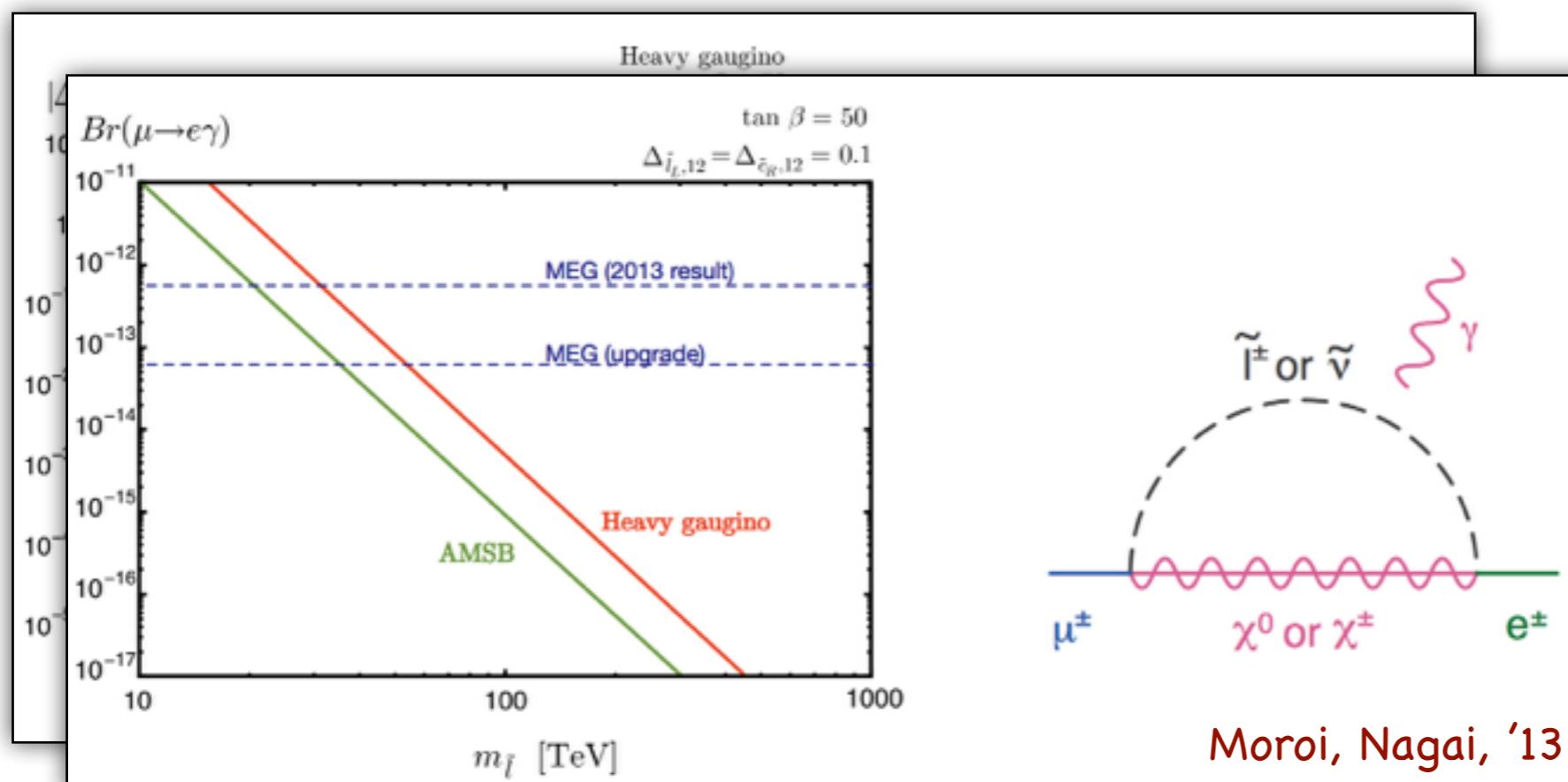
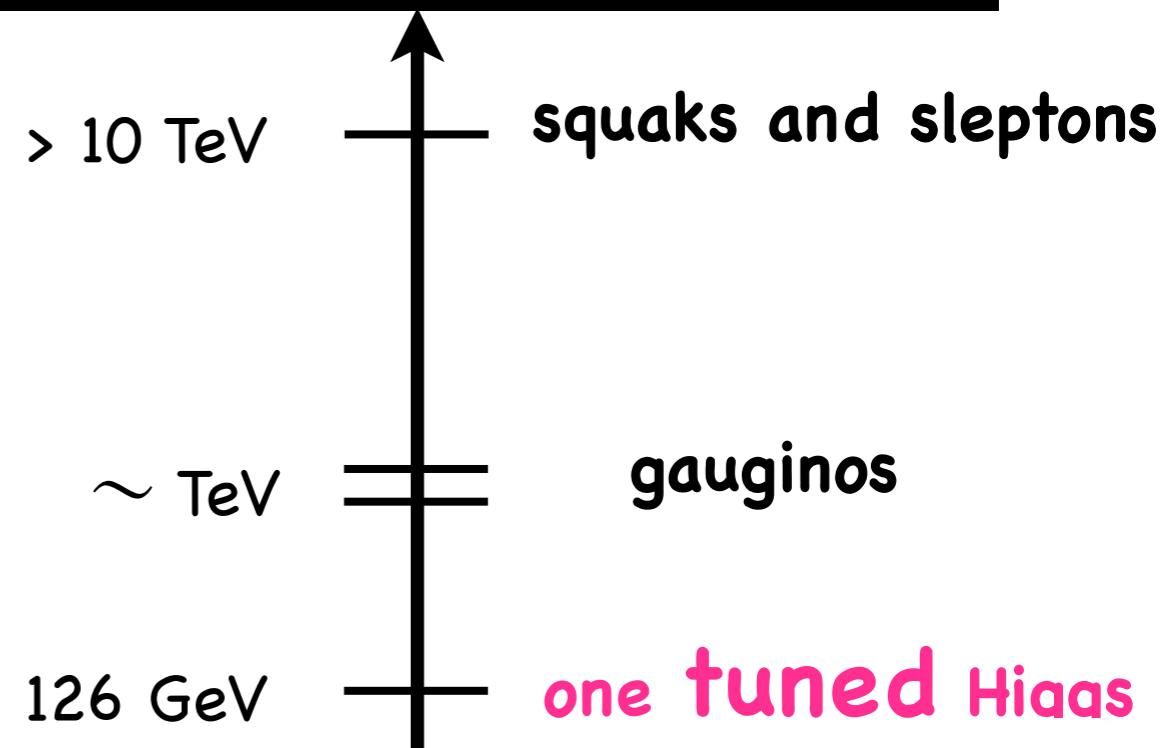
Figures from talk by
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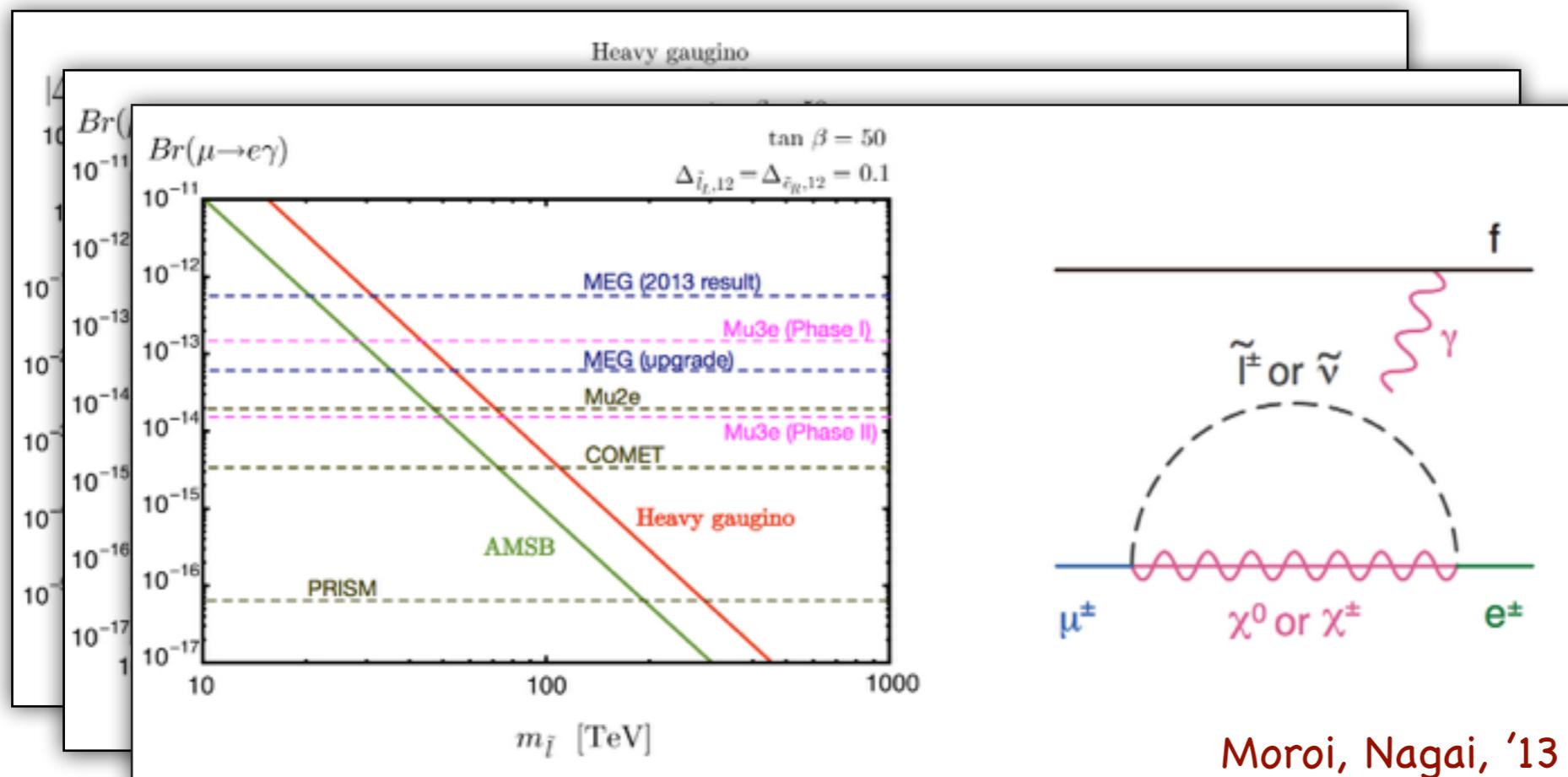
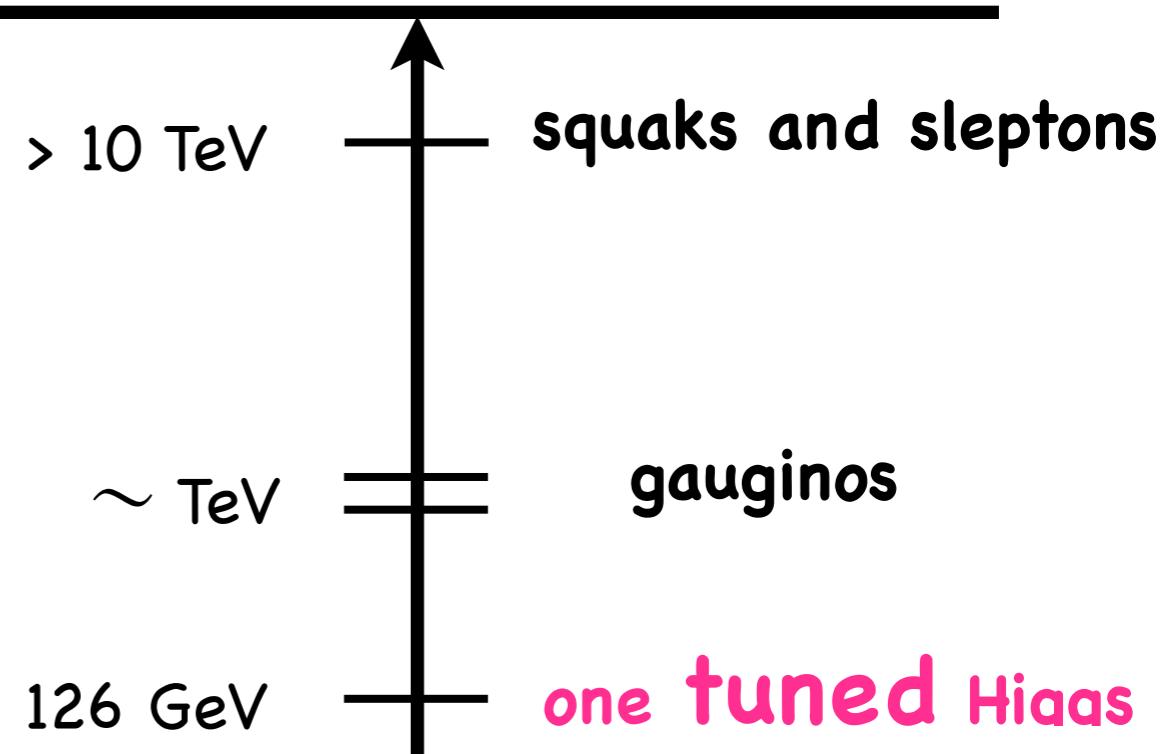
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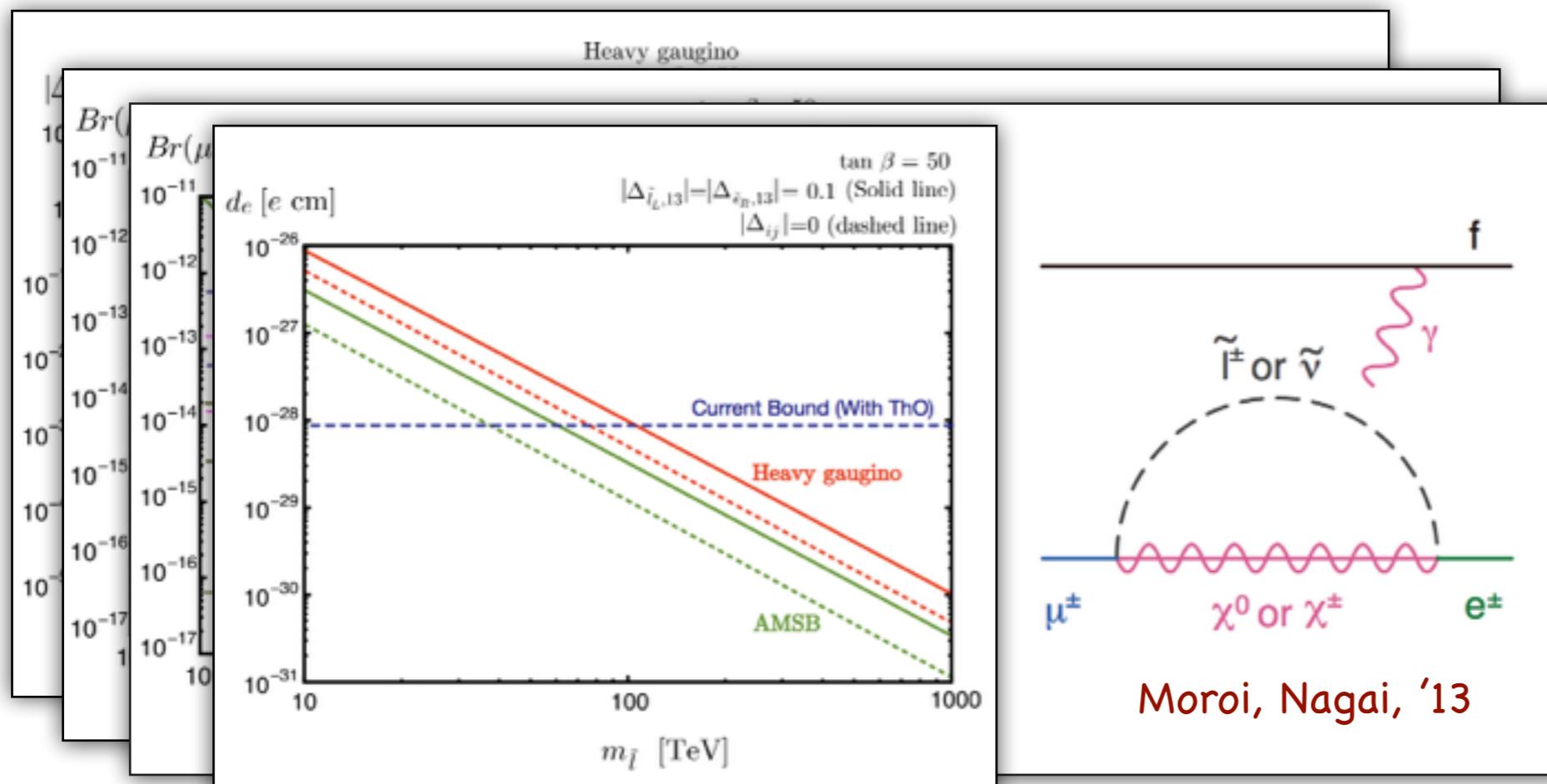
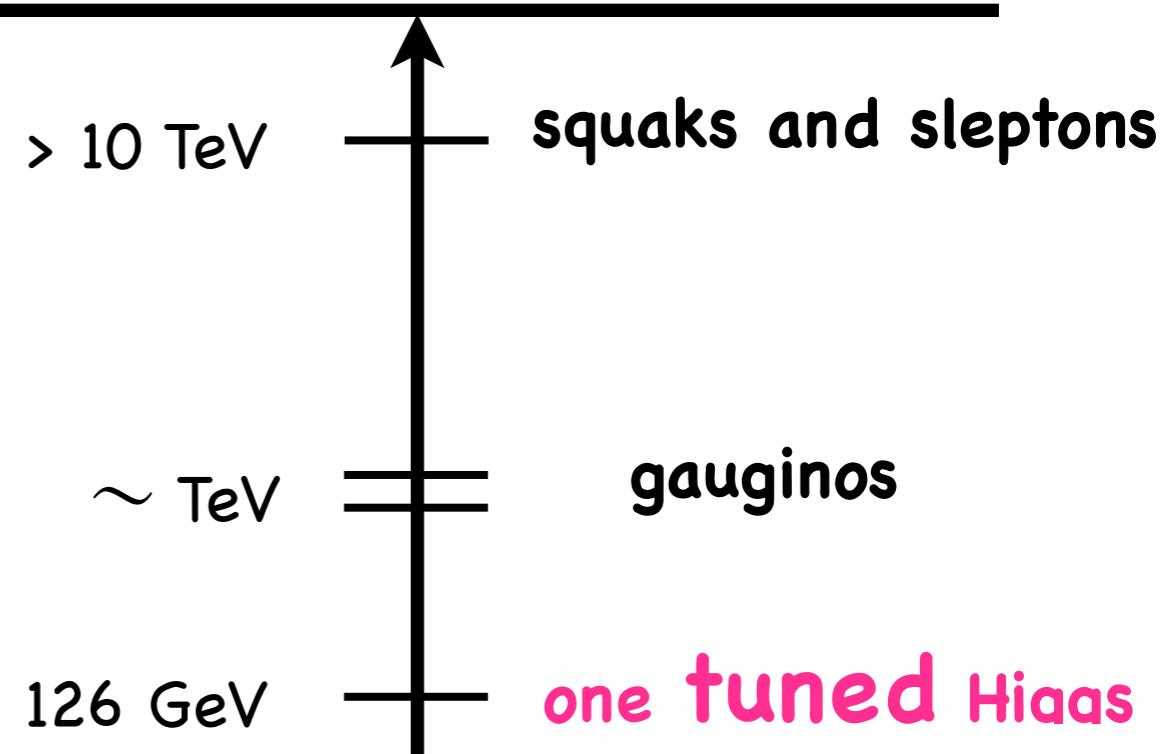
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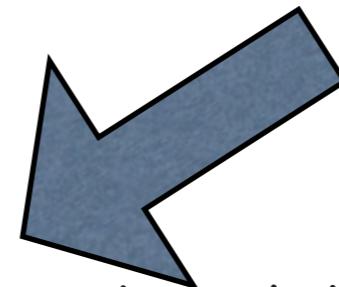
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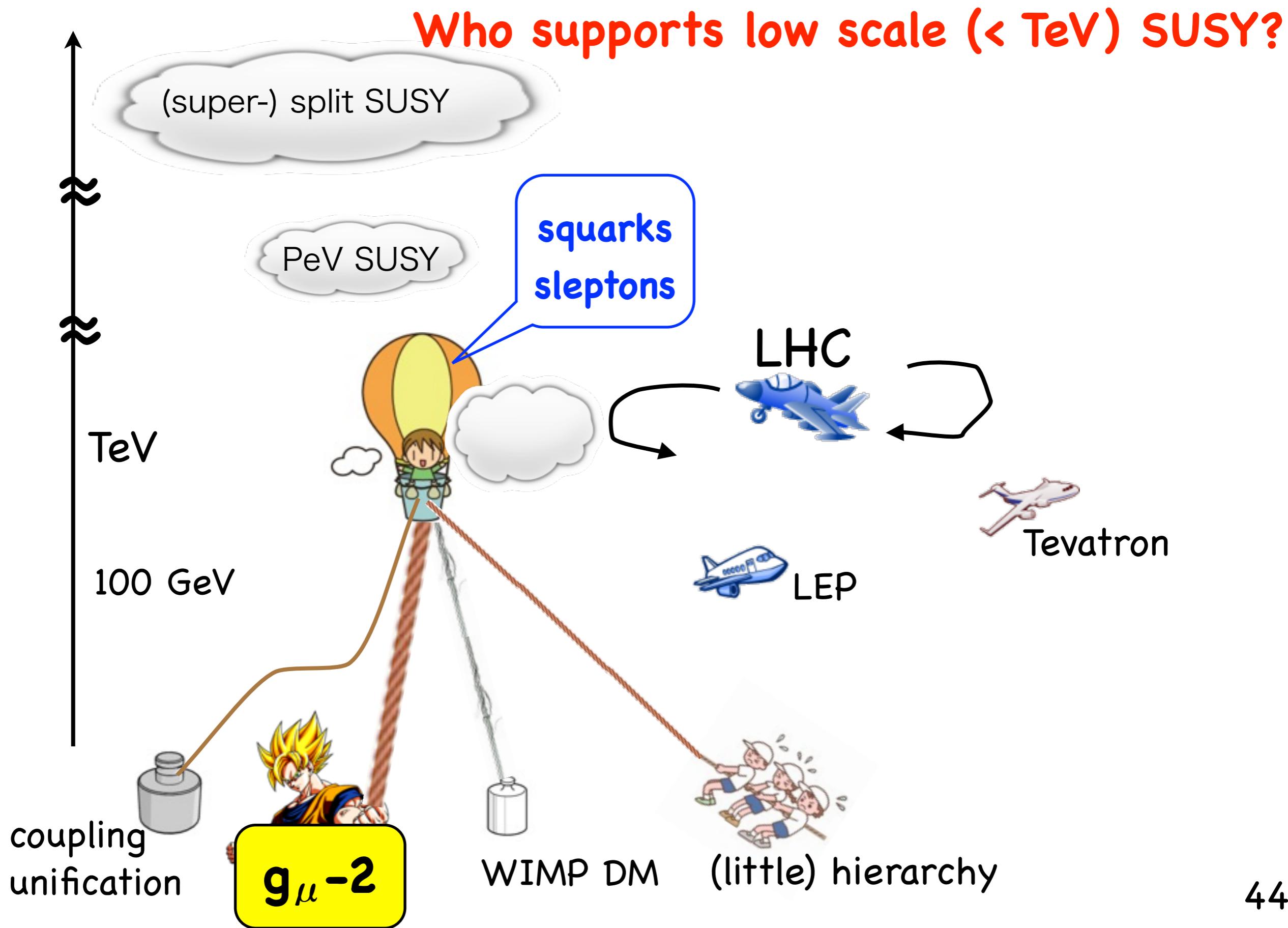
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one more motivation for TeV scale SUSY...

