הטכניון
מכון טכנולוגי
לישראל
TECHNION
Israel Institute
of Technology

SUSY with light electroweakino

—A self introduction

Sho IWAMOTO（岩本　祥）

17 Dec. 2014

Joint HEP Seminar @ Tel Aviv University

References:

* M. Endo, K. Hamaguchi, S. I., and T. Yoshinaga [1303.4256]
* S. I., T. T. Yanagida, N. Yokozaki [1407.4226]

- **SUSY × LHC**
  - × ILC
  - × astrophys (AMS-02)
  - × cosmology (baryogenesis)

- Tevatron top forward-backward anomaly

- CMS *W'* searches at LHC

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  - × ILC
  - × astrophys (AMS-02)
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- CMS *W'* searches at LHC

Experiments × Phenomenology

0. Introduction

- Why I like SUSY?
- A nightmare
- Muon g-2 anomaly

1. Muon g-2 v.s. LHC

2. CP-safe Gravity Mediation

MSSM (with *R*-parity)

- ✓ Fermion $\Longleftrightarrow$ Boson ("unification")
- ✓ Radiative EWSB [Electroweak symmetry breaking]
  … $m_h \sim 125\,\mathrm{GeV}$
- ✓ Dark matter
- ✓ $(g-2)_\mu$ anomaly
- ✓ Hierarchy problem

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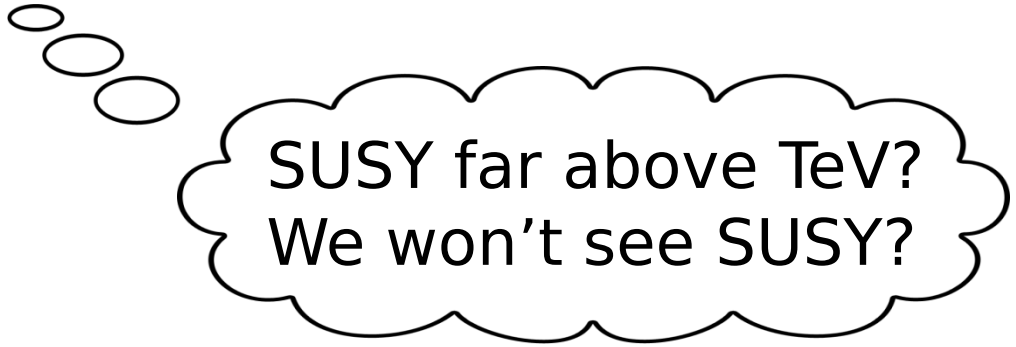
$m_h \sim 125\,\text{GeV}$

$\Longrightarrow$ $\Delta(m_h)^{\text{loop}}$: large

$\Longrightarrow$ $m_{\tilde{t}} = \text{O}(1\text{–}10)\,\text{TeV}$ in MSSM

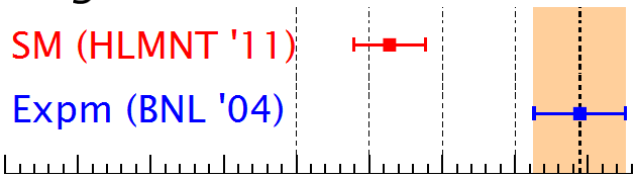


$$m_h^2(\text{MSSM}) \approx \underbrace{m_Z^2}_{\text{tree}} + \underbrace{\frac{3g_W^2 m_t^4}{8\pi^2 m_W^2}\left(\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{12\alpha^2 - \alpha^4}{12}\right)}_{\Delta\left(m_h^2\right)^{\text{loop}}}$$

where $\alpha := A_t/m_{\tilde{t}}$.
(stop mixing parameter)

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

Muon $g-2$ [anomalous magnetic moment]



$a_\mu^{\rm SM} = (116\,591\,828 \pm 49) \times 10^{-11}$

$a_\mu^{\rm exp} = (116\,592\,089 \pm 63) \times 10^{-11}$

3.3σ

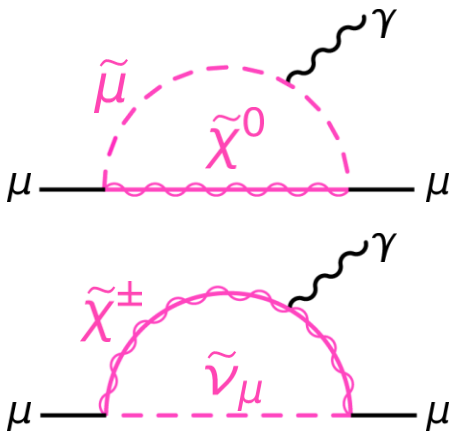
Hagiwara, Liao, Martin, Nomura, Teubner [1105.3149]

$\Longrightarrow$ Loop contrib. from

EWKino with m=O(100) GeV

$(\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm)$

(and large tan β, positive μ).



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

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

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

- Higgs mass

  $\Rightarrow \tilde{t} = \mathrm{O}(1\text{–}10)\,\mathrm{TeV}$

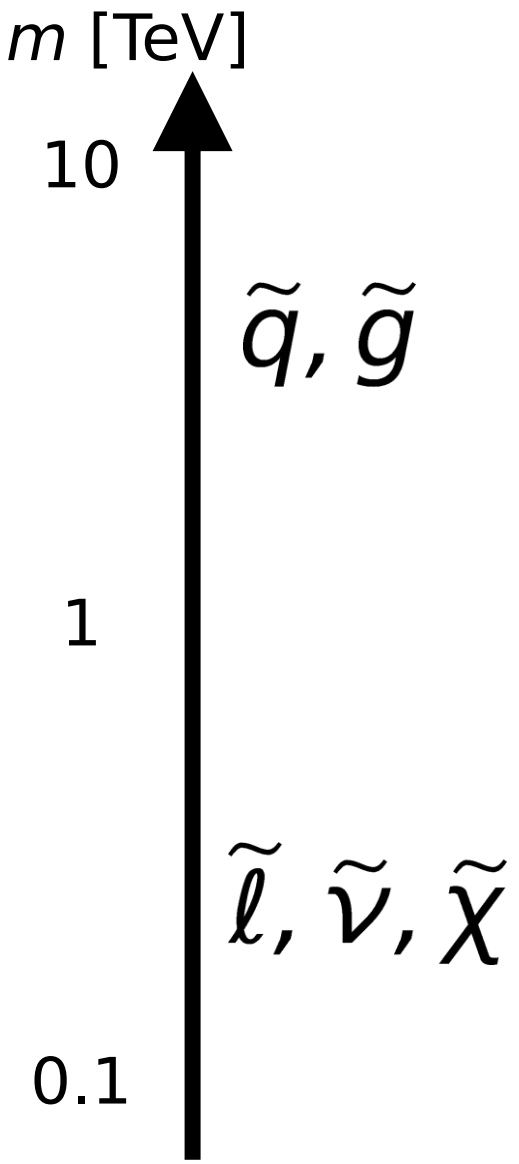
  - Together with 8TeV LHC

    $\Rightarrow$ colored $= \mathrm{O}(1\text{–}10)\,\mathrm{TeV}$

- $(g-2)_\mu$ anomaly

  $\Rightarrow$ EWKino $= \mathrm{O}(100)\,\mathrm{GeV}$

  (non-colored)



if EWKino = O(100)GeV,

SUSY → ☑ $(g-2)_\mu$

$\tilde{\ell}, \tilde{\nu}, \tilde{\chi}^0, \tilde{\chi}^\pm$

$(g-2)_\mu$ anomaly

↓

O(100)GeV EWKino

↓

Discovery @ LHC!

if EWKino = O(100)GeV,

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Discovery @ LHC!

Which channel?

Reach?

~~SUSY~~ Model?

