CP-safe gravity mediation and $(g\text{-}2)_\mu$

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25th Aug. 2014

SI2014-ph @ Fuji calm, Fuji-Yoshida

Reference)

S.I., Tsutomu T. Yanagida, Norimi Yokozaki [1407.4226].

- SI 2009 @ 富士吉田 ← My first SI.
- SI 2010 @ 富士吉田
- SI 2011 @ 富士吉田
- SI 2012 @ 日月潭
- SI 2013 @ 지리산국립공원
- SI 2014 @ 富士吉田

3 yrs.

	SI 2011	SI 2014
Mt. Fuji:	a mountain.	a world heritage.
I am…	young.	get old.
I …	climb Fuji.	see Fuji.
We…	searching for Higgs.	have Higgs.
and…	**NO SUSY.**	**NO SUSY.**

	SI 2011	SI 2014
Mt. Fuji:	a mountain.	a world
I ...	climb Fuji.	see Fuji.
We...	searching for Higgs.	have Higgs.
and...	**NO SUSY.**	**NO SUSY.**

e.

Where is SUSY?

Okada, Yamaguchi, Yanagida (1991) etc.

tree | one-loop level (top-stop)

$$m_h^2 \approx m_Z^2 + \frac{3 g_W^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} - \frac{(\alpha^2-6)^2}{12} + 3\right]$$

where $\alpha := A_t / m_{\tilde{t}}$.

(stop mixing parameter)

$$m_h = 126\,\text{GeV} \implies m_{\tilde{t}} \sim \begin{cases} \text{1–2 TeV} & (\alpha \sim \pm\sqrt{6}) \\ \text{O(10) TeV} & (\alpha \sim 0) \end{cases}$$

Ibe, Yanagida [1112.2462]
Draper, Meade, Reece, Shih [1112.3068]

$\tilde{q}, \tilde{g}$ searches $\implies \tilde{q}, \tilde{g} >$ 1–2 TeV

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Mt. Fuji:	a mountain.	a world heritage.
I am…	young.	get old.
I …	climb Fuji.	see Fuji.
We…	searching for Higgs.	have Higgs.
and…	**waiting for SUSY@LHC.**	**Giving up SUSY@LHC.**

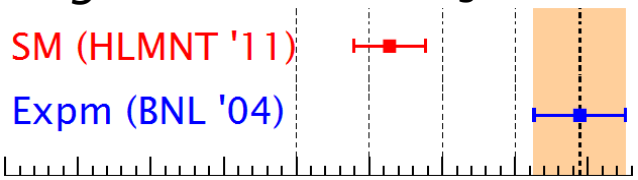
Don’t give up;

there’s a hope,

$(g-2)_\mu$.

$$\left(a_\mu := \frac{g_\mu - 2}{2}\right)$$

Muon g-2 (anomalous magnetic moment)



$$a_\mu^{\mathrm{SM}} = (116\,591\,828 \pm 49) \times 10^{-11}$$
$$a_\mu^{\mathrm{exp}} = (116\,592\,089 \pm 63) \times 10^{-11}$$

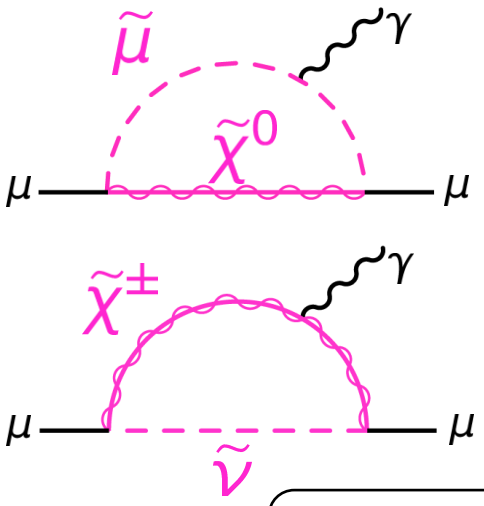
Hagiwara, Liao, Martin, Nomura, Teubner [1105.3149]

3.3σ discrepancy

↳ **SUSY** with O(100)GeV electroweakino.

$(\tilde{l}, \tilde{\nu}, \tilde{\chi}^0, \tilde{\chi}^+)$

Lopez, Nanopoulos, Wang [ph/9308336]
Chattopadhyay, Nath [ph/9507386]
Moroi [ph/9512396]



$$a_\mu^{\mathrm{SUSY}}\left(\tilde{\chi}^0, \tilde{\mu}\right) \approx \frac{g_Y^2}{(4\pi)^2} \frac{m_\mu^2}{m_{\mathrm{soft}}^2} \mathrm{sgn}(\mu) \tan\beta + \cdots,$$

$$a_\mu^{\mathrm{SUSY}}\left(\tilde{\chi}^\pm, \tilde{\nu}\right) \approx \frac{g_2^2}{(4\pi)^2} \frac{m_\mu^2}{m_{\mathrm{soft}}^2} \mathrm{sgn}(\mu) \tan\beta.$$

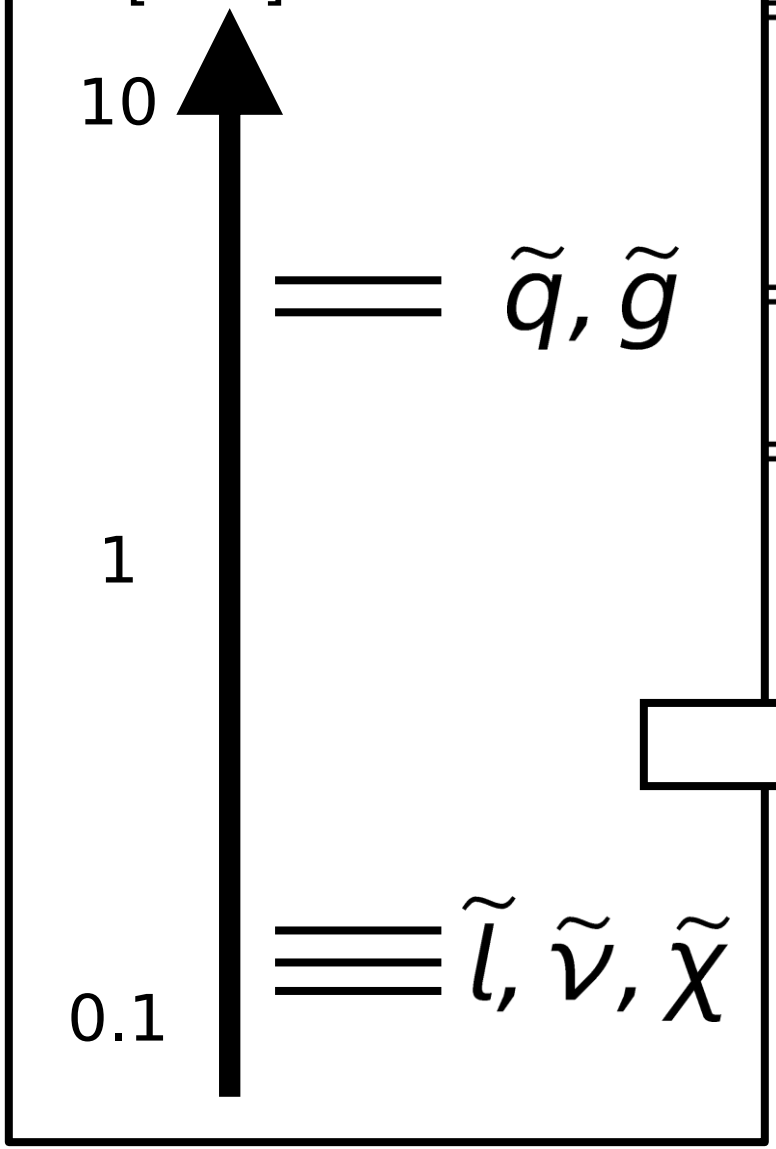
$W \ni \mu H_{\mathrm{u}} H_{\mathrm{d}}$ (Higgsino mass term), $\tan\beta = \langle H_{\mathrm{u}} \rangle / \langle H_{\mathrm{d}} \rangle$,
m_{soft} : SUSY-particle mass-scale, g_i : Gauge couplings.

$$m_h = 126\,\text{GeV} \implies m_{\tilde{t}} \sim \begin{cases} 1\text{–}2\,\text{TeV} & (\alpha \sim \pm\sqrt{6}) \\ \text{O}(10)\,\text{TeV} & (\alpha \sim 0) \end{cases}$$

$$\tilde{q}, \tilde{g}\ \text{searches} \implies \tilde{q}, \tilde{g} > 1\text{–}2\,\text{TeV}$$

$$(g-2)_\mu \implies (\tilde{l}, \tilde{\nu}, \tilde{\chi}^0, \tilde{\chi}^+) = \mathcal{O}(100)\,\text{GeV}$$