muon g-2

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

> 3σ deviation !

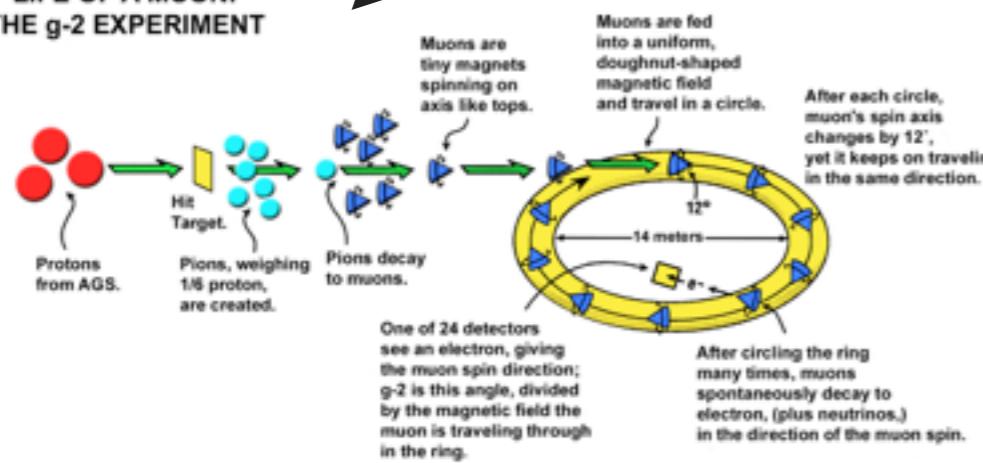
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LIFE OF A MUON:
THE g-2 EXPERIMENT



from E821 muon g-2 Home Page

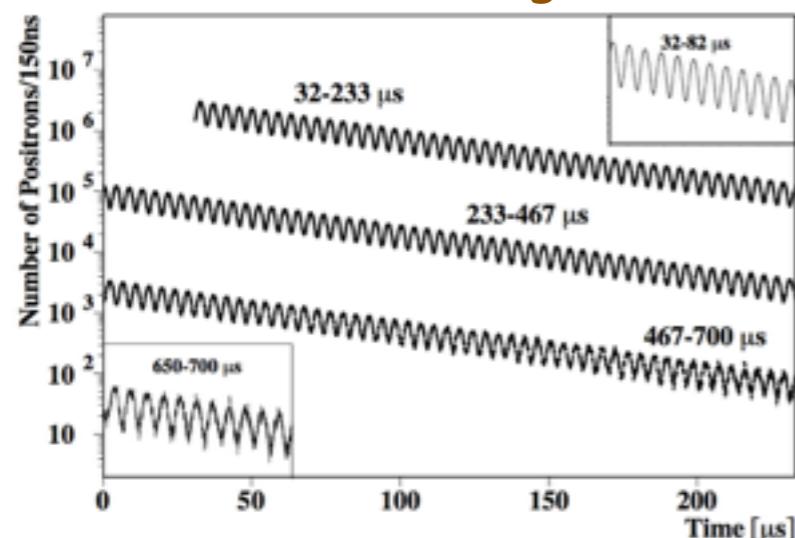


FIG. 3. Positron time spectrum overlaid with the fitted 10 parameter function ($\chi^2/\text{dof} = 3818/3799$). The total event sample of $0.95 \times 10^9 e^+$ with $E \geq 2.0 \text{ GeV}$ is shown.