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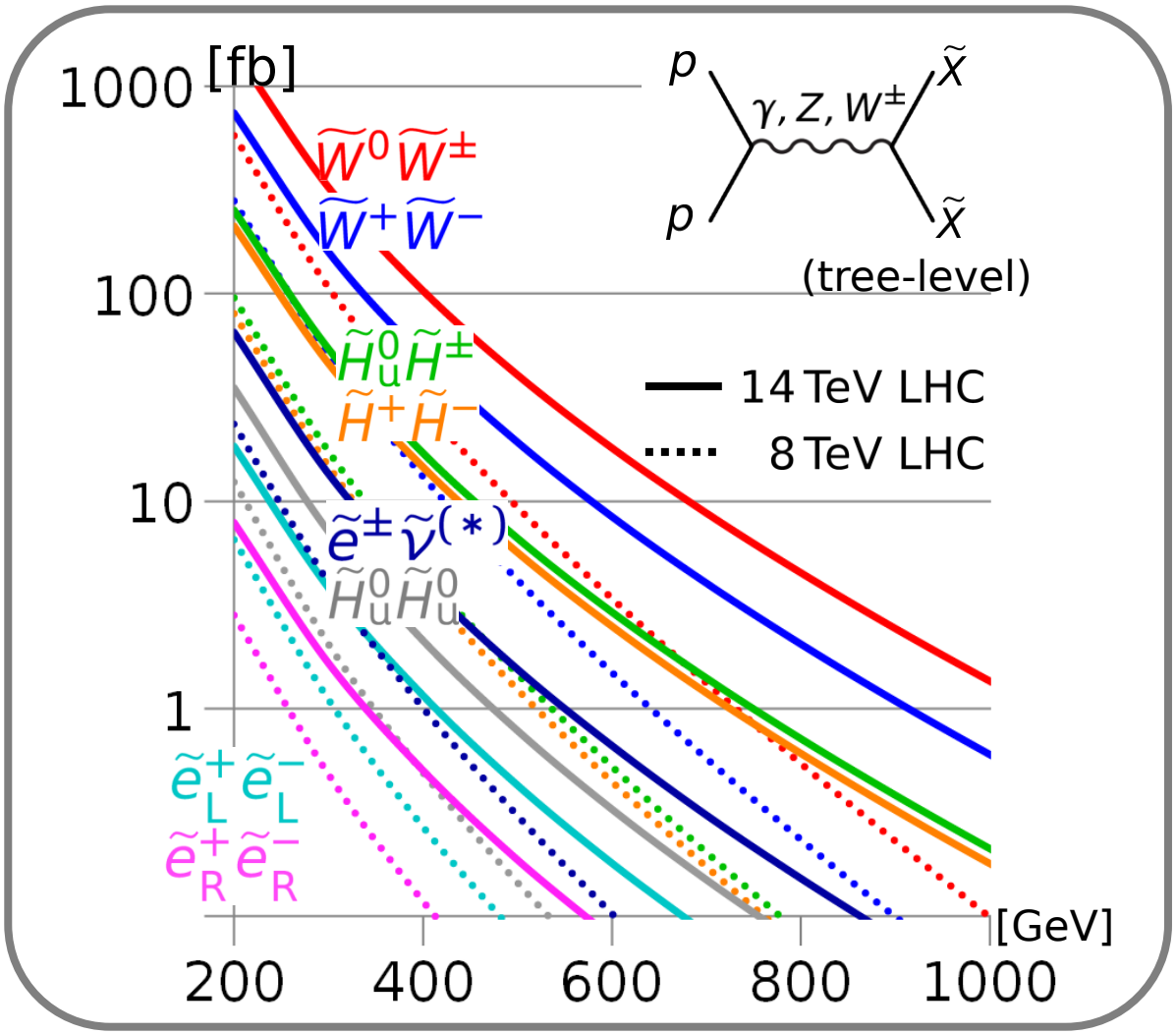
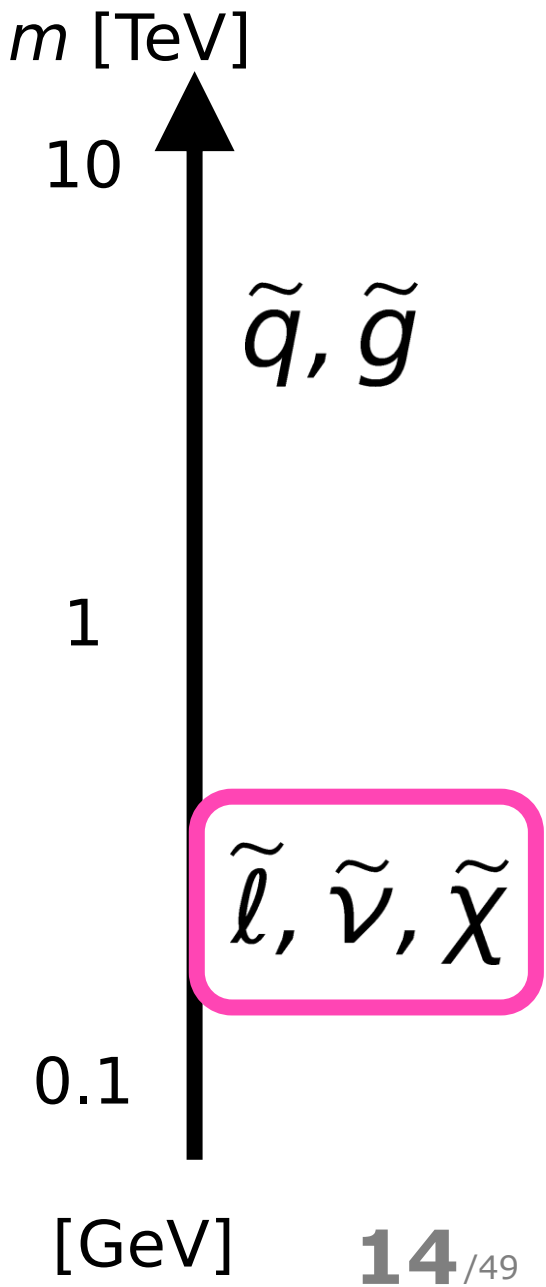
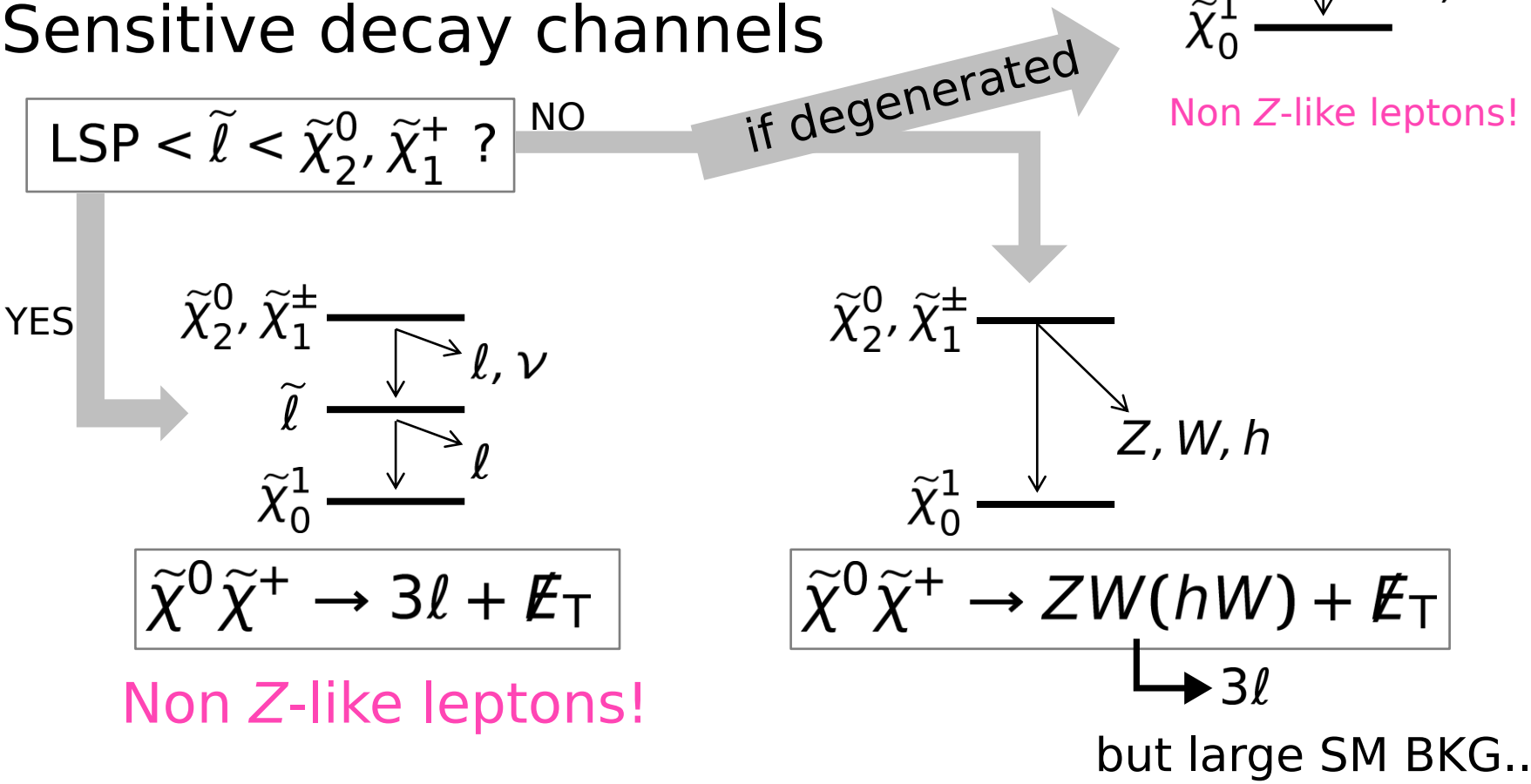
Production

- $pp \to \tilde{\chi}^0\tilde{\chi}^+, \tilde{\chi}^+\tilde{\chi}^-$ (Wino-like)

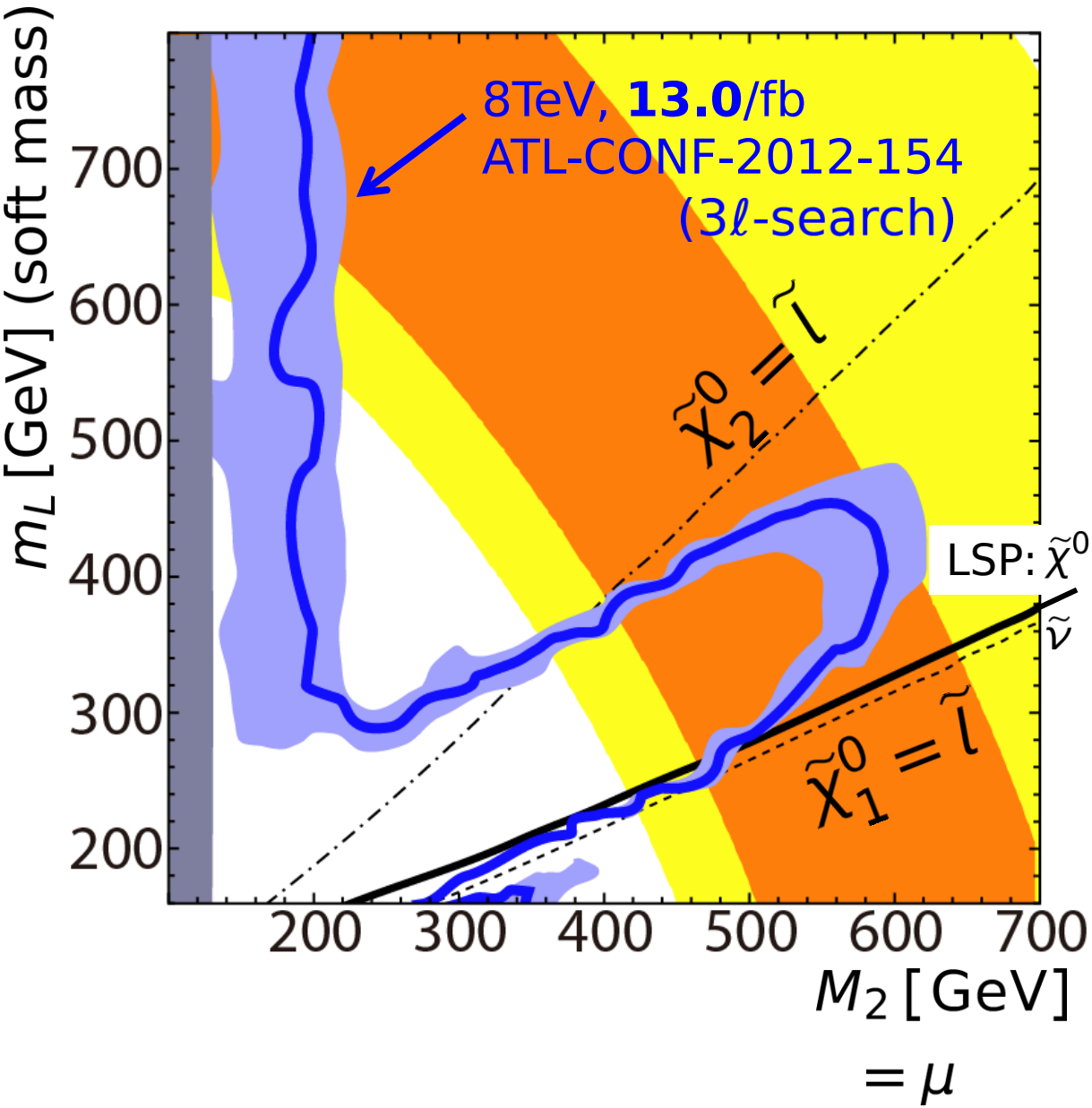




- Production
  - $pp \to \tilde{\chi}^0\tilde{\chi}^+, \tilde{\chi}^+\tilde{\chi}^-$ (Wino-like)
- Sensitive decay channels