SOLUTION



$\Rightarrow m_{\tilde{t}} \sim \begin{cases} 1\text{–}2\,\text{TeV} & (\alpha \sim \pm\sqrt{6}) \\ \text{O}(10)\,\text{TeV} & (\alpha \sim 0) \end{cases}$

$\Rightarrow \tilde{q}, \tilde{g} > 1\text{–}2\,\text{TeV}$

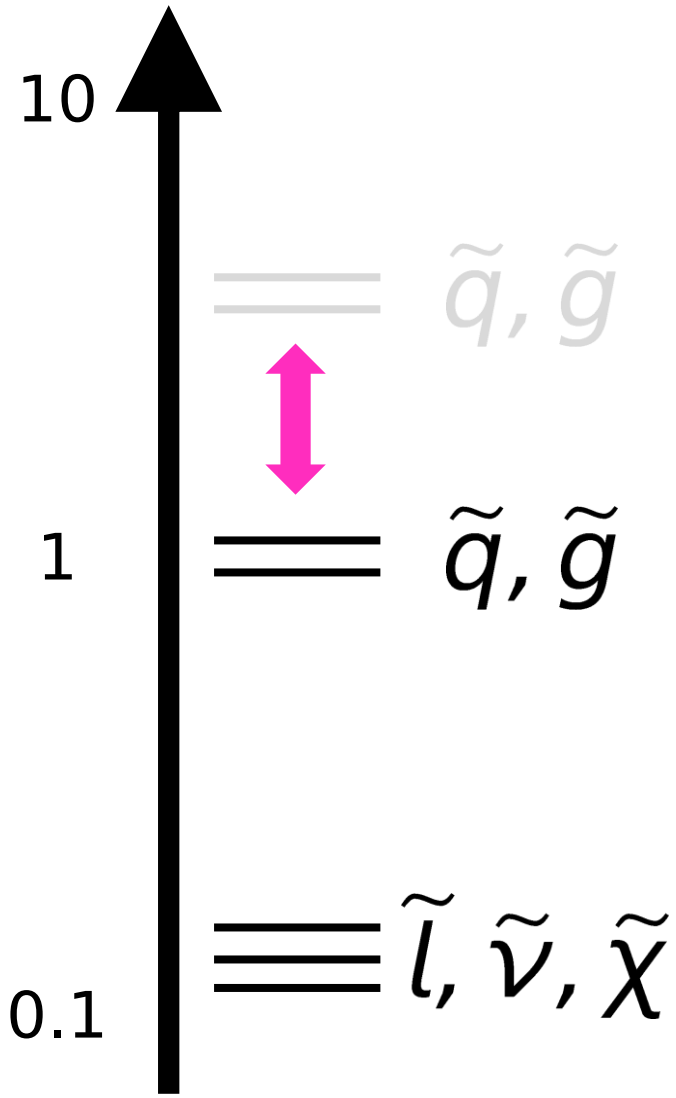
$\Rightarrow (\tilde{l}, \tilde{\nu}, \tilde{\chi}^0, \tilde{\chi}^+) = \mathcal{O}(100)\,\text{GeV}$

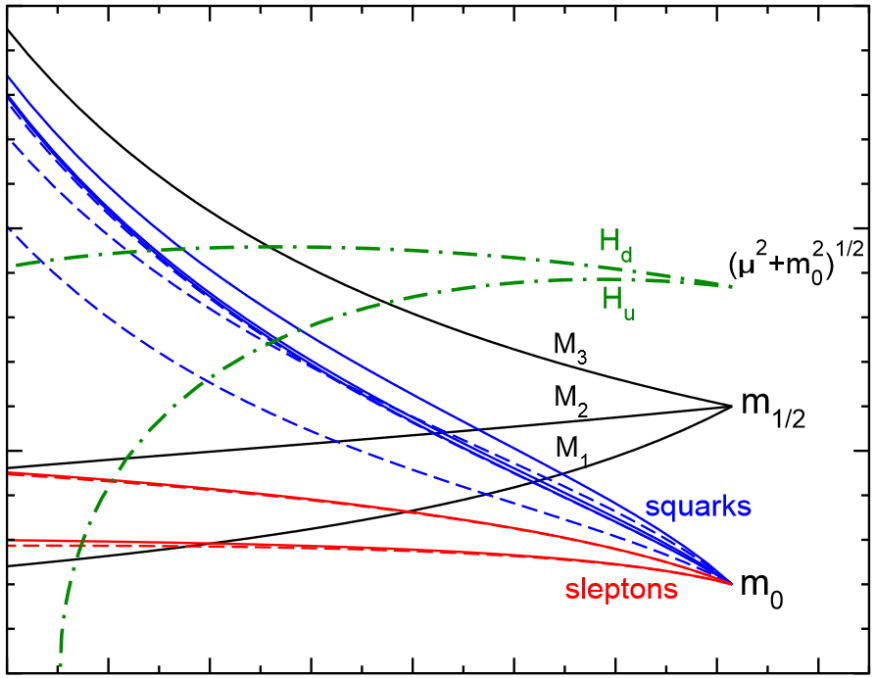
FAQ

Do you have **models** for such spectra?

Difficult in CMSSM, mGMSB.

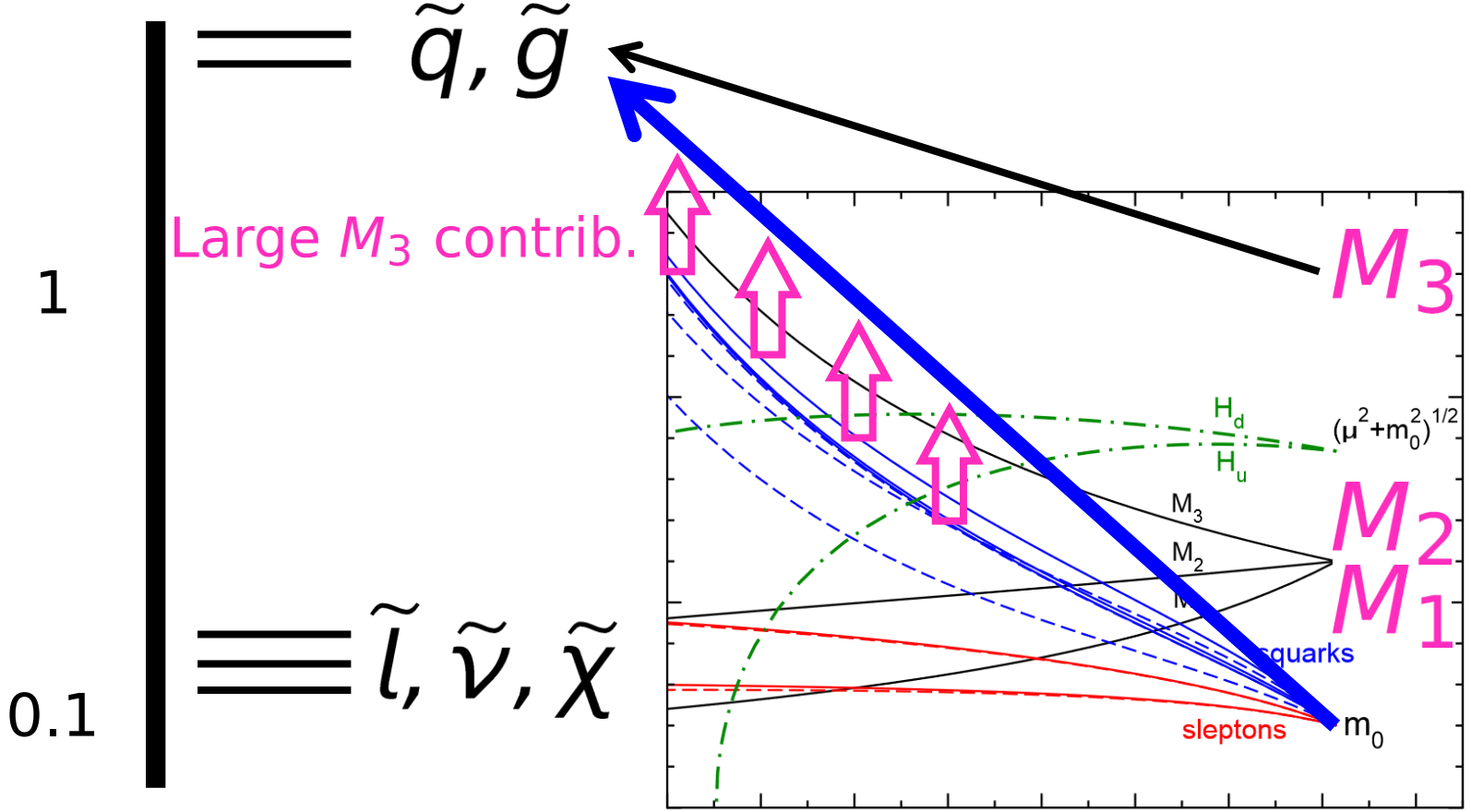
[constrained MSSM]
[minimal gauge-mediated SUSY breaking]





- Difficult in CMSSM, mGMSB.
- Possible in CMSSM w. non-universal M_i.