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)*	γ
	[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

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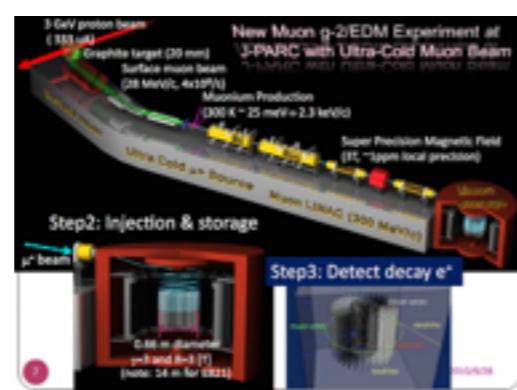
> 3 σ deviation !

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

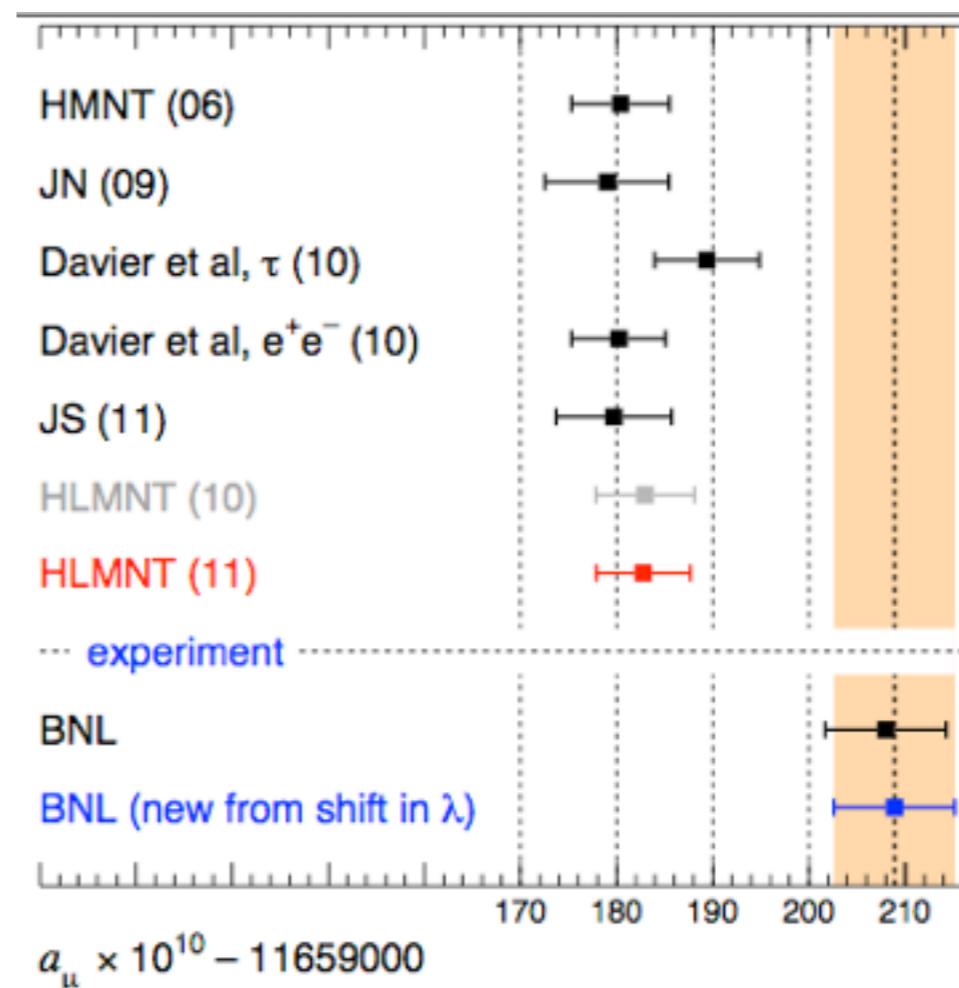
New experiments also planned.



FermiLab Muon g-2



J-PARC g-2/EDM

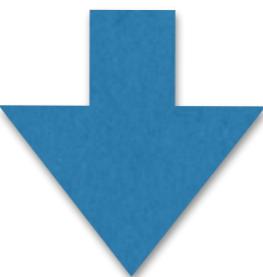


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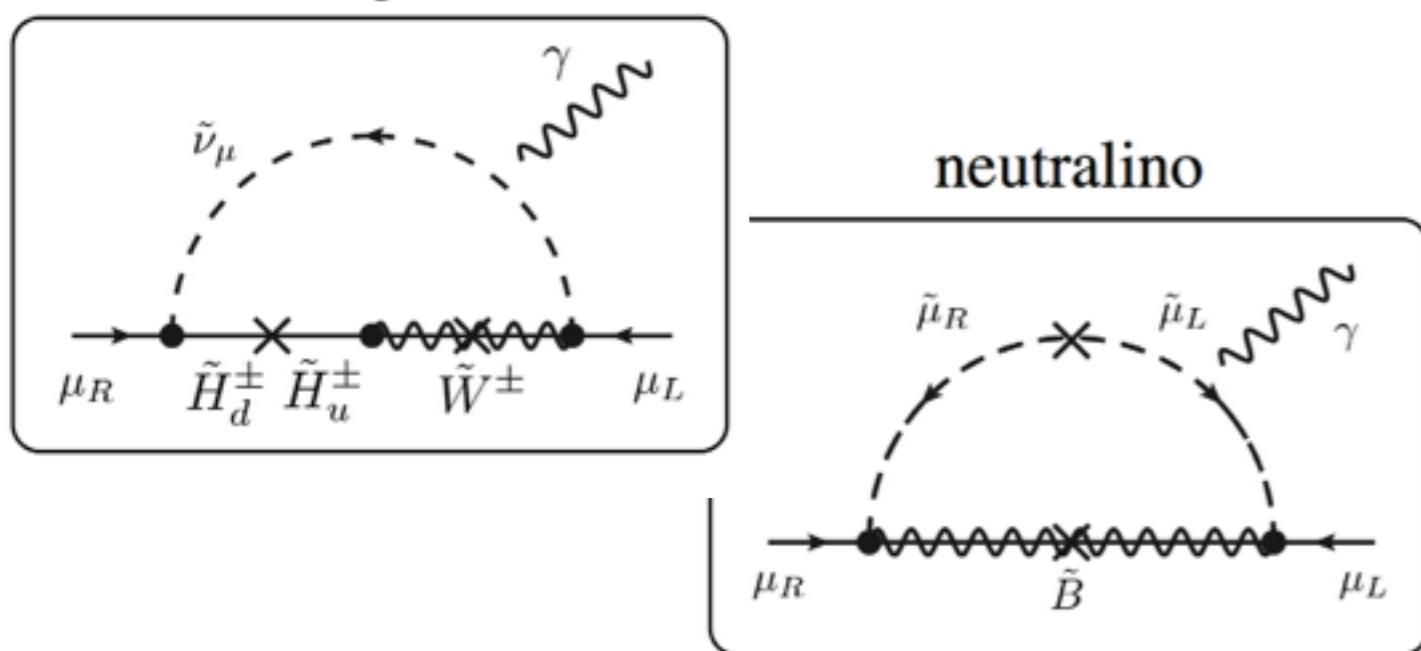
$$a_{\mu}^{\text{EXP}} - a_{\mu}^{\text{SM}} = (26.1 \pm 8.0) \cdot 10^{-10}$$

> 3σ deviation !



...can be explained by SUSY.

chargino



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

126 GeV Higgs + SUSY + $g_\mu - 2$

heavy stop

light smuon/ inos

difficult to reconcile in typical models

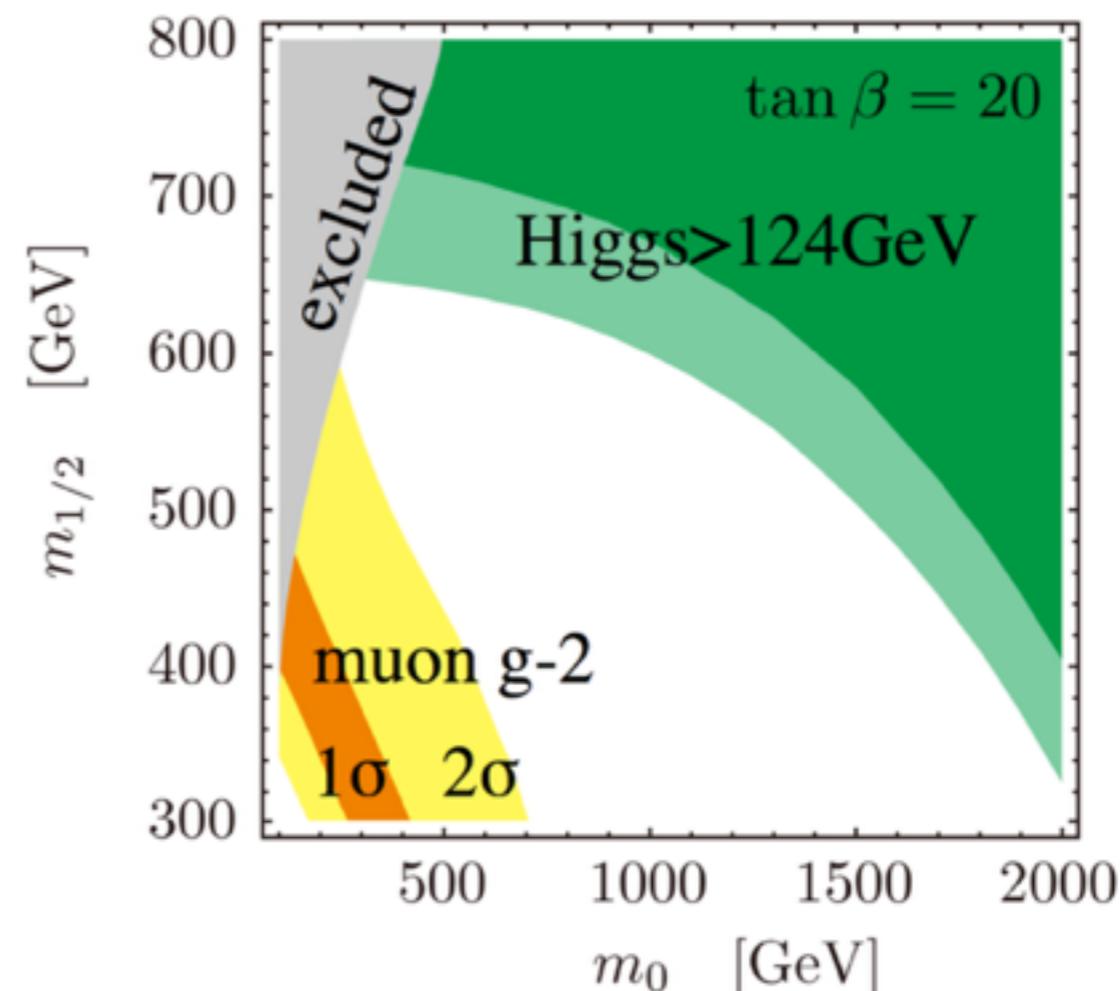
(mSUGRA/GMSB/AMSB/NMSSM (small $\tan\beta$) ...)

Example in CMSSM/mSUGRA:

Higgs mass is maximized by A-term,
while $b \rightarrow s\gamma$ constraint is satisfied.

(Figure thanks to Motoi Endo.)