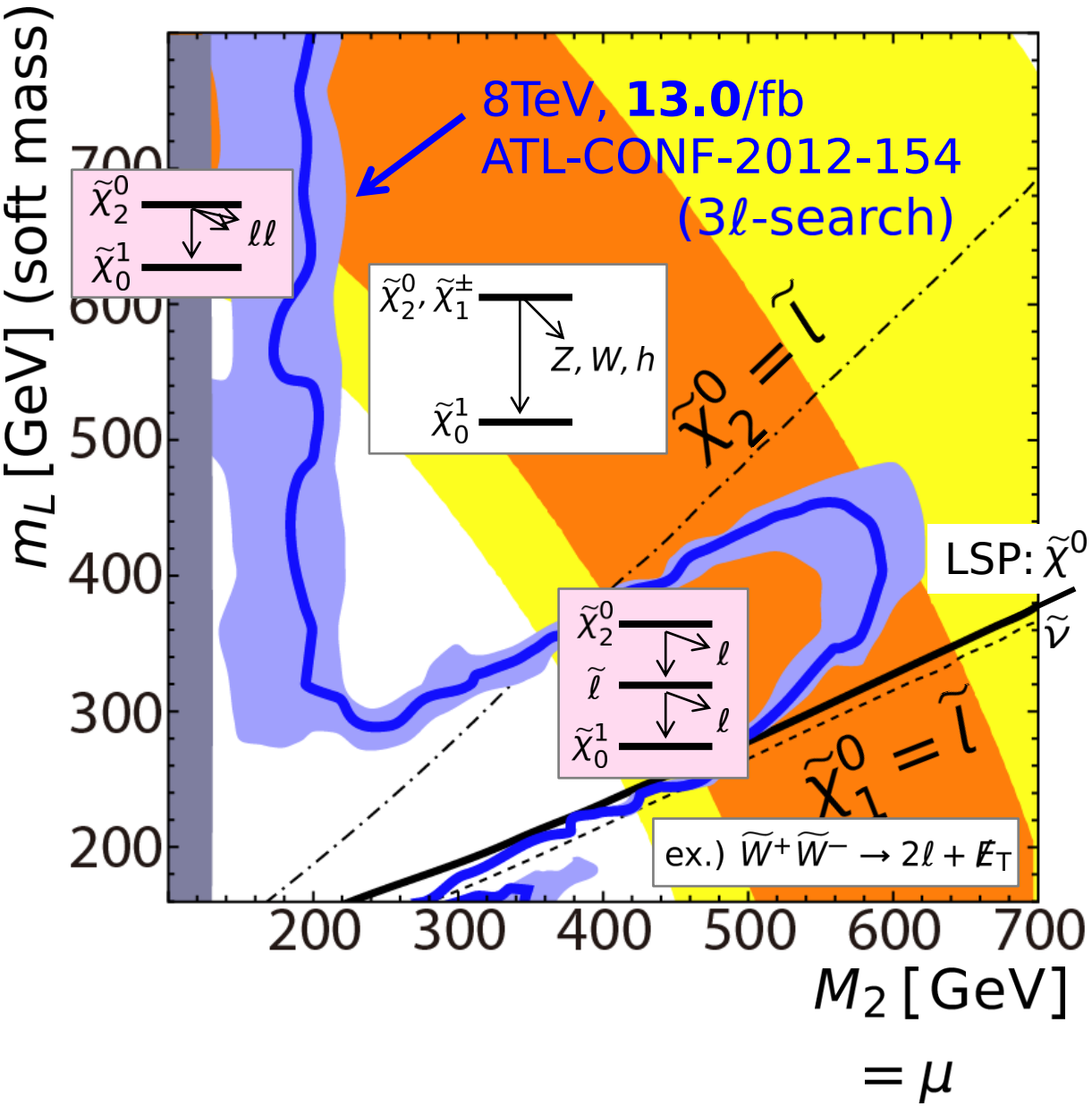


Endo, Hamaguchi, SI, Yoshinaga [1303.4256]



$g-2$ 1σ 2σ

- $\tan\beta = 40$
- $M_1 = M_2/2$
- $\tilde{\ell}_R \gg 1\,\mathrm{TeV}$
  (as well as $\tilde{q}$ & $\tilde{g}$)
- $\tilde{\tau}_{L,R} \gg 1\,\mathrm{TeV}$
- Long-lived LSP
  (R-parity)
- Ω_{DM} not cared



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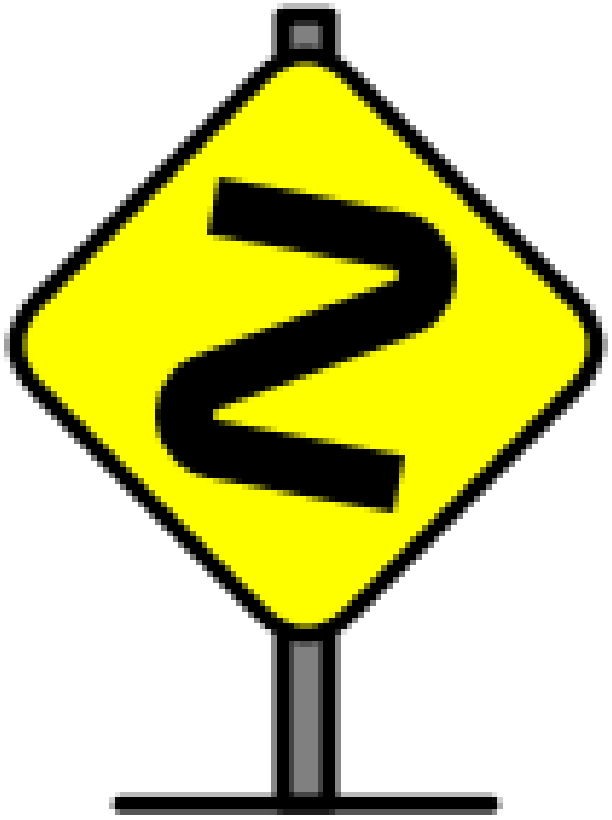
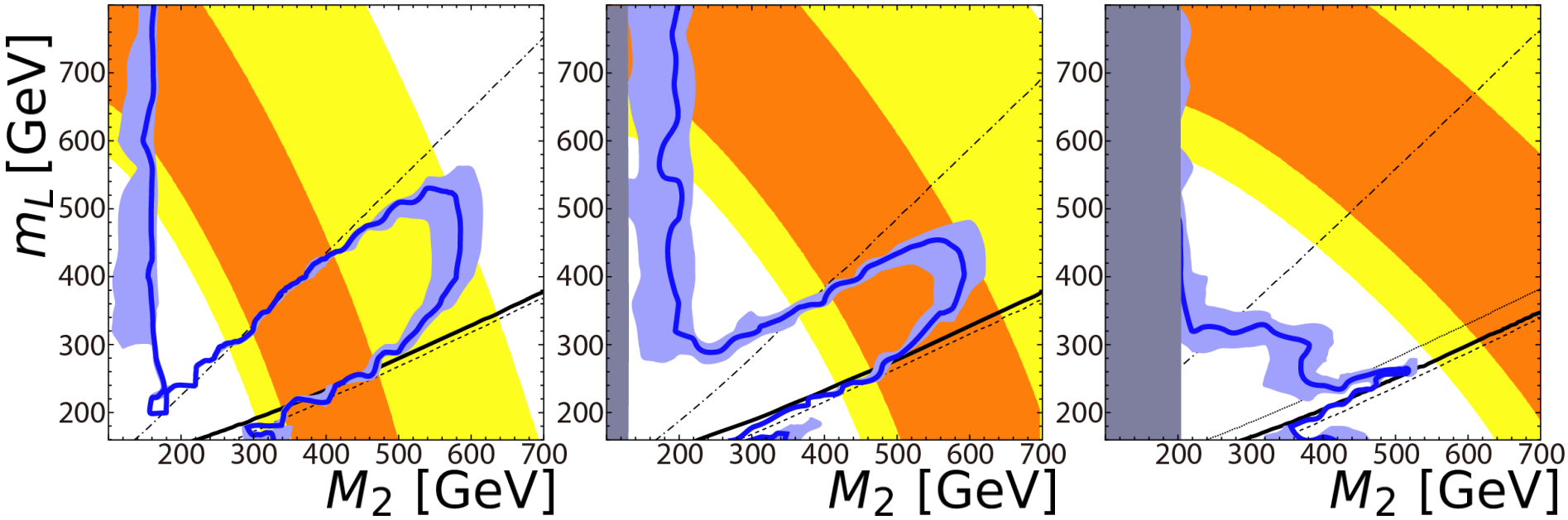


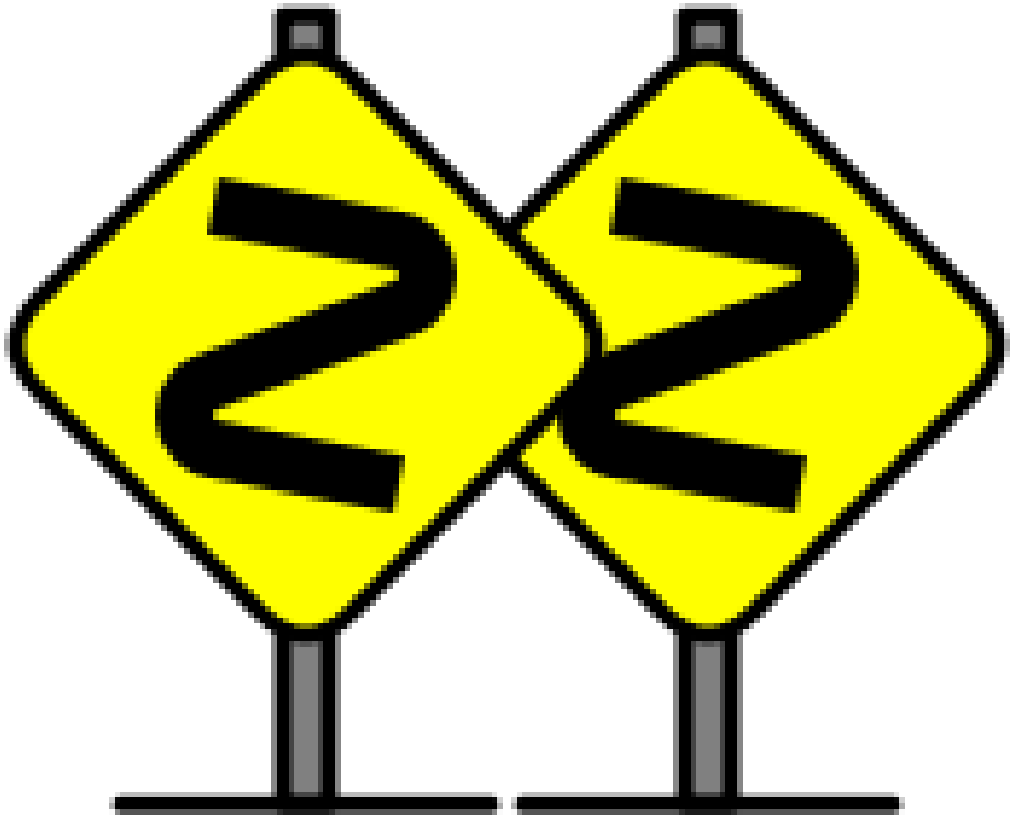
Endo, Hamaguchi, SI, Yoshinaga [1303.4256]

