הטכניון
מכון טכנולוגי
לישראל
TECHNION
Israel Institute
of Technology

(g-2)$_\mu$–SUSY and the LHC

Sho IWAMOTO（岩本　祥）

2 Sep. 2015

Joint Particle Seminar @ UC Irvine

References

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

*U.Tokyo　**Kavli IPMU　***INFN

LHC Run I : 2010-2012

- SM established!

$$m_H = 125.09(21)^{\text{stat}}(11)^{\text{syst}} \quad (125.09 \pm 0.21 \pm 0.11)$$

ATLAS+CMS [1503.07589]

LHC Run II : 2015-2018 or more

- Beyond SM
  - SUSY?
  - Extra dimensions?
  - Extended Higgs sector?

before LHC Run I

- ✓ dark matter
- ✓ muon *g*-2 anomaly
- ✓ radiative EWSB [Electroweak symmetry breaking]
- ✓ naturalness
- ✓ gauge-coupling unification

LHC Run I : 2010-2012

- SM established!

$$m_H = 125.09(21)^{\mathrm{stat}}(11)^{\mathrm{syst}}$$

ATLAS+CMS [1503.07589]

Heavier than "our" expectation based on **MSSM**

[minimal supersymmetric standard model]

tree | one-loop level (top-stop)

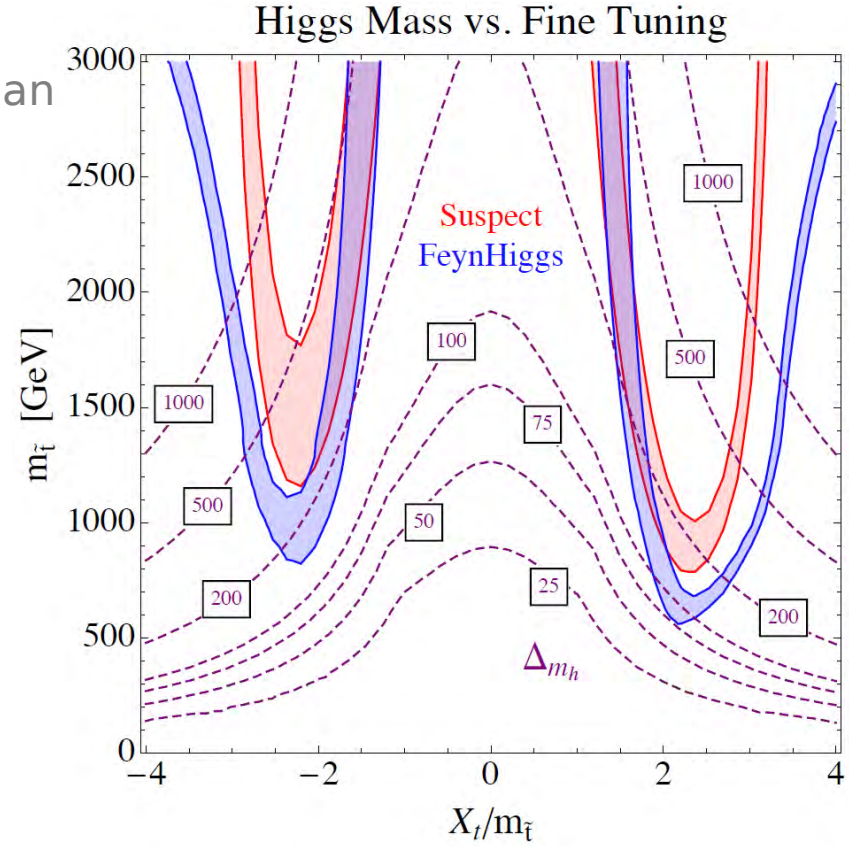
$$m_H^2 \approx m_Z^2 + \frac{3g_W^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} - \frac{(\alpha^2-6)^2}{12} + 3\right]$$

$(\alpha \equiv A_t/m_{\tilde{t}})$

(stop mixing parameter)

Okada, Yamaguchi, Yanagida (1991),
Ellis, Ridolfi, Zwirner (1991),
Haber, Hempfling (1991).

famous figure by
Hall, Pinner, Ruderman
[1112.2703]



LHC Run I

⇩

$m_{\tilde{t}} \gtrsim \mathrm{O}(1)\,\mathrm{TeV}$
&
nature seems
not natural

tree | one-loop level (top-stop)

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

$(\alpha \equiv A_t/m_{\tilde{t}})$

(stop mixing parameter)

Okada, Yamaguchi, Yanagida (1991),
Ellis, Ridolfi, Zwirner (1991),
Haber, Hempfling (1991).

- LHC Run I : 2010-2012
  - SM established!

$$m_H = 125.09(21)^{\text{stat}}(11)^{\text{syst}}$$ ATLAS+CMS [1503.07589]

- LHC Run II : 2015-2018 or more
  - Beyond SM
    - SUSY?
    - Extra dimensions?
    - Extended Higgs sector?

before LHC Run I

- ✓ dark matter
- ✓ muon *g*-2 anomaly
- ✓ radiative EWSB
- ✓ naturalness
- ✓ gauge-coupling unification

- LHC Run I : 2010-2012
  - SM established!

$$m_H = 125.09(21)^{\text{stat}}(11)^{\text{syst}}$$ ATLAS+CMS [1503.07589]

- LHC Run II : 2015-2018 or more
  - Beyond SM
    - SUSY?
    - Extra dimensions?
    - Extended Higgs sector?

After LHC Run I

- ✓ dark matter
- ✓ muon *g*-2 anomaly
- ✓ radiative EWSB: **125 GeV**
- ✓ naturalness
- ✓ gauge-coupling unification

$(g-2)_\mu$ anomaly $\longrightarrow$ $\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm = \mathbf{O(100)\,GeV}$

SUSY models to explain $\Delta(g-2)_\mu$

"CP-safe" gravity mediation

SI, Yanagida, Yokozaki [1407.4226]

LHC signatures

- (case 1) $\mu \sim M_2$
- (case 2) $\mu \gg M_2$

Endo, Hamaguchi, SI, Yoshinaga [1303.4256]

8 TeV summary & 14 TeV prospects

$(g-2)_\mu$ anomaly $\longrightarrow$ $\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm = \mathbf{O(100)\,GeV}$

SUSY models to explain $\Delta(g-2)_\mu$

“CP-safe” gravity mediation

SI, Yanagida, Yokozaki [1407.4226]

LHC signatures

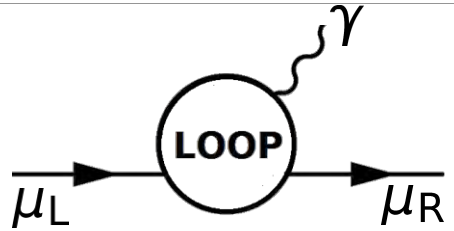
- (case 1) $\mu \sim M_2$
- (case 2) $\mu \gg M_2$

Endo, Hamaguchi, SI, Yoshinaga [1303.4256]

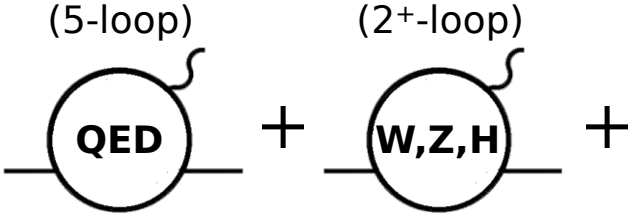
8 TeV summary & 14 TeV prospects

Muon *g*-2 SM expectation : discrepancy!

$$a_\mu = \frac{(g-2)_\mu}{2} =$$



$$a_\mu^{\mathrm{SM}} \simeq$$



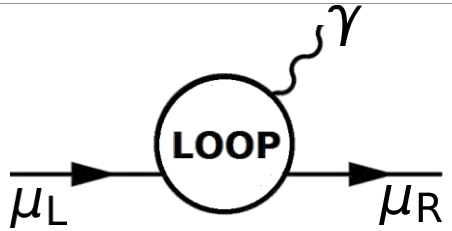
$$a_\mu(\mathrm{QED}) = \quad (11\,658\,471.8951 \pm 0.0080) \times 10^{-10},$$
$$a_\mu(\mathrm{EW}) = \quad (\qquad 15.36 \quad \pm 0.1 \quad) \times 10^{-10},$$

QED: Aoyama, Hayakawa, Kinoshita, Nio [1205.5370].
EW: Gnendiger, Stöckinger, Stöckinger-Kim [1306.5546].
HVP: Hagiwara, Liao, Martin, Nomura, Teubner [1105.3149].
HLbL: Prades, De Rafael, Vainshtein [0901.0306].

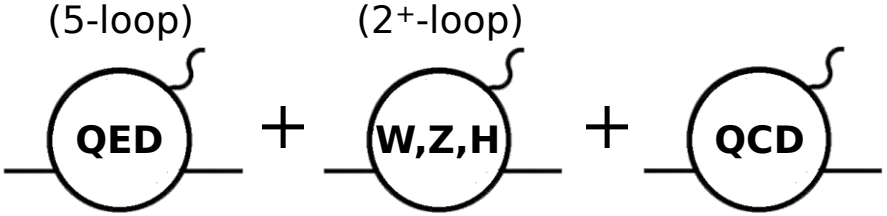
See also:
HVP-LO: Davier, Hoecker, Malaescu, Zhang [1010.4180],
HVP-HO: Kurz, Liu, Marquard, Steinhauser [**1403.6400**],
HLbL: Jegerlehner, Nyffeler [0902.3360],
Colangelo, Hoferichter, Nyffeler, Passera, Stoffer [**1403.7512**]

Muon *g*-2 SM expectation : discrepancy!

$$a_\mu = \frac{(g-2)_\mu}{2} =$$



$$a_\mu^{\mathrm{SM}} \simeq$$



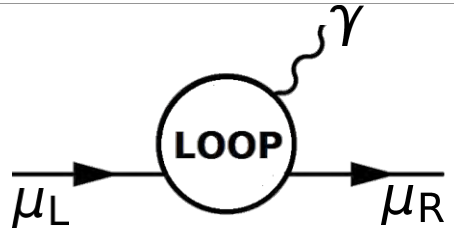
$$a_\mu(\mathrm{QED}) = \quad (11\,658\,471.8951 \pm 0.0080) \times 10^{-10},$$
$$a_\mu(\mathrm{EW}) = \quad (\qquad 15.36 \quad \pm 0.1 \quad) \times 10^{-10},$$

QED: Aoyama, Hayakawa, Kinoshita, Nio [1205.5370].
EW: Gnendiger, Stöckinger, Stöckinger-Kim [1306.5546].
HVP: Hagiwara, Liao, Martin, Nomura, Teubner [1105.3149].
HLbL: Prades, De Rafael, Vainshtein [0901.0306].

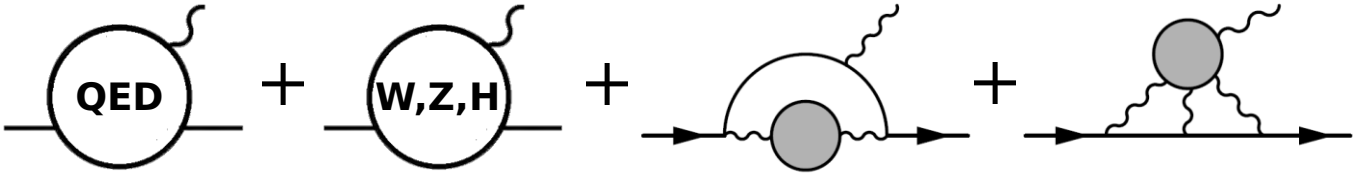
See also:
HVP-LO: Davier, Hoecker, Malaescu, Zhang [1010.4180],
HVP-HO: Kurz, Liu, Marquard, Steinhauser [**1403.6400**],
HLbL: Jegerlehner, Nyffeler [0902.3360],
Colangelo, Hoferichter, Nyffeler, Passera, Stoffer [**1403.7512**]

Muon *g*-2 SM expectation : discrepancy!

$$a_\mu = \frac{(g-2)_\mu}{2} =$$



$$a_\mu^{\mathrm{SM}} \simeq$$



$$\begin{aligned}
a_\mu(\mathrm{QED}) &= (11\,658\,471.8951 \pm 0.0080) \times 10^{-10},\\
a_\mu(\mathrm{EW}) &= (15.36 \pm 0.1) \times 10^{-10},\\
a_\mu(\mathrm{HVP\text{-}LO}) &= (694.91 \pm 4.27) \times 10^{-10},\\
a_\mu(\mathrm{HVP\text{-}HO}) &= -(9.84 \pm 0.07) \times 10^{-10},\\
a_\mu(\mathrm{HLbL}) &= (10.5 \pm 2.6) \times 10^{-10}.
\end{aligned}$$

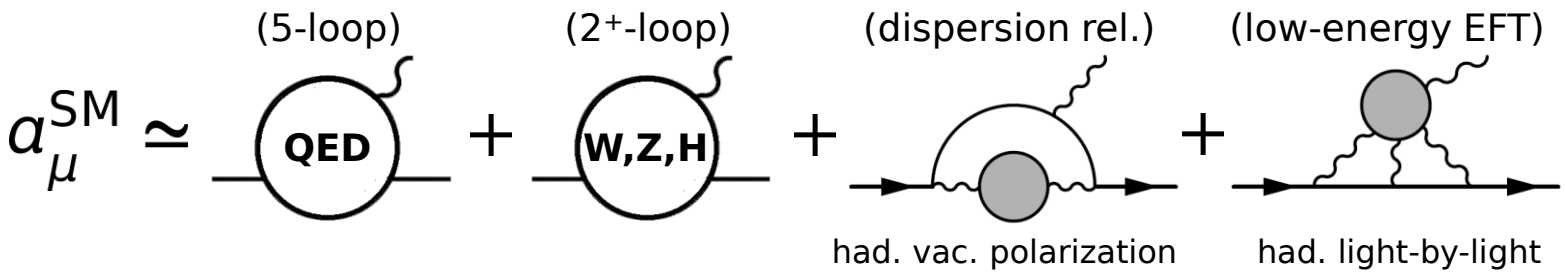
$$+)$$

$$a_\mu^{\mathrm{SM}} = (11\,659\,182.8 \pm 5.0) \times 10^{-10}$$

QED: Aoyama, Hayakawa, Kinoshita, Nio [1205.5370].
EW: Gnendiger, Stöckinger, Stöckinger-Kim [1306.5546].
HVP: Hagiwara, Liao, Martin, Nomura, Teubner [1105.3149].
HLbL: Prades, De Rafael, Vainshtein [0901.0306].

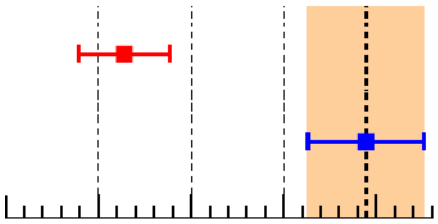
See also:
HVP-LO: Davier, Hoecker, Malaescu, Zhang [1010.4180],
HVP-HO: Kurz, Liu, Marquard, Steinhauser [**1403.6400**],
HLbL: Jegerlehner, Nyffeler [0902.3360],
Colangelo, Hoferichter, Nyffeler, Passera, Stoffer [**1403.7512**]

$$\Delta a_\mu = (26.4 \pm 8.0) \times 10^{-10} \quad \cdots \mathbf{3.3\sigma} \text{ anomaly}$$



$$\begin{aligned}
a_\mu(\text{QED}) &= (11\,658\,471.8951 \pm 0.0080) \times 10^{-10}, \\
a_\mu(\text{EW}) &= (15.36 \pm 0.1) \times 10^{-10}, \\
a_\mu(\text{HVP-LO}) &= (694.91 \pm 4.27) \times 10^{-10}, \\
a_\mu(\text{HVP-HO}) &= -(9.84 \pm 0.07) \times 10^{-10}, \\
a_\mu(\text{HLbL}) &= (10.5 \pm 2.6) \times 10^{-10}.
\end{aligned}$$

+)



$$a_\mu^{\rm SM} = (11\,659\,182.8 \pm 5.0) \times 10^{-10}$$

$$a_\mu^{\rm exp} = (11\,659\,209.2 \pm 6.3) \times 10^{-10} \quad (\text{BNL '04}_{+\text{CODATA '14}})$$

[future: ±1.6]

QED: Aoyama, Hayakawa, Kinoshita, Nio [1205.5370].
EW: Gnendiger, Stöckinger, Stöckinger-Kim [1306.5546].
HVP: Hagiwara, Liao, Martin, Nomura, Teubner [1105.3149].
HLbL: Prades, De Rafael, Vainshtein [0901.0306].

See also:
HVP-LO: Davier, Hoecker, Malaescu, Zhang [1010.4180],
HVP-HO: Kurz, Liu, Marquard, Steinhauser [**1403.6400**],
HLbL: Jegerlehner, Nyffeler [0902.3360],
Colangelo, Hoferichter, Nyffeler, Passera, Stoffer [**1403.7512**]

$$\Delta a_\mu = (26.4 \pm 8.0) \times 10^{-10} \quad \cdots \mathbf{3.3\sigma} \text{ anomaly}$$

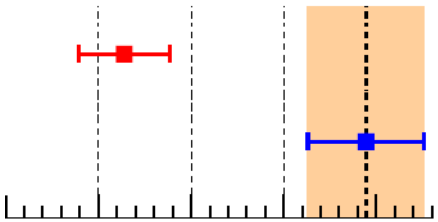
μ_L μ_R

$$a_\mu^{\rm SM} \simeq$$

(5-loop) QED + (2⁺-loop) W,Z,H + (dispersion rel.) had. vac. polarization + (low-energy EFT) had. light-by-light

$$\begin{aligned}
a_\mu(\text{QED}) &= (11\,658\,471.8951 \pm 0.0080) \times 10^{-10}, \\
a_\mu(\text{EW}) &= (15.36 \pm 0.1) \times 10^{-10}, \\
a_\mu(\text{HVP-LO}) &= (694.91 \pm 4.27) \times 10^{-10}, \\
a_\mu(\text{HVP-HO}) &= -(9.84 \pm 0.07) \times 10^{-10}, \\
a_\mu(\text{HLbL}) &= (10.5 \pm 2.6) \times 10^{-10}.
\end{aligned}$$

$$+) \quad a_\mu(\text{NP})? \quad \ldots \quad 10 \times 10^{-10} \quad \sim a_\mu(\text{EW})$$



$$a_\mu^{\rm SM} = (11\,659\,182.8 \pm 5.0) \times 10^{-10}$$

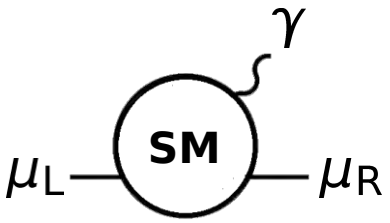
$$a_\mu^{\rm exp} = (11\,659\,209.2 \pm 6.3) \times 10^{-10} \quad (\text{BNL '04}_{+\text{CODATA '14}})$$

[future: ±1.6]

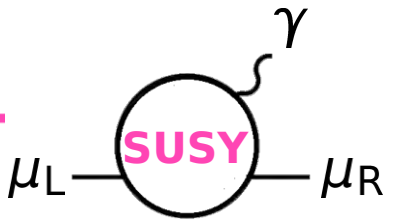
QED: Aoyama, Hayakawa, Kinoshita, Nio [1205.5370].
EW: Gnendiger, Stöckinger, Stöckinger-Kim [1306.5546].
HVP: Hagiwara, Liao, Martin, Nomura, Teubner [1105.3149].
HLbL: Prades, De Rafael, Vainshtein [0901.0306].

See also:
HVP-LO: Davier, Hoecker, Malaescu, Zhang [1010.4180],
HVP-HO: Kurz, Liu, Marquard, Steinhauser [**1403.6400**],
HLbL: Jegerlehner, Nyffeler [0902.3360],
Colangelo, Hoferichter, Nyffeler, Passera, Stoffer [**1403.7512**]

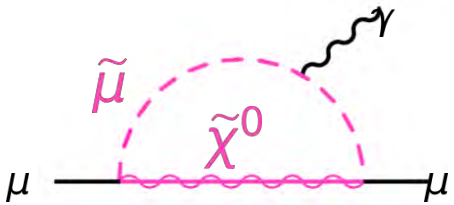
$$a_\mu = \frac{(g-2)_\mu}{2} =$$



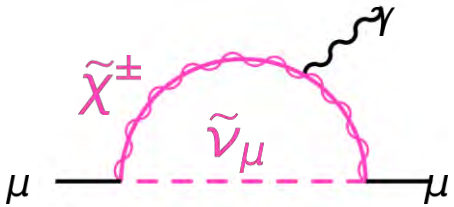
+



?



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



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

if $\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm$ = O(100)GeV,

SUSY → ☑ $(g-2)_\mu$

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.