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



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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 matter

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 + SUSY + $g_\mu - 2$

MSSM + vector-like matter

Idea:

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

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

$$\begin{aligned} \delta m_{\text{Higgs}}^2 &\propto \lambda_H (\simeq 0.13) \\ &= \lambda_H^{(\text{tree})} + \delta \lambda_H^{(\text{loop})} \end{aligned}$$

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



126 GeV Higgs + SUSY + $g_\mu - 2$

MSSM + vector-like matter

Idea:

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

--> Add new vector-like matters

with a Yukawa coupling to Higgs.

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

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

$$\delta m_{\text{Higgs}}^2 \propto \lambda_H (\simeq 0.13)$$

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

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

$$+ Y'^4 \cdot (\text{new vector-loop})$$



126 GeV Higgs + SUSY + $g_\mu - 2$

Results

for "V-GMSB"

= gauge mediation (GMSB) + vector-like matter

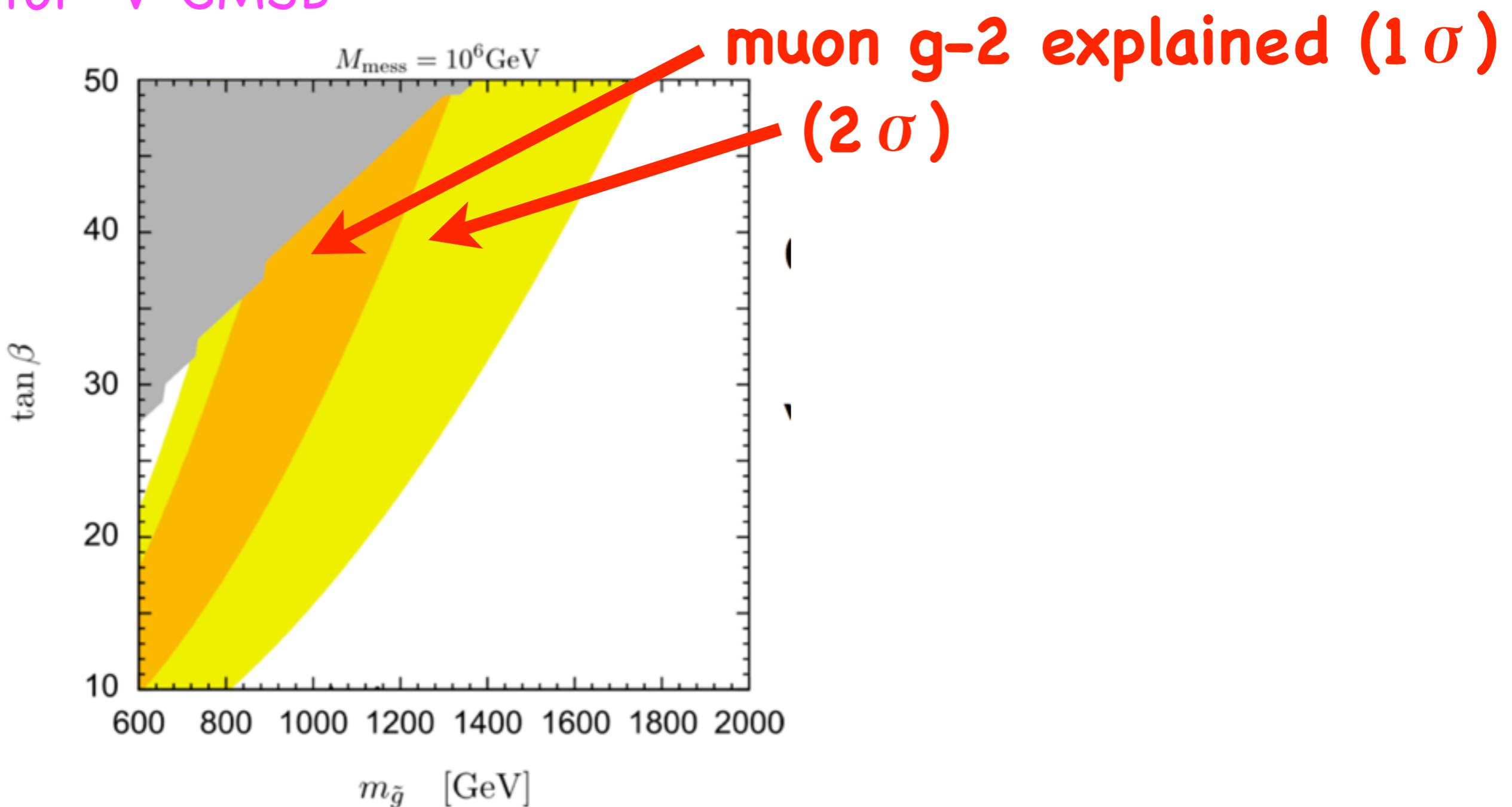
M.Endo, KH, K.Ishikawa, S.Iwamoto, N.Yokozaki, arXiv:1212.3935

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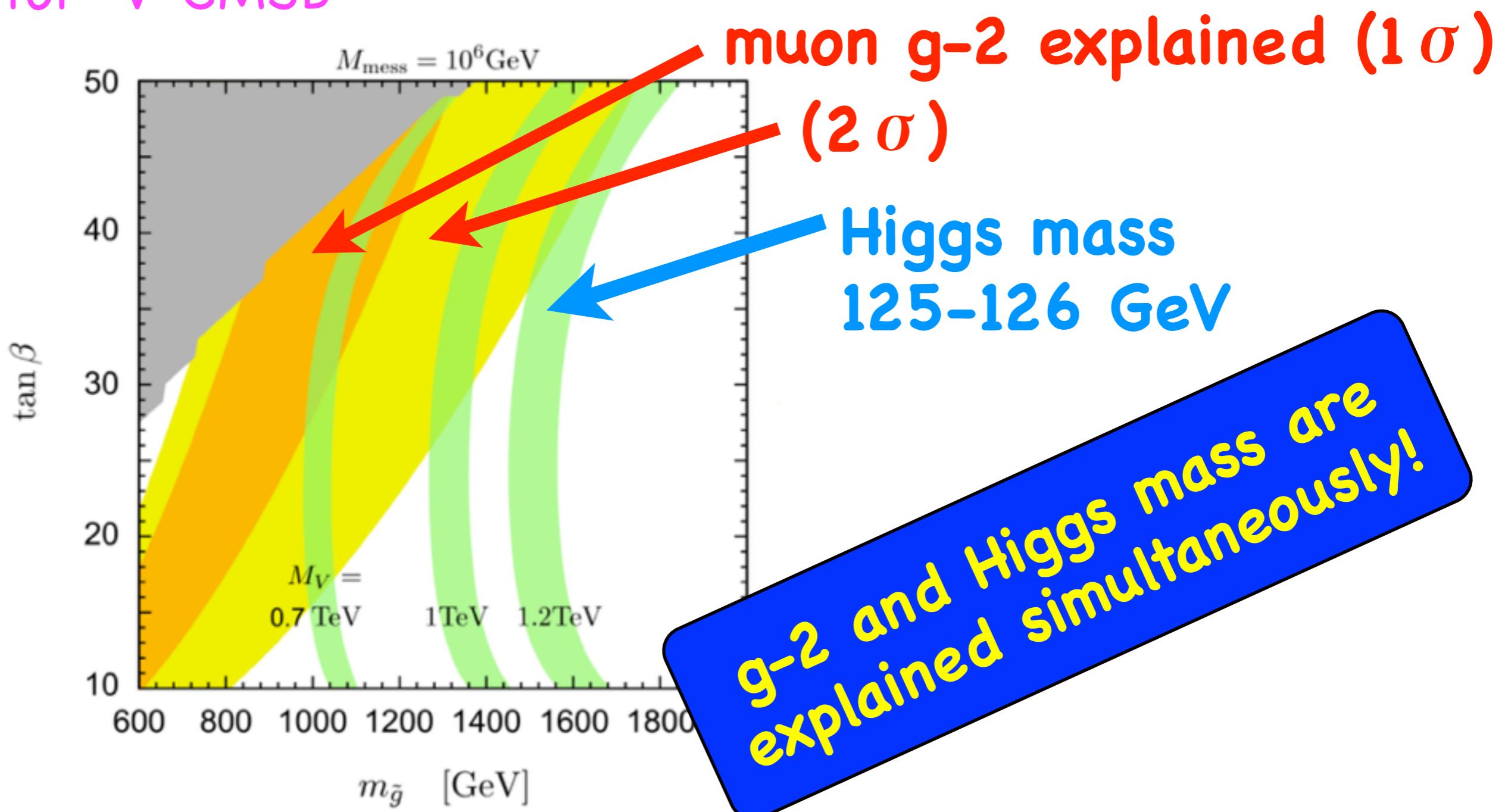


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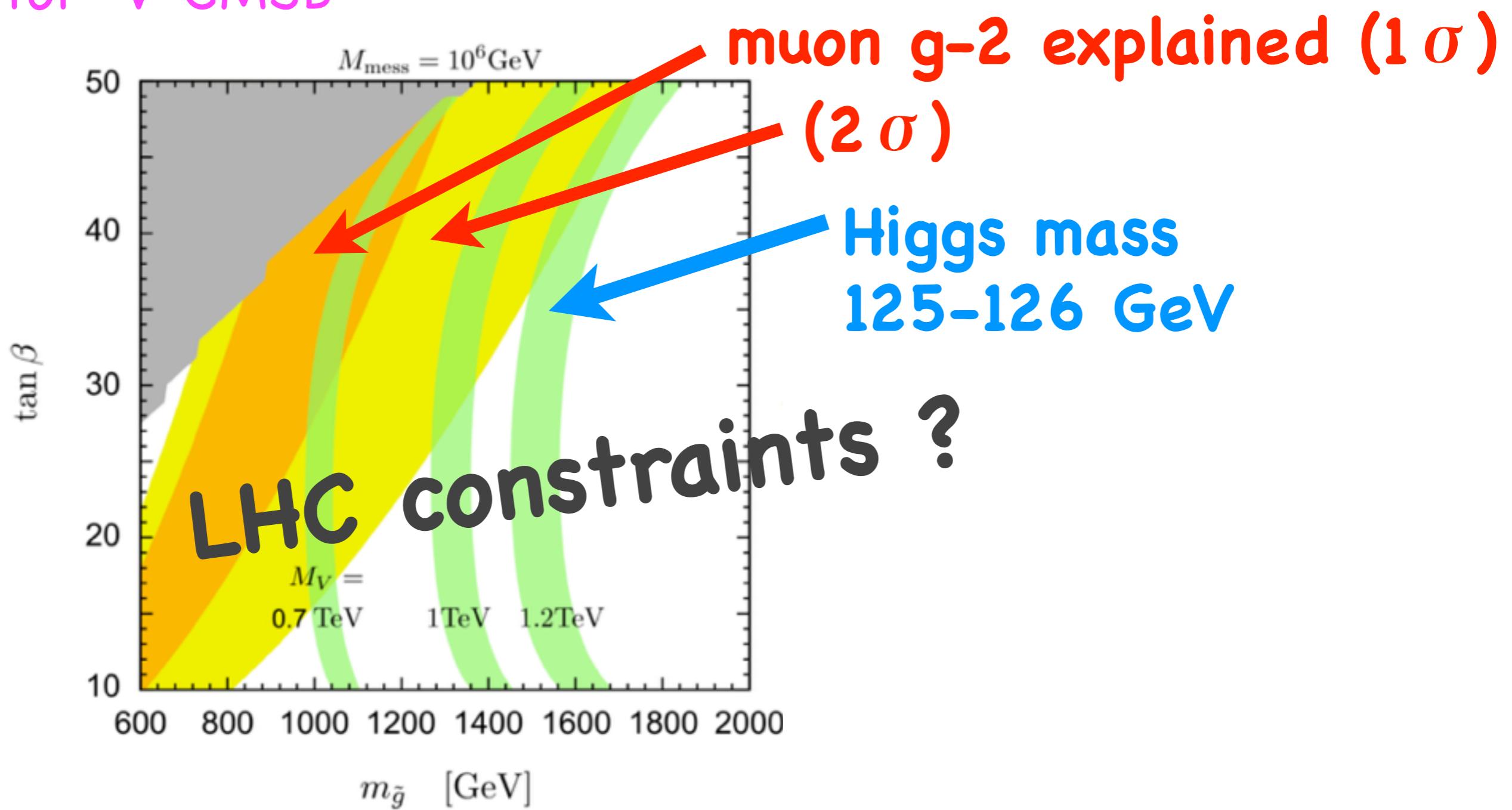