"NUGM (non-universal gaugino mass) model"



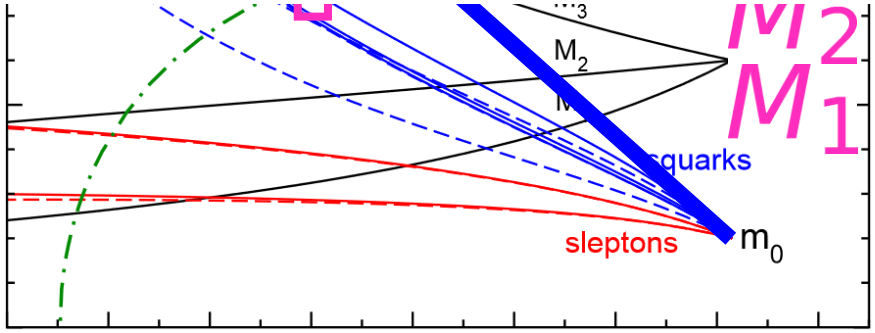
- Difficult in CMSSM, mGMSB.
- Possible in CMSSM w. non-universal M_i.

"NUGM (non-universal gaugino mass) ~~model~~"
parameter set

But...

- Just a "parameter set".
- Flavor & CP problems.

0.1 $\equiv\equiv \tilde{l}, \tilde{\nu}, \tilde{\chi}$



- Difficult in CMSSM, mGMSB.
- Possible in CMSSM w. non-universal M_i.

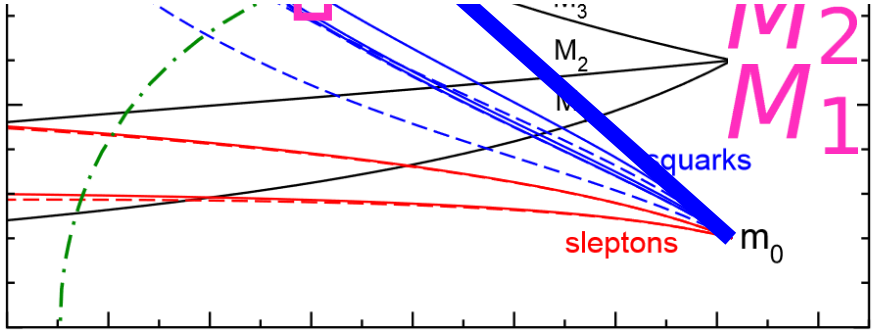
"NUGM (non-universal gaugino mass) ~~model~~"
parameter set

But...

- Just a "parameter set". ✓
- Flavor & CP problems. ✓

We made a model with CP-problem solved.

0.1 $\equiv\equiv \tilde{l}, \tilde{\nu}, \tilde{\chi}$



1. **Introduction**
2. **CP? Why broken?**
3. **CP-safe Gravity Mediation**
4. **Muon *g*-2**

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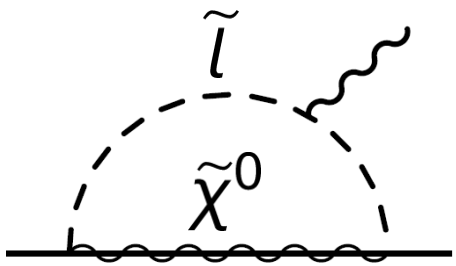
CP problem?

- MSSM: Many complex parameters. ($A_{u,d,e}, M_{1,2,3}, \mu, B$)
- Unaligned phases → CP-violation.
- Generic problem in O(100)GeV SUSY.

ACME collab. [1310.7534]

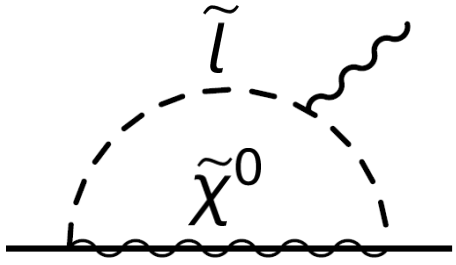
$$\text{EDM} \propto \text{Im}\left[\quad\right] < 8.7 \times 10^{-29} e\,\text{cm} \text{ (electron)}$$

[electric dipole moment]



$$\tilde{l}, \tilde{\chi}^0 = \mathcal{O}(100)\,\text{GeV} \Longrightarrow \text{phase misalign.} \lesssim 10^{-3}\text{–}10^{-4}.$$

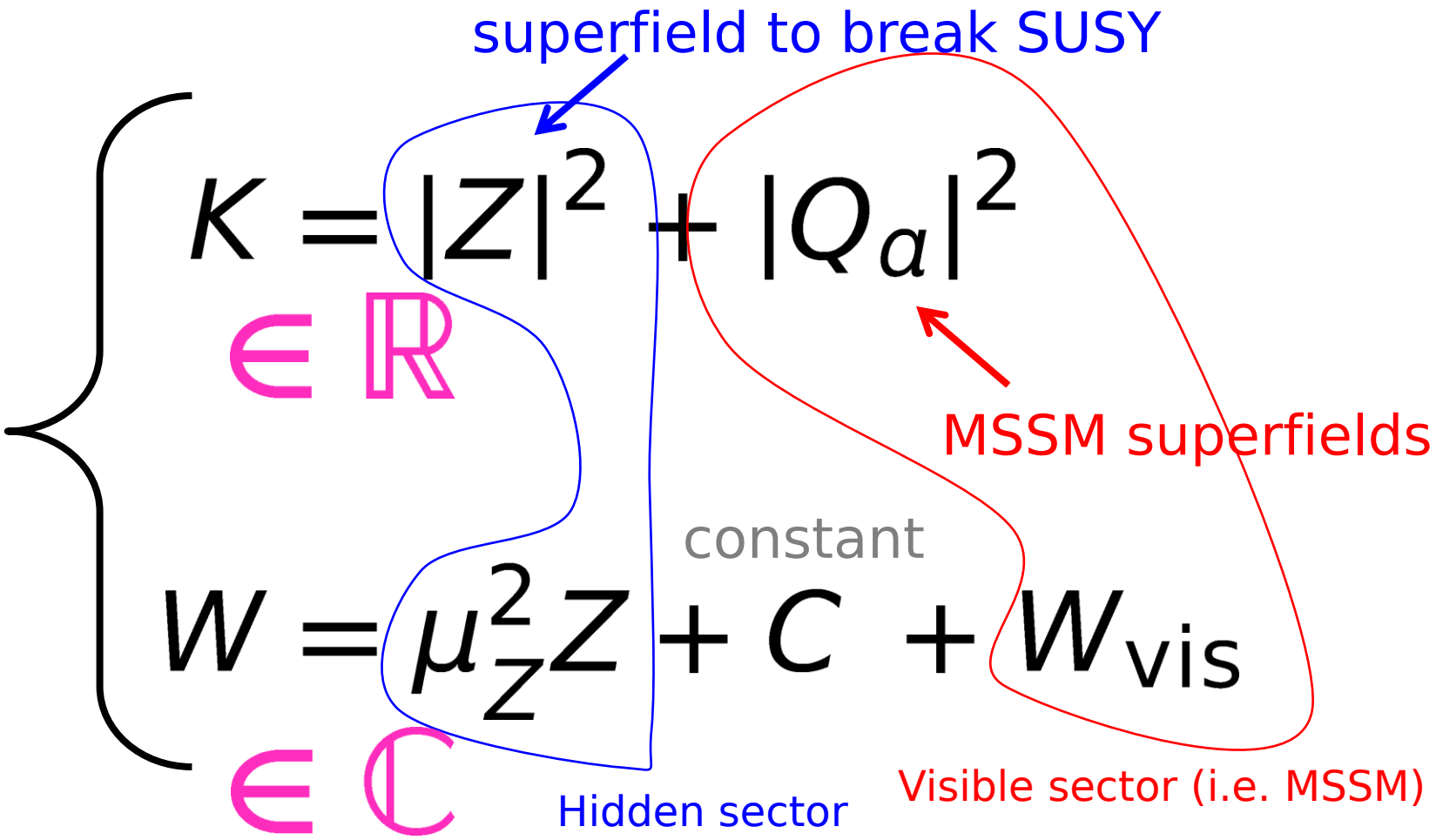
$$g-2 \propto \text{Re}\left[\quad\right]$$



$$\Longrightarrow \tilde{l}, \tilde{\chi}^0 = \mathcal{O}(100)\,\text{GeV}$$

$$\mathcal{L} = \int d^2\theta d^2\bar{\theta} K(\Phi, \bar{\Phi}) + \left(\int d^2\theta W(\Phi) + \text{h.c.} \right) + \cdots$$