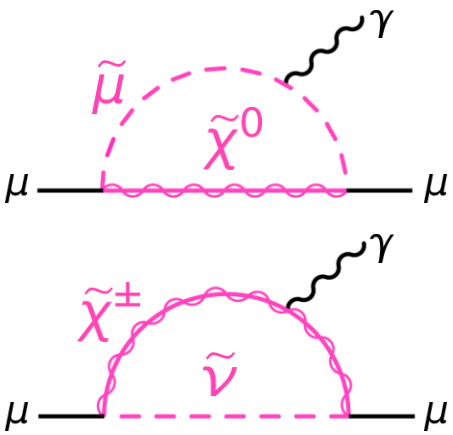
$\mu = 2M_2$ $\mu = M_2$ $\mu = 0.5M_2$



$\tilde{H}$ is irrelevant
↓
$\widetilde{W}$ simply to 3ℓ
via $\tilde{\ell}$

$\widetilde{W}$ can decay
via $\tilde{H}$
↓
Less/softer ℓ





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

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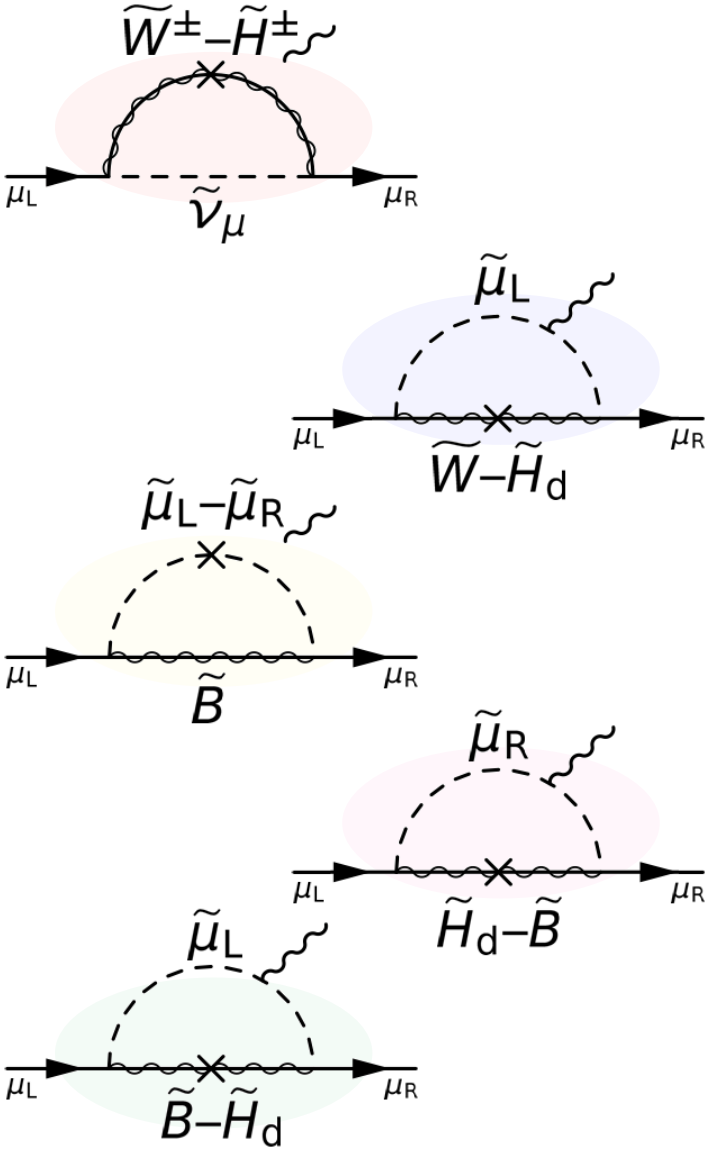
$W \ni \mu H_{\mathrm{u}} H_{\mathrm{d}}$ (Higgsino mass term), $\tan\beta = \langle H_{\mathrm{u}} \rangle / \langle H_{\mathrm{d}} \rangle$,
m_{soft} : SUSY-particle mass-scale, g_i : Gauge couplings.



$$\frac{g_2^2 m_\mu^2}{8\pi^2}\frac{M_2\mu\tan\beta}{m^4_{\tilde{\nu}_\mu}}\cdot F_a\left(\frac{M_2}{m_{\tilde{\nu}_\mu}},\frac{\mu}{m_{\tilde{\nu}_\mu}}\right)$$

$$-\frac{g_2^2 m_\mu^2}{16\pi^2}\frac{M_2\mu\tan\beta}{m^4_{\tilde{\mu}_L}}\cdot F_b\left(\frac{M_2}{m_{\tilde{\mu}_L}},\frac{\mu}{m_{\tilde{\mu}_L}}\right)$$

$$\frac{g_Y^2 m_\mu^2}{8\pi^2}\frac{\mu\tan\beta}{M_1^3}\cdot F_b\left(\frac{m_{\tilde{\mu}_L}}{M_1},\frac{m_{\tilde{\mu}_R}}{M_1}\right)$$

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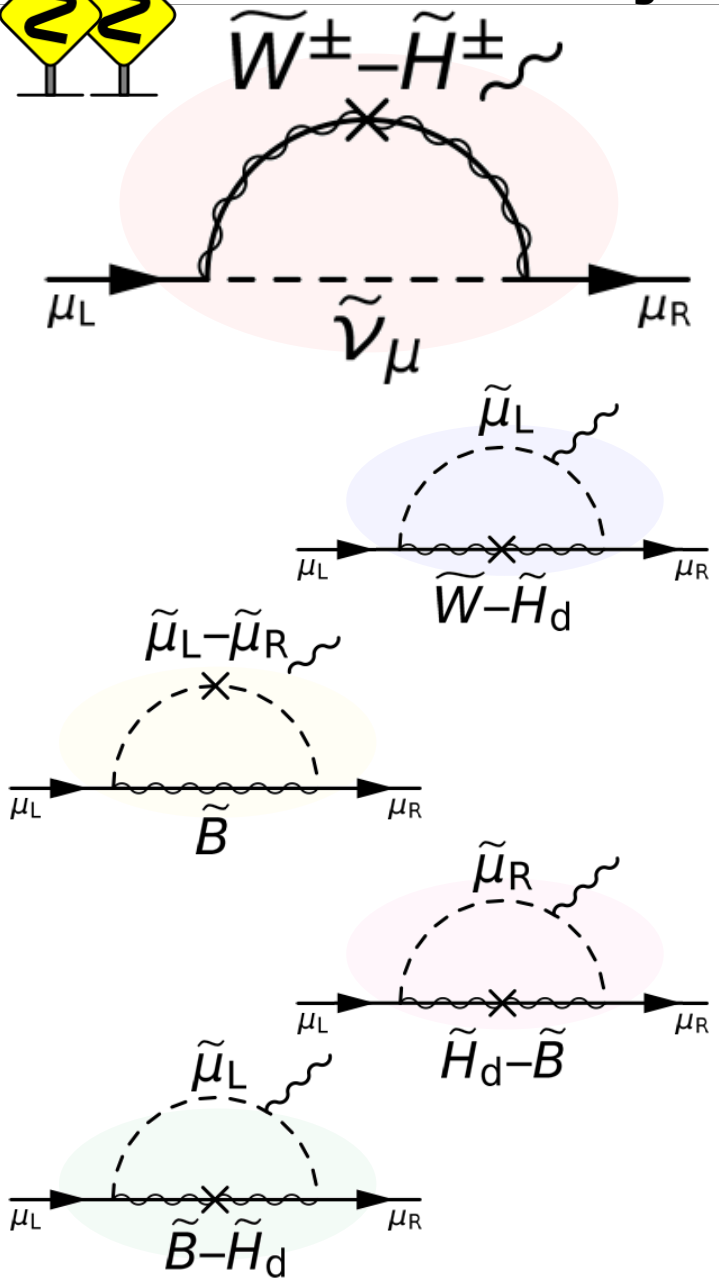
* F_a, F_b are loop functions (>0).