$(g-2)_\mu$ anomaly $\longrightarrow$ $\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm = \mathrm{O}(100)\,\mathrm{GeV}$

SUSY models to explain $\Delta(g-2)_\mu$

"CP-safe" gravity mediation

SI, Yanagida, Yokozaki [1407.4226]

LHC signatures

- (case 1) $\mu \sim M_2$
- (case 2) $\mu \gg M_2$

Endo, Hamaguchi, SI, Yoshinaga [1303.4256]

8 TeV summary & 14 TeV prospects

$(g-2)_\mu$ anomaly $\longrightarrow$ $\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm = \mathrm{O}(100)\,\mathrm{GeV}$

SUSY models to explain $\Delta(g-2)_\mu$

"CP-safe" gravity mediation

SI, Yanagida, Yokozaki [1407.4226]

LHC signatures

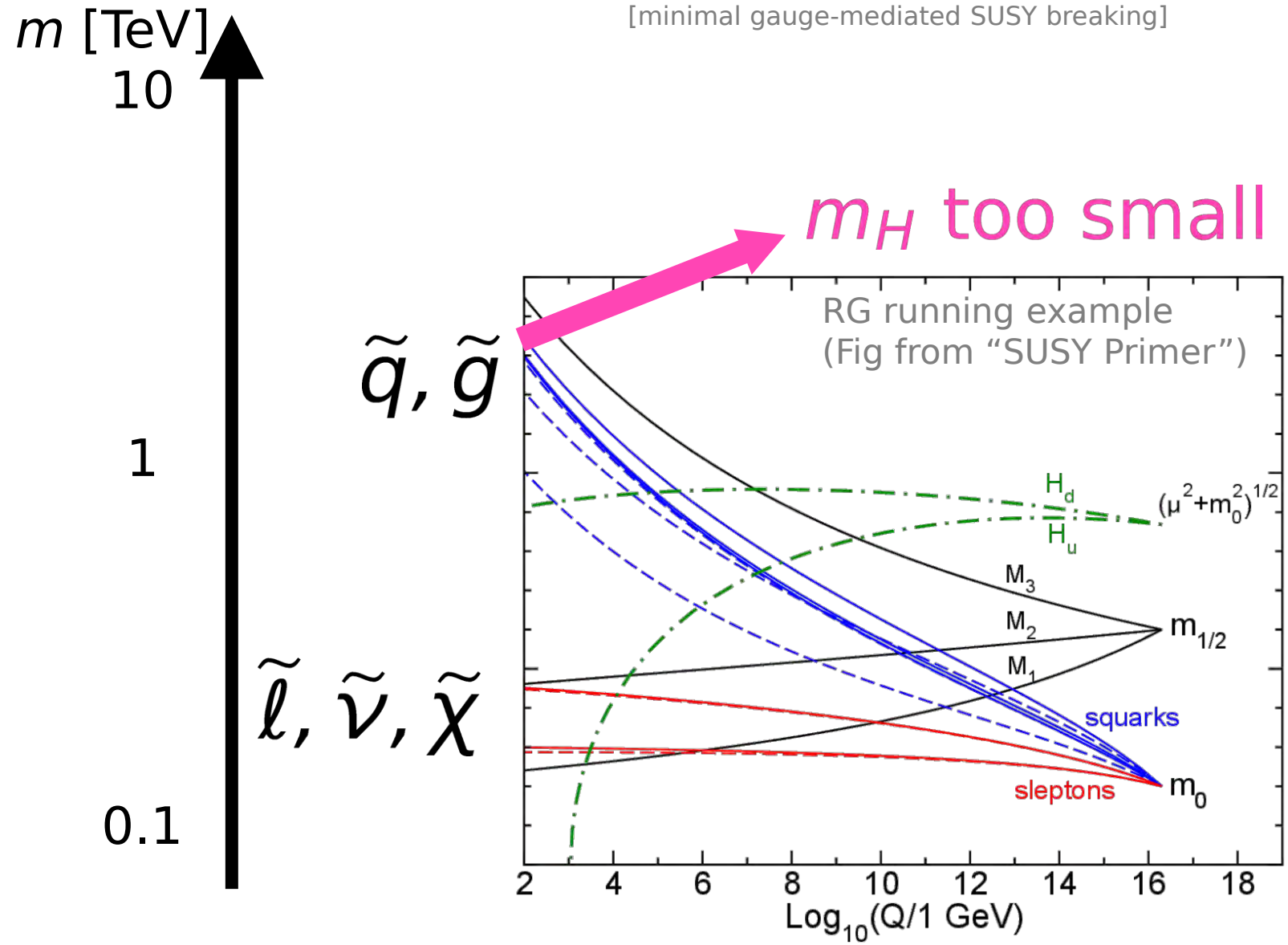
- (case 1) $\mu \sim M_2$
- (case 2) $\mu \gg M_2$

Endo, Hamaguchi, SI, Yoshinaga [1303.4256]

8 TeV summary & 14 TeV prospects

- SUSY model? → ~~CMSSM~~, ~~mGMSB~~

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



- 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)

m [TeV]

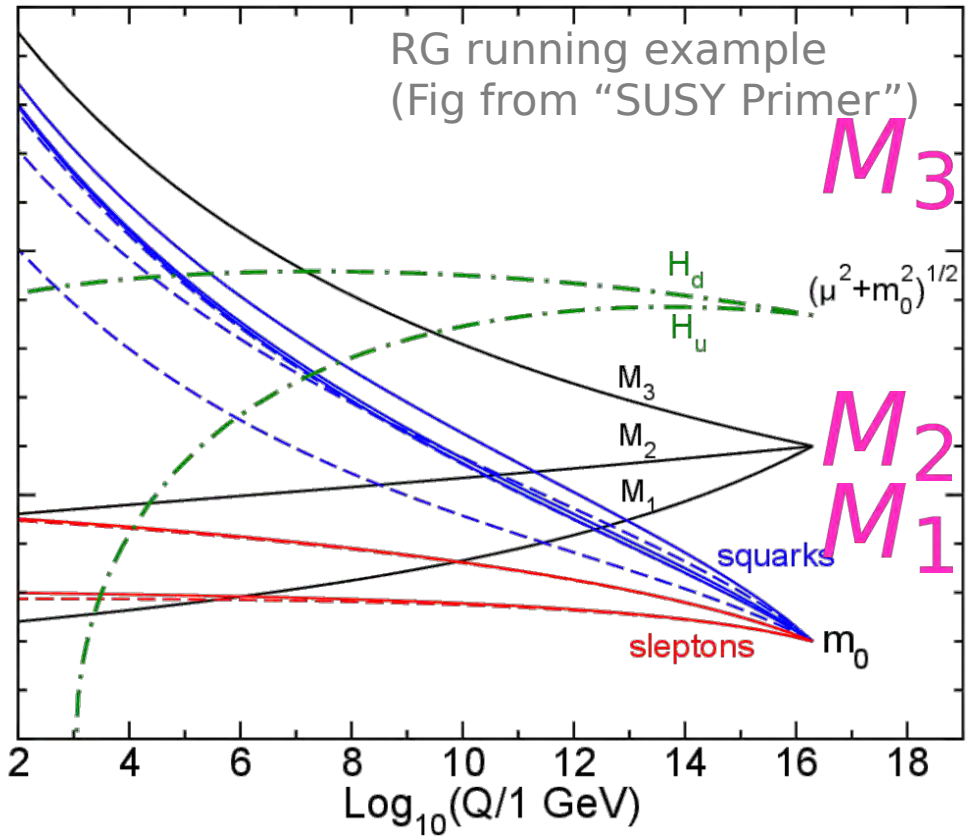
10

1

0.1

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

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

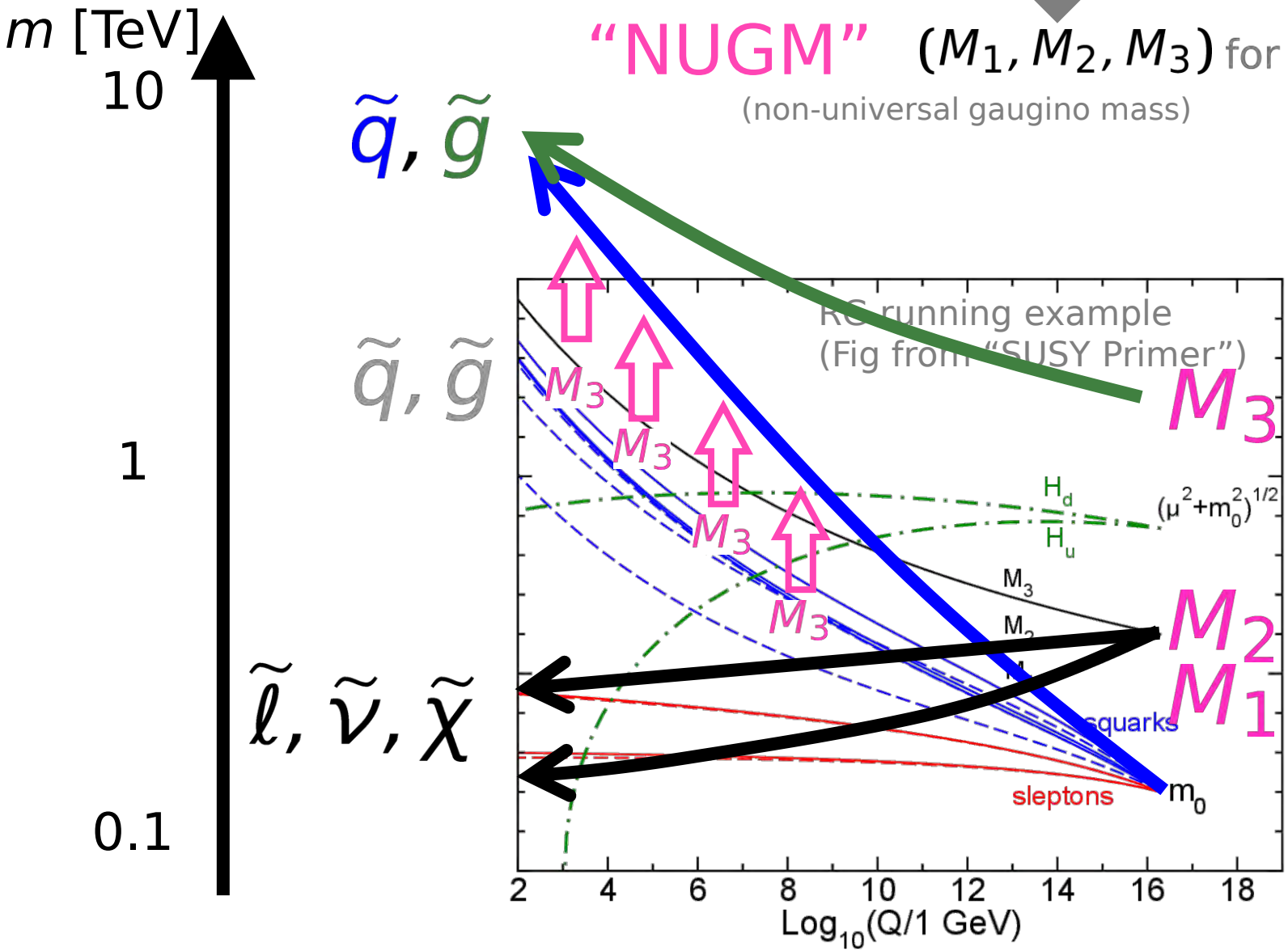


- SUSY model? → ~~CMSSM~~ $= (m_0, M_{1/2}, A_0, \tan\beta, \mathrm{sgn}\,\mu)$

EXTEND

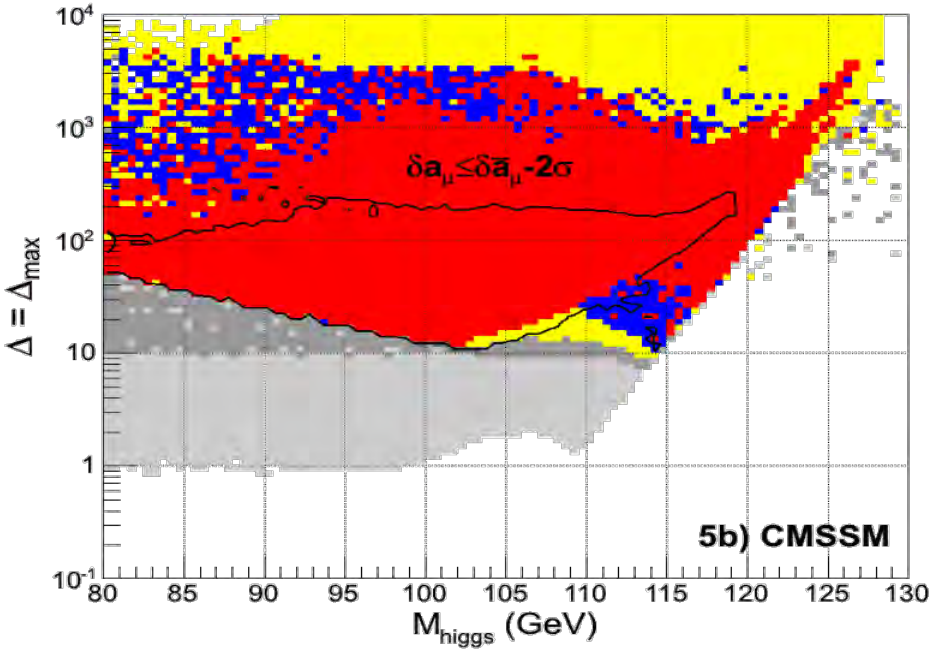
"NUGM" (M_1, M_2, M_3) for $\tilde{B}, \tilde{W}, \tilde{g}$

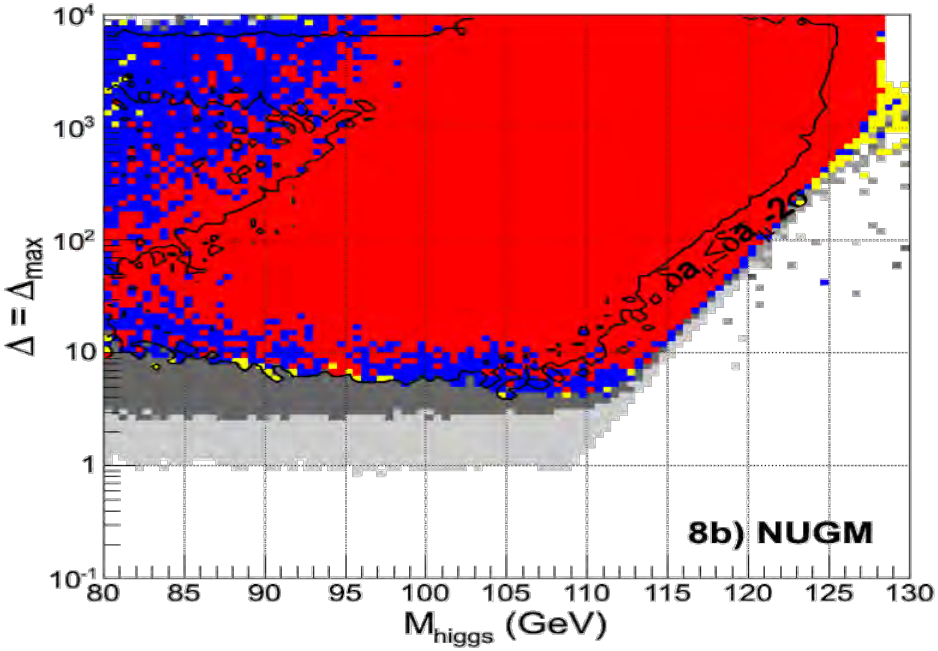
(non-universal gaugino mass)

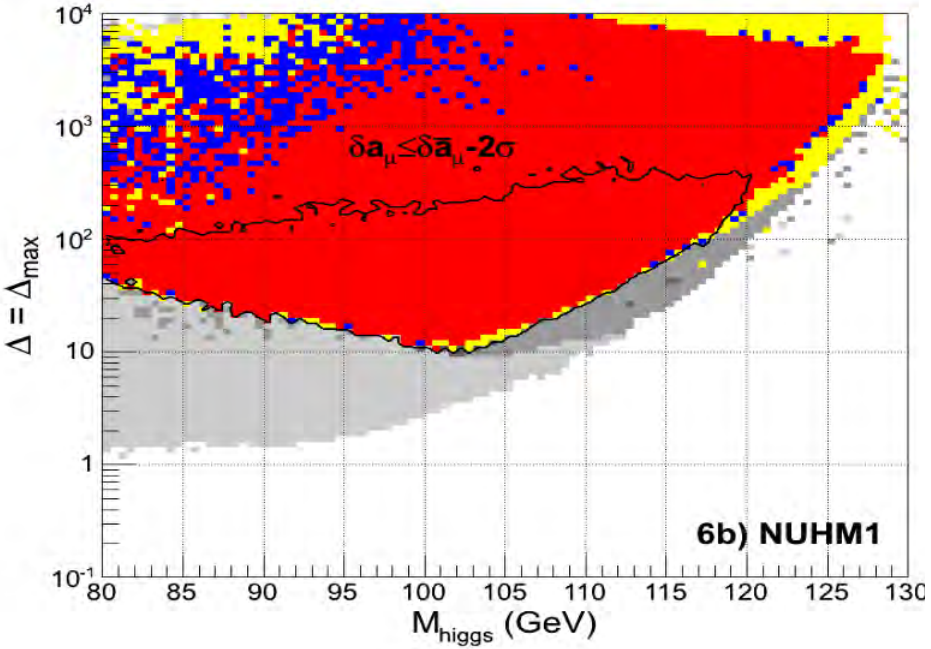


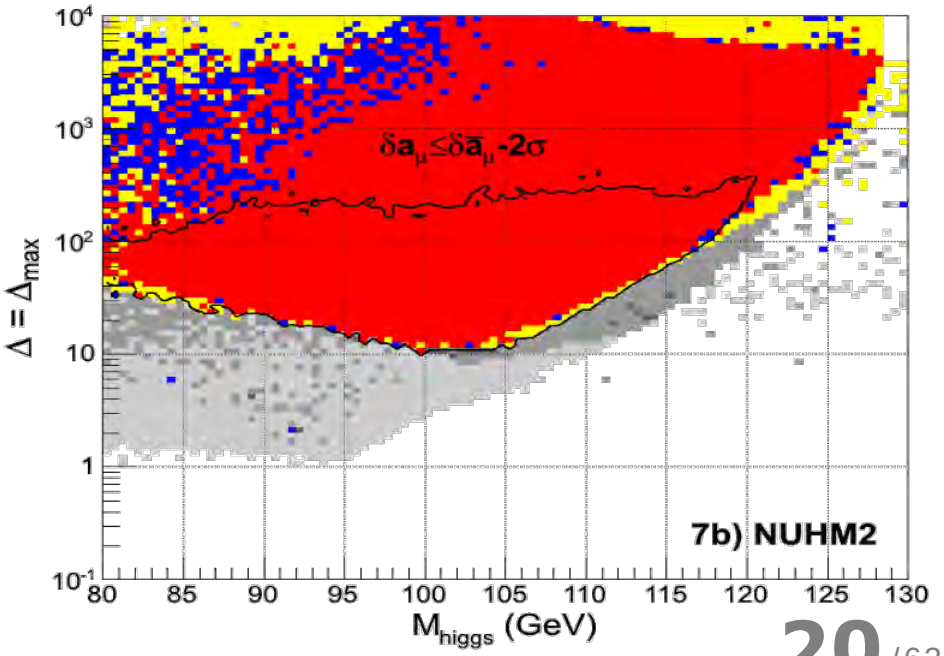
SUSY model for muon g-2?

Ghilencea, Lee, Park [1203.0569]









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

EXTEND

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

(non-universal gaugino mass)

CP phases

CP problem [EDM etc.]

"CP-safe Gravity Mediation"

SI, Yanagida, Yokozaki [1407.4226]

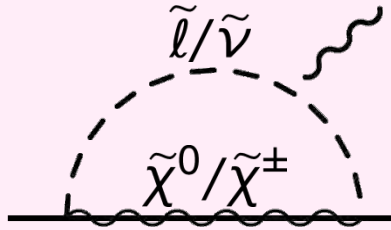
- Grav. med. model for NUGM
- CP-problems partially solved.