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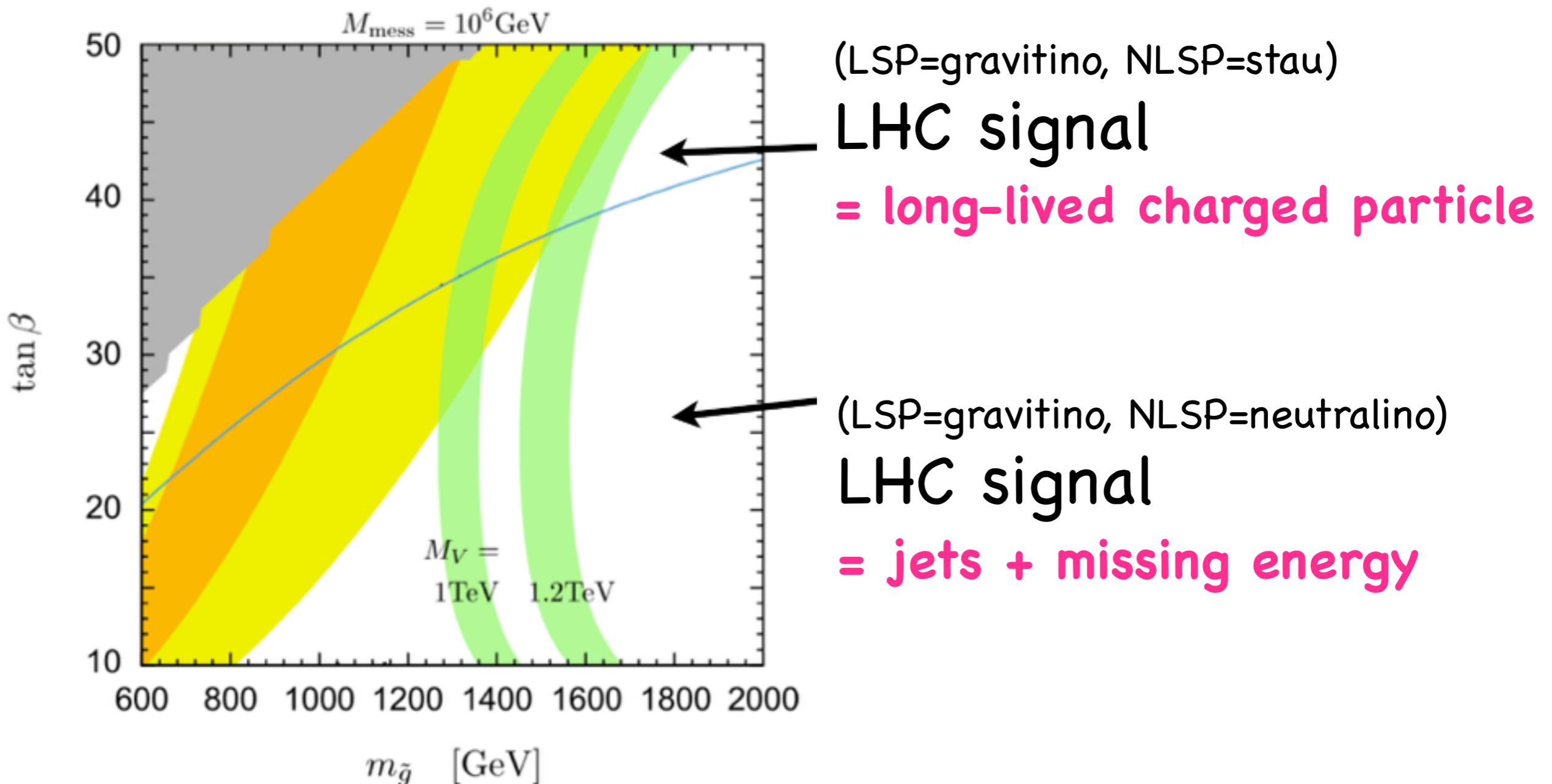


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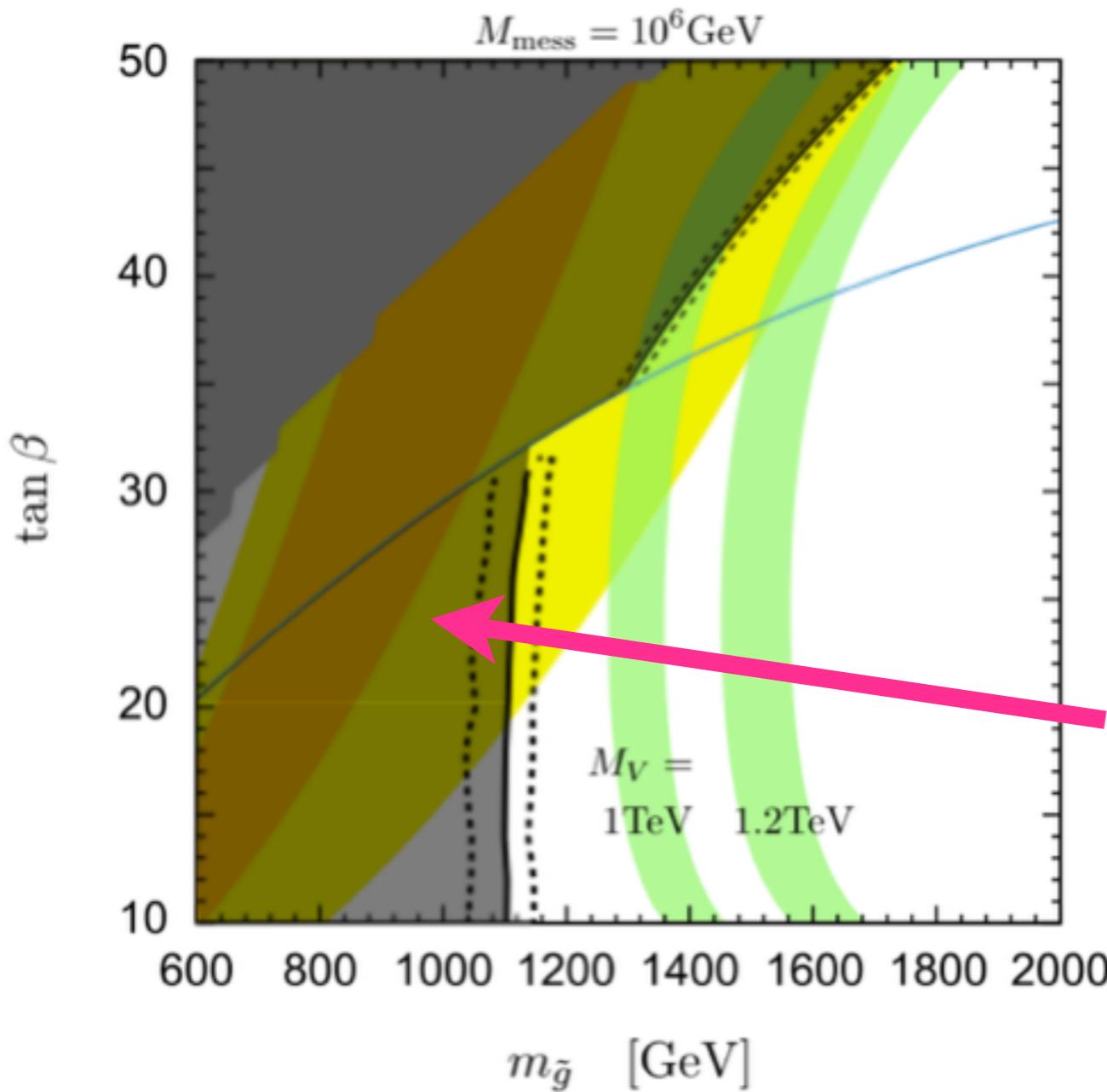
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M.Endo, KH, K.Ishikawa, S.Iwamoto, N.Yokozaki, arXiv:1212.3935

New LHC results
were reported
after our analysis.

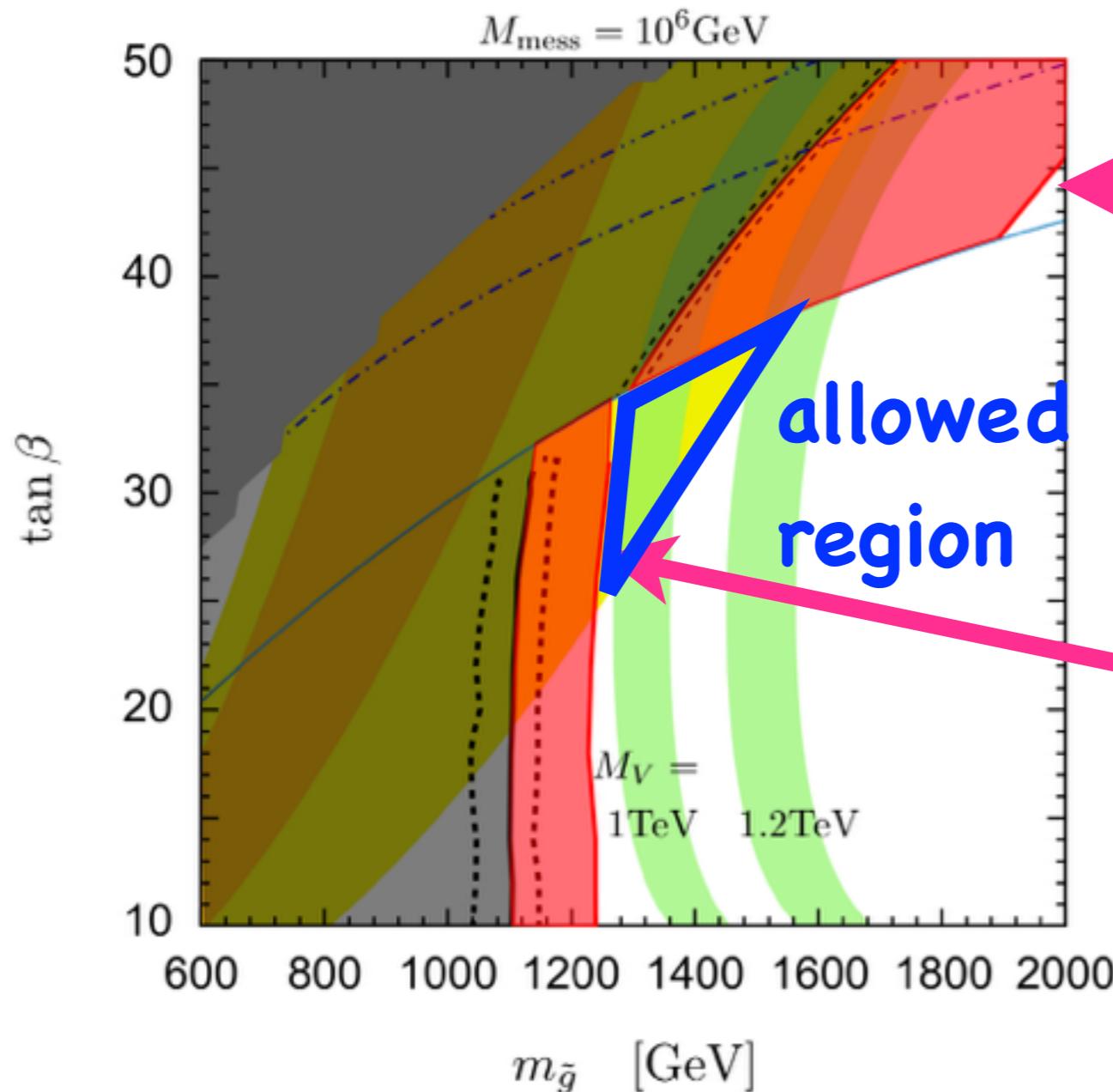
already
excluded

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

126 GeV Higgs + SUSY + $g_\mu - 2$

Results

for "V-GMSB"



Now...

The region of long-lived charged particle is completely excluded.
(CMS: $m(\text{stau}) > 339 \text{ GeV}$ with Drell-Yang direct)

jets + missing energy region is still allowed.
 $8 \text{ TeV } 20 \text{ fb}^{-1}$
[ATLAS-CONF-2013-047]

New analysis: thanks to Kazuya Ishikawa.