Ex.) Polonyi model



$$\mathcal{L} = \int d^2\theta d^2\bar{\theta} K(\Phi, \bar{\Phi}) + \left(\int d^2\theta W(\Phi) + \text{h.c.} \right) + \cdots$$

- Ex.) Polonyi model

$$\begin{cases} K = |Z|^2 + |Q_a|^2 \\ \quad \in \mathbb{R} \\ W = \mu_Z^2 Z + C + W_{\text{vis}} \\ \qquad \in \mathbb{C} \qquad \in \mathbb{C} \end{cases}$$

→ unaligned phases.

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- CP-safe gravity mediation :

Shift sym. of Z & ~~SUSY~~ in K

$(Z \to Z + i\mathcal{R})$ $(\mathcal{R} \in \mathbb{R})$

Izawa, Kugo, Yanagida [1008.4641]

$\Rightarrow \langle Z \rangle \in \mathbb{R}$

$$K = s(Z + Z^*) + |Q_a|^2$$

$s \in \mathbb{R}$: complicated function

→ SUSY breaking

$$W = C + W_{\text{vis}}$$

Only one phase.

Note for professionals: $R(H_u H_d) = 2$;
$m_{3/2} = \mathcal{O}(100)\,\text{GeV}$.

- CP-safe gravity mediation :

Shift sym. of Z & ~~SUSY~~ in K

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$s \in \mathbb{R}$: complicated function

→ SUSY breaking

Example:

$$s(x) = -3 + c_1 x + c_2 x^2 + c_3 x^3 + c_4 x^4$$

$$\text{with } c_2 = 3c_3^2/8c_4, 768c_4^3 + 64c_1 c_3 c_4^2 - 3c_3^4 > 0.$$

$$\Longrightarrow \langle x \rangle = -c_3/4c_4.$$

Note for professionals: $R(H_u H_d) = 2$;

$m_{3/2} = \mathcal{O}(100)\,\text{GeV}$.

$x = \langle Z + Z^* \rangle$

Calculate $M_i, A_0, B/\mu$:

$$\langle V \rangle = 0 \quad \text{(vanishing cosmo. const.)} \iff \frac{s'(x)^2}{M_P^2 s''(x)} = 3,$$

$$\left\langle \frac{\partial V}{\partial Z} \right\rangle = 0 \quad (Z\text{-stationary cond.}) \iff \frac{\partial}{\partial x} \frac{s'(x)^2}{s''(x)} = 0.$$

$$\Rightarrow \langle Z \rangle \in \mathbb{R} \ (\because \text{shift sym.}), \quad \langle F_Z \rangle = -\mathrm{e}^{s/2M_P^2} \frac{C^*}{M_P^2} \frac{s'(x)}{s''(x)}.$$

$$\Rightarrow \begin{cases} B_\mu/\mu = 2m_{3/2}\mathrm{e}^{-i\arg C} \\ A_0 = 3m_{3/2}\mathrm{e}^{-i\arg C} \\ m_0^2 = m_{3/2}^2 \end{cases} \quad \text{where } m_{3/2}^2 = |C|^2 \mathrm{e}^{s/M_P^2}/M_P^4$$

$$V = \mathrm{e}^{K/M_P^2} \left(\frac{s'(x)^2}{M_P^2\, s''(x)} - 3 \right) \frac{|W|^2}{M_P^2} + \mathrm{e}^{K/M_P^2} \left| \frac{\partial W}{\partial Q_a} + \frac{\partial K}{\partial Q_a} \frac{W}{M_P^2} \right|^2$$

$x = \langle Z + Z^* \rangle$

Calculate $M_i, A_0, B/\mu$:

$$\langle V \rangle = 0 \quad (\text{vanishing cosmo. const.}) \iff \frac{s'(x)^2}{M_P^2 s''(x)} = 3,$$

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$$V = \mathrm{e}^{K/M_P^2} \left(\frac{\partial W}{\partial Q_a} + \frac{\partial K}{\partial Q_a} \frac{W}{M_P^2} \right) \left(\frac{\partial W}{\partial Q_a} + \frac{\partial K}{\partial Q_a} \frac{W}{M_P^2} \right)^*$$

$$\supset \mathrm{e}^{K/M_P^2} \left(\left| \frac{\partial W_{\text{vis}}}{\partial Q_a} \right|^2 + \frac{C^*}{M_P^2} Q \frac{\partial W_{\text{vis}}}{\partial Q} + \frac{|C|^2}{M_P^4} |Q|^2 \right)$$

$x = \langle Z + Z^* \rangle$

Calculate $M_i, A_0, B/\mu$:

$$\mathcal{L} \ni \int \mathrm{d}^2\theta \left(\frac{1}{4g_i^2} + k_i \frac{Z}{M_P} \right) W^\alpha W_\alpha$$

from anomaly of (broken) shift sym.

$(\therefore k_i \in \mathbb{R})$

$$\begin{cases} B_\mu/\mu = 2m_{3/2} \mathrm{e}^{-i \arg C} \\ A_0 = 3m_{3/2} \mathrm{e}^{-i \arg C} \\ m_0^2 = m_{3/2}^2 \end{cases} \quad \text{where } m_{3/2}^2 = |C|^2 \mathrm{e}^{s/M_P^2} / M_P^4$$

and $$M_i = k_i g_i^2 \frac{\langle F_Z \rangle}{M_P} = -3 k_i g_i^2 m_{3/2} \frac{M_P}{s'(x)} \mathrm{e}^{-i \arg C}$$

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Parameters: $M_i, \tan\beta, \mathrm{sgn}\,\mu$

Unknown → regarded as parameters.

Fixed by EWSB conditions.