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

EXTEND

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

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



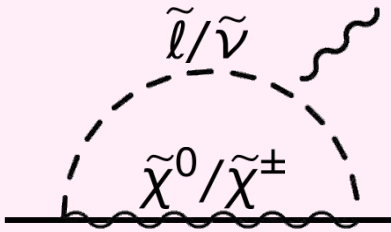
[electric dipole moment]

(electron)

ACME collab. [1310.7534]

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

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



$(g-2)_\mu$ anomaly $\longrightarrow$ $\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm = \mathrm{O}(100)\,\mathrm{GeV}$

SUSY models to explain $\Delta(g-2)_\mu$

"CP-safe" gravity mediation

SI, Yanagida, Yokozaki [1407.4226]

LHC signatures

- (case 1) $\mu \sim M_2$
- (case 2) $\mu \gg M_2$

Endo, Hamaguchi, SI, Yoshinaga [1303.4256]

8 TeV summary & 14 TeV prospects

$(g-2)_\mu$ anomaly $\longrightarrow$ $\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm = \mathrm{O}(100)\,\mathrm{GeV}$

SUSY models to explain $\Delta(g-2)_\mu$

"CP-safe" gravity mediation

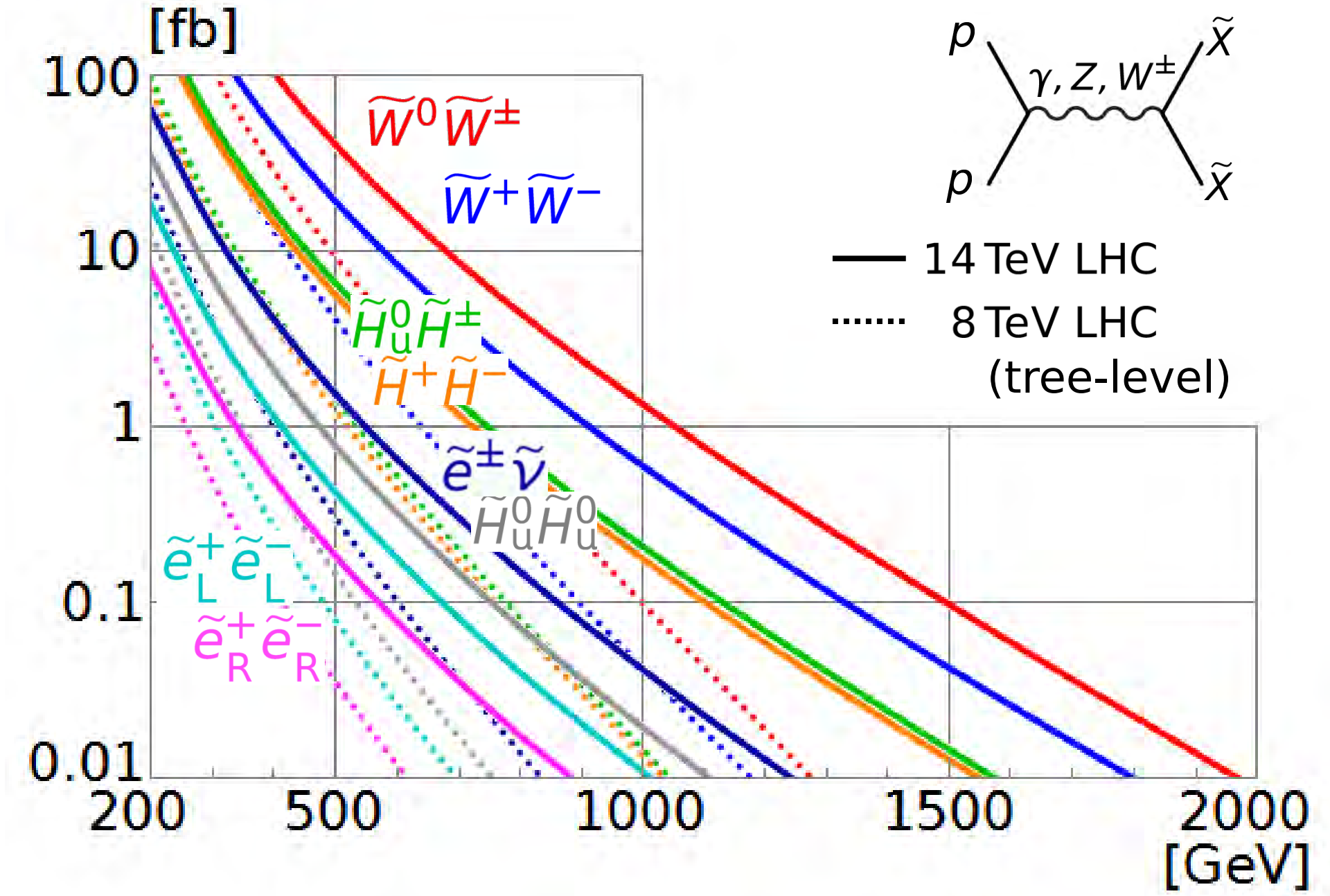
SI, Yanagida, Yokozaki [1407.4226]

LHC signatures

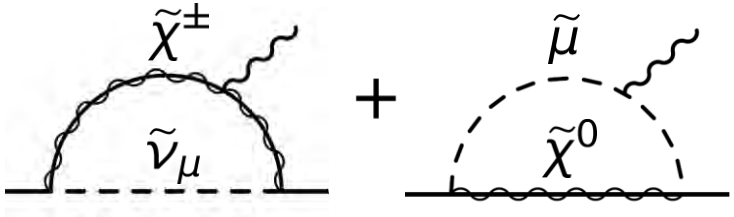
- (case 1) $\mu \sim M_2$
- (case 2) $\mu \gg M_2$

Endo, Hamaguchi, SI, Yoshinaga [1303.4256]

8 TeV summary & 14 TeV prospects

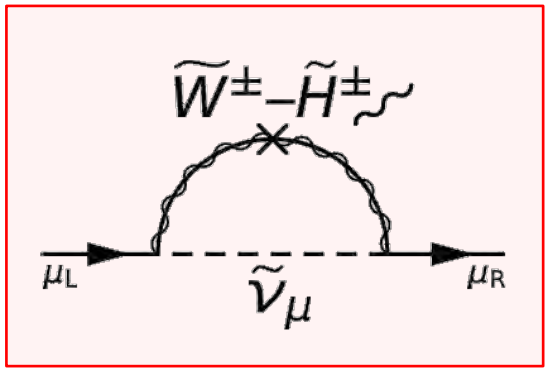

[fb]
100
10
1
0.1
0.01
200
500
1000
1500
2000
[GeV]
$\widetilde{W}^0\widetilde{W}^\pm$
$\widetilde{W}^+\widetilde{W}^-$
$\tilde{H}_u^0\tilde{H}^\pm$
$\tilde{H}^+\tilde{H}^-$
$\tilde{e}^\pm\tilde{\nu}$
$\tilde{H}_u^0\tilde{H}_u^0$
$\tilde{e}_L^+\tilde{e}_L^-$
$\tilde{e}_R^+\tilde{e}_R^-$
p
p
$\gamma, Z, W^\pm$
$\tilde{x}$
$\tilde{x}$
14 TeV LHC
8 TeV LHC
(tree-level)

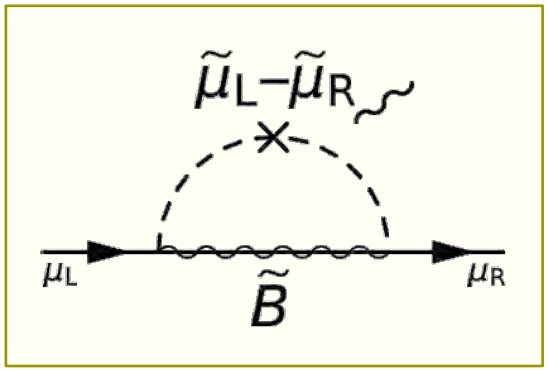
$$a_\mu^{\mathrm{SUSY}} \simeq$$

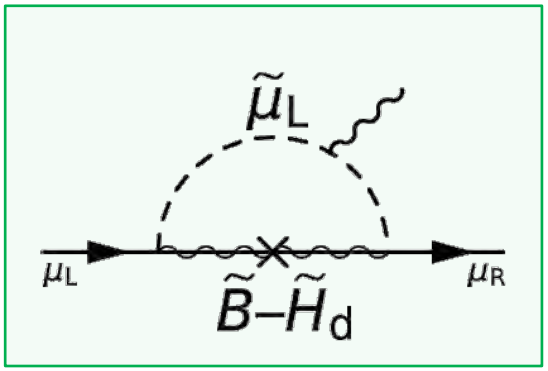


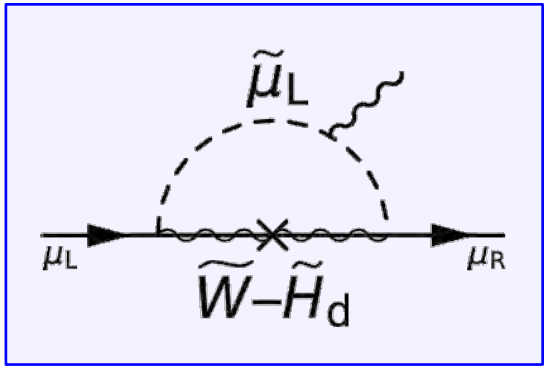
$$= a_\mu^{\mathrm{SUSY}}(\, M_1, M_2, \mu, m(\mu_{\mathrm{L}}), m(\mu_{\mathrm{R}}), \tan\beta, A_\mu)$$

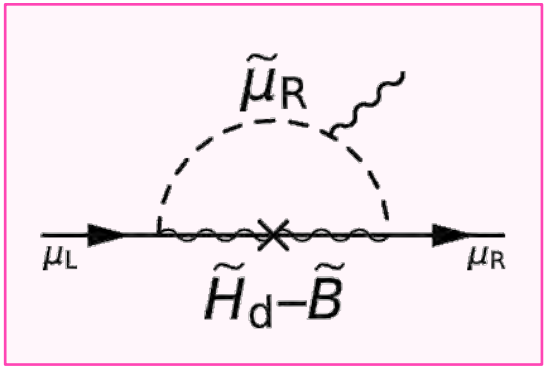
“mass insertion”

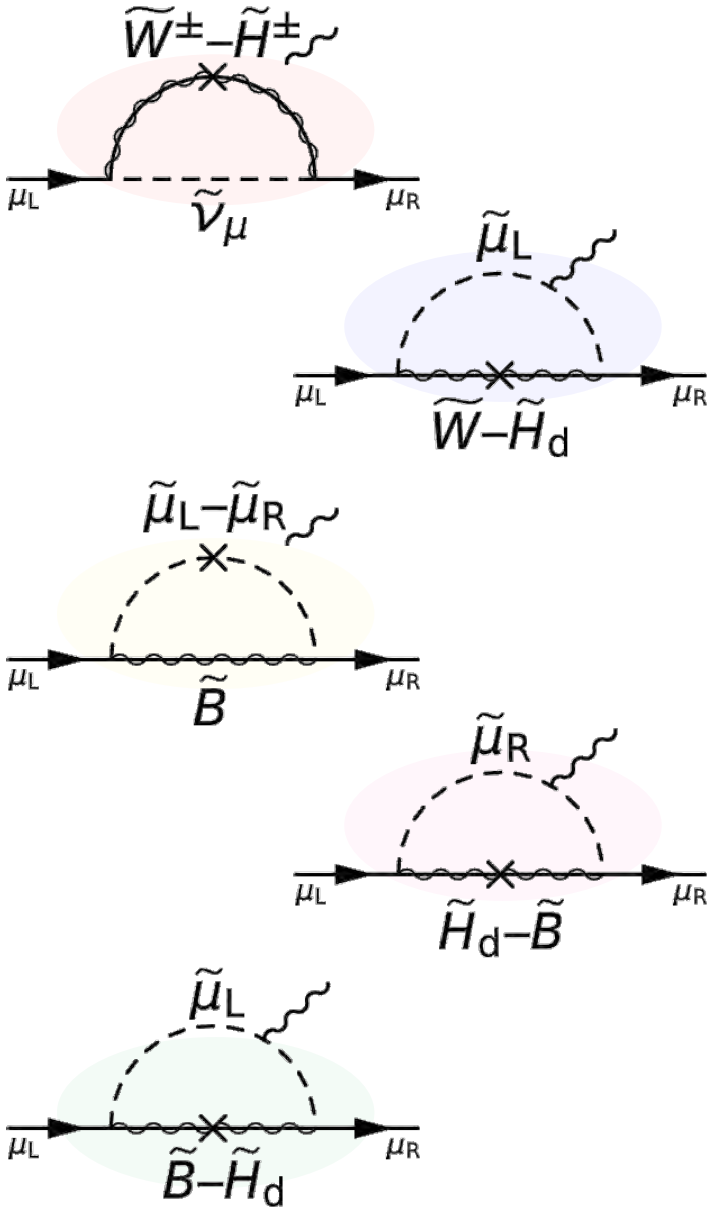












$$\frac{g_2^2 m_\mu^2}{8\pi^2}\frac{M_2\mu\tan\beta}{m^4_{\tilde{\nu}_\mu}}\cdot F_a\left(\frac{M_2}{m_{\tilde{\nu}_\mu}},\frac{\mu}{m_{\tilde{\nu}_\mu}}\right)$$

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

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

$$-\frac{g_Y^2 m_\mu^2}{8\pi^2}\frac{M_1\mu\tan\beta}{m^4_{\tilde{\mu}_R}}\cdot F_b\left(\frac{M_1}{m_{\tilde{\mu}_R}},\frac{\mu}{m_{\tilde{\mu}_R}}\right)$$

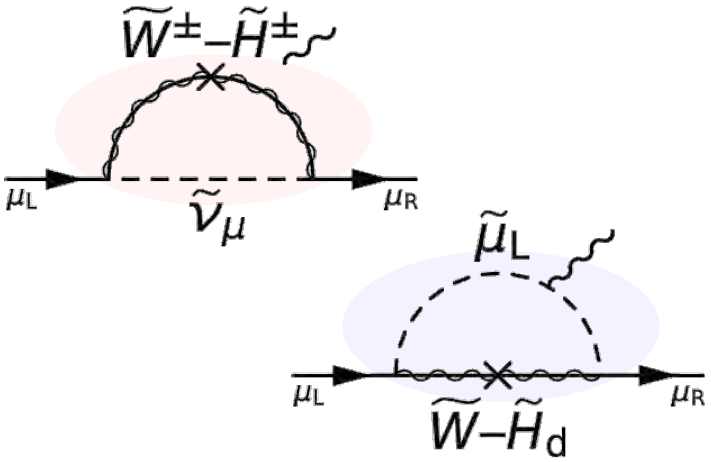
$$\frac{g_Y^2 m_\mu^2}{16\pi^2}\frac{M_1\mu\tan\beta}{m^4_{\tilde{\mu}_L}}\cdot F_b\left(\frac{M_1}{m_{\tilde{\mu}_L}},\frac{\mu}{m_{\tilde{\mu}_L}}\right)$$

F_a, F_b are loop functions ($F > 0$):

$$F_a(x,y)=\frac{1}{2}\frac{C_1(x^2)-C_1(y^2)}{x^2-y^2},\qquad F_b(x,y)=-\frac{1}{2}\frac{N_2(x^2)-N_2(y^2)}{x^2-y^2};$$

$$C_1(x)=\frac{3-4x+x^2+2\log x}{(1-x)^3},\qquad N_2(x)=\frac{1-x^2+2x\log x}{(1-x)^3}.$$

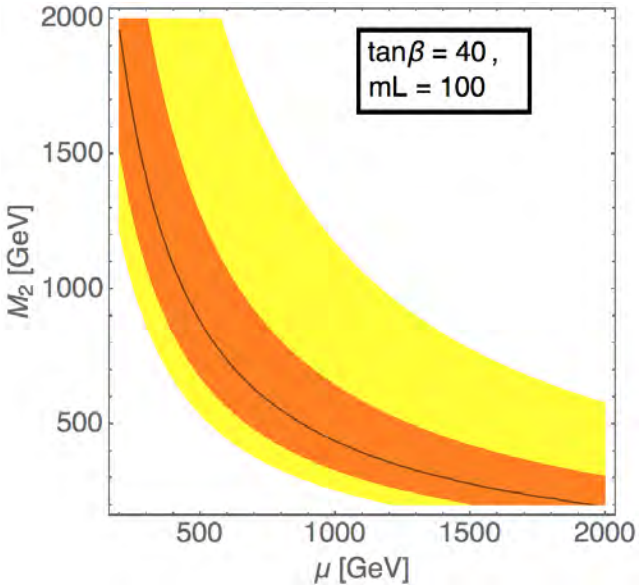
(1) Wino-dominant case: $\mu \sim M2$

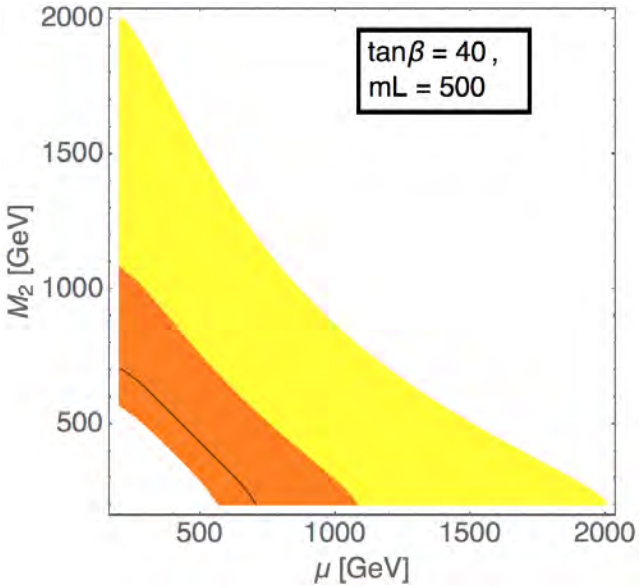


$$\frac{g_2^2 m_\mu^2}{8\pi^2} \frac{M_2 \mu \tan\beta}{m^4_{\tilde{\nu}_\mu}} \cdot F_a\left(\frac{M_2}{m_{\tilde{\nu}_\mu}}, \frac{\mu}{m_{\tilde{\nu}_\mu}}\right)$$

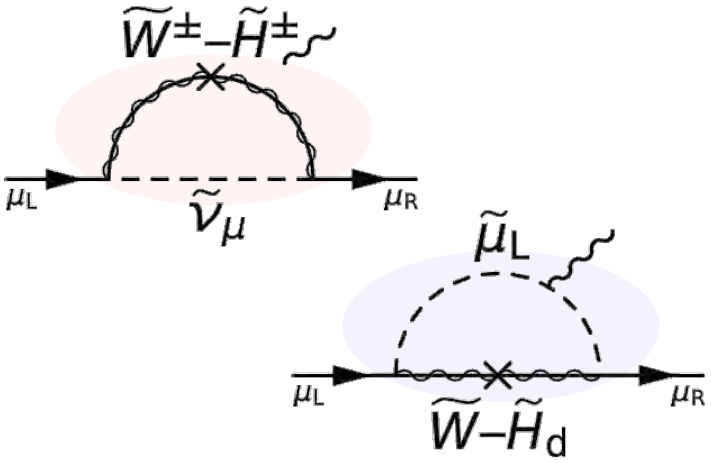
$$-\frac{g_2^2 m_\mu^2}{16\pi^2} \frac{M_2 \mu \tan\beta}{m^4_{\tilde{\mu}_L}} \cdot F_b\left(\frac{M_2}{m_{\tilde{\mu}_L}}, \frac{\mu}{m_{\tilde{\mu}_L}}\right)$$

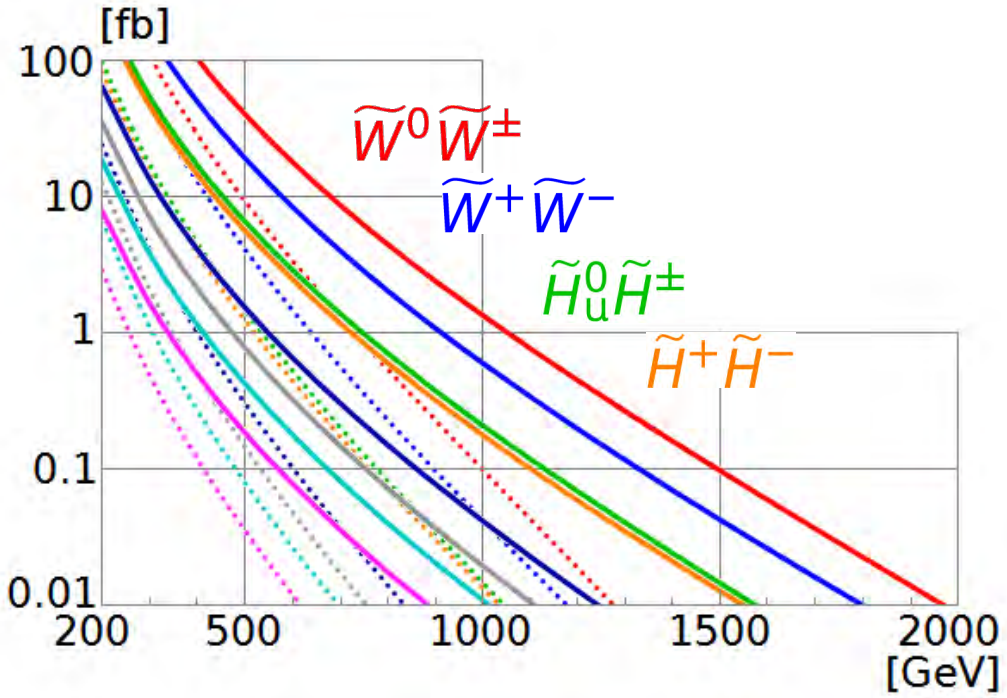
Wino contributions [red+blue; tree; slep=sneu]



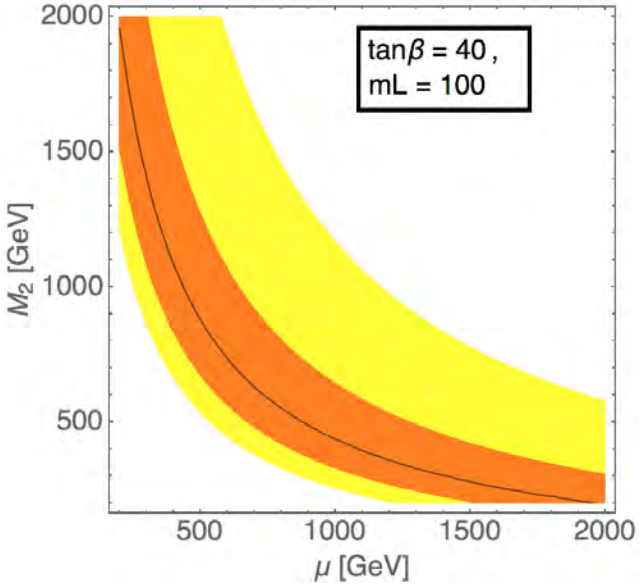


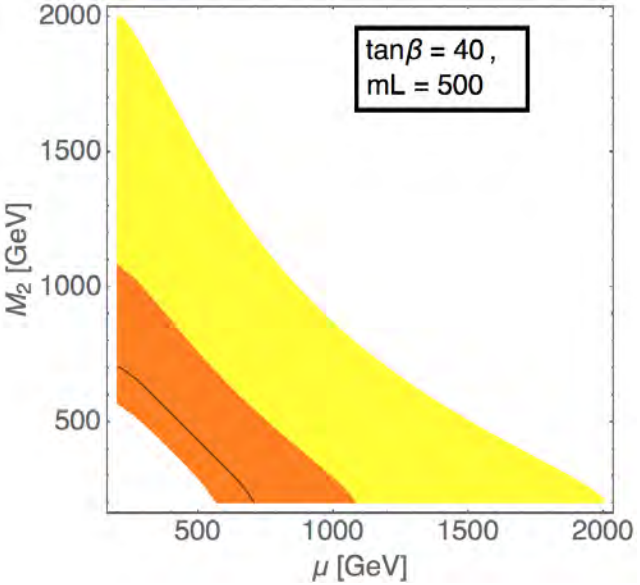
(1) Wino-dominant case: $\mu \sim M2$





Wino contributions [red+blue; tree; slep=sneu]



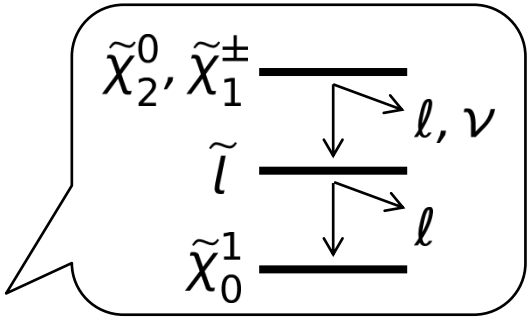


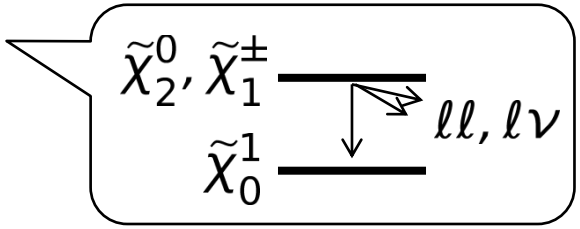
(τ possible, but less promising)

$$pp \to \tilde{\chi}^0\tilde{\chi}^\pm, \tilde{\chi}^+\tilde{\chi}^-$$

$\to$ • multi-lepton signal

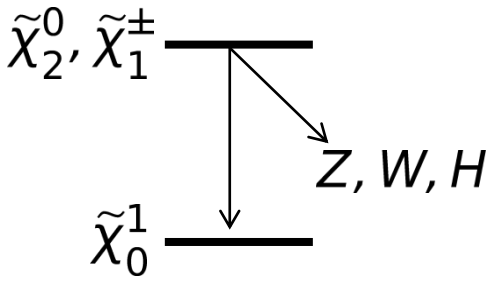
if { $\tilde{\ell}$ -mediated
degenerated





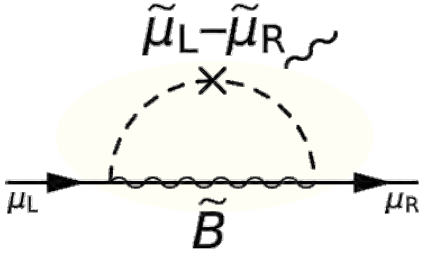
less SM bkg; clear.
difficult in soft ℓ-cases?