SUSY contribution to g-2 : gauge basis



$$\frac{g_2^2 m_\mu^2}{8\pi^2}\frac{M_2\mu\tan\beta}{m^4_{\widetilde{\nu}_\mu}}\cdot F_a\left(\frac{M_2}{m_{\widetilde{\nu}_\mu}},\frac{\mu}{m_{\widetilde{\nu}_\mu}}\right)$$

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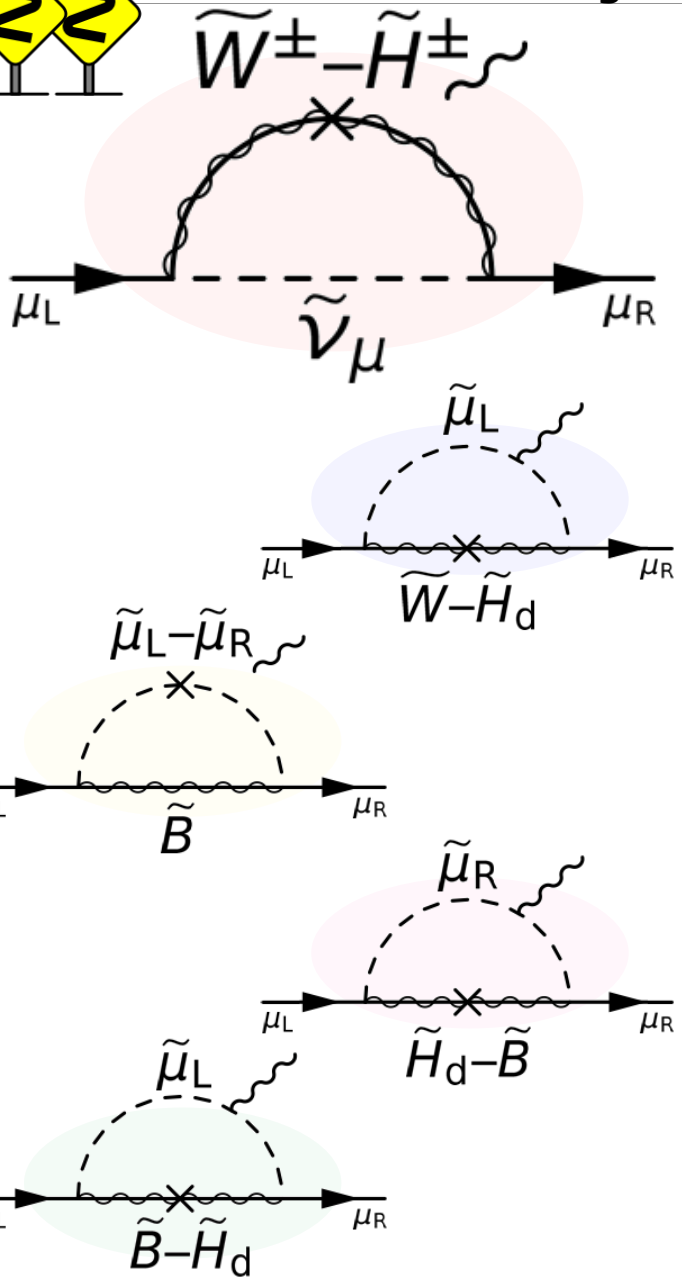


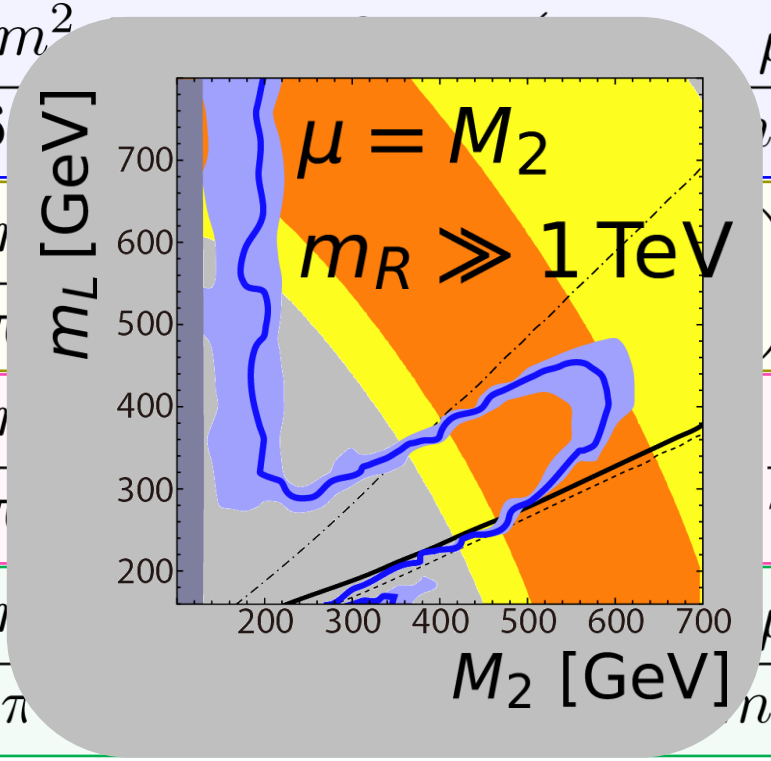
$$\frac{g_2^2 m_\mu^2}{8\pi^2}\frac{M_2\mu\tan\beta}{m_{\tilde{\nu}_\mu}^4}\cdot F_a\left(\frac{M_2}{m_{\tilde{\nu}_\mu}},\frac{\mu}{m_{\tilde{\nu}_\mu}}\right)$$

$$-\frac{g_2^2 m^2}{16}\qquad\qquad\frac{\mu}{m_{\tilde{\mu}_L}}\Big)$$

$$\frac{g_Y^2}{8\pi}$$

$$-\frac{g_Y^2}{8\pi}\qquad\qquad\frac{\mu}{m_{\tilde{\mu}_R}}\Big)$$

$$\frac{g_Y^2}{16\pi}\qquad\qquad\frac{\mu}{m_{\tilde{\mu}_L}}\Big)$$



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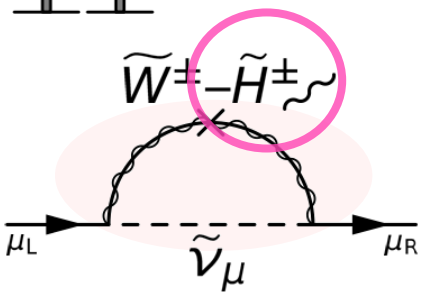

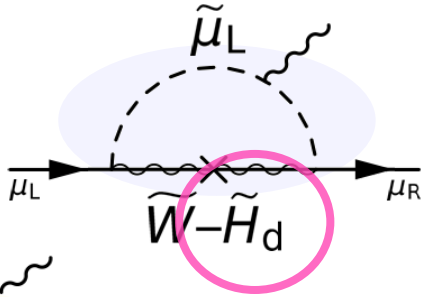

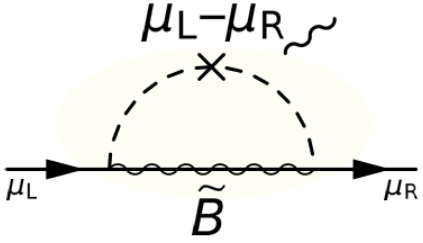

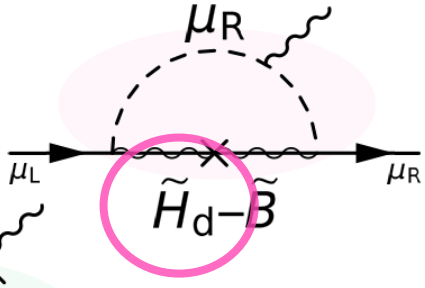

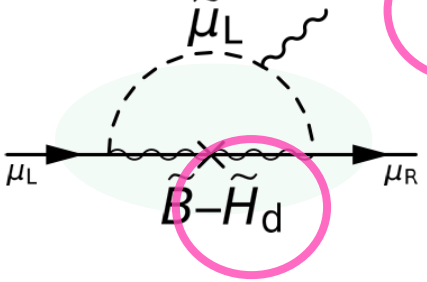

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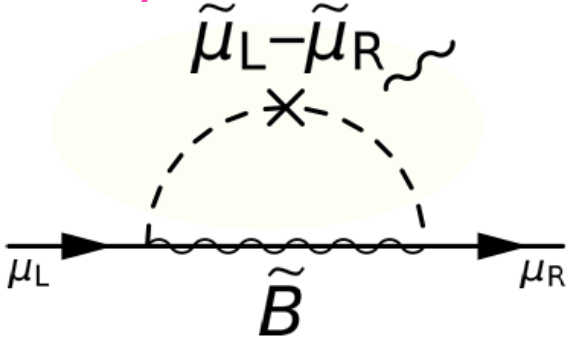
$$M^2_{\widetilde{\mu}}=\begin{pmatrix} m(l_L)^2 & m_\mu(A_\mu^*-\mu\tan\beta)\\ m_\mu(A_\mu^*-\mu\tan\beta) & m(l_R)^2\end{pmatrix}.$$

For $\mu \gg 100\,\mathrm{GeV}$,



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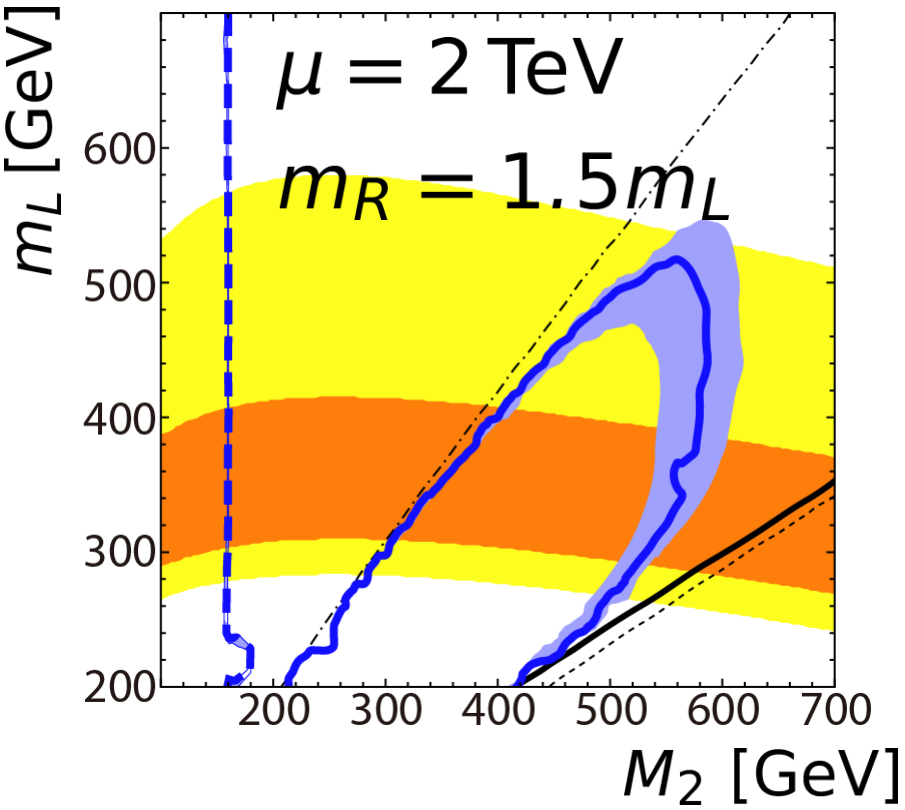

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if EWKino = O(100)GeV,

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$\tilde{\ell}, \tilde{\nu}, \tilde{\chi}^0, \tilde{\chi}^\pm$

$(g-2)_\mu$ anomaly

O(100)GeV EWK

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Discovery @ LHC!