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

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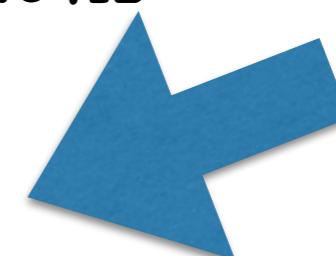
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126 GeV Higgs + SUSY + $g_\mu - 2$

"g-2 motivated" MSSM

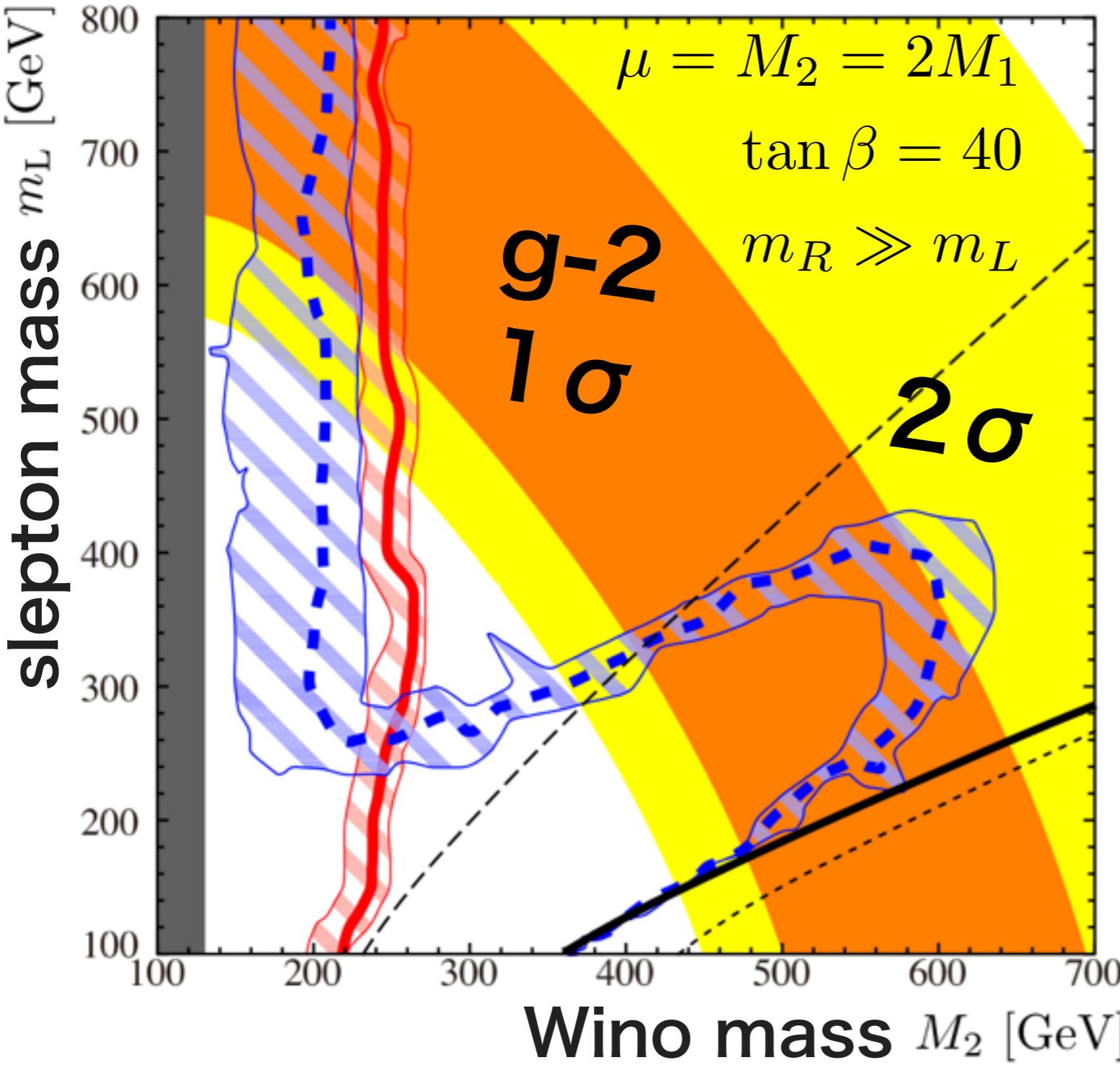
$$m_{\tilde{q}} \gg m_{\tilde{\ell}}, m_{\tilde{\chi}^\pm}, m_{\tilde{\chi}^0},$$


 $\gg 1 \text{ TeV}$
to explain
Higgs mass


 $= O(100 \text{ GeV})$
to explain muon g-2

Can we test it ??

muon g-2 vs LHC in SUSY

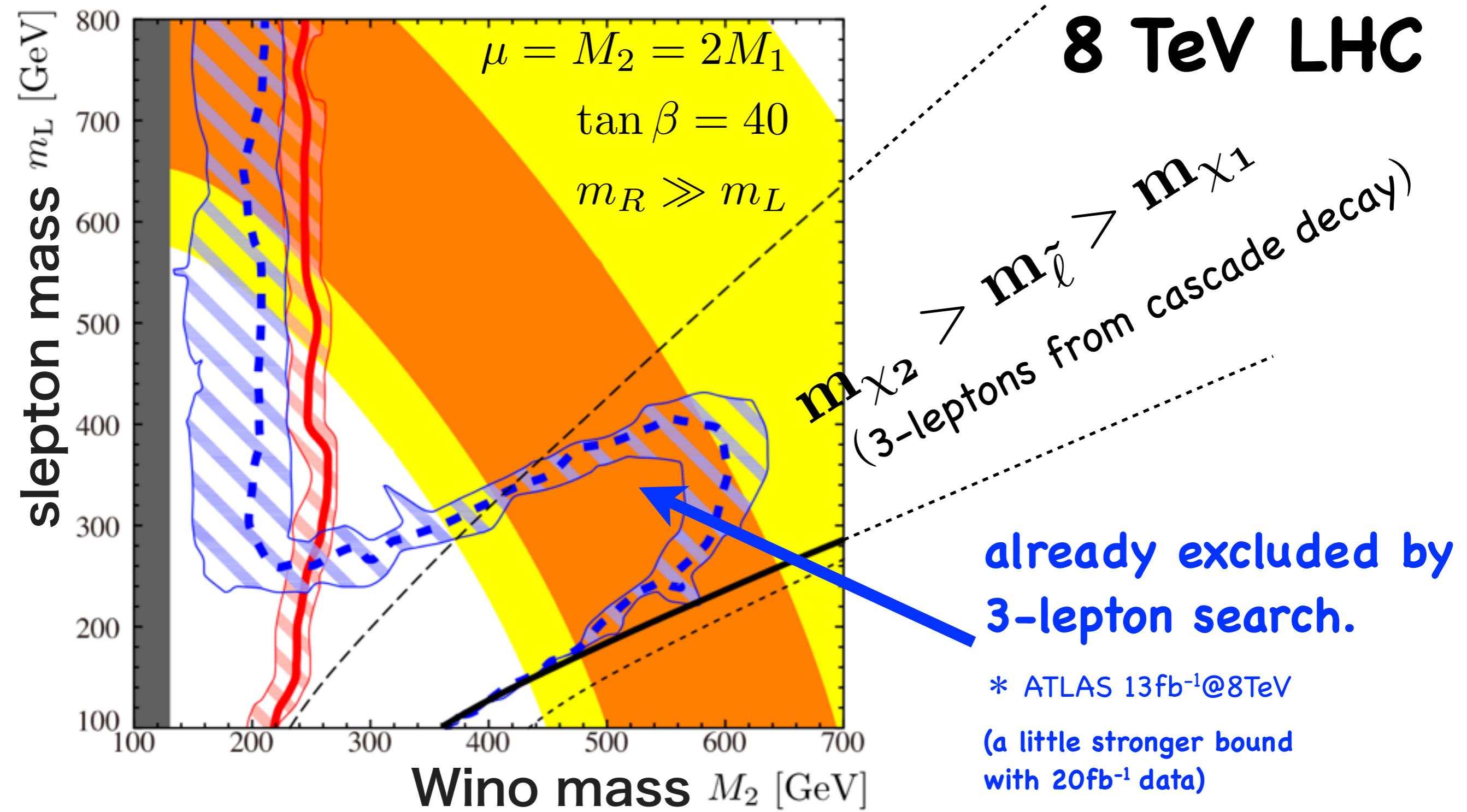


M.Endo, KH, S.Iwamoto, T.Yoshinaga [arXiv:1303.4256]

See also related works, e.g., Das, Guchait, Roy, [1406.6925],

M.Chakraborti, U.Chattpadhyay, A.Choudhury, A.Datta, S.Poddar [1404.4841], and refs therein.

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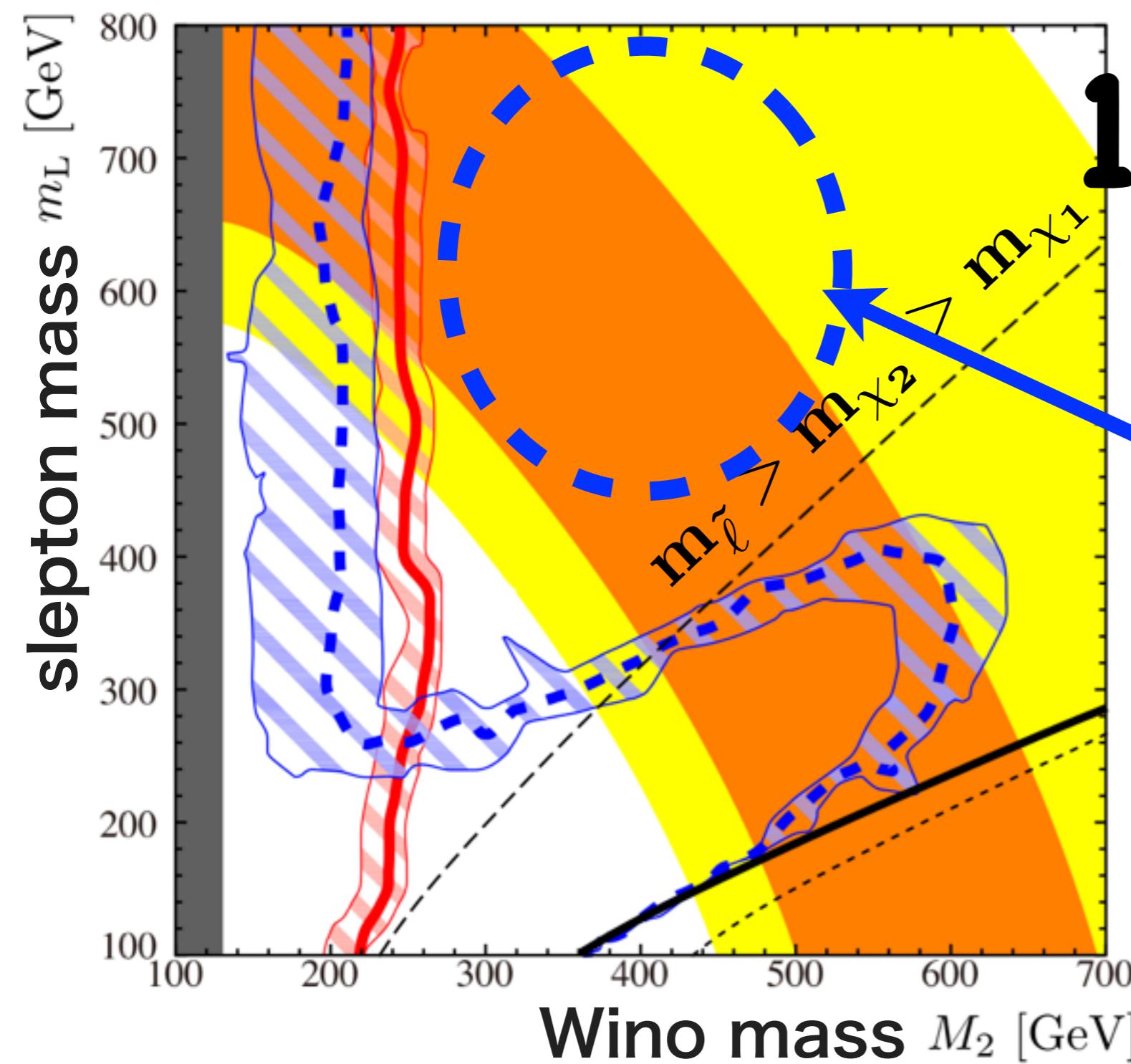


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**13~14 TeV
(2015~)**

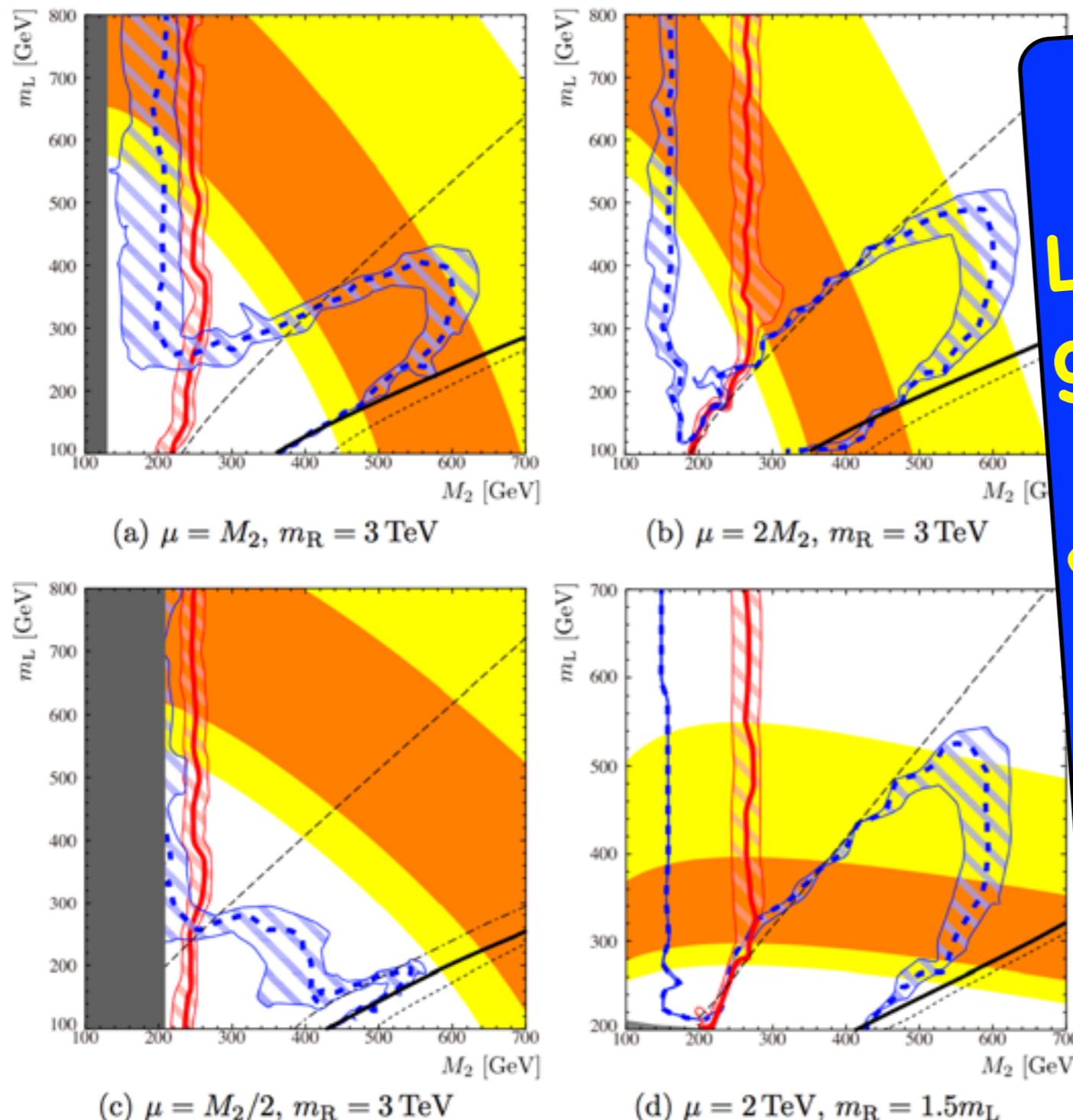
New signals like
 $\chi_2 \rightarrow \chi_1 + W/Z/h$
 may cover
 this region at 13~14 TeV !