• boson signal



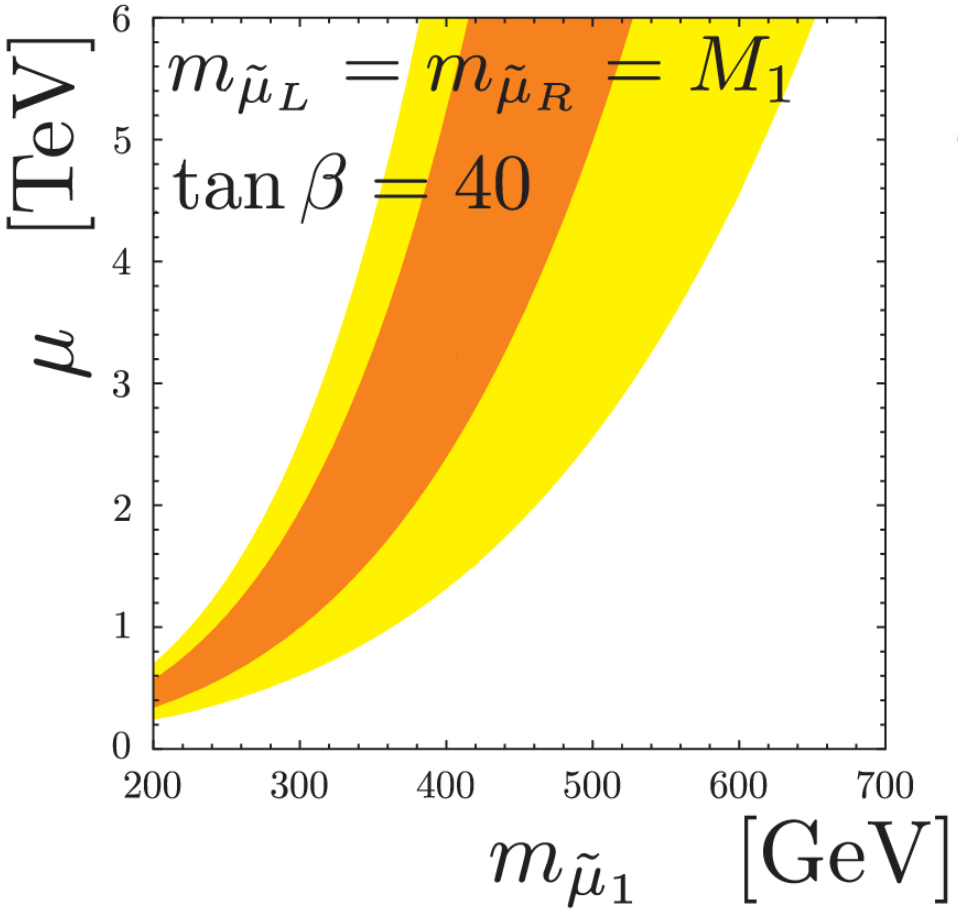
($W, Z \to$ leptonic decay, $h \to b\bar{b}$)

large SM bkg → large $\not{E}_T$ better



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

from $M_{\tilde{\mu}}^2 = \begin{pmatrix} m(l_L)^2 & m_\mu(A_\mu^* - \mu\tan\beta) \\ m_\mu(A_\mu^* - \mu\tan\beta) & m(l_R)^2 \end{pmatrix}$



μ tanβ has upper bounds:

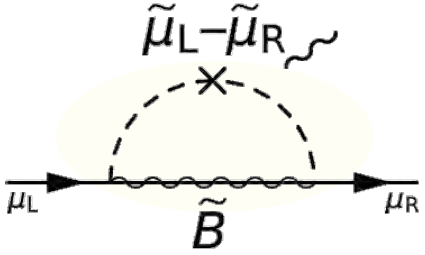
$$V_{\rm Higgs} \supset -\left(m_\tau\,\mu\tan\beta\cdot\tilde{\tau}_L^*\tilde{\tau}_R h + m_\mu\,\mu\tan\beta\cdot\tilde{\mu}_L^*\tilde{\mu}_R h\right)$$

$m_{\tilde{\tau}}/m_{\tilde{\mu}}$

$= 1 \Rightarrow m_{\tilde{\mu}} \lesssim 300(420)$ GeV

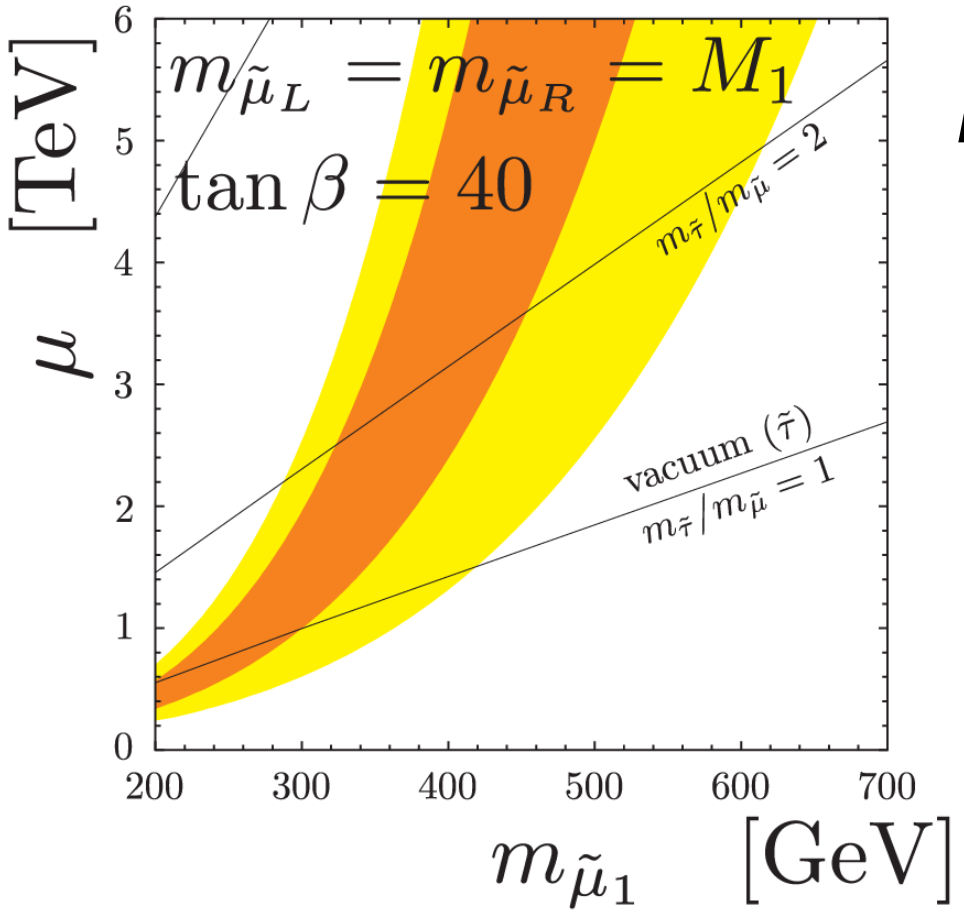
$= 2 \Rightarrow \lesssim 440(620)$ GeV

$= \infty \Rightarrow \lesssim 1.4(1.9)$ TeV



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

from $M_{\tilde{\mu}}^2 = \begin{pmatrix} m(l_L)^2 & m_\mu(A_\mu^* - \mu\tan\beta) \\ m_\mu(A_\mu^* - \mu\tan\beta) & m(l_R)^2 \end{pmatrix}$



μ tanβ has upper bounds:

$$V_{\rm Higgs} \supset -\left(m_\tau\,\mu\tan\beta\cdot\tilde{\tau}_L^*\tilde{\tau}_R h + m_\mu\,\mu\tan\beta\cdot\tilde{\mu}_L^*\tilde{\mu}_R h\right)$$

$$m_{\tilde{\tau}}/m_{\tilde{\mu}}$$

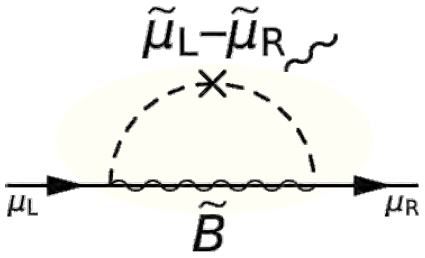
$$= 1 \Rightarrow m_{\tilde{\mu}} \lesssim 300(420)\,\text{GeV}$$

$$= 2 \Rightarrow \lesssim 440(620)\,\text{GeV}$$

$$= \infty \Rightarrow \lesssim 1.4(1.9)\,\text{TeV}$$

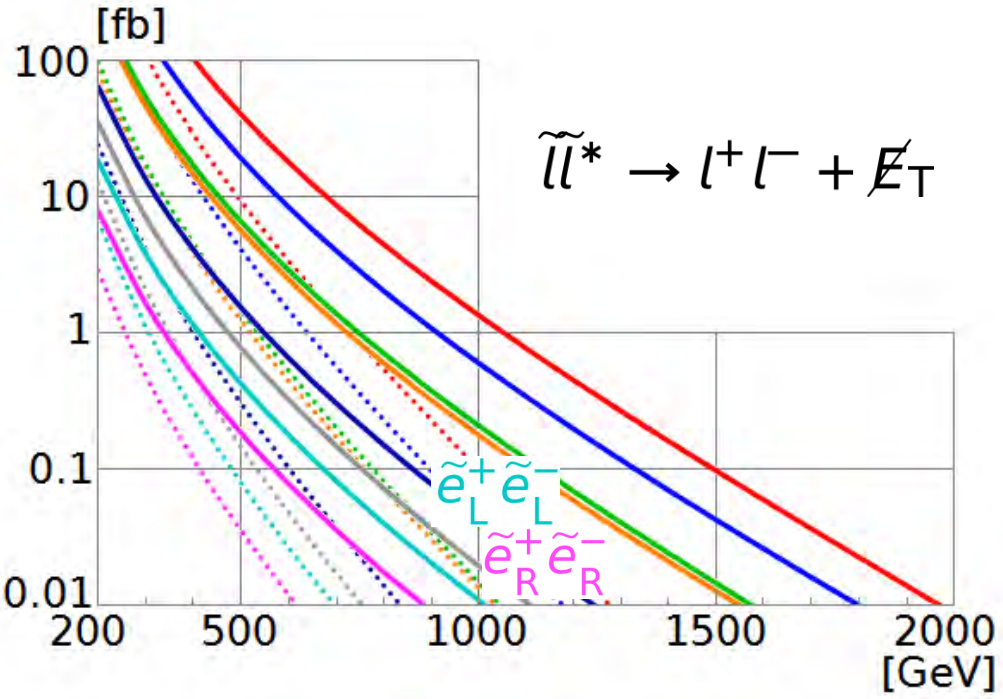
(2) "Pure-bino contirbution": μ >> M1

Endo, Hamaguchi, Kitahara, Yoshinaga [1309.3065]

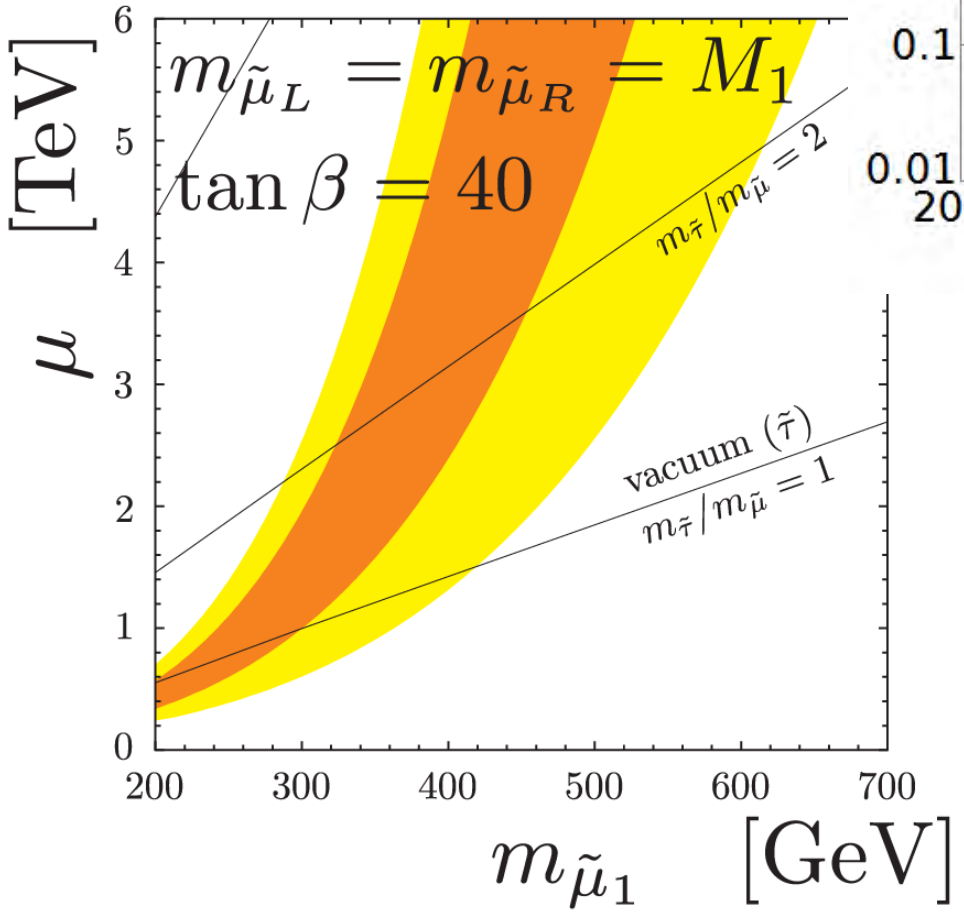


$$\frac{g_Y^2 m_\mu^2}{8\pi^2}\,\mu$$

from



$$+ m_\mu\,\mu\tan\beta\cdot\mu_L\mu_R n)$$



$$m_{\tilde{\tau}}/m_{\tilde{\mu}}$$

$$= 1 \quad \Rightarrow m_{\tilde{\mu}} \lesssim 300(420)\,\mathrm{GeV}$$

$$= 2 \quad \Rightarrow \quad \lesssim 440(620)\,\mathrm{GeV}$$

$$= \infty \quad \Rightarrow \quad \lesssim 1.4(1.9)\,\mathrm{TeV}$$

$(g-2)_\mu$ anomaly $\longrightarrow$ $\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm = \mathrm{O}(100)\,\mathrm{GeV}$

SUSY models to explain $\Delta(g-2)_\mu$

"CP-safe" gravity mediation

SI, Yanagida, Yokozaki [1407.4226]

LHC signatures

- (case 1) $\mu \sim M_2$
- (case 2) $\mu \gg M_2$

Endo, Hamaguchi, SI, Yoshinaga [1303.4256]

8 TeV summary & 14 TeV prospects

$(g-2)_\mu$ anomaly $\longrightarrow$ $\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm = \mathrm{O}(100)\,\mathrm{GeV}$

SUSY models to explain $\Delta(g-2)_\mu$

"CP-safe" gravity mediation

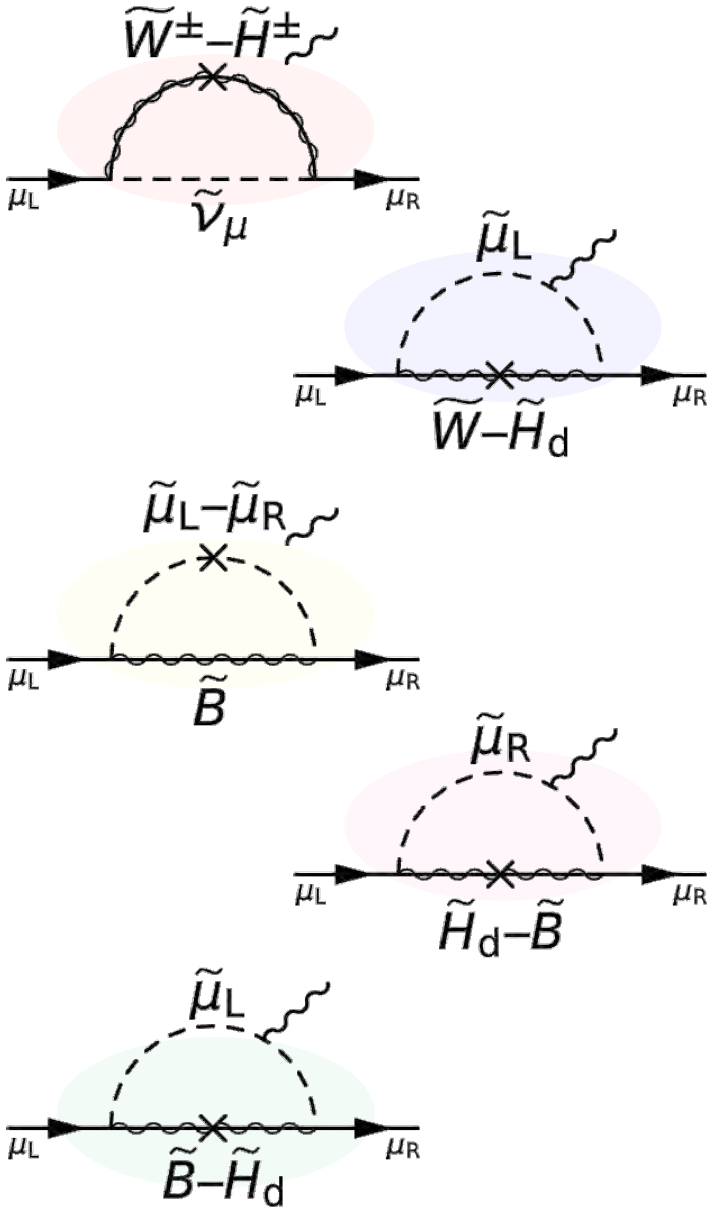
SI, Yanagida, Yokozaki [1407.4226]

LHC signatures

- (case 1) $\mu \sim M_2$
- (case 2) $\mu \gg M_2$

Endo, Hamaguchi, SI, Yoshinaga [1303.4256]