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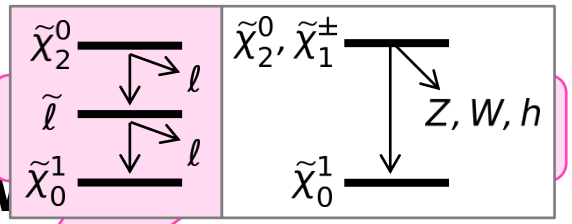

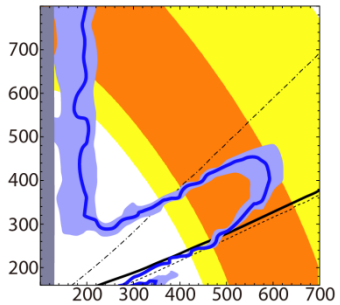

Discovery @ LHC!

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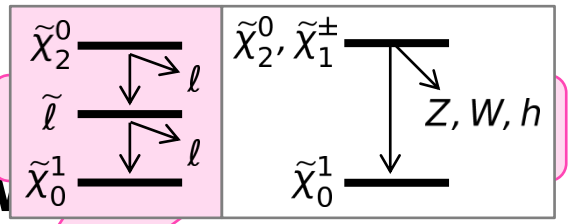

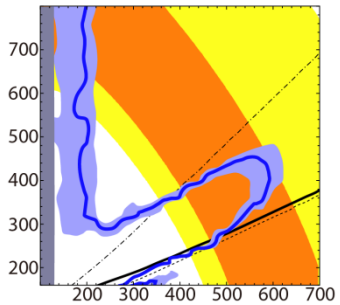

SUSY Model?

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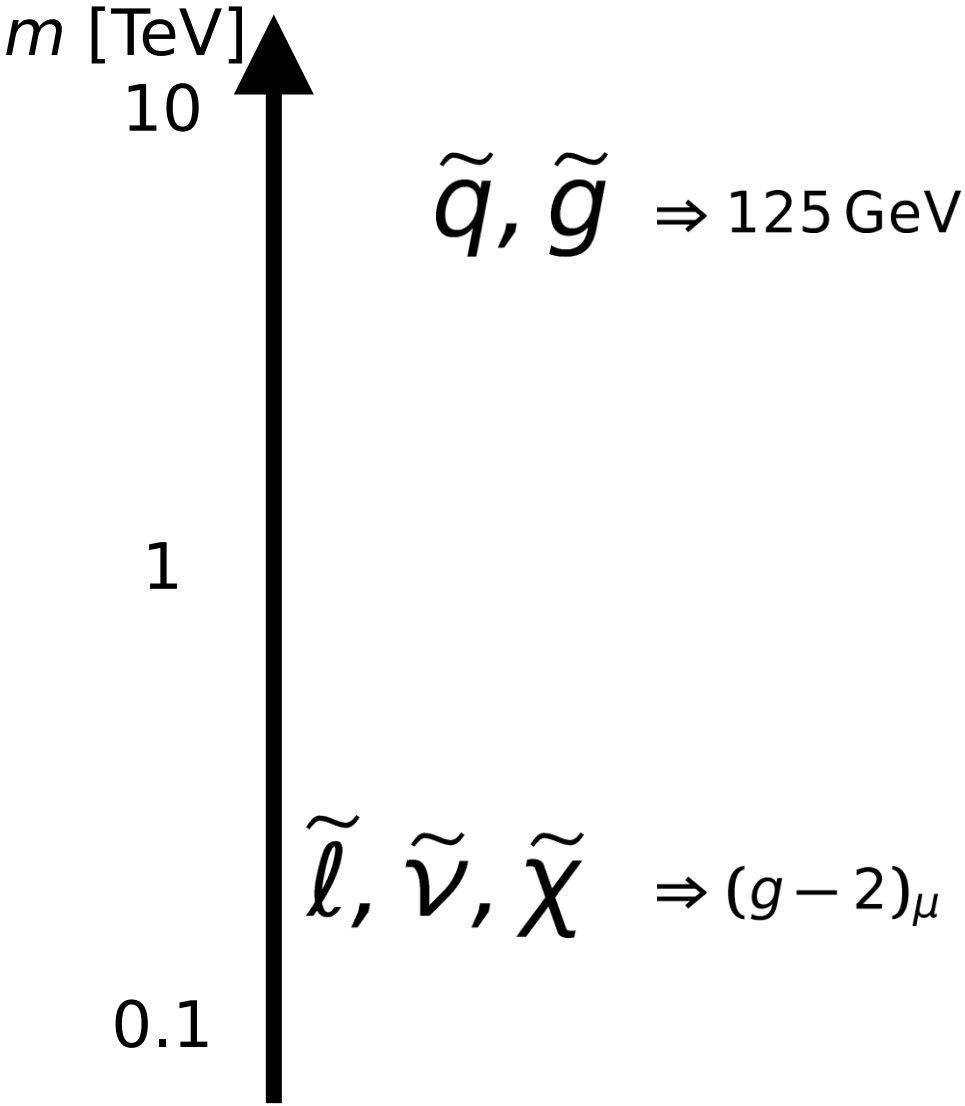
- SUSY model?


m [TeV]
10
1
0.1
$\tilde{q}, \tilde{g} \Rightarrow 125\,\mathrm{GeV}$
$\tilde{\ell}, \tilde{\nu}, \tilde{\chi} \Rightarrow (g-2)_\mu$

Ghilencea, Lee, Park [1203.0569]

See also:
Endo, Hamaguchi, SI, Yokozaki [1108.3071]
EHSI + Nakayama [1112.6412]

- SUSY model? → ~~CMSSM~~, ~~mGMSB~~

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

m [TeV]

10

$\tilde{q}, \tilde{g}$ ⇒ ~~125 GeV~~

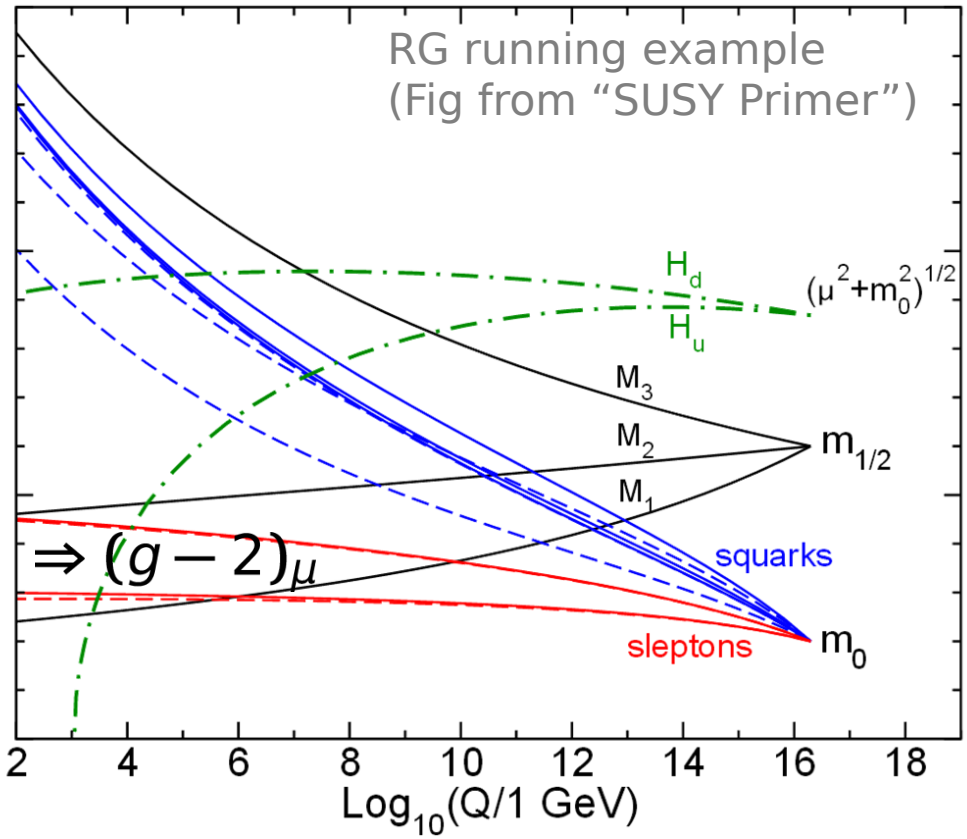
$\tilde{q}, \tilde{g}$

1

$\tilde{\ell}, \tilde{\nu}, \tilde{\chi}$

$\Rightarrow (g-2)_\mu$

0.1



- SUSY model? → ~~CMSSM~~ $= (m_0, M_{1/2}, A_0, \tan\beta, \mathrm{sgn}\,\mu)$

EXTEND

"NUGM" (M_1, M_2, M_3) for $\tilde{B}, \tilde{W}, \tilde{g}$

(non-universal gaugino mass)

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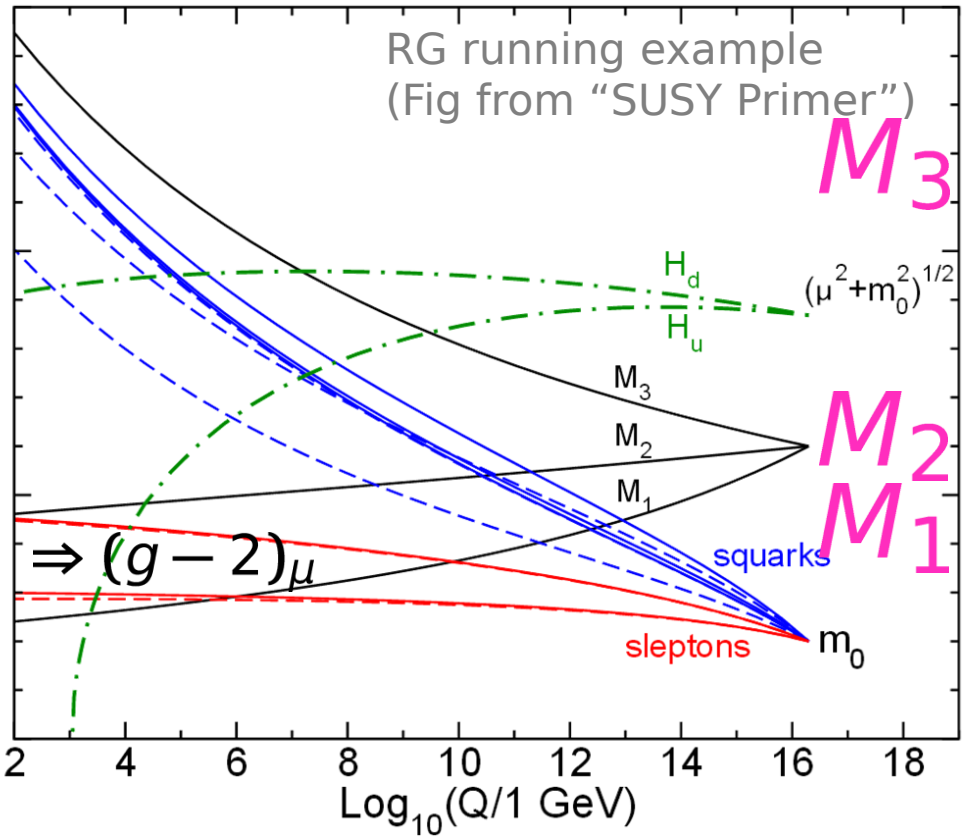