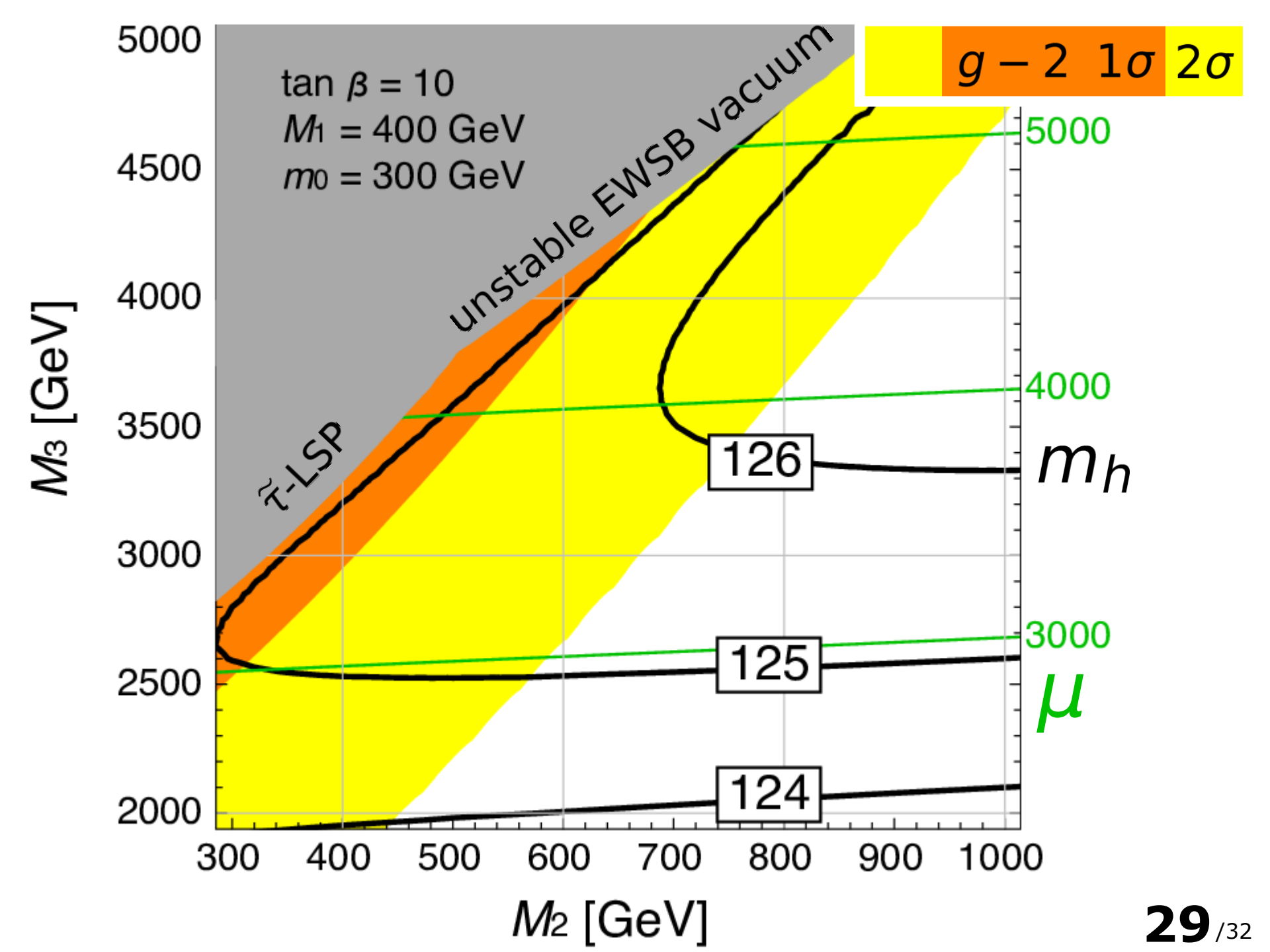
$$\begin{cases} B_\mu/\mu = 2m_{3/2}\mathrm{e}^{-i\arg C} \\ A_0 = 3m_{3/2}\mathrm{e}^{-i\arg C} \\ m_0^2 = m_{3/2}^2 \qquad \text{where } m_{3/2}^2 = |C|^2\mathrm{e}^{s/M_P^2}/M_P^4 \end{cases}$$

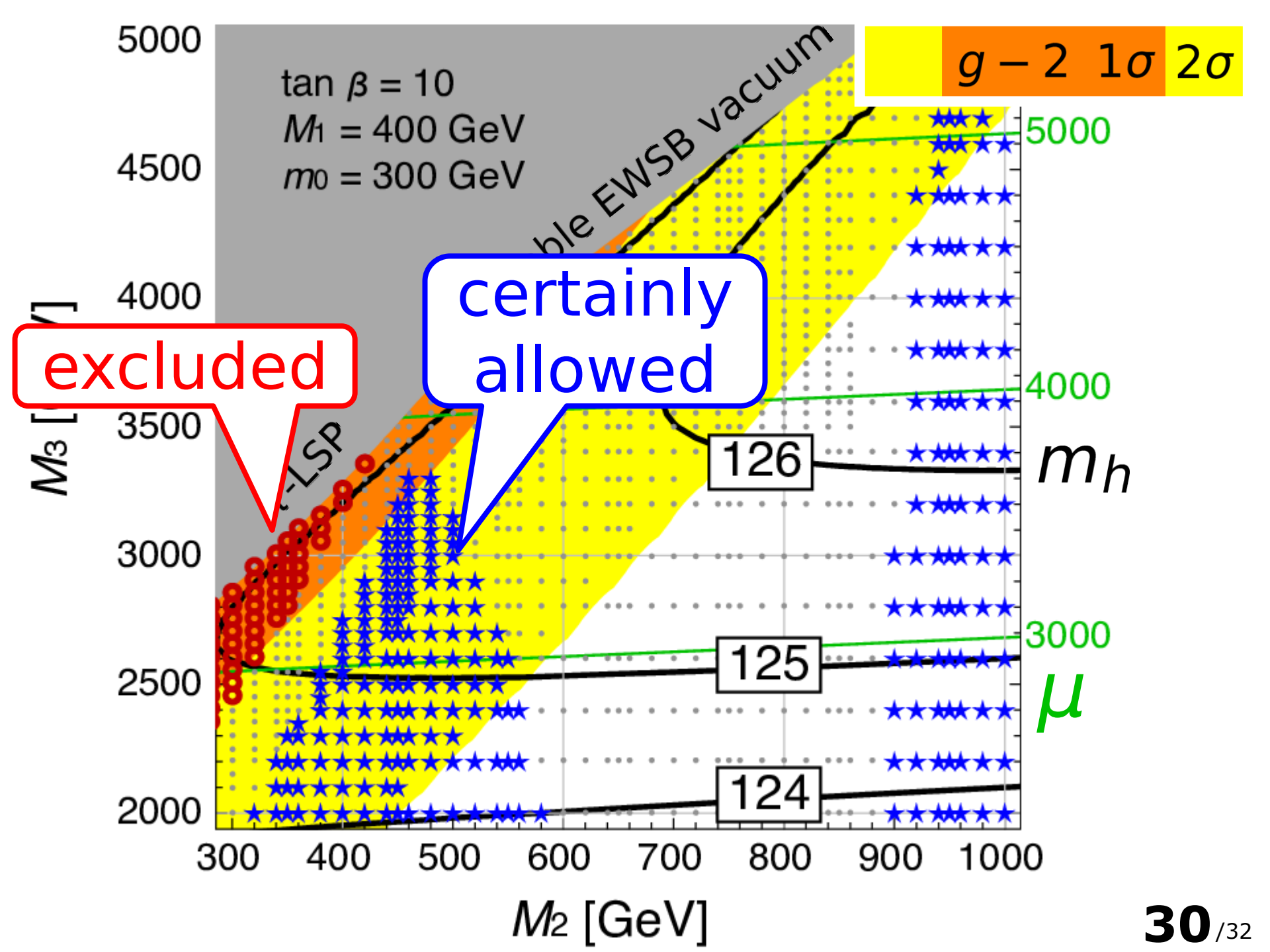
$$M_i = k_i g_i^2 \frac{\langle F_Z\rangle}{M_P} = -3k_i g_i^2 m_{3/2}\frac{M_P}{s'(x)}\mathrm{e}^{-i\arg C}$$

Parameters: $M_i, \tan\beta, \mathrm{sgn}\,\mu$ and m_0^2

$$\begin{cases} K = s(Z+Z^*) + |Q_\alpha|^2 \\ \qquad + \dfrac{1+\alpha_1(Z+Z^*)+\alpha_2(Z+Z^*)^2}{1+\alpha_1 <Z+Z^*> +\alpha_2 <Z+Z^*>^2}|Q_\alpha|^2 \\ W = C + W_{\mathrm{vis}} \end{cases}$$

with $\alpha_i \in \mathbb{R}$ ($\because$ Kähler).


$g-2$ 1σ 2σ
tan β = 10
M_1 = 400 GeV
m_0 = 300 GeV
unstable EWSB vacuum
$\tilde{\tau}$-LSP
126
125
124
5000
4000
3000
m_h
μ
M_3 [GeV]
M_2 [GeV]
5000
4500
4000
3500
3000
2500
2000
300
400
500
600
700
800
900
1000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M_3 [
M_2 [GeV]

Summary

$K = s(Z + Z^*) + |Q_\alpha|^2$
$W = C + W_{\rm vis}$

◉ CP-safe gravity mediation

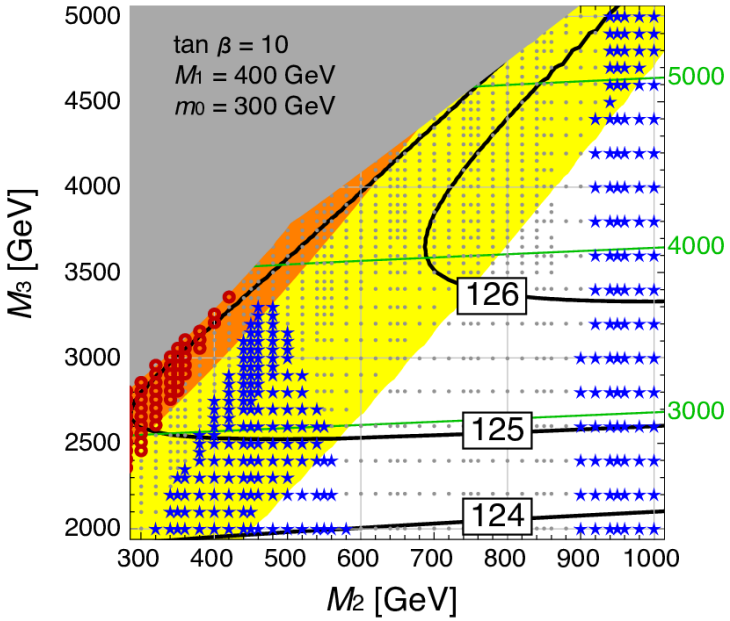
= Shift sym. of Z & ~~SUSY~~ in K

✓ SUSY CP problem mostly solved.