8 TeV summary
& 14 TeV prospects



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

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

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

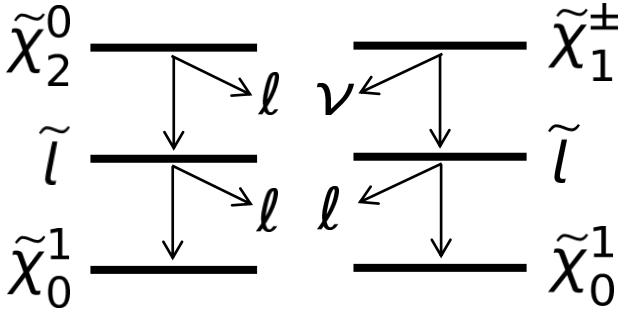
$$-\frac{g_Y^2 m_\mu^2}{8\pi^2}\frac{M_1\mu\tan\beta}{m^4_{\tilde{\mu}_R}}\cdot F_b\left(\frac{M_1}{m_{\tilde{\mu}_R}},\frac{\mu}{m_{\tilde{\mu}_R}}\right)$$

$$\frac{g_Y^2 m_\mu^2}{16\pi^2}\frac{M_1\mu\tan\beta}{m^4_{\tilde{\mu}_L}}\cdot F_b\left(\frac{M_1}{m_{\tilde{\mu}_L}},\frac{\mu}{m_{\tilde{\mu}_L}}\right)$$

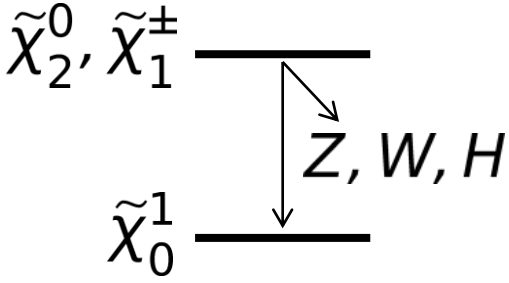
(1) Wino-contr. dominant ($\mu \sim M_2$)

(2) Pure-bino dominant ($\mu >> M_2$)

- $\tilde{\chi}^{\pm}\tilde{\chi}^{0} \rightarrow (\tilde{e}, \tilde{\mu}, \tilde{\tau}) \rightarrow \text{LSP} : 3(e, \mu, \tau)$
- $\rightarrow \tilde{\tau} \rightarrow \text{LSP} : 3(e, \mu, \tau)\ /\ 2^{+}\tau$
- $\longrightarrow \text{LSP} : WZ\ /\ Wh$



- $\tilde{\chi}^{+}\tilde{\chi}^{-} \rightarrow (\tilde{e}, \tilde{\mu}, \tilde{\tau}) \rightarrow \text{LSP} : 2(e, \mu)$
- $\rightarrow \tilde{\tau} \rightarrow \text{LSP} : 2^{+}\tau$
- $\longrightarrow \text{LSP} : WW$



- $\tilde{l}\,\tilde{l}^{*} \longrightarrow \text{LSP} : 2l$

- $\tilde{\chi}^{\pm}\tilde{\chi}^{0} \rightarrow (\tilde{e}, \tilde{\mu}, \tilde{\tau}) \rightarrow$ LSP : $3(e, \mu, \tau)$ / SS-l (MVA) / $3l$ (soft, ISR)
- $\rightarrow \tilde{\tau} \rightarrow$ LSP : $3(e, \mu, \tau)$ / $2^{+}\tau$
- $\longrightarrow$ LSP : WZ / Wh

- $\tilde{\chi}^{+}\tilde{\chi}^{-} \rightarrow (\tilde{e}, \tilde{\mu}, \tilde{\tau}) \rightarrow$ LSP : $2(e, \mu)$ / $l^{+}l^{-}$ + ISR
- $\rightarrow \tilde{\tau} \rightarrow$ LSP : $2^{+}\tau$
- $\longrightarrow$ LSP : WW

- $\tilde{l}\,\tilde{l}^{*} \longrightarrow$ LSP : $2l$

- $\tilde{\chi}_{2}^{0}\tilde{\chi}_{3}^{0} \rightarrow (\tilde{e}, \tilde{\mu}) \rightarrow$ LSP : $3^{+}(e, \mu)$
- VBF-$\tilde{\chi}^{\pm}\tilde{\chi}^{\pm} \rightarrow \tilde{l} \rightarrow$ LSP : VBF-jets + SS-l

- $\tilde{\chi}^{\pm}\tilde{\chi}^{0} \rightarrow (\tilde{e}, \tilde{\mu}, \tilde{\tau}) \rightarrow$ LSP : $3(e, \mu, \tau)$ / SS-l (MVA) / $3l$ (soft, ISR)
- $\rightarrow \tilde{\tau} \rightarrow$ LSP : $3(e, \mu, \tau)$ / $2^{+}\tau$
- $\longrightarrow$ LSP : WZ / Wh

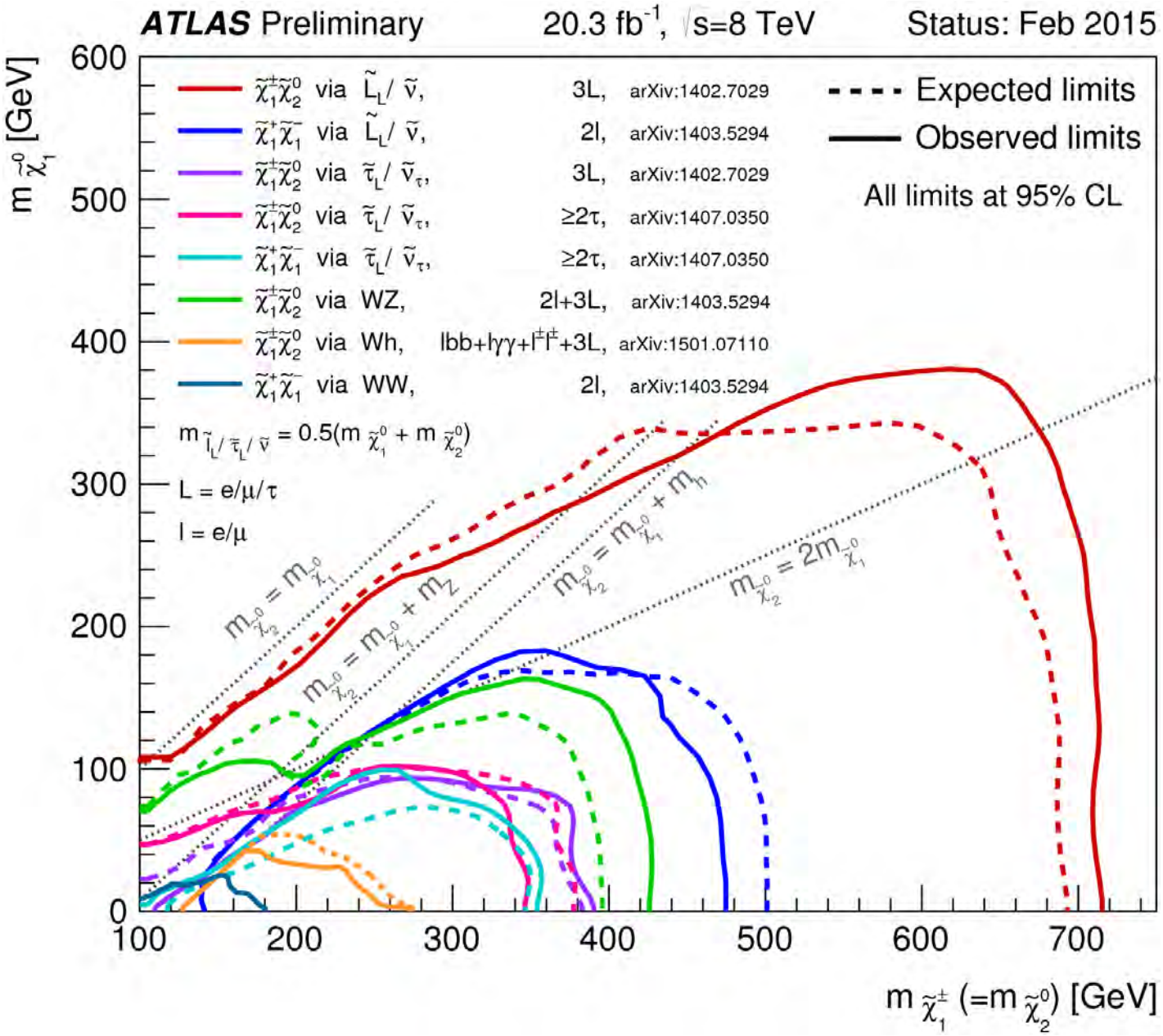
- $\tilde{\chi}^{+}\tilde{\chi}^{-} \rightarrow (\tilde{e}, \tilde{\mu}, \tilde{\tau}) \rightarrow$ LSP : $2(e, \mu)$ / $l^{+}l^{-}$ + ISR
- $\rightarrow \tilde{\tau} \rightarrow$ LSP : $2^{+}\tau$
- $\longrightarrow$ LSP : WW

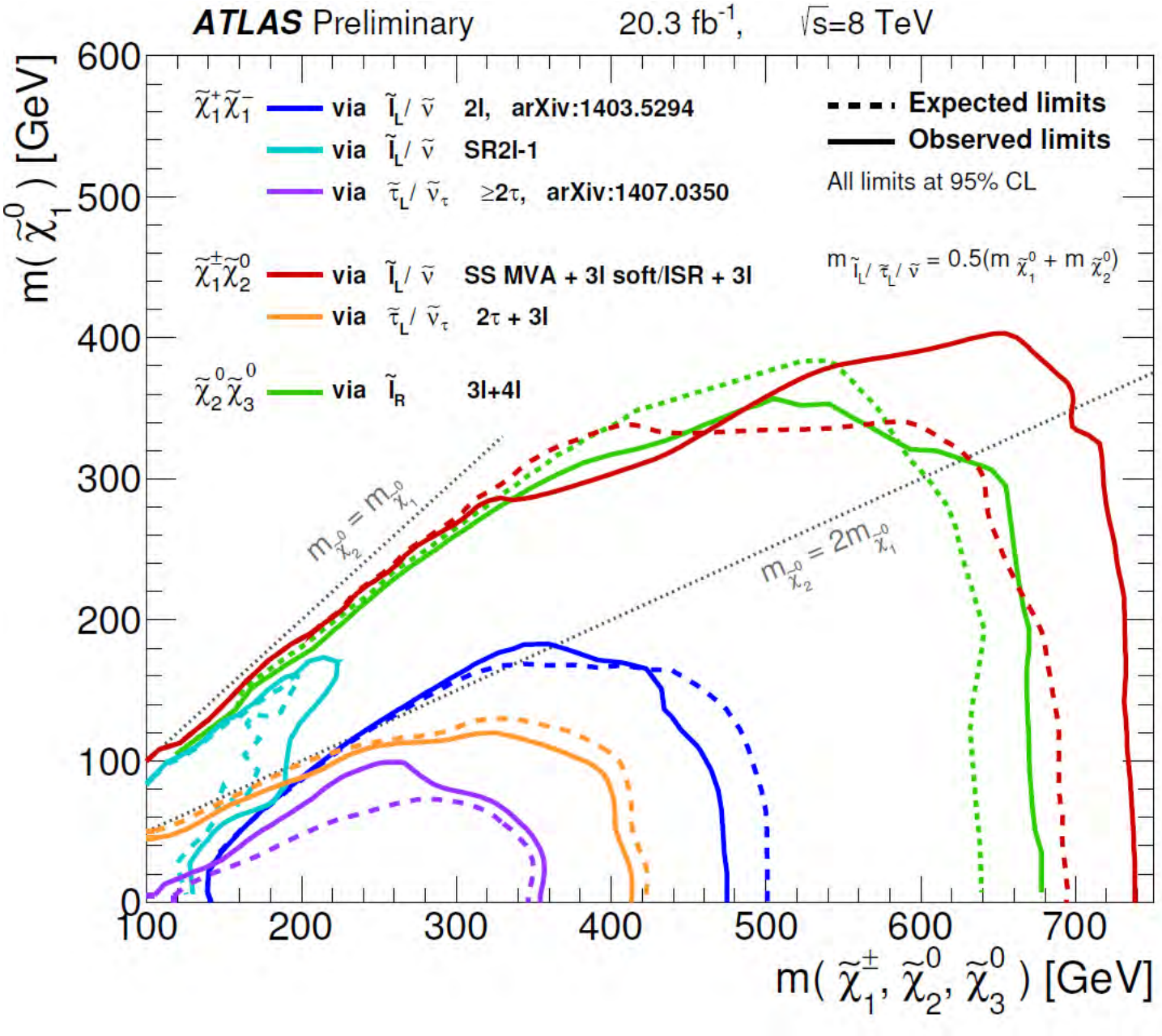
- $\tilde{l}\,\tilde{l}^{*} \longrightarrow$ LSP : $2l$

- $\tilde{\chi}_{2}^{0}\tilde{\chi}_{3}^{0} \rightarrow (\tilde{e}, \tilde{\mu}) \rightarrow$ LSP : $3^{+}(e, \mu)$
- VBF-$\tilde{\chi}^{\pm}\tilde{\chi}^{\pm} \rightarrow \tilde{l} \rightarrow$ LSP : VBF-jets + SS-l

(New results seem still internal; soon will be public.)

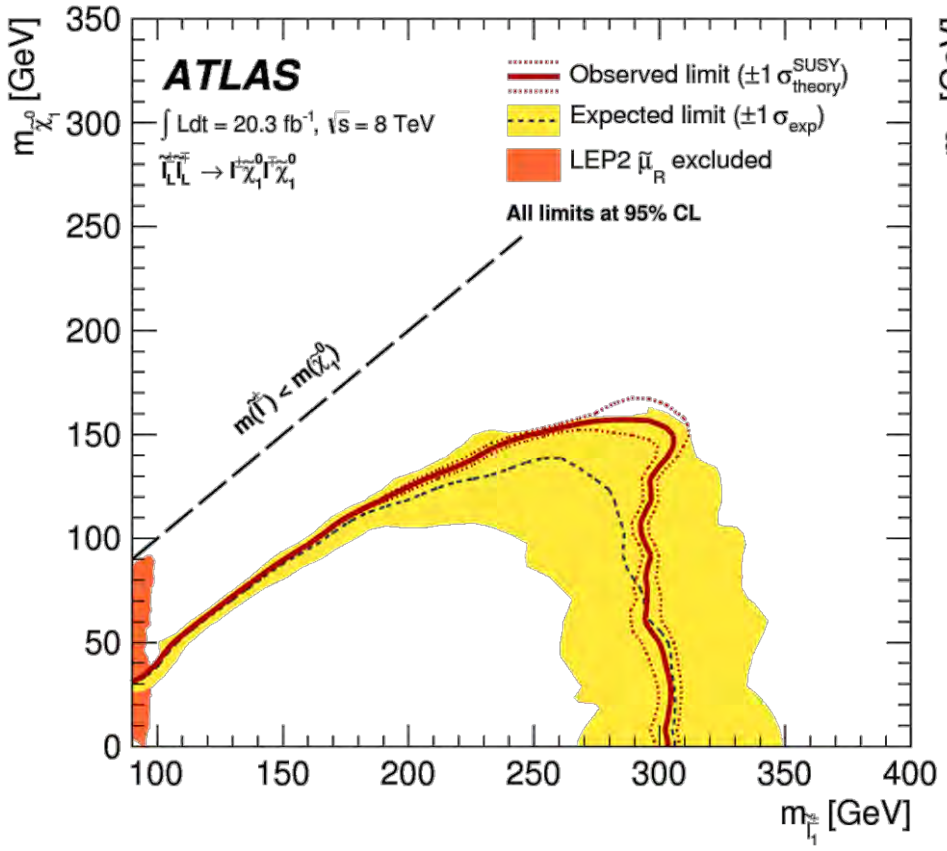
LHC Run I EW-SUSY summary : ATLAS chargino-neutralino (old)

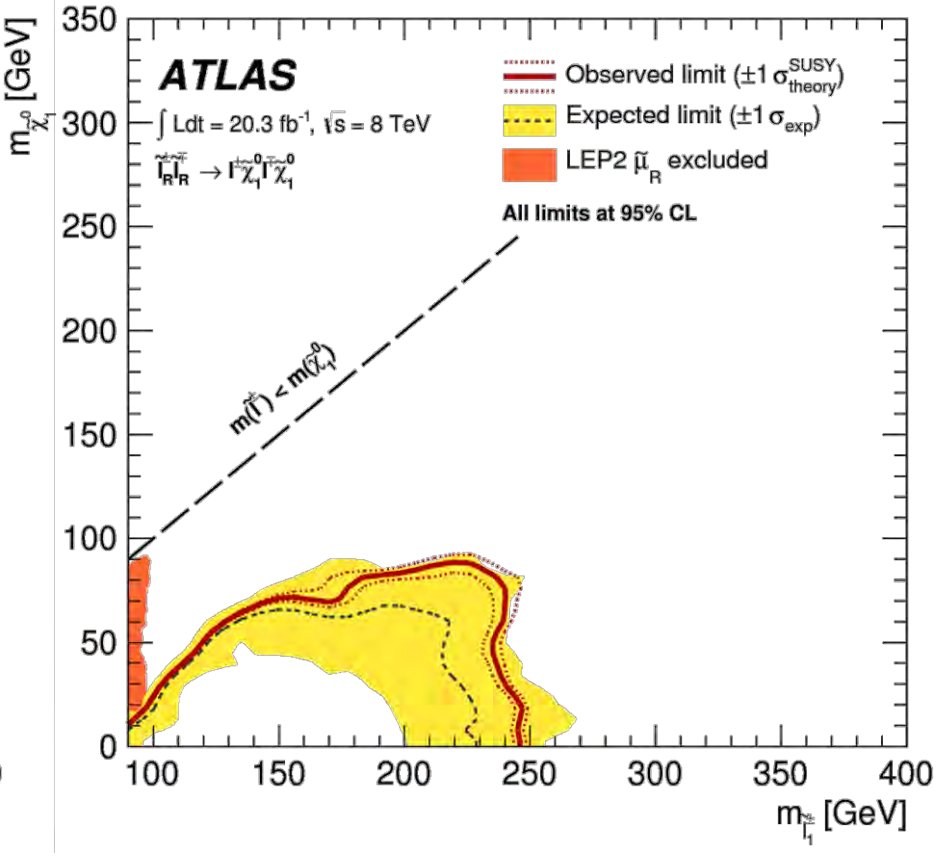


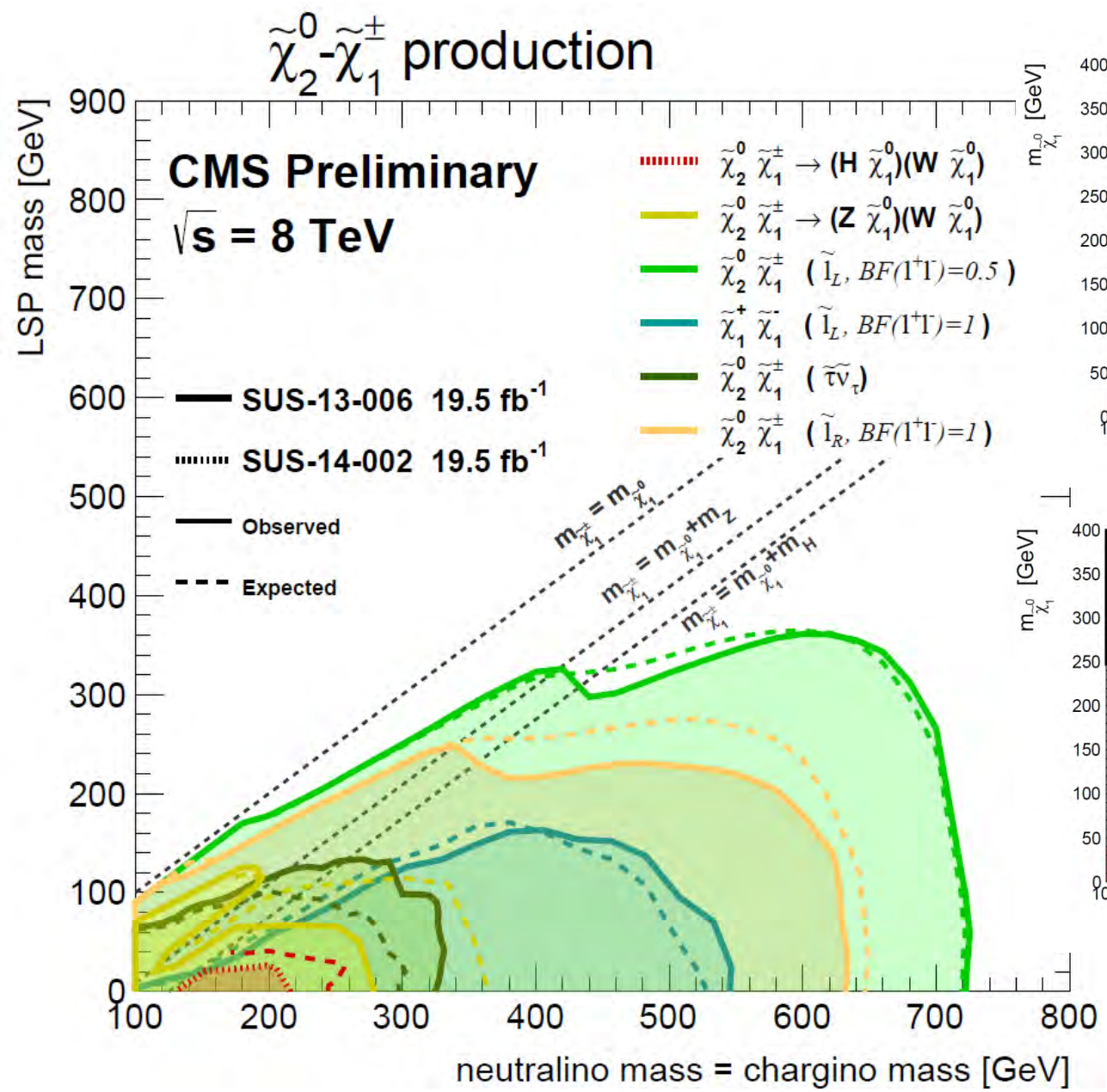


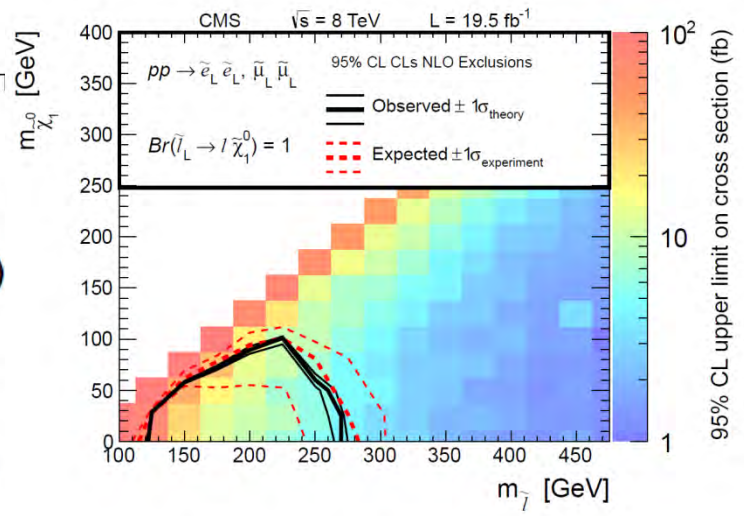
(New results seem still internal; soon will be public.)