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

See also related works, e.g., Das, Guchait, Roy, [1406.6925],

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muon g-2 vs LHC in SUSY



LHC started exclude
g-2 motivated regions !

- 13-14 TeV LHC will test more regions.
- If discovered at LHC,
--> further test may be possible at ILC

M.Endo, KH, S.Iwamoto, T.Yoshinaga [arXiv:13]

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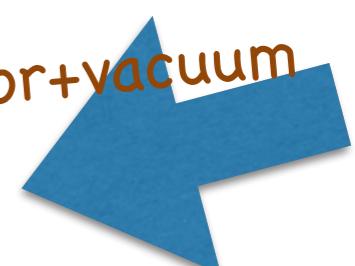
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M.Endo, KH, S.Iwamoto, T.Yoshinaga, arXiv:1303.4256 LHC

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



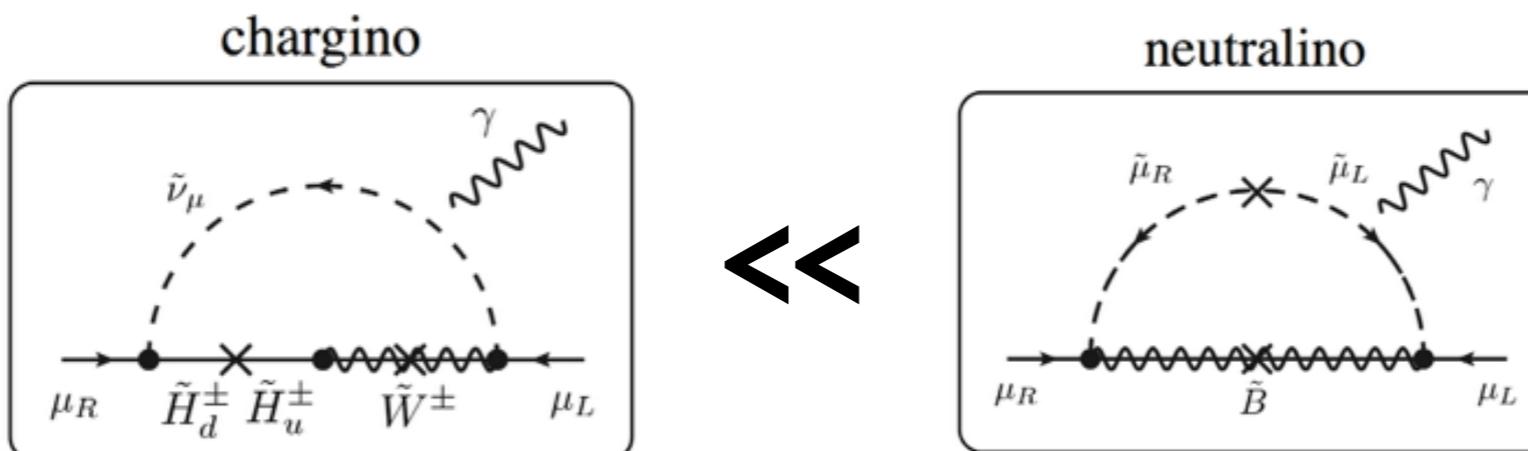
muon g-2 vs ILC

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{l} denotes selectrons and smuons.

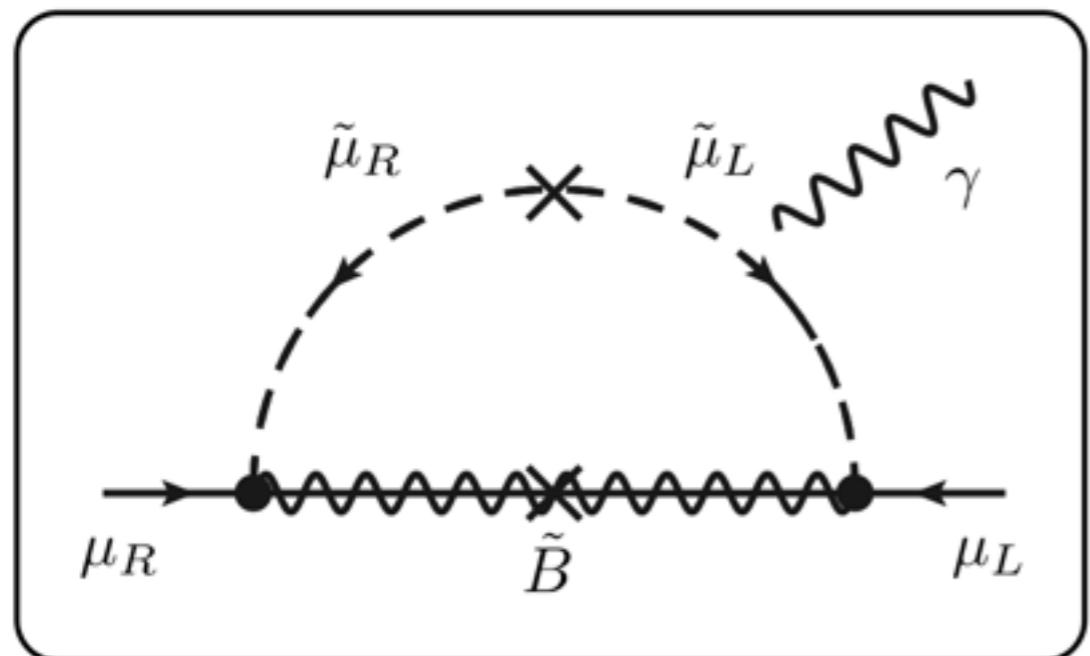
Parameters	$m_{\tilde{e}_1}$	$m_{\tilde{e}_2}$	$m_{\tilde{\tau}_1}$	$m_{\tilde{\tau}_2}$	$m_{\tilde{\chi}_1^0}$	$\sin \theta_{\tilde{\mu}}$	$a_\mu^{(\text{ILC})}$
Values	126	200	108	210	90	0.027	2.6×10^{-9}



this one
dominates

muon g-2 vs ILC

neutralino



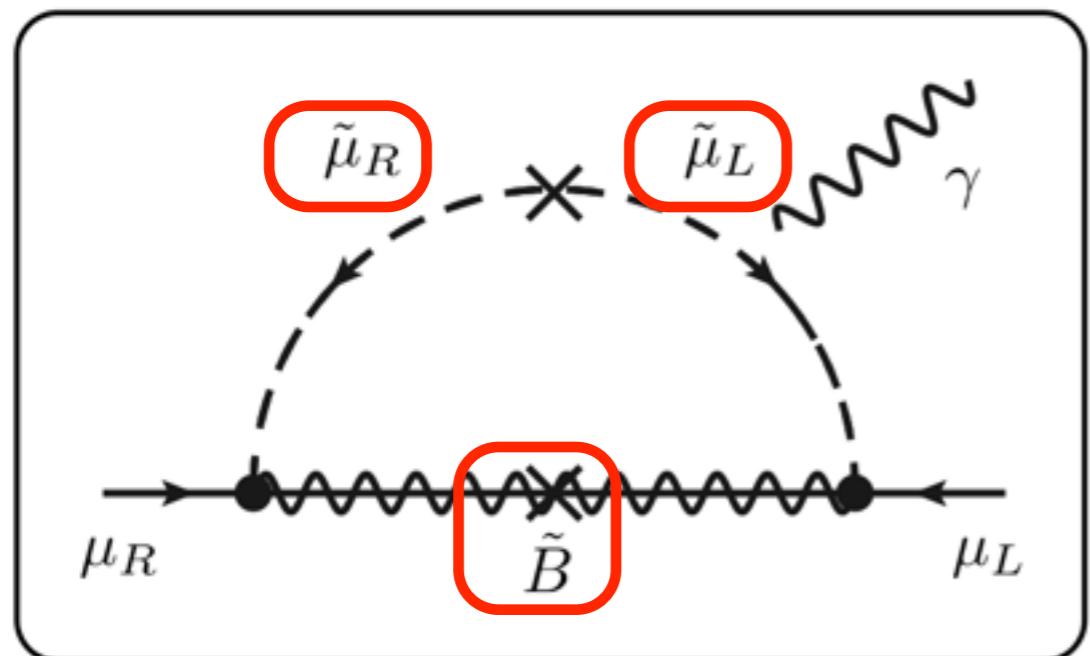
Can we reconstruct the contribution of this loop-diagram by using ILC measurements?

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

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

muon g-2 vs ILC

neutralino



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

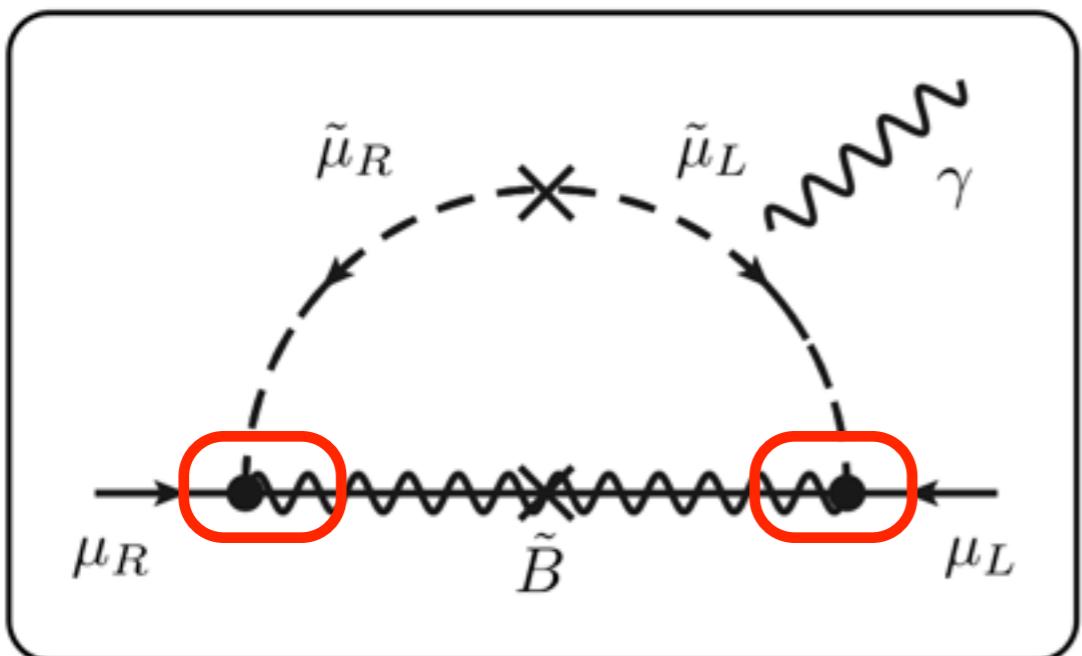
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particle
masses

muon g-2 vs ILC

neutralino

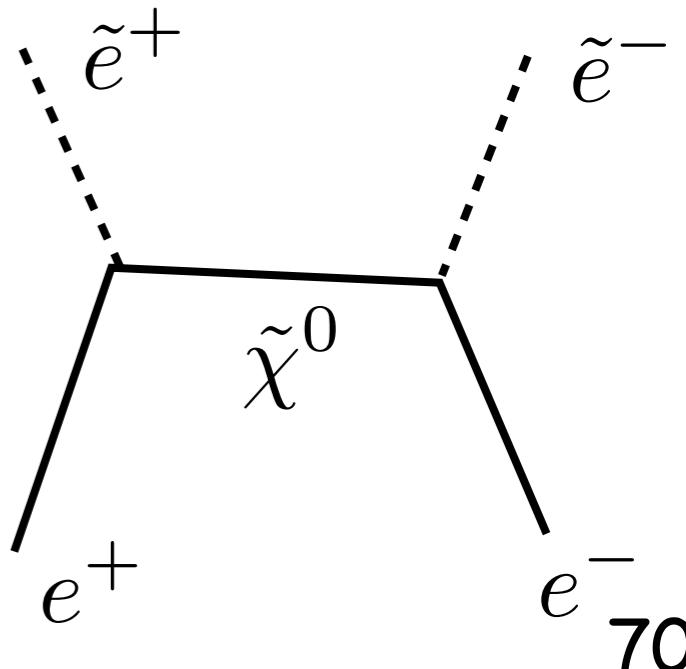


Can we reconstruct the contribution of this loop-diagram by using ILC measurements?