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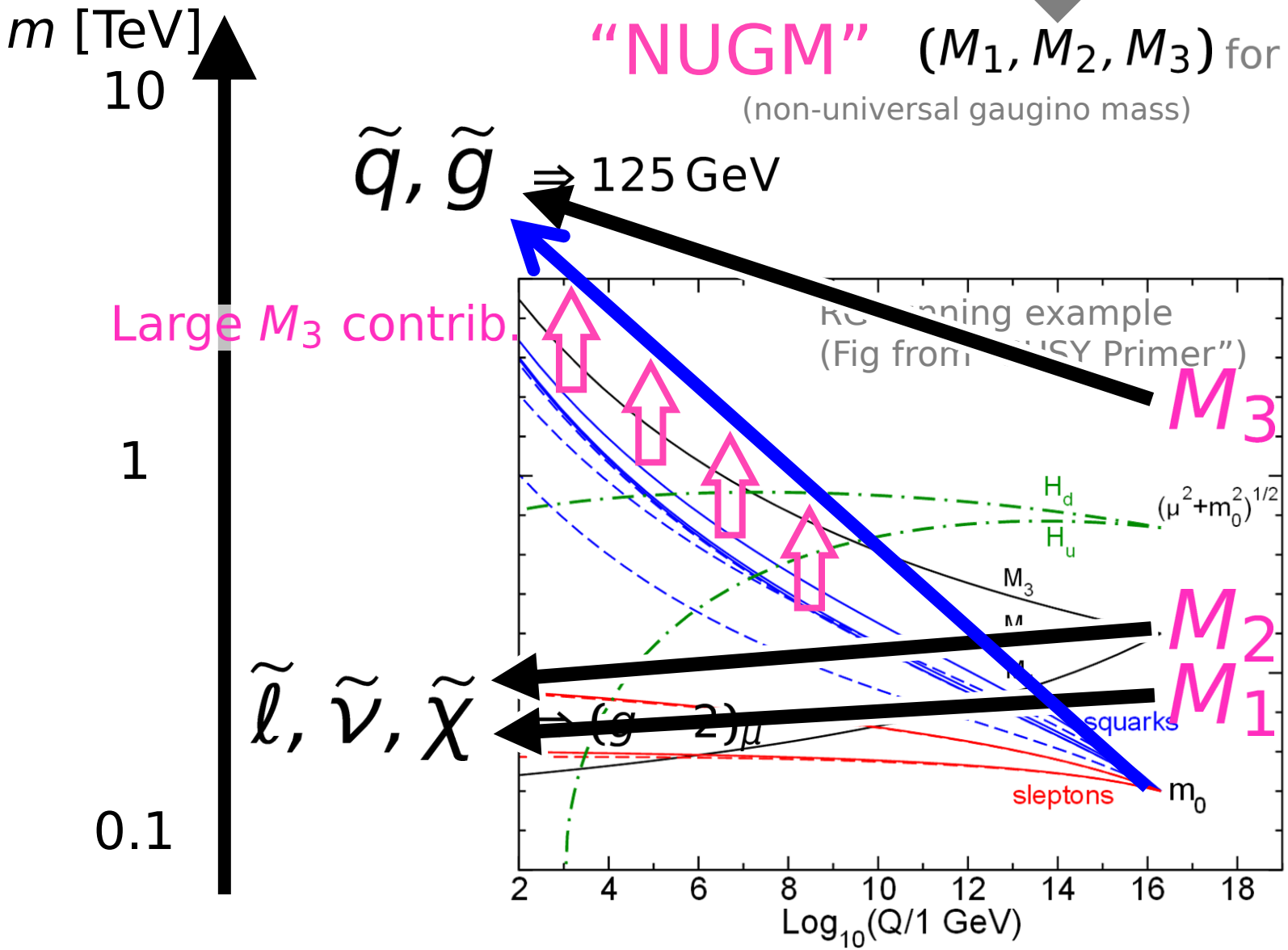

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- Just a "parameter set".
- Flavor & CP problems.

"CP-safe Gravity Mediation"

- Models for NUGM.
- CP-problems partially solved.

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CP problem?

- MSSM ... $\mathbb{C}$ -parameters $(A_{u,d,e}, M_{1,2,3}, \mu, B)$
- Unaligned → CP-violation

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

[electric dipole moment]

(electron)

ACME collab. [1310.7534]

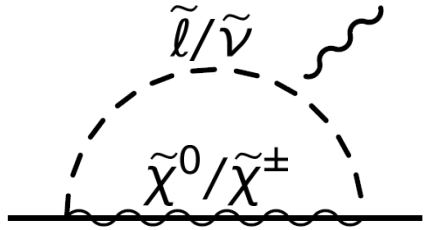
$$m = \text{O}(100)\,\text{GeV} \implies \Delta(\text{phases}) \lesssim 10^{-3}\text{–}10^{-4}.$$

$$g-2 \propto \text{Re}\left[\quad\right] \implies m = \text{O}(100)\,\text{GeV}$$

CP problem?

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

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



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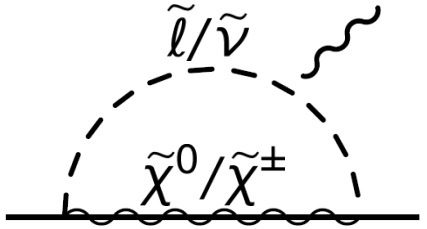
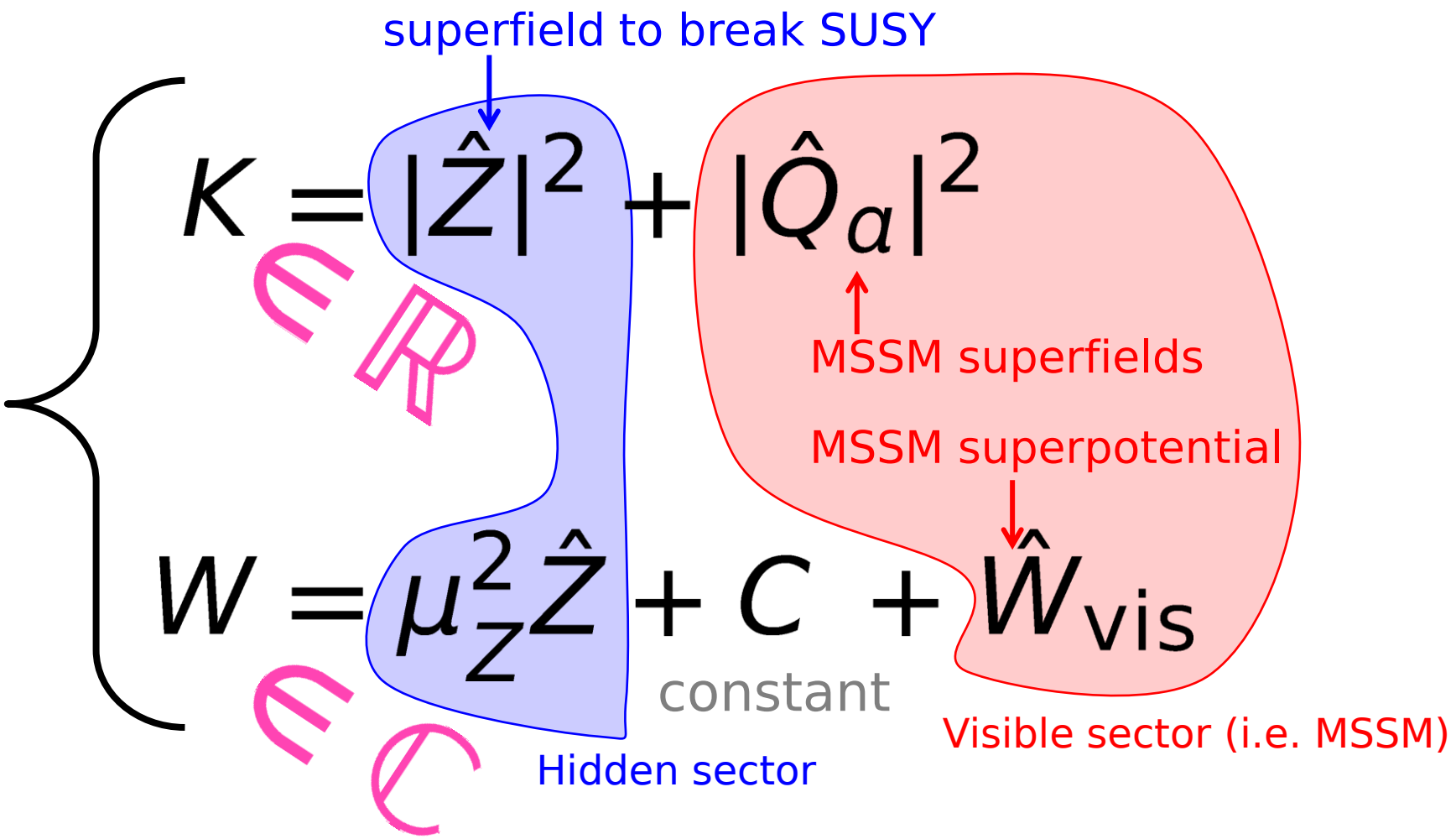


$$\mathcal{L} = \int \mathrm{d}^2\theta \mathrm{d}^2\bar{\theta}\, K(\Phi, \bar{\Phi}) + \left(\int \mathrm{d}^2\theta\, W(\Phi) + \mathrm{h.c.} \right) + \cdots$$

Ex.) Polonyi model



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Ex.) Polonyi model

superfield to break SUSY $(\ldots \mathbb{C})$

$$\begin{cases} K = |\hat{Z}|^2 + |\hat{Q}_a|^2 \\ W = \mu_Z^2 \hat{Z} + C + \hat{W}_{\mathrm{vis}} \end{cases}$$

$\mu_Z^2 \in \mathbb{C}$

$C \in \mathbb{C}$

→ unaligned phases

→ CP-viol.