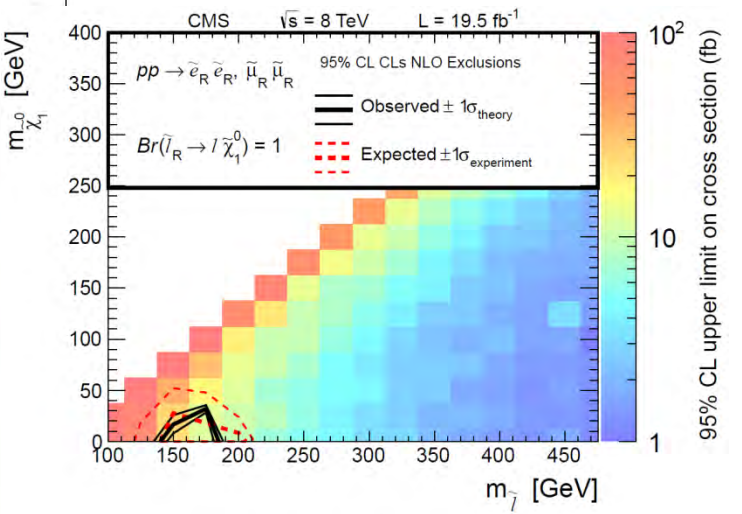
LHC Run I EW-SUSY summary : ATLAS slepton



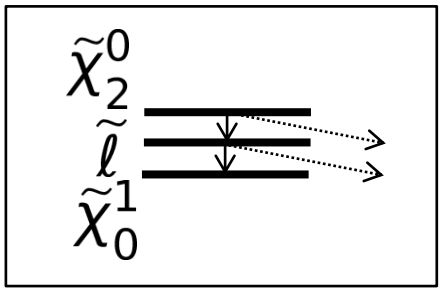


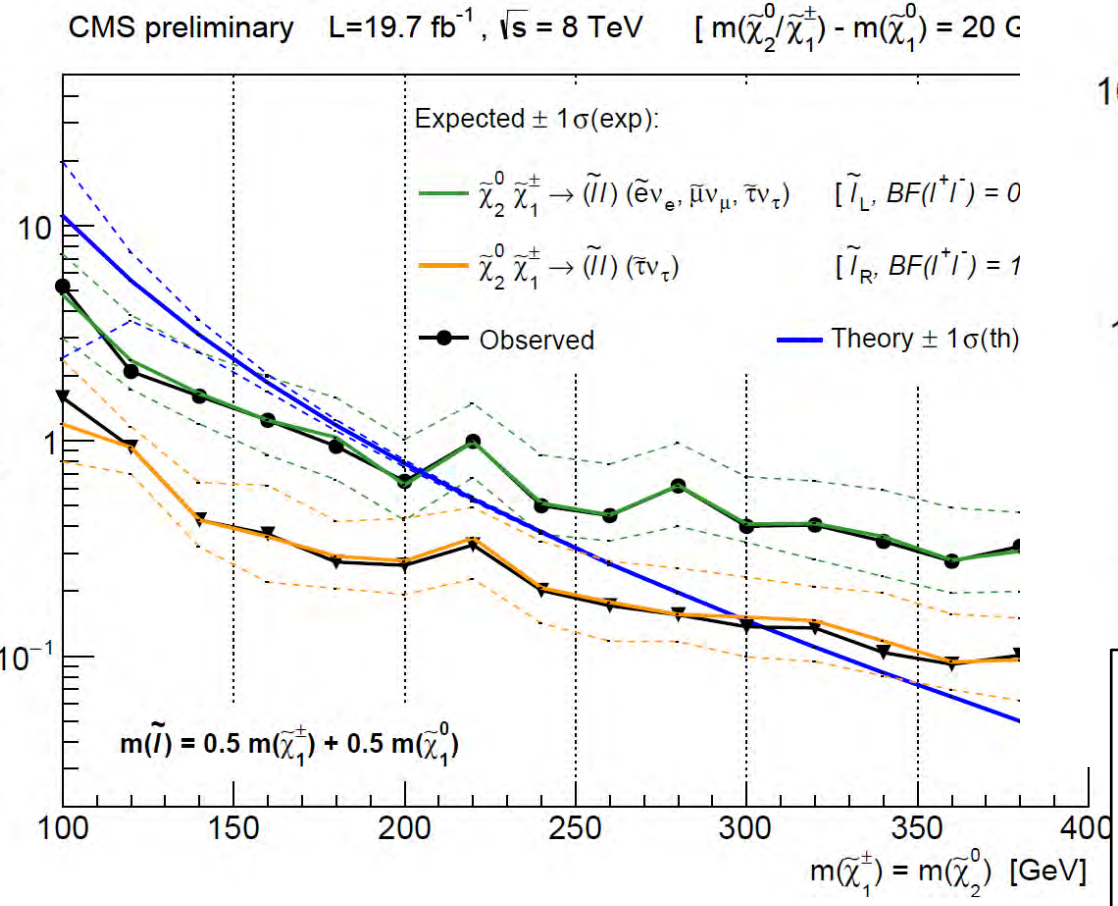

$\tilde{\chi}_2^0$-$\tilde{\chi}_1^\pm$ production
CMS Preliminary
$\sqrt{s}$ = 8 TeV
SUS-13-006 19.5 fb^{-1}
SUS-14-002 19.5 fb^{-1}
Observed
Expected
$\tilde{\chi}_2^0\,\tilde{\chi}_1^\pm \to (H\,\tilde{\chi}_1^0)(W\,\tilde{\chi}_1^0)$
$\tilde{\chi}_2^0\,\tilde{\chi}_1^\pm \to (Z\,\tilde{\chi}_1^0)(W\,\tilde{\chi}_1^0)$
$\tilde{\chi}_2^0\,\tilde{\chi}_1^\pm$ ($\tilde{l}_L$, $BF(l^+l^-)=0.5$)
$\tilde{\chi}_1^+\,\tilde{\chi}_1^-$ ($\tilde{l}_L$, $BF(l^+l^-)=1$)
$\tilde{\chi}_2^0\,\tilde{\chi}_1^\pm$ ($\tilde{\tau}\tilde{\nu}_\tau$)
$\tilde{\chi}_2^0\,\tilde{\chi}_1^\pm$ ($\tilde{l}_R$, $BF(l^+l^-)=1$)
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + m_Z$
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + m_H$
LSP mass [GeV]
neutralino mass = chargino mass [GeV]


CMS $\sqrt{s}$ = 8 TeV L = 19.5 fb^{-1}
95% CL CLs NLO Exclusions
$pp \to \tilde{e}_L\tilde{e}_L, \tilde{\mu}_L\tilde{\mu}_L$
$Br(\tilde{l}_L \to l\,\tilde{\chi}_1^0) = 1$
Observed $\pm 1\sigma_{theory}$
Expected $\pm 1\sigma_{experiment}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{l}}$ [GeV]
95% CL upper limit on cross section (fb)

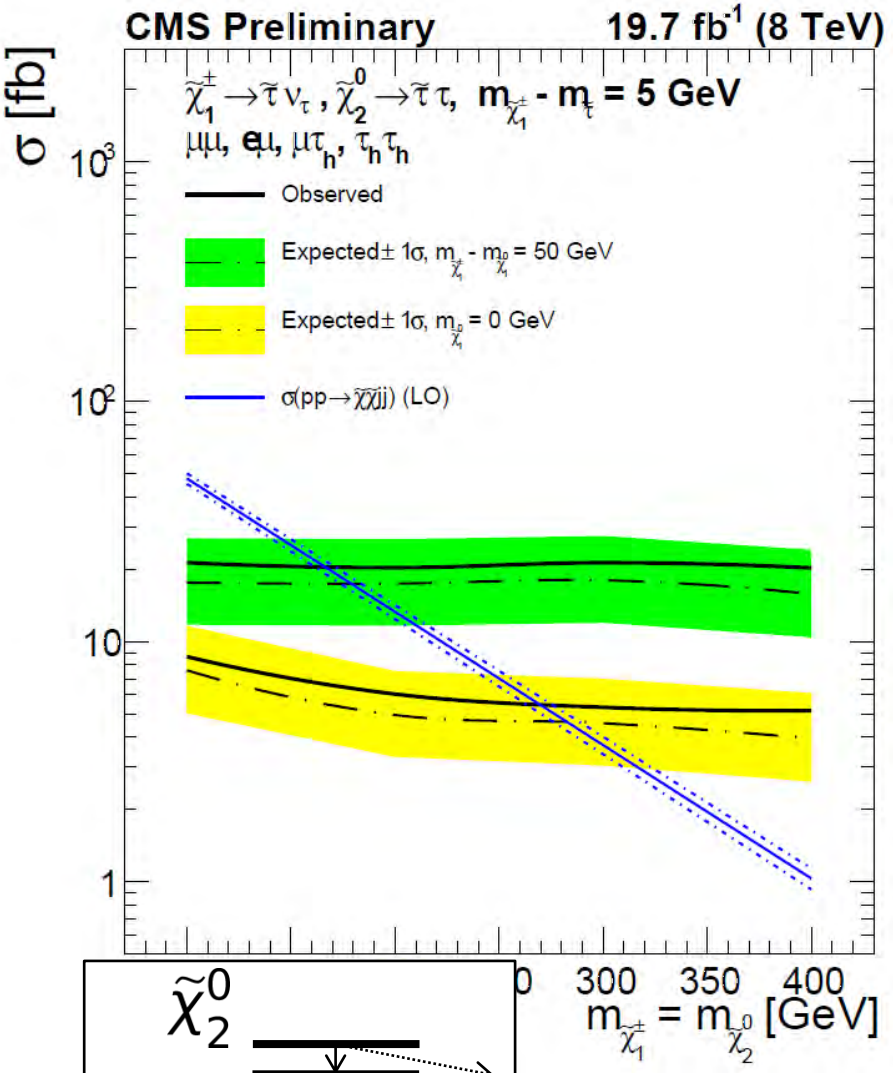

CMS $\sqrt{s}$ = 8 TeV L = 19.5 fb^{-1}
95% CL CLs NLO Exclusions
$pp \to \tilde{e}_R\tilde{e}_R, \tilde{\mu}_R\tilde{\mu}_R$
$Br(\tilde{l}_R \to l\,\tilde{\chi}_1^0) = 1$
Observed $\pm 1\sigma_{theory}$
Expected $\pm 1\sigma_{experiment}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{l}}$ [GeV]
95% CL upper limit on cross section (fb)

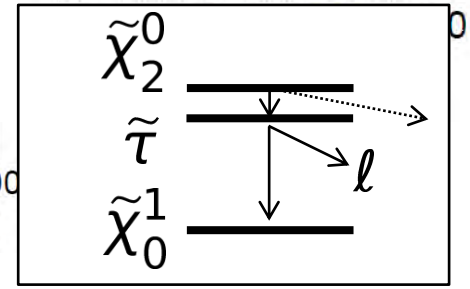
ISR + 2-lepton

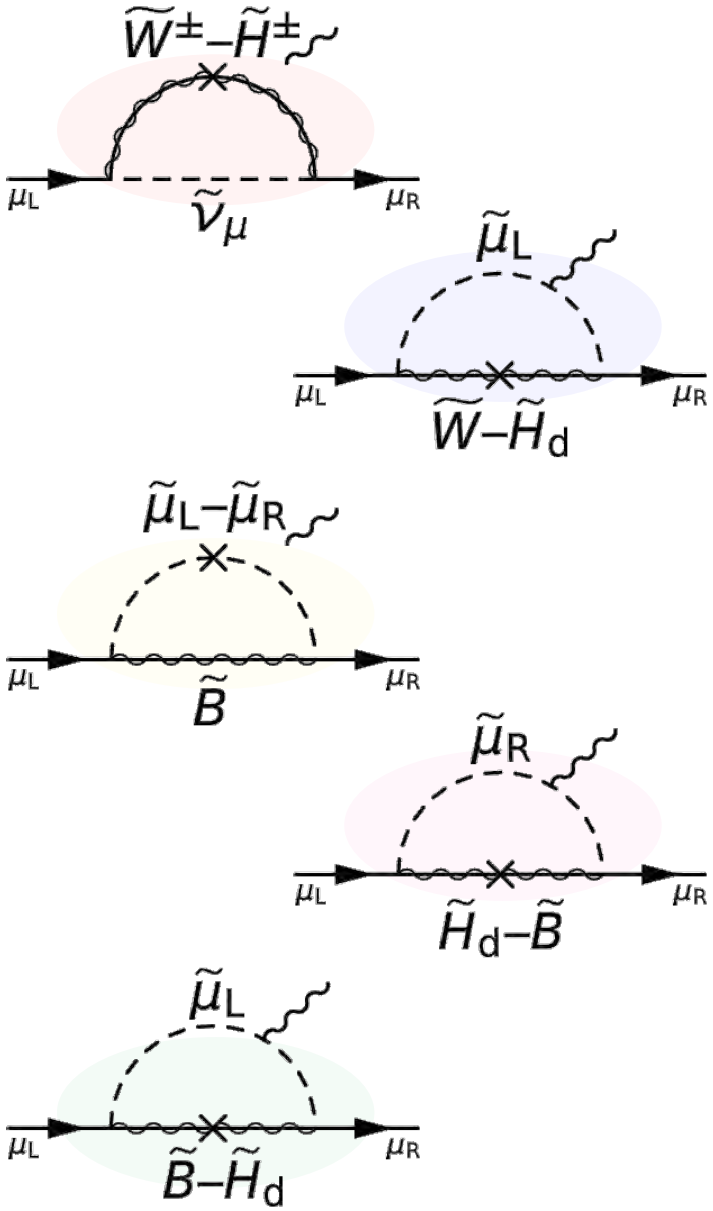




VBF + 2-lepton







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

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

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

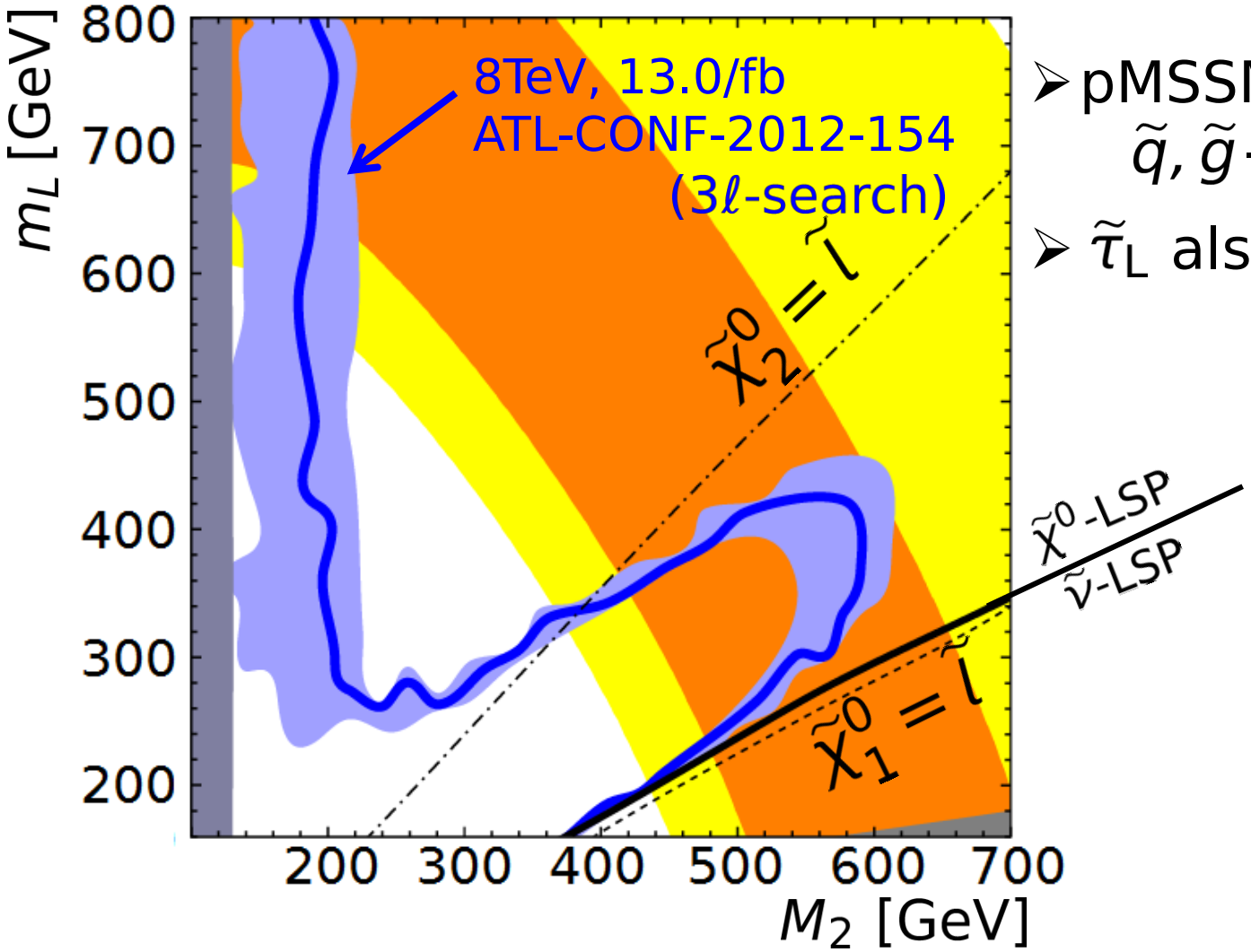
$$-\frac{g_Y^2 m_\mu^2}{8\pi^2}\frac{M_1\mu\tan\beta}{m^4_{\tilde{\mu}_R}}\cdot F_b\left(\frac{M_1}{m_{\tilde{\mu}_R}},\frac{\mu}{m_{\tilde{\mu}_R}}\right)$$

$$\frac{g_Y^2 m_\mu^2}{16\pi^2}\frac{M_1\mu\tan\beta}{m^4_{\tilde{\mu}_L}}\cdot F_b\left(\frac{M_1}{m_{\tilde{\mu}_L}},\frac{\mu}{m_{\tilde{\mu}_L}}\right)$$

(1) Wino-contr. dominant ($\mu \sim M_2$)

(2) Pure-bino dominant ($\mu >> M_2$)