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

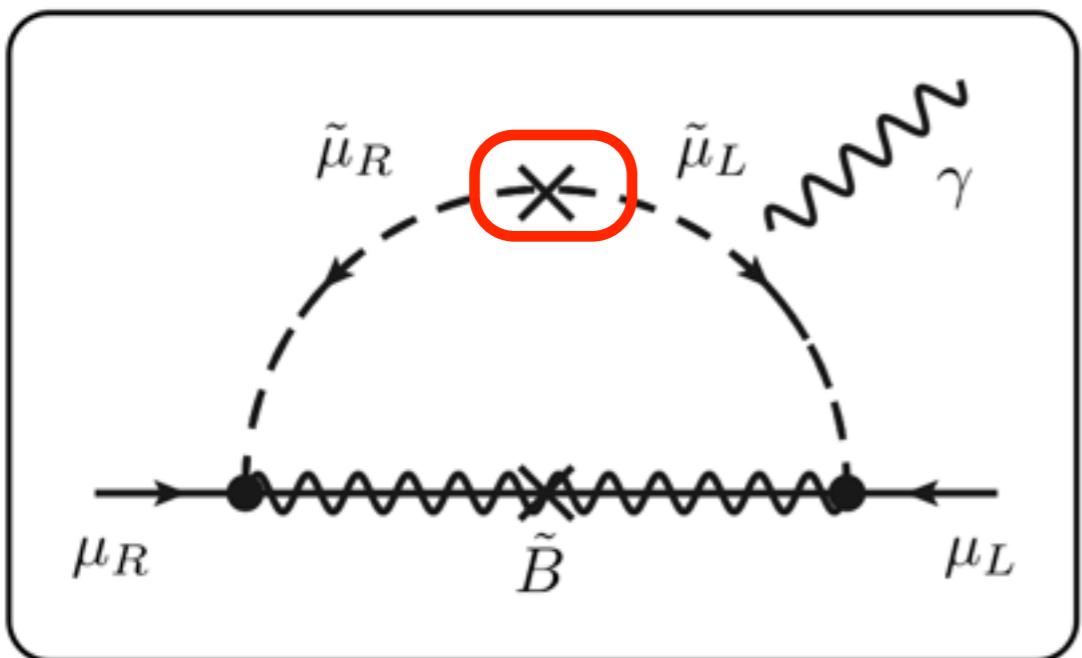
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couplings



muon g-2 vs ILC

neutralino



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

mixing can also be reconstructed

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

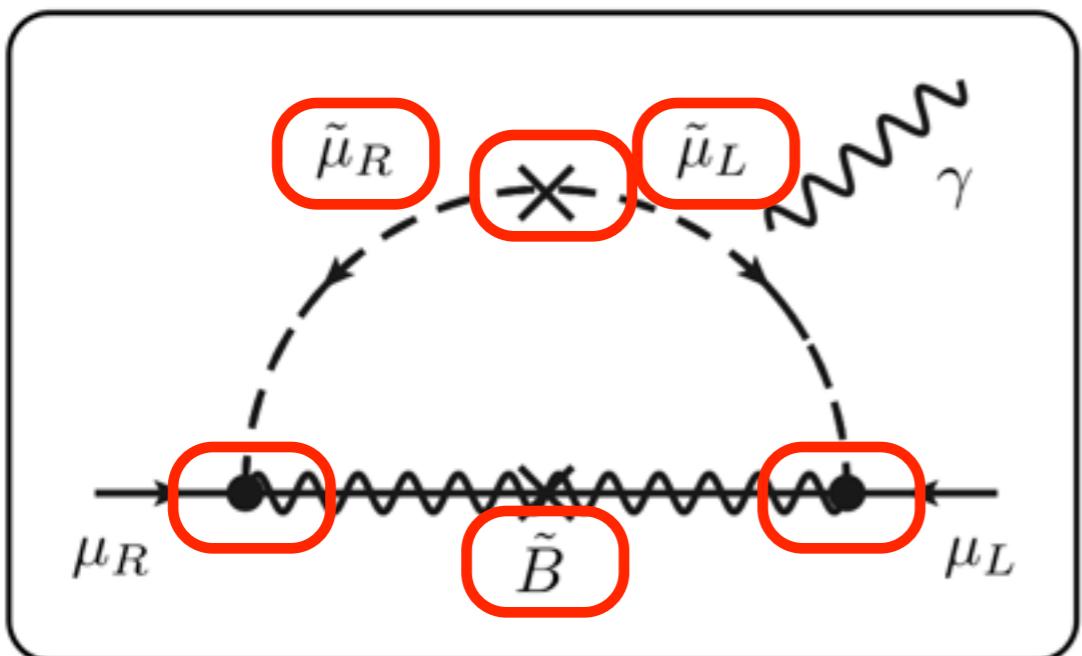
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$$m_{\tilde{\mu}LR}^2 = \frac{m_\mu}{m_\tau} m_{\tilde{\tau}LR}^2.$$

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

muon g-2 vs ILC

neutralino



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

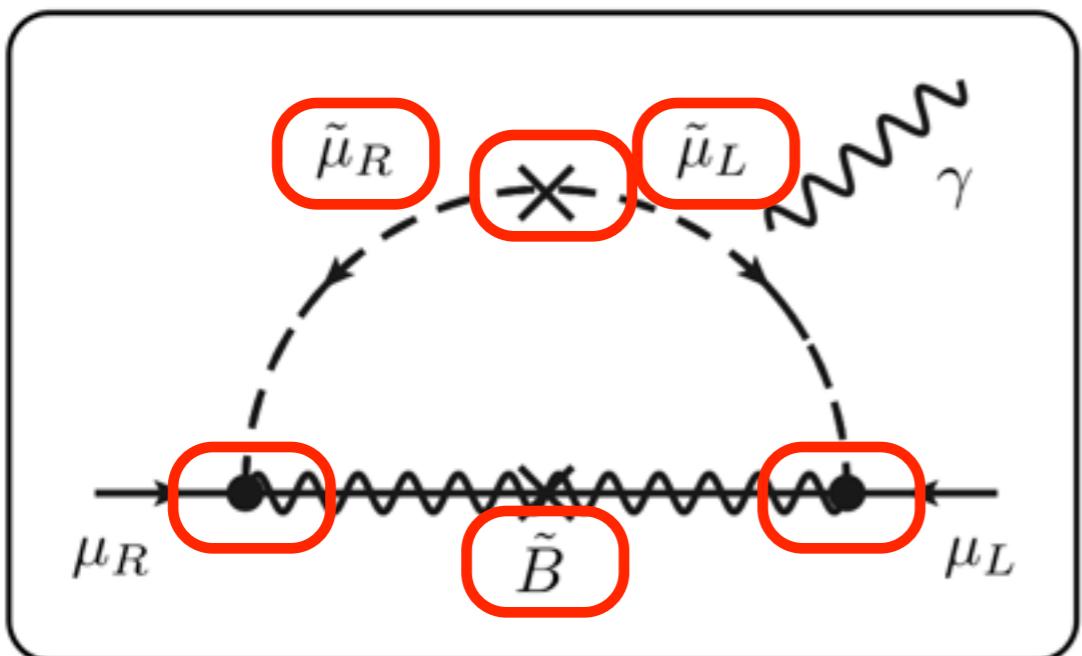
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all measurable!

muon g-2 vs ILC

neutralino



Can we reconstruct the contribution of this loop-diagram by using ILC measurements?
at this model point,

Table 2: Observables necessary for the reconstruction of $a_\mu^{(\text{ILC})}$, at $\sqrt{s} = 500 \text{ GeV}$ and $\mathcal{L} \sim 500\text{--}1000 \text{ fb}^{-1}$. Processes relevant to determination of $m_{\tilde{\chi}_1^0}$, analyses of the production of selectrons and the uncertainties in $\tilde{g}_{1,L}^{(\text{eff})}$ are also shown. The second and third rows are the information to determine of $m_{\tilde{\tau}_2}$, analyses of the productions of selectrons and the uncertainties in $\tilde{g}_{1,L}^{(\text{eff})}$ are also shown. The second and third rows are the information to determination of $m_{\tilde{\chi}_1^0}$, analyses of the productions of selectrons and the uncertainties in $\tilde{g}_{1,L}^{(\text{eff})}$ are those from the experiment and the

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

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

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126 GeV Higgs and SUSY: 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..... (but it may still be probed by, .e.g, **Flavor Physics** !)
 - ▶ Many other possibilities which I didn't discuss:
NMSSM and other modifications, RpV, light stop, compressed SUSY, etc etc...
-

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

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

→ may be tested at **13-14 TeV LHC ! (and ILC !)**

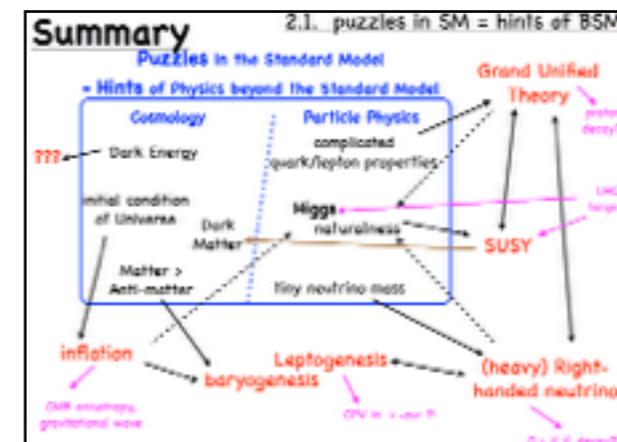
Higgs Physics and Beyond the Standard Model

126 GeV Higgs

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

$$\rightarrow \begin{cases} (H^\dagger H)^2 = \frac{m^2}{2\lambda_{H\bar{H}}} & \text{we know}\\ m_{H\text{loop}}^2 = 2m^2 & \text{Now we also know} \end{cases} \simeq (174 \text{ GeV})^2$$

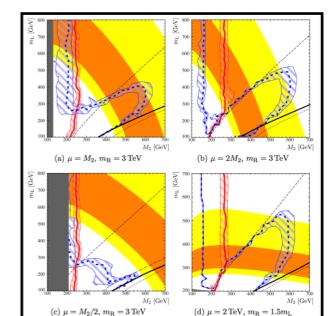
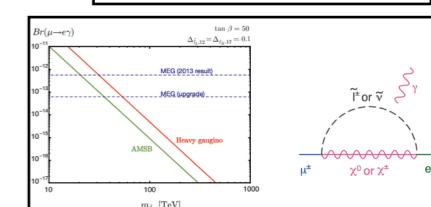
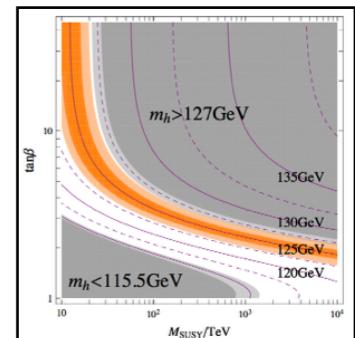
$$\rightarrow \begin{cases} m^2 = \frac{m_{H\text{loop}}^2}{2} \simeq (89 \text{ GeV})^2 \\ \lambda_{H\bar{H}} = \frac{m_{H\text{loop}}^2}{4(H^\dagger H)^2} = 0.13 \end{cases}$$



spin

quark	q	$1/2 \leftrightarrow 0$	squark	\tilde{q}
lepton	ℓ	$1/2 \leftrightarrow 0$	slepton	$\tilde{\ell}$
Higgs	H_u, H_d	$0 \leftrightarrow 1/2$	Higgsino	\tilde{h}
gauge bosons	γ, Z, W, g	$1 \leftrightarrow 1/2$	gaugino	$\tilde{B}, \tilde{W}, \tilde{g}$
MSSM (minimal SUSY Standard Model)				

0. Introduction
1. Higgs
2. Beyond the Standard Model
3. SUSY
4. SUSY after Higgs discovery



Thank you!