$(A_{u,d,e}, M_{1,2,3}, \mu, B)$

⇨ A strong support for

- $\mathcal{O}(100)$ GeV SUSY,
- Non-universal M_i,
  such as $(g-2)_\mu$-MSSM.



CP-violation from sfermion $(m_0^2)_{ij}$ still remains.

→ should be solved together with flavor problem.

(OR: $m_0^2 = 0$?)

Gaugino Mass in Detail

$$\mathcal{L} \ni \int \mathrm{d}^2\theta \left(\frac{1}{4g_i^2} + k_i \frac{Z}{M_P} \right) W^\alpha W_\alpha$$

Forbidden by shift sym.;

→ ~~SUSY~~ ($\langle Z \rangle \neq 0$) breaks shift sym.

→ Generated by anomaly of shift sym.

($\therefore k_i \in \mathbb{R}$)

$M_1, M_2 \ll M_3$?

… depends on “above-GUT” structure.

Ex.) $SU(5) \times U(3) \to SU(3) \times SU(2) \times U(1) \times SU(3) \times U(1)$

$$\to SU(3)_C \times SU(2)_L \times U(1)_Y$$

$$\vdots \qquad \vdots \qquad \vdots$$

$$k_5 + k_3 \qquad k_5 \qquad k_5 + k_1$$

$$\mathcal{L} \ni \int \mathrm{d}^2\theta \left(\frac{1}{4g_i^2} + k_i \frac{Z}{M_P} \right) W^\alpha W_\alpha$$

Postponed the origin of M_i to "above-GUT".
$\Longleftrightarrow$ M_i tells us "above-GUT" structure.

$(\therefore k_i \in \mathbb{R})$

$M_1, M_2 \ll M_3$?

... depends on "above-GUT" structure.

Ex.) $\mathrm{SU}(5) \times \mathrm{U}(3) \to \mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1) \times \mathrm{SU}(3) \times \mathrm{U}(1)$

$$\to \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

$$k_5 + k_3 \qquad k_5 \qquad k_5 + k_1$$

Phenomenology in Detail

Parameters: $M_i, \tan\beta, \mathrm{sgn}\,\mu$ and m_0^2

$m_0 = 300\,\mathrm{GeV}$,
$M_1 = 400\,\mathrm{GeV}$,
$M_2 \simeq 500\,\mathrm{GeV}$,
$M_3 = 2000\text{–}5000\,\mathrm{GeV}$

$\Rightarrow$ heavy $\tilde{g}$

RGE → heavy $\tilde{q}$ ($\sim 5\,\mathrm{TeV}$)

$\Rightarrow$ 126 GeV Higgs

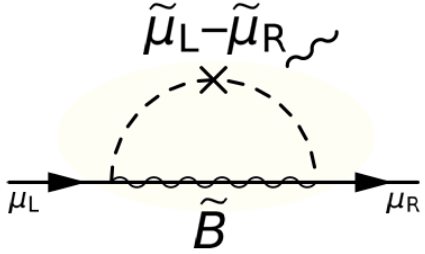
(Note: $A_0 \lesssim 1\,\mathrm{TeV}$)