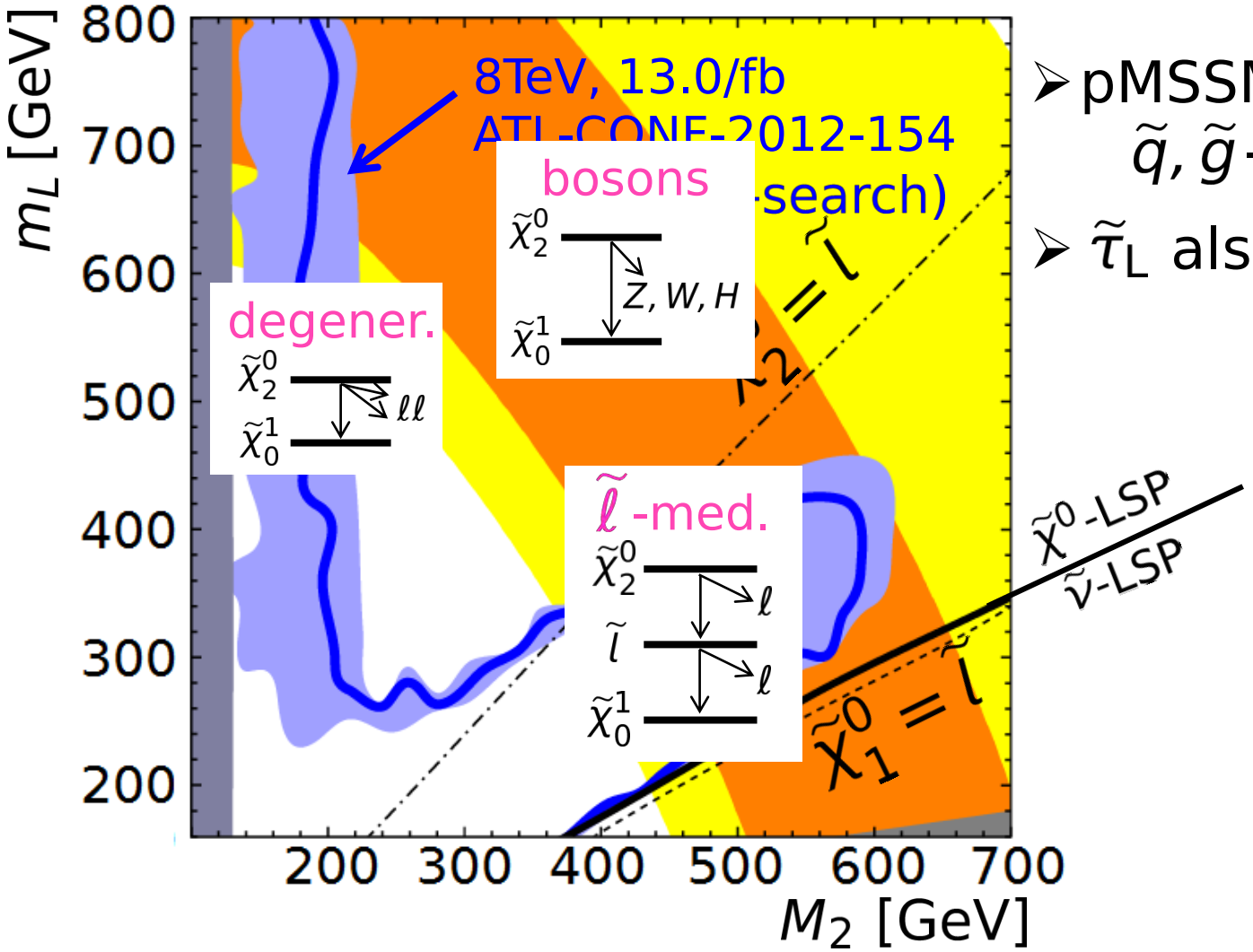
Endo, Hamaguchi, SI, Yoshinaga [1303.4256]



- pMSSM w. $\tilde{q}, \tilde{g}$-decoupled.
- $\tilde{\tau}_L$ also decoupled.

$$M_1,\ M_2,\ \mu,\ m(l_{\rm L}),\ m(l_{\rm R}),\ \tan\beta.$$
$$\| \qquad \| \qquad \| \qquad \|$$
$$M_2/2 \qquad M_2 \qquad 3\,{\rm TeV} \qquad 40$$

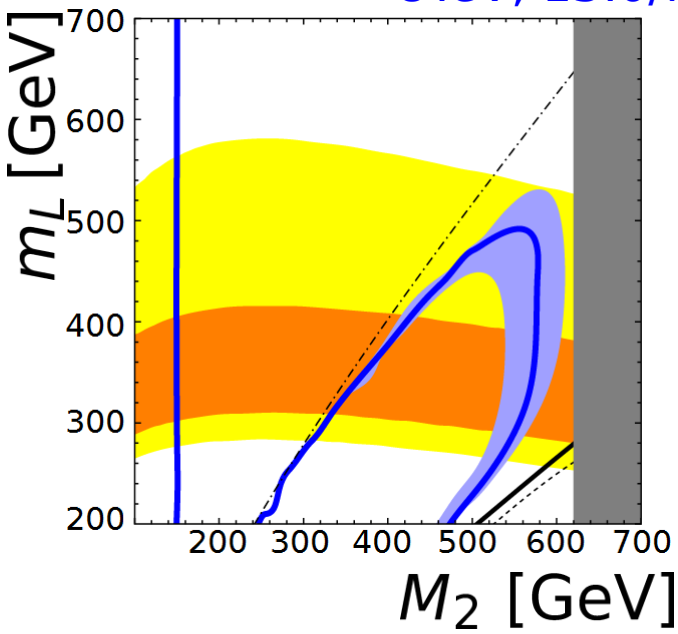
Endo, Hamaguchi, SI, Yoshinaga [1303.4256]



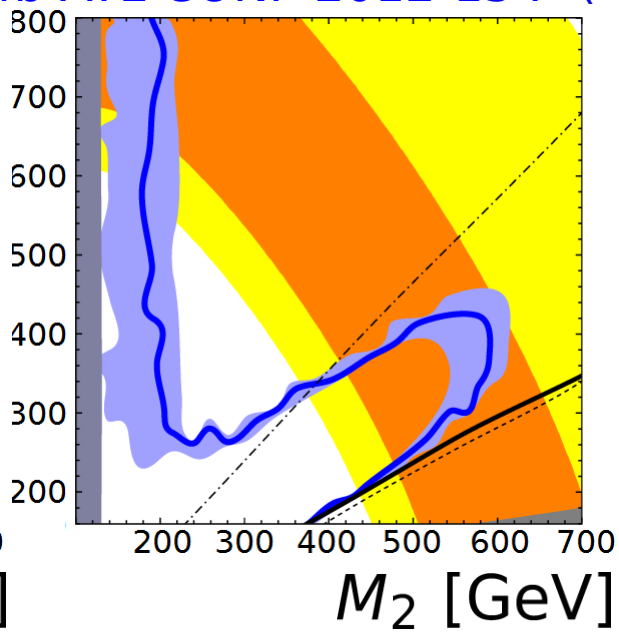
- pMSSM w. $\tilde{q}, \tilde{g}$-decoupled.
- $\tilde{\tau}_L$ also decoupled.

$$\begin{array}{cccccc} M_1, & M_2, & \mu, & m(l_{\rm L}), & m(l_{\rm R}), & \tan\beta. \\ \| & \| & & \| & \| \\ M_2/2 & M_2 & & 3\,{\rm TeV} & 40 \end{array}$$

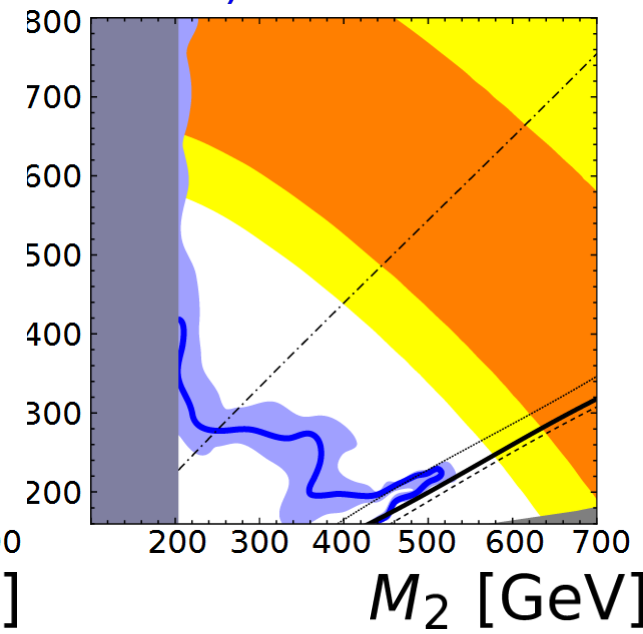
8TeV, 13.0/fb ATL-CONF-2012-154 (3ℓ-search)



$\mu = 2M_2$



$\mu = M_2$



$\mu = 0.5M_2$

lighter $\tilde{H}$

↓

$\widetilde{W}$ decays via $\tilde{H}\&\tilde{l}$

↓

softer, weaker limit

$(g-2)_\mu$ anomaly $\longrightarrow$ $\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm = \mathrm{O}(100)\,\mathrm{GeV}$

SUSY models to explain $\Delta(g-2)_\mu$

"CP-safe" gravity mediation

SI, Yanagida, Yokozaki [1407.4226]

LHC signatures

- (case 1) $\mu \sim M_2$
- (case 2) $\mu \gg M_2$

Endo, Hamaguchi, SI, Yoshinaga [1303.4256]

8 TeV summary
& 14 TeV prospects

$(g-2)_\mu$ anomaly $\longrightarrow$ $\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm = \mathrm{O}(100)\,\mathrm{GeV}$

SUSY models to explain $\Delta(g-2)_\mu$

"CP-safe" gravity mediation

SI, Yanagida, Yokozaki [1407.4226]

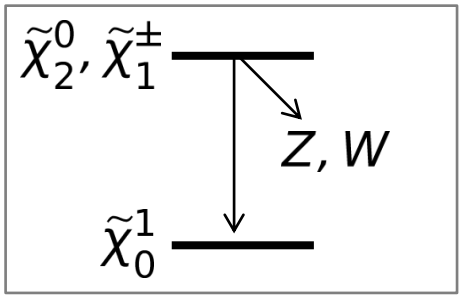
LHC signatures

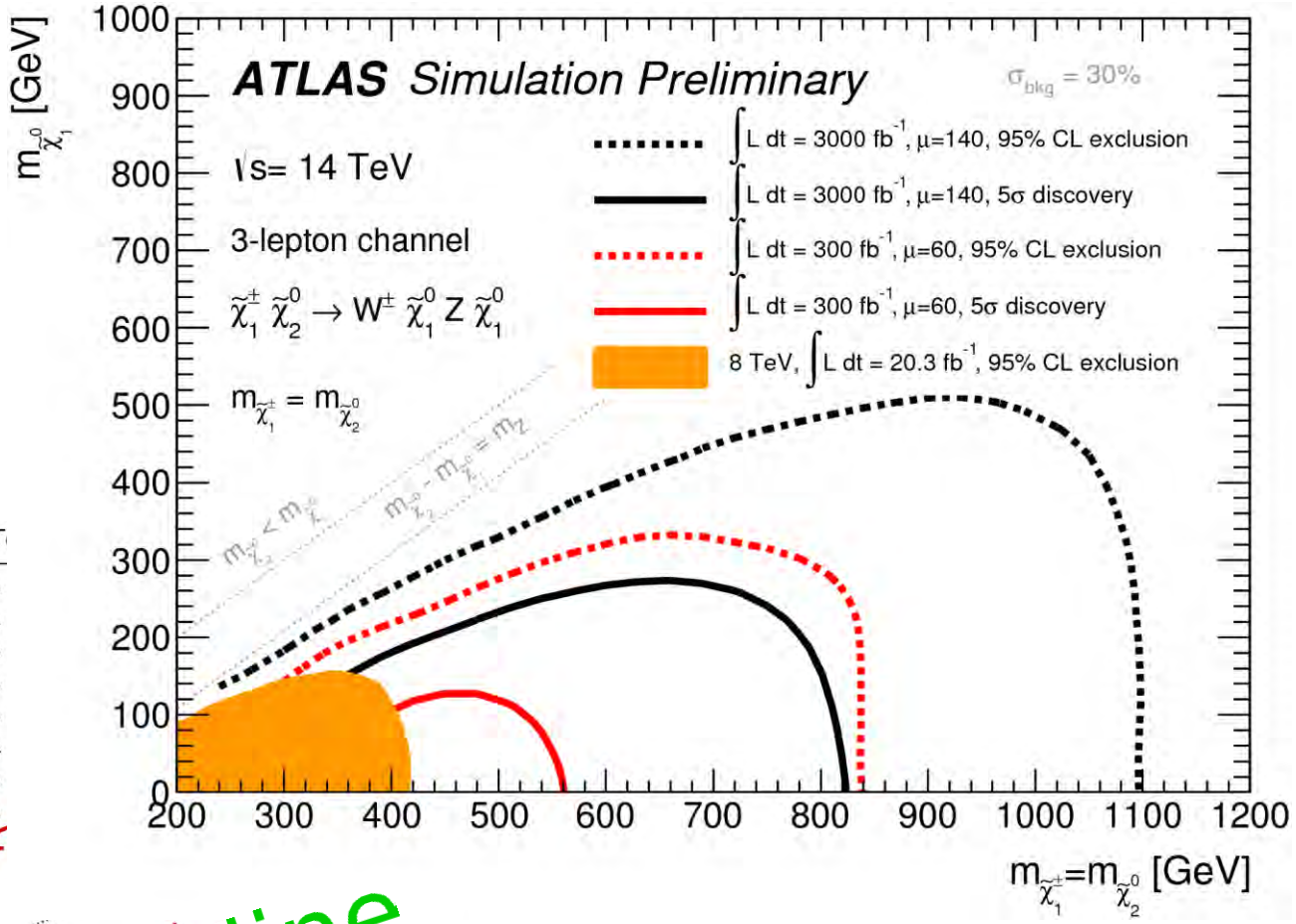
- (case 1) $\mu \sim M_2$
- (case 2) $\mu \gg M_2$

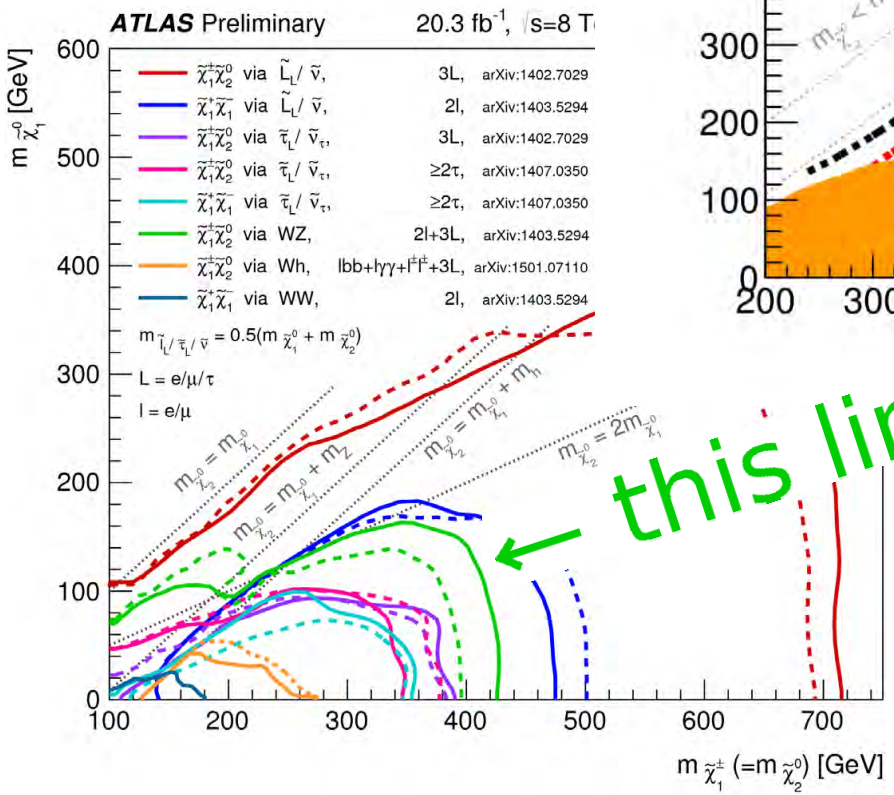
Endo, Hamaguchi, SI, Yoshinaga [1303.4256]

8 TeV summary & 14 TeV prospects

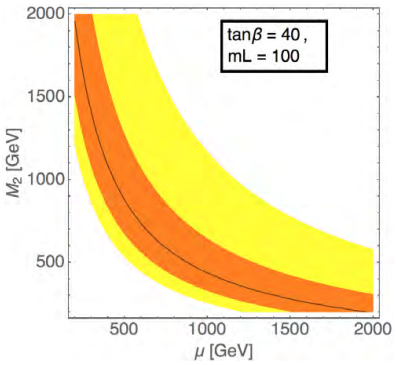
(1) Wino-dominant case: future prospect (ZW-channel)

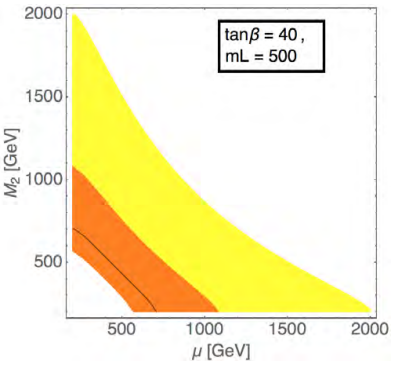




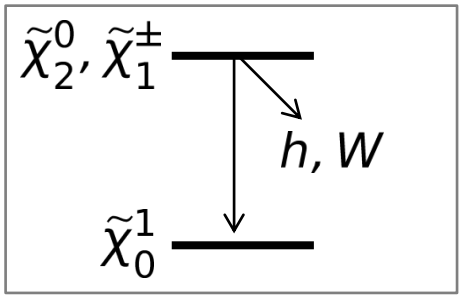


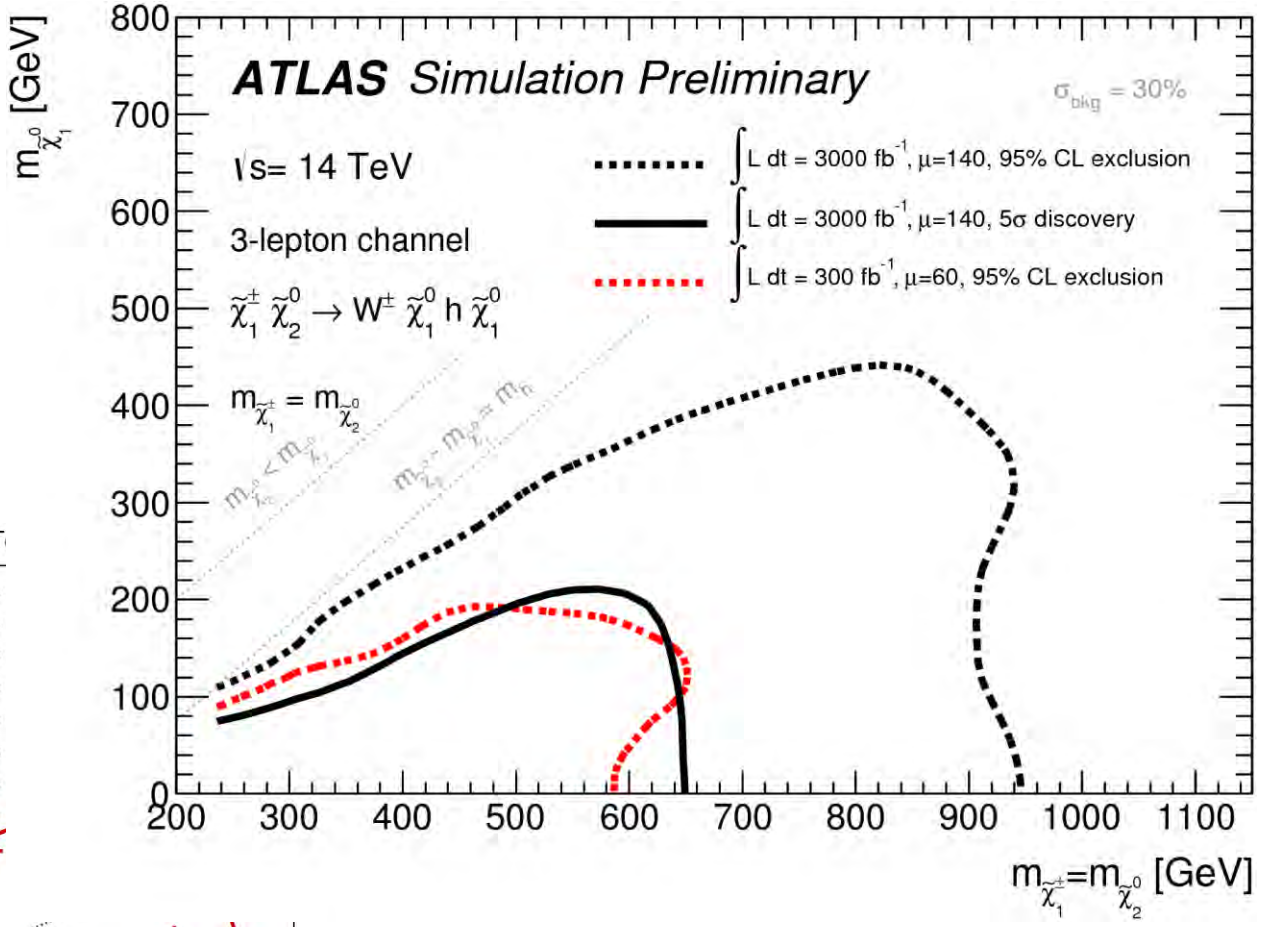
this line

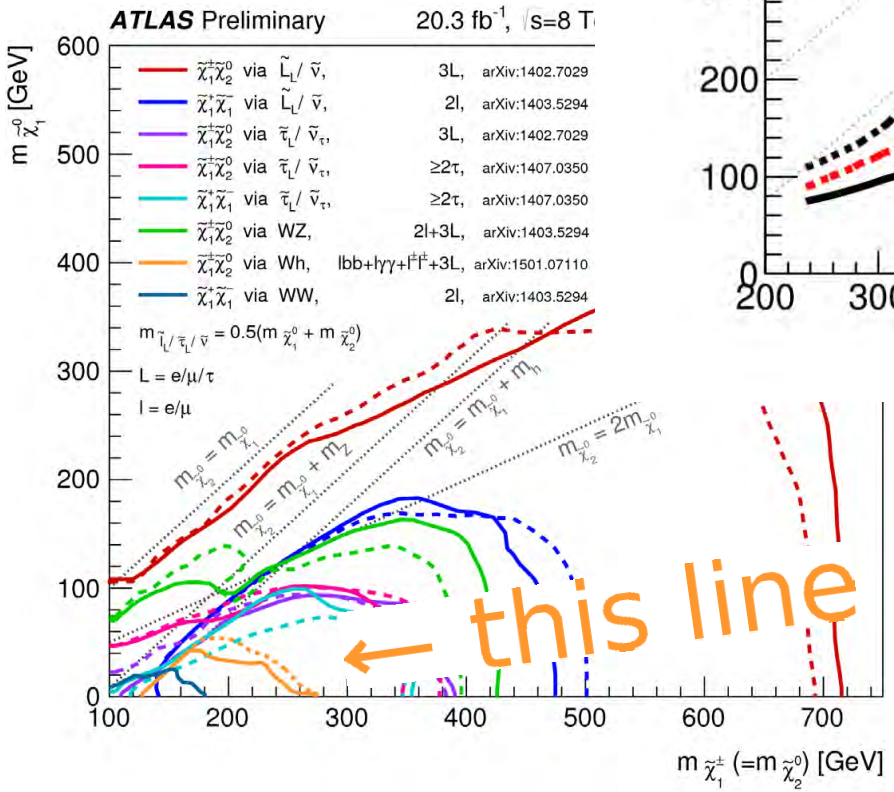




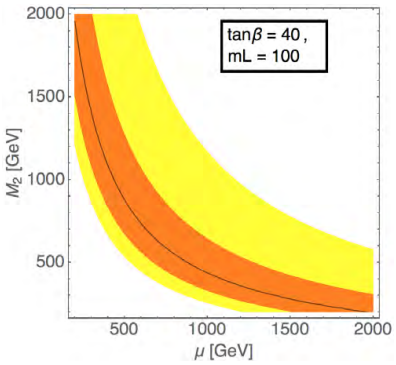
(1) Wino-dominant case: future prospect (hW-channel)