Polonyi model: analysis

$$K = |Z|^2 + |Q_a|^2$$
$$W = \mu_Z^2 Z + C + W_{\rm vis}$$

$$V = K_i^j F_j F^{i*} - 3\mathrm{e}^{K/M_{\rm P}^2}|W/M_{\rm P}|^2 + (D\text{-term})$$

$$\langle V\rangle = 0, \quad \left\langle \frac{\partial V}{\partial Z}\right\rangle = 0$$

[vanishing cosmo. const.]

$$\langle Z\rangle = (\sqrt{3}-1)e^{\mathrm{i}\arg(C/\mu_Z^2)} M_P \equiv z$$
$$\langle F_Z\rangle = -e^{K/2M_P^2}\left(\frac{\partial W^*}{\partial Z^*} + \frac{\partial K}{\partial Z^*}\frac{W^*}{M_P^2}\right)$$
$$= -\sqrt{3}\mathrm{e}^{\sqrt{3}-2}\mu_Z^{2*}$$

$$\Longrightarrow \langle Z\rangle \neq 0, \quad \langle F_Z\rangle \neq 0 \quad (\text{SUSY})$$

$$V \ni -\mathrm{e}^{K/2M_{\rm P}^2}\frac{\langle F_Z\rangle}{M_{\rm P}^2}\left\langle\frac{\partial K}{\partial Z}\right\rangle W_{\rm vis} + \mathrm{e}^{K/M_{\rm P}^2}\frac{\langle W^*\rangle}{M_{\rm P}^2}\left[\frac{\partial W}{\partial Q_a}Q_a - 3W_{\rm vis}\right]$$

$$\Longrightarrow B_\mu = (2/\sqrt{3}-1)e^{-\mathrm{i}\arg C}\frac{|\langle F_Z\rangle|}{M_{\rm P}}\mu, \qquad A_{ijk} = (\sqrt{3}-1)e^{-\mathrm{i}\arg C}\frac{|\langle F_Z\rangle|}{M_{\rm P}}$$

$$\mathcal{L} \supset \int \mathrm{d}^2\theta \left(\frac{1}{4g_i^2} + k\frac{Z}{M_{\rm P}}\right) W^{i\alpha}W^i_\alpha \Longrightarrow M_i = 2kg_i^2\frac{\langle F_Z\rangle}{M_{\rm P}}$$

(set $k \in \mathbb{R}$ by rotation of Z)

SUSY model? → CMSSM $= (m_0, M_{1/2}, A_0, \tan\beta, \mathrm{sgn}\,\mu)$

EXTEND

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- Just a "parameter set". ✓
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② "CP-safe Gravity Mediation"

- Models for NUGM.
- CP-problems partially solved.

Feature: ➢ Shift symmetry on Z $(Z \to Z + i\mathcal{R})$ $(\mathcal{R} \in \mathbb{R})$

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

➢ ~~SUSY~~ in Kähler K

Izawa, Kugo, Yanagida [1008.4641]

$$\begin{cases} K = \underline{s(x)} + |Q_a|^2 \\ \text{complicated function} \\ W = \underline{C} + W_{\rm vis} \\ \text{...only one } \mathbb{C} \to \text{no misalignment} \end{cases}$$

where $x \equiv Z + Z^*$ [invariant]

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

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➢ ~~SUSY~~ in Kähler K

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$$K = s(x) + |Q_a|^2$$

complicated function but $\mathbb{R}$ $(\because K \in \mathbb{R})$

→ ~~SUSY~~

Example:

$$s(x) = -3\log\frac{-f(x)}{3};\ f(x) = -3 + c_1 x + c_2 x^2 + c_3 x^3 + c_4 x^4$$

$$\text{with } c_2 = 3c_3^2/8c_4,\ 768c_4^3 + 64c_1c_3c_4^2 - 3c_3^4 > 0.$$

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

where $x \equiv Z + Z^*$ [invariant]

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

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

$$V = K_i^j F_j F^{i*} - 3\mathrm{e}^{K/M_{\rm P}^2}|W/M_{\rm P}|^2 + (D\text{-term})$$

$$\langle V \rangle = 0, \quad \left\langle \frac{\partial V}{\partial Z} \right\rangle = 0 \quad \Longleftrightarrow \quad \frac{s'(x)^2}{M_P^2 s''(x)} = 3, \quad \frac{\partial}{\partial x}\frac{s'(x)^2}{s''(x)} = 0$$

[vanishing cosmo. const.]

(constraints on the function s)

$$\Longrightarrow \langle F_Z \rangle = -3\mathrm{e}^{s/2M_P^2} C^*/s' \quad (\cancel{\rm SUSY}),$$
$$\langle Z \rangle \neq 0$$

$$V \ni -\mathrm{e}^{K/2M_{\rm P}^2}\frac{\langle F_Z\rangle}{M_{\rm P}^2}\left\langle \frac{\partial K}{\partial Z}\right\rangle W_{\rm vis} + \mathrm{e}^{K/M_{\rm P}^2}\frac{\langle W^*\rangle}{M_{\rm P}^2}\left[\frac{\partial W}{\partial Q_a}Q_a - 3W_{\rm vis}\right]$$
$$= 3\mathrm{e}^{K/M_{\rm P}^2}\frac{C^*}{M_{\rm P}^2}W_{\rm vis} + \mathrm{e}^{K/M_{\rm P}^2}\frac{C^*}{M_{\rm P}^2}\left[\frac{\partial W_{\rm vis}}{\partial Q_a}Q_a - 3W_{\rm vis}\right]$$

$$B_\mu/\mu = 2m_{3/2}\mathrm{e}^{-\mathrm{i}\arg C}$$
$$A_0 = 3m_{3/2}\mathrm{e}^{-\mathrm{i}\arg C}$$
$$m_0^2 = m_{3/2}^2 \qquad \text{where } m_{3/2}^2 = |C|^2\mathrm{e}^{s/M_{\rm P}^2}/M_{\rm P}^4$$

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

From anomaly of (broken) shift sym. $(\Longrightarrow k_i \in \mathbb{R})$

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

$M_1, M_2 \ll M_3$ from "above-GUT" structure.

Ex.) SU(5) × U(3) → SU(3) × SU(2) × U(1) × SU(3) × U(1)

→ $\mathrm{SU}(3)_{\rm C} \times \mathrm{SU}(2)_{\rm L} \times \mathrm{U}(1)_Y$

$k_3 = a_5 + a_3$ $\quad k_2 = a_5$ $\quad k_1 = a_5 + a_1$

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

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

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

$k_3 = a_5 + a_3 \quad k_2 = a_5 \quad k_1 = a_5 + a_1$

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$M_1, M_2, M_3, B_\mu, A_u, A_d, A_e$ are aligned.

CP-violation from sfermion $(m_0^2)_{ij}$ still remains.
→ should be solved together with flavor problem.

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

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

$K = s(x) + |Q_a|^2$
$W = C + W_{\rm vis}$

Summary

if EWKino = O(100)GeV,

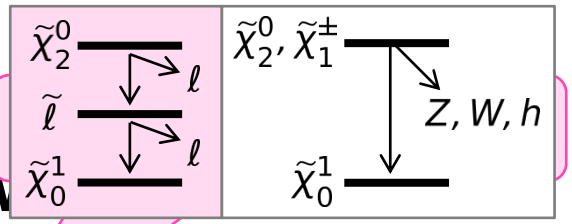
SUSY → ☑ $(g-2)_\mu$

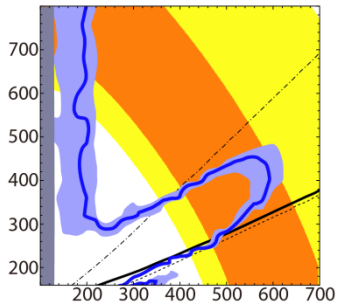
$\tilde{\ell}, \tilde{\nu}, \tilde{\chi}^0, \tilde{\chi}^\pm$

$(g-2)_\mu$ anomaly

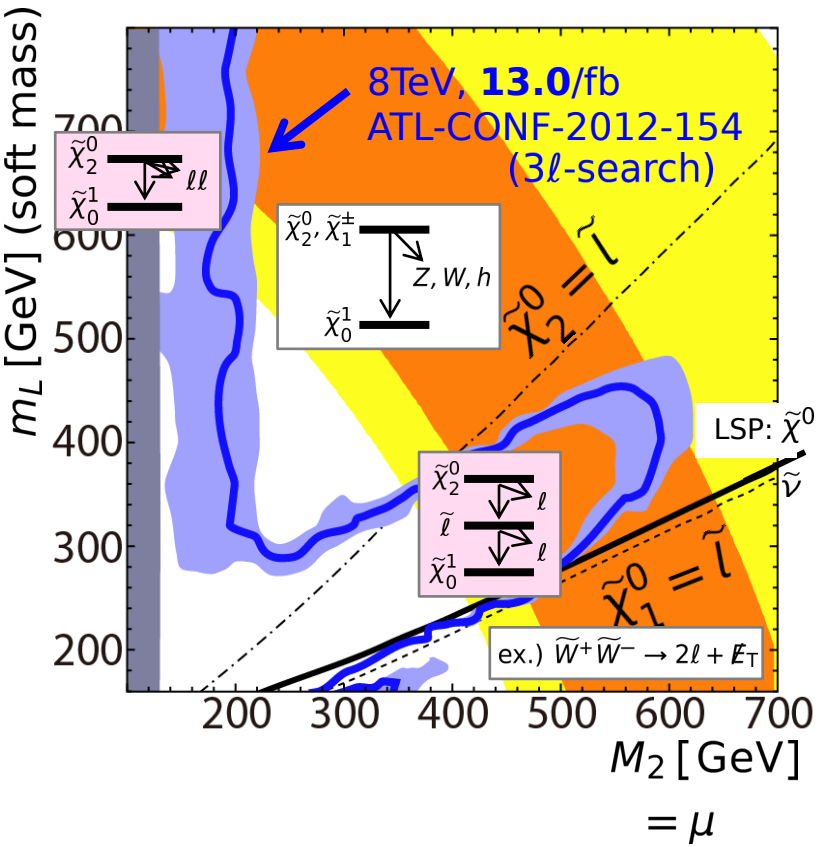
O(100)GeV EW

Discovery @ LHC!





“CP-safe GM”← SUSY Model?



“CP-safe Gravity Mediation”

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

- Models for **NUGM**.
- **CP**-problems partially solved.

$$K = s(x) + |Q_a|^2$$

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

where $x \equiv Z + Z^*$

SUSY from the viewpoint of $(g-2)_\mu$