$\mathcal{O}(100)\,\mathrm{GeV}$ $\tilde{l}, \tilde{\nu}, \tilde{\chi}^{\pm,0}$

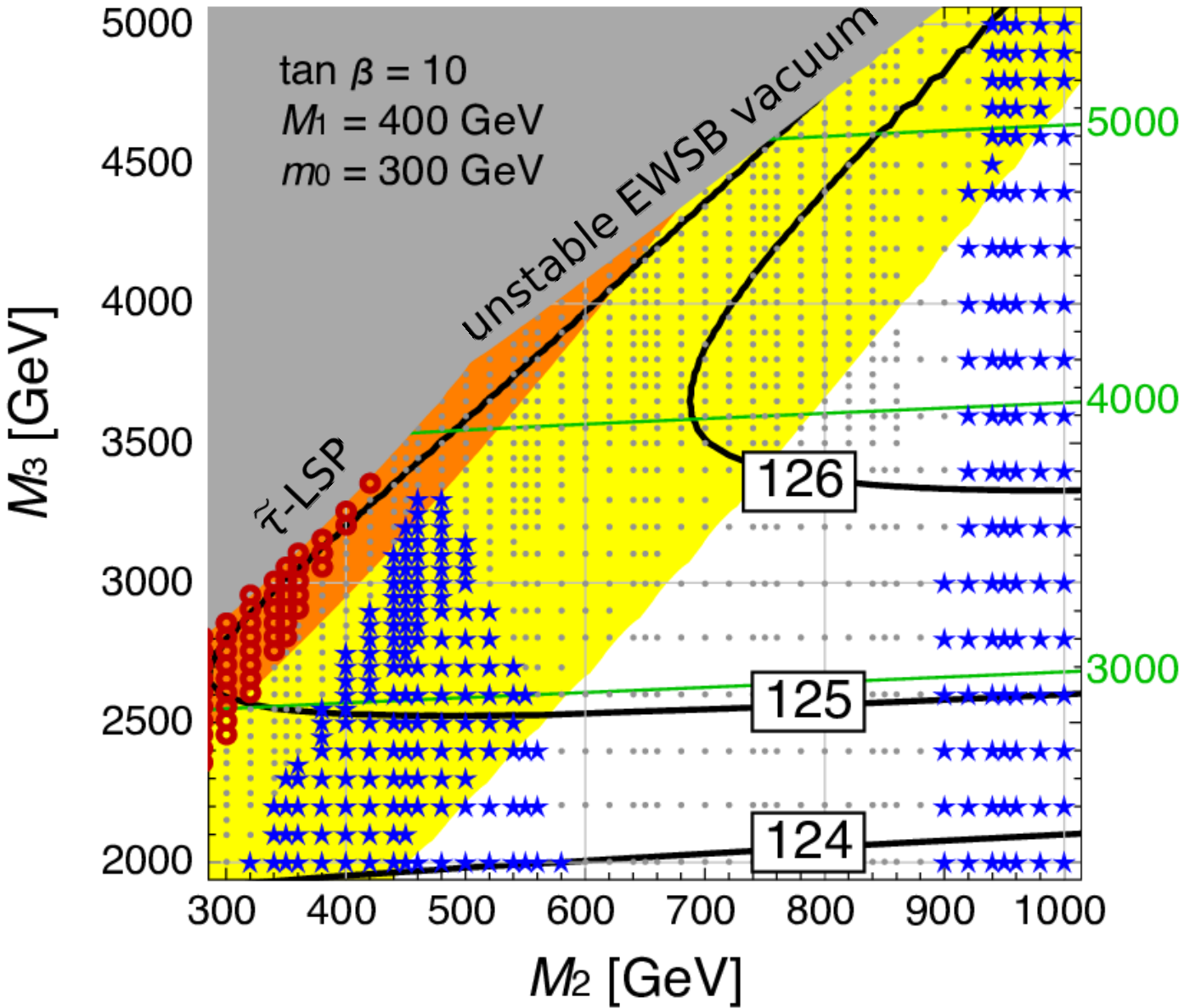
large μ

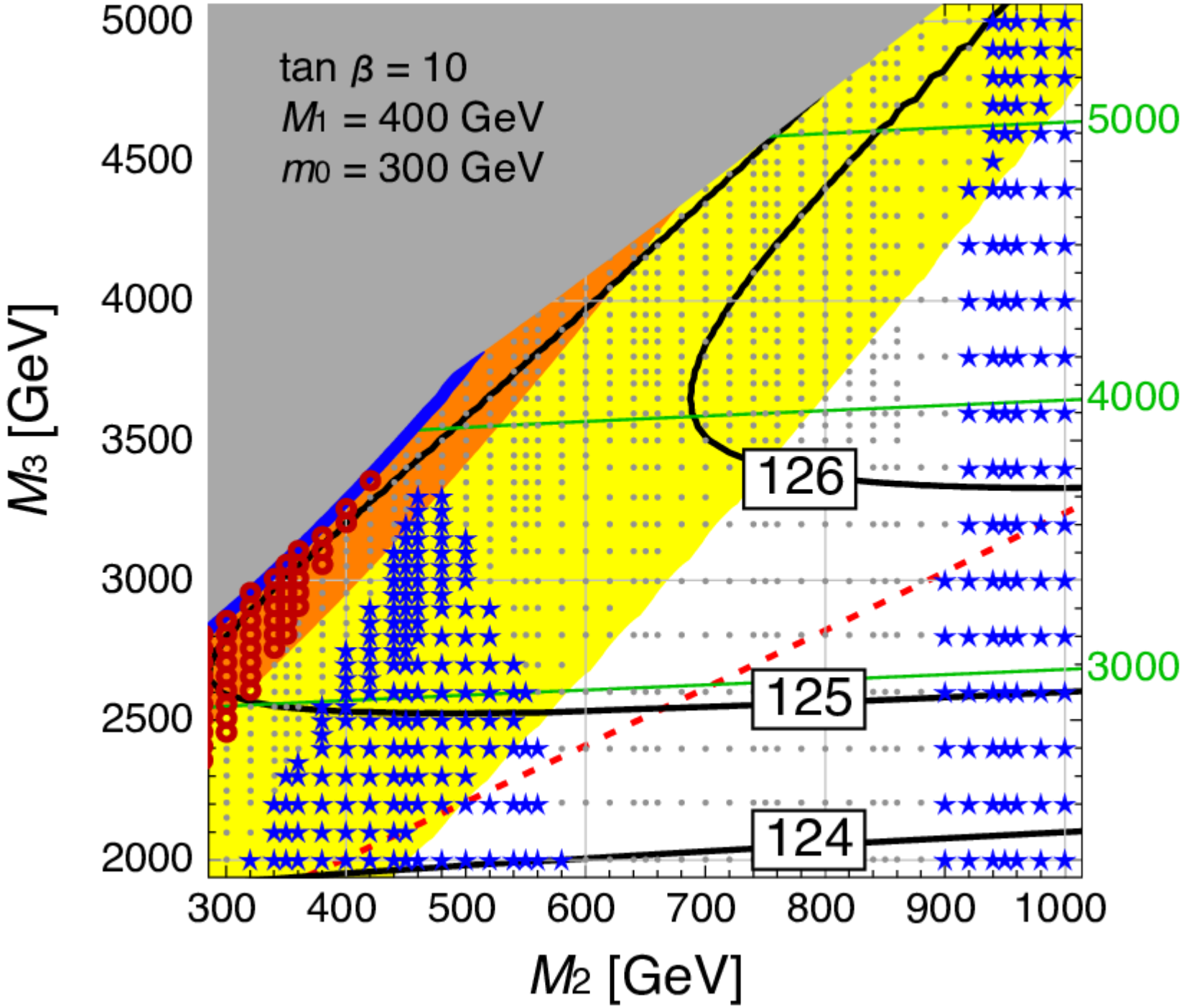
$\Rightarrow$ large $\tilde{l}_L$–$\tilde{l}_R$ mix.

$(g-2)_\mu$



(M_2, M_3)	$\tilde{\chi}_2^0, \tilde{\chi}_1^\pm$	$\tilde{l}_L$	$\tilde{l}_R$	$\tilde{\tau}_1$	$\tilde{\tau}_2$	$\tilde{\chi}_1^0$	m_h	$\Delta a_\mu^{\rm SUSY} \times 10^{10}$
$(460, 3300)$	333	329	348	182	400	150	125.3	18.8 (0.9σ)
$(1000, 5000)$	774	578	365	247	589	142	126.5	11.2 (1.9σ)