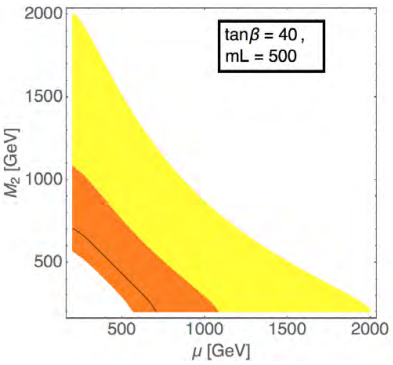






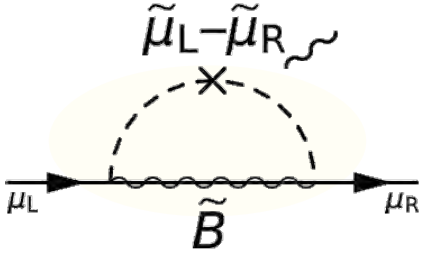
this line





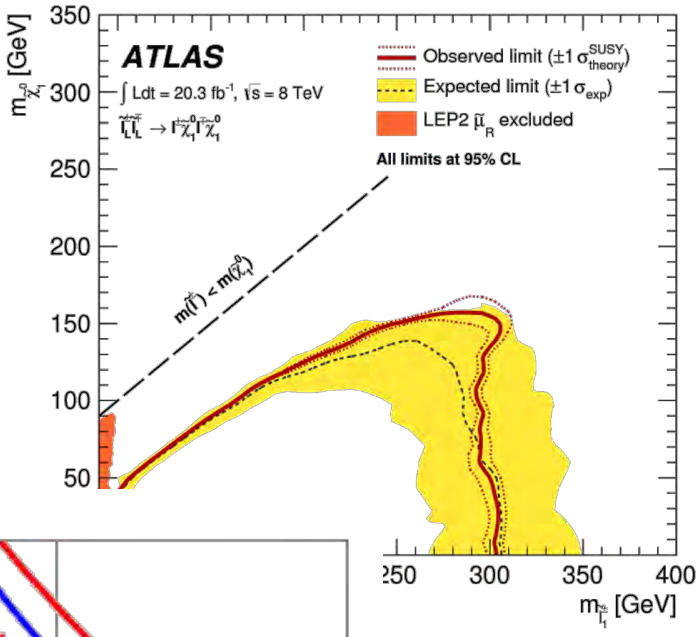
(2) "Pure-bino contirbution": μ >> M1

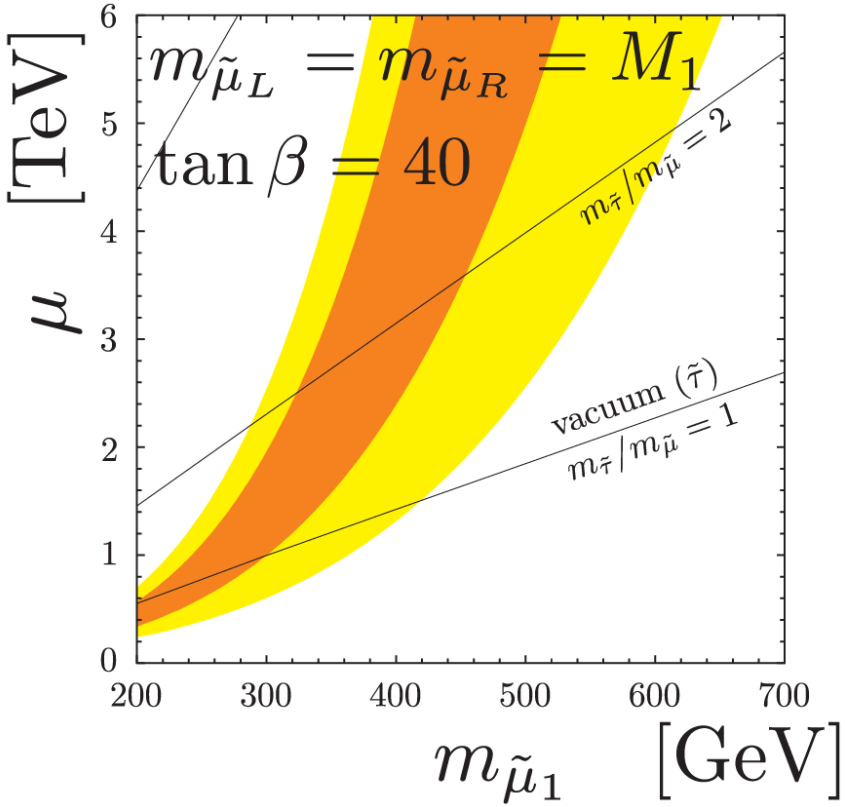
Endo, Hamaguchi, Kitahara, Yoshinaga [1309.3065]

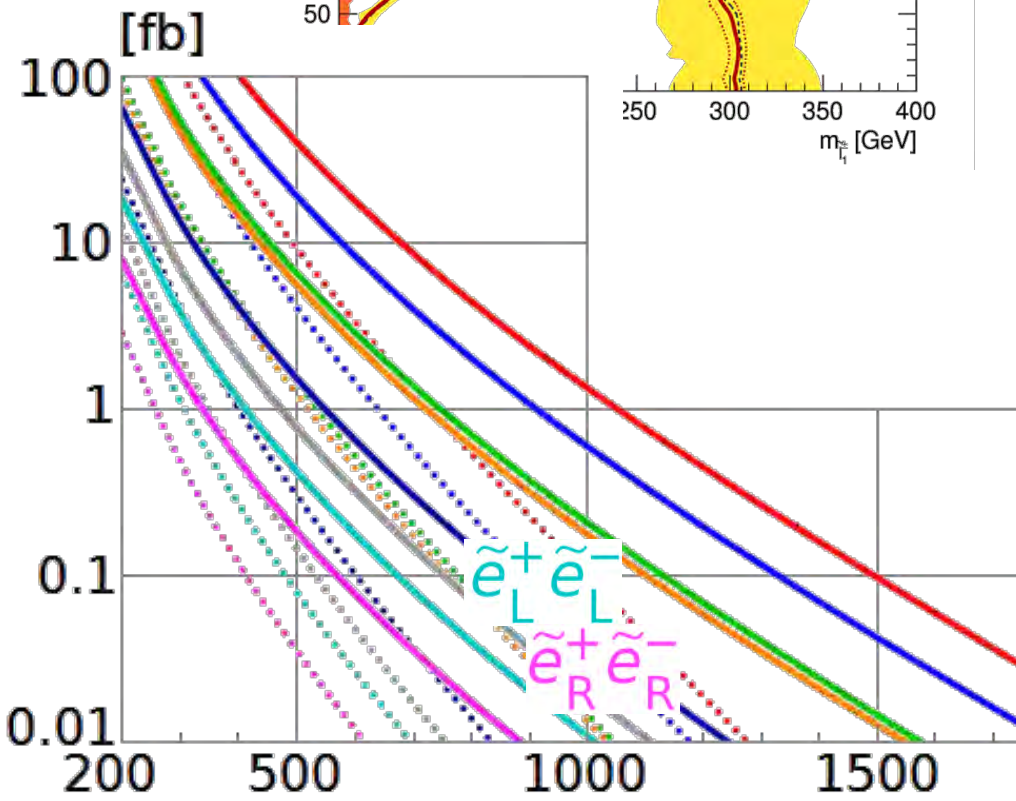


Vacuum stability:

$$m_{\tilde{\tau}}/m_{\tilde{\mu}}$$
$$= 1 \Rightarrow m_{\tilde{\mu}} \lesssim 300(420)\,\mathrm{GeV}$$
$$= 2 \Rightarrow \lesssim 440(620)\,\mathrm{GeV}$$
$$= \infty \Rightarrow \lesssim 1.4(1.9)\,\mathrm{TeV}$$







$(g-2)_\mu$ anomaly $\longrightarrow$ $\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm = \mathrm{O}(100)\,\mathrm{GeV}$

SUSY models to explain $\Delta(g-2)_\mu$

"CP-safe" gravity mediation

SI, Yanagida, Yokozaki [1407.4226]

LHC signatures

- (case 1) $\mu \sim M_2$
- (case 2) $\mu \gg M_2$

Endo, Hamaguchi, SI, Yoshinaga [1303.4256]

8 TeV summary & 14 TeV prospects

$(g-2)_\mu$ anomaly $\longrightarrow$ $\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm = \mathbf{O(100)\,GeV}$

NUGM: $M_3 \gg M_1, M_2$?
$\longrightarrow$ CP-dangerous

“CP-safe” gravity mediation

SI, Yanagida, Yokozaki [1407.4226]

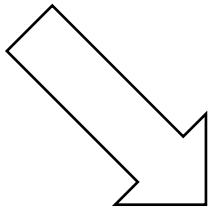
LHC signatures

- (case 1) $\mu \sim M_2$
- (case 2) $\mu \gg M_2$

Endo, Hamaguchi, SI, Yoshinaga [1303.4256]

8 TeV summary & 14 TeV prospects

$(g-2)_\mu$ anomaly $\longrightarrow$ $\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm = \mathbf{O(100)\,GeV}$

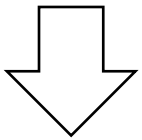


LHC signatures

- (case 1) $\mu \sim M_2$
- (case 2) $\mu \gg M_2$

$\tilde{\chi}^0\tilde{\chi}^\pm \to (3l \text{ or } ZW, hW) + \not{E}_T$

Endo, Hamaguchi, SI, Yoshinaga [1303.4256]



8 TeV summary & 14 TeV prospects

$(g-2)_\mu$ anomaly $\longrightarrow$ $\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm = \mathbf{O(100)\,GeV}$

LHC signatures

$\tilde{\chi}^0\tilde{\chi}^\pm \to (3l \text{ or } ZW, hW) + \not{E}_T$

(case 1) $\mu \sim M_2$

$\tilde{l}\tilde{l}^* \to 2l + \not{E}_T$ ... weak

(case 2) $\mu \gg M_2$

Endo, Hamaguchi, SI, Yoshinaga [1303.4256]

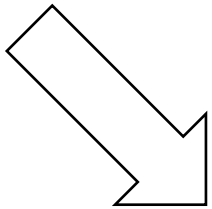
even degenerate case!

eV summary
& 14 TeV prospects

... How to search for “case 2”?

One more thing

$(g-2)_\mu$ anomaly $\longrightarrow$ $\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm = \mathbf{O(100)\,GeV}$



LHC signatures

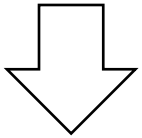
$\tilde{\chi}^0\tilde{\chi}^\pm \to (3l \text{ or } ZW, hW) + \not{E}_T$

(case 1) $\mu \sim M_2$

$\tilde{l}\tilde{l}^* \to 2l + \not{E}_T$ ... weak

(case 2) $\mu \gg M_2$

Endo, Hamaguchi, SI, Yoshinaga [1303.4256]



even degenerate case!

eV summary
& 14 TeV prospects

... How to search for “case 2”?

$(g-2)_\mu$ anomaly $\longrightarrow$ $\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm = \mathbf{O(100)\,GeV}$

if long-lived...

...C signatures

...case 1) $\mu \sim M_2$

$\tilde{l}\tilde{l}^* \to 2l + \not{E}_T$ ... weak

...e 2) $\mu \gg M_2$

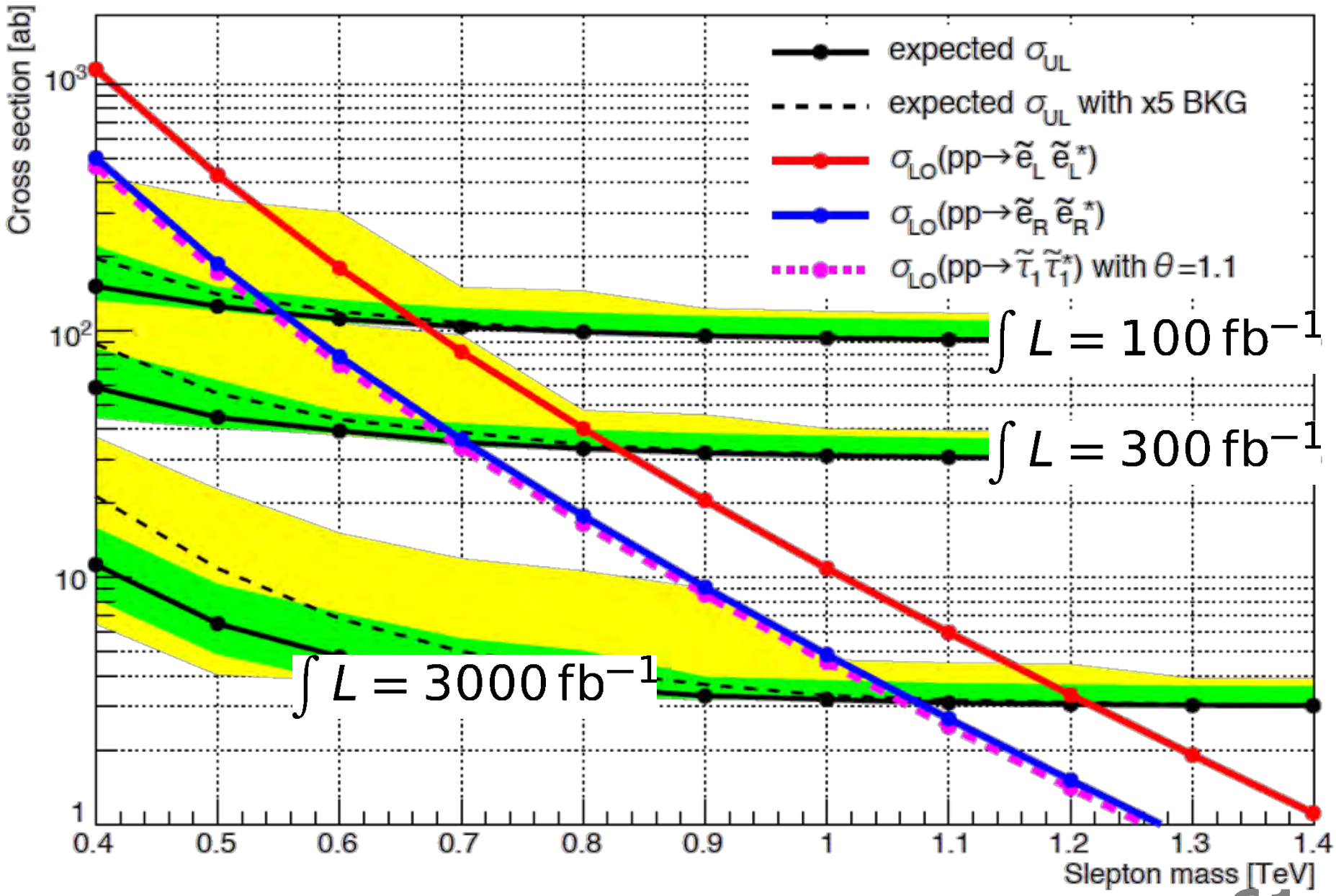
Endo, Hamaguchi, SI, Yoshinaga [1303.4256]

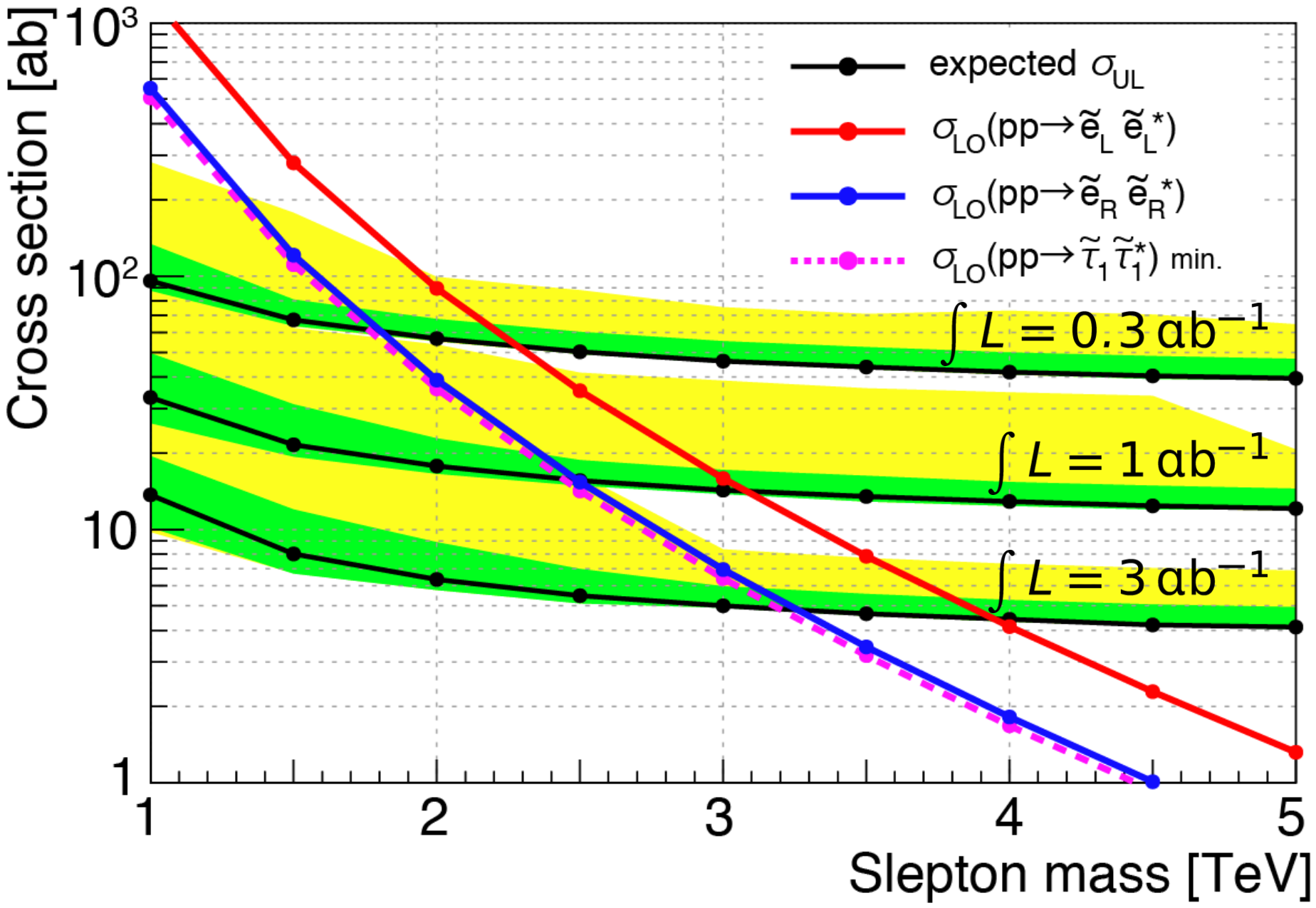
long-lived charged particle

even degenerate case!

...eV summary
& 14 TeV prospects

... How to search for “case 2”?


Cross section [ab]
10^3
10^2
10
1
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
Slepton mass [TeV]
expected σ_{UL}
expected σ_{UL} with x5 BKG
$\sigma_{LO}(pp\to\tilde{e}_L\,\tilde{e}_L^*)$
$\sigma_{LO}(pp\to\tilde{e}_R\,\tilde{e}_R^*)$
$\sigma_{LO}(pp\to\tilde{\tau}_1\tilde{\tau}_1^*)$ with θ=1.1
$\int L = 100\,\mathrm{fb}^{-1}$
$\int L = 300\,\mathrm{fb}^{-1}$
$\int L = 3000\,\mathrm{fb}^{-1}$


Cross section [ab]
10^3
10^2
10
1
1
2
3
4
5
Slepton mass [TeV]
expected σ_{UL}
$\sigma_{LO}(pp\to\tilde{e}_L\,\tilde{e}_L^*)$
$\sigma_{LO}(pp\to\tilde{e}_R\,\tilde{e}_R^*)$
$\sigma_{LO}(pp\to\tilde{\tau}_1\,\tilde{\tau}_1^*)$ min.
$\int L = 0.3\,ab^{-1}$
$\int L = 1\,ab^{-1}$
$\int L = 3\,ab^{-1}$

Feng, SI, Shadmi, Tarem [1505.02996]