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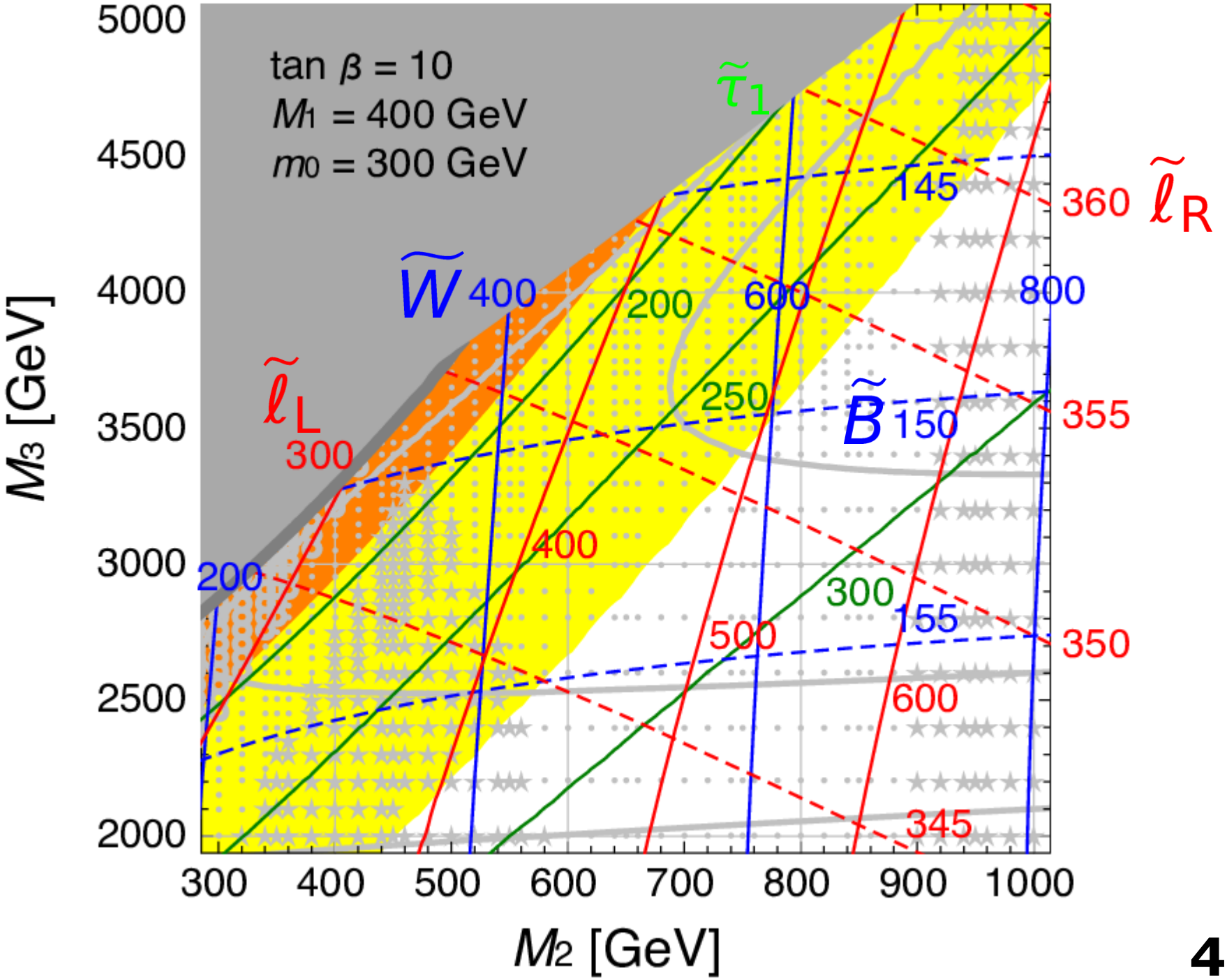
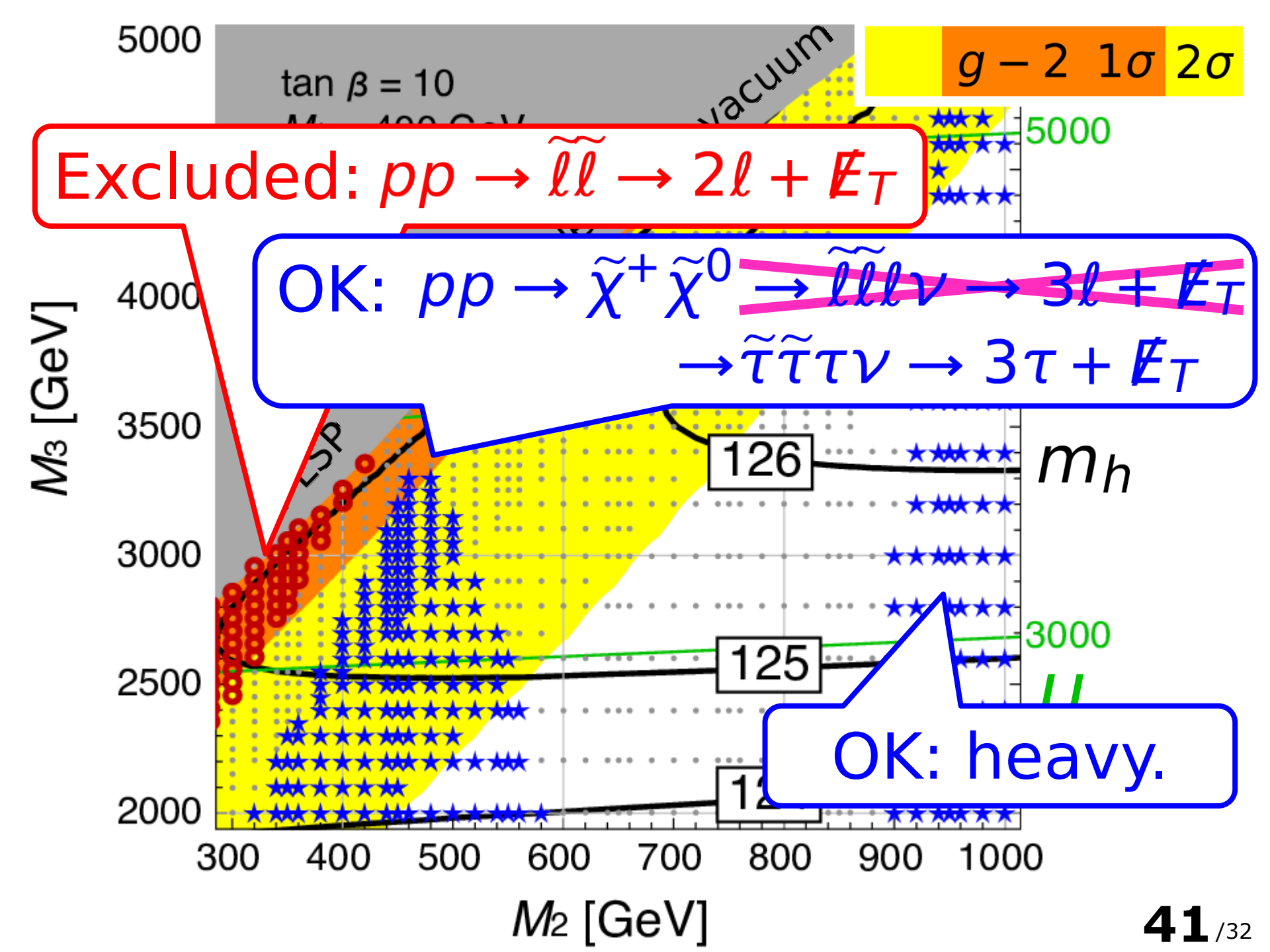
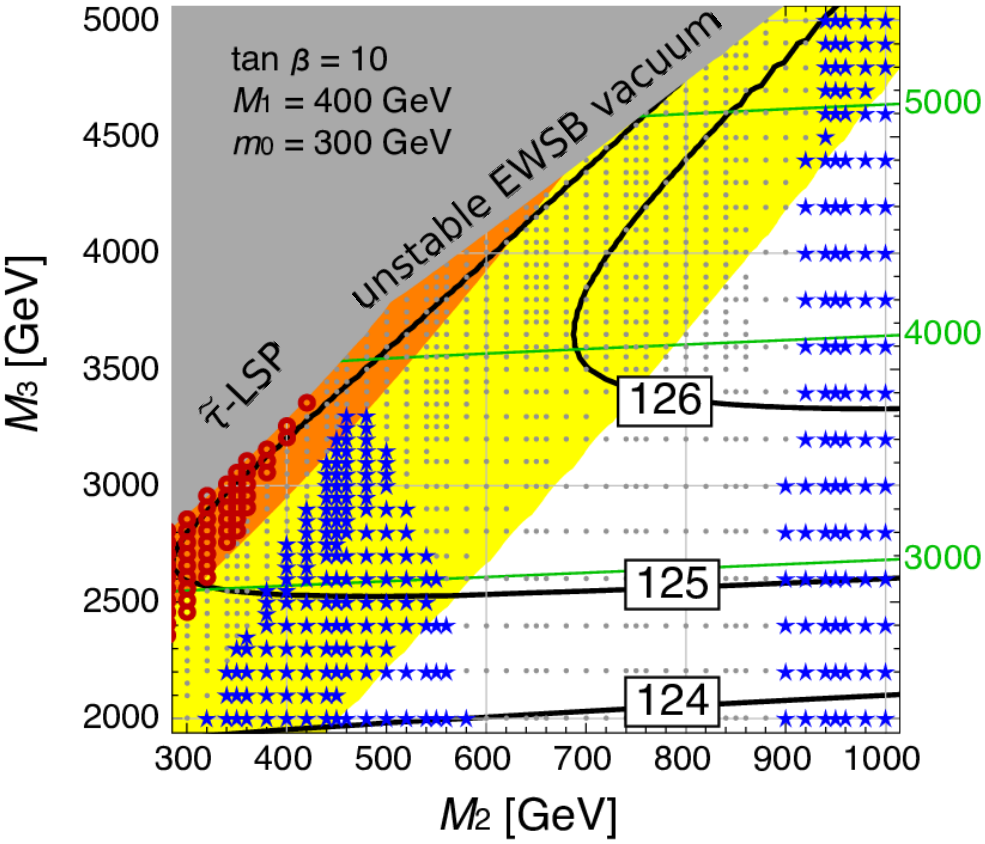
2500
2000
300
400
500
600
700
800
900
1000


tan β = 10
M1 = 400 GeV
m0 = 300 GeV
$\tilde{\tau}_1$
$\widetilde{W}$
400
$\tilde{\ell}_L$
300
200
$\tilde{B}$
150
145
155
$\tilde{\ell}_R$
360
355
350
345
800
600
500
400
300
250
200
M3 [GeV]
M2 [GeV]
5000
4500
4000
3500
3000
2500
2000
300
400
500
600
700
800
900
1000


$g-2$ 1σ 2σ
Excluded: $pp \to \tilde{\ell}\tilde{\ell} \to 2\ell + \not{E}_T$
OK: $pp \to \tilde{\chi}^+\tilde{\chi}^0 \to \tilde{\ell}\tilde{\ell}\ell\nu \to 3\ell + \not{E}_T$
$\to \tilde{\tau}\tilde{\tau}\tau\nu \to 3\tau + \not{E}_T$
OK: heavy.
tan β = 10
vacuum
LSP
126
125
m_h
5000
4000
3500
3000
2500
2000
300
400
500
600
700
800
900
1000
M_3 [GeV]
M_2 [GeV]

- $(g-2)_\mu$ + Universal $(\tilde{e}, \tilde{\mu}, \tilde{\tau})$ mass
  - $pp \to \tilde{\ell}\tilde{\ell}$: Silver bullet, but less events.
  - $pp \to \tilde{\chi}^+\tilde{\chi}^0$: Many events, but τ-signal.



Considered constarints

- $2\ell + \not{E}_T$ ATLAS [1403.5294]
  - $pp \to \tilde{\ell}_{L/R}\tilde{\ell}_{L/R}$
  - $pp \to \tilde{\chi}^+\tilde{\chi}^-$ (WW)
  - $pp \to \tilde{\chi}^+\tilde{\chi}^-$ (0.5-slep med.)
- $2\tau + \not{E}_T$ ATLAS [1407.0350]
  - $pp \to \tilde{\tau}_{1,2}\tilde{\tau}_{1,2}$
  - $pp \to \tilde{\chi}^+\tilde{\chi}^-$ (WW)
  - $pp \to \tilde{\chi}^+\tilde{\chi}^-$ (0.5-stau med.)
- $3(\ell, \tau) + \not{E}_T$ ATLAS [1402.7029]
  - $pp \to \tilde{\chi}^+\tilde{\chi}^0$ (0.5-slep med.)
- $2\ell + \not{E}_T$ and $3(\ell, \tau) + \not{E}_T$
  - $pp \to \tilde{\chi}^+\tilde{\chi}^0$ (WZ)
- $4\ell + \not{E}_T$ ATLAS [1405.5086]
  - $pp \to \tilde{\chi}_2^0\tilde{\chi}_2^0$ (0.5-slep med.)