$(g\text{-}2)_\mu$ があるからSUSYは軽いよ

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新学術領域「先端加速器LHC…」
やっぱり軽いSUSY **ミニ研究会** @ **東京大学**

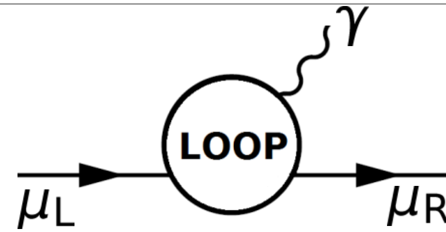
Primary references)

M. Endo, K. Hamaguchi, SI, T. Yoshinaga [1303.4256],
M. Endo, K. Hamaguchi, T. Kitahara, T. Yoshinaga [1309.3065];
ATLAS/CMS Supersymmetry public results.
[ATLAS-CONF-2013-028/035/049/093, ATL-PHYS-PUB-2013-002,
CMS PAS SUS-13-006, SUS-13-017, FTR-13-014]

$(g-2)_\mu$ ⇒ SUSY粒子の一部が O(100)GeV ⇒ それらをLHCで見よう

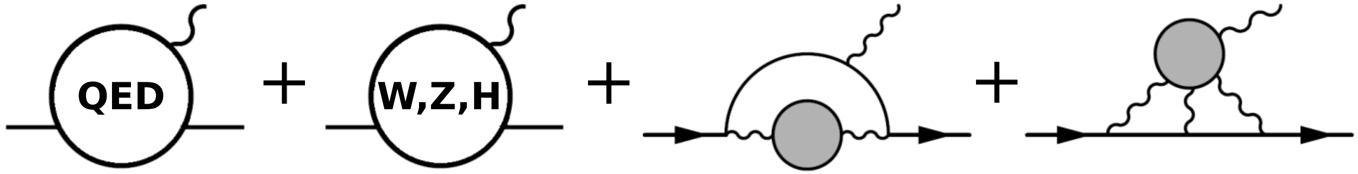
- ✓ MSSM かつ R-parity 保存。
- ✓ Colored SUSY粒子は重い。（←126GeV Higgs）
  （Naturalness は無視！）

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



(5-loop) (2⁺-loop) (分散関係) (低energy有効理論)

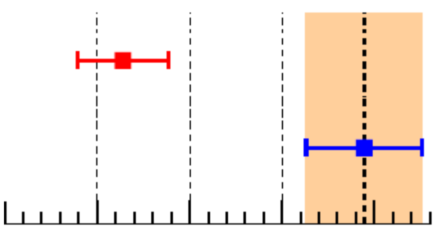
$$a_\mu^{\rm SM} \simeq$$



had. vac. polarization Had. light-by-light

$$\begin{aligned}
a_\mu(\text{QED}) &= (11\,658\,471.8951 \pm 0.0080) \times 10^{-10}, \\
a_\mu(\text{EW}) &= (\quad 15.4 \pm 0.2 \quad) \times 10^{-10}, \\
a_\mu(\text{HVP-LO}) &= (\quad 694.91 \pm 4.27 \quad) \times 10^{-10}, \\
a_\mu(\text{HVP-HO}) &= -(\quad 9.84 \pm 0.07 \quad) \times 10^{-10}, \\
a_\mu(\text{HLbL}) &= (\quad 10.5 \pm 2.6 \quad) \times 10^{-10}.
\end{aligned}$$

+)



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

$$a_\mu^{\rm exp} = (11\,659\,208.9 \pm 6.3) \times 10^{-10} \quad \text{(BNL '04)}$$

QED: Aoyama, Hayakawa, Kinoshita, Nio [1205.5370].
EW: Gnendiger, Stöckinger, Stöckinger-Kim [1306.5546].
HVP: Hagiwara, Liao, Martin, Nomura, Teubner [1105.3149].
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See also:
EW: Knecht, Peris, Perrottet, De Rafael [ph/0205102], Czarnecki, Marciano, Vainshtein [ph/0212229].
HVP: Davier, Hoecker, Malaescu, Zhang [1010.4180].
HLbL: Nyffeler [0901.1172], Jegerlehner, Nyffeler [0902.3360].

$$\Delta a_\mu = (26.1 \pm 8.0)\times 10^{-10} \quad \cdots \mathbf{3.3\sigma}\ \text{anomaly}$$

① 理論値 or 実験の不確かさに問題がある。

② 新物理からの寄与のせいである。

$$
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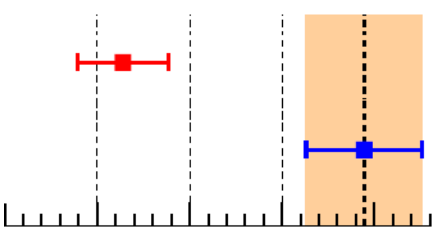
+)\quad a_\mu(\text{NP}) &= O(10^{-9})
\end{aligned}
$$



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(5-loop) (2⁺-loop) (分散関係) (低energy有効理論)

a_μ^{SM}

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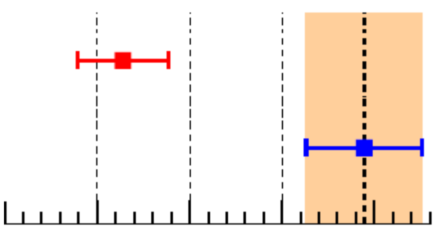

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a_μ^{S} これは**SUSY粒子**の寄与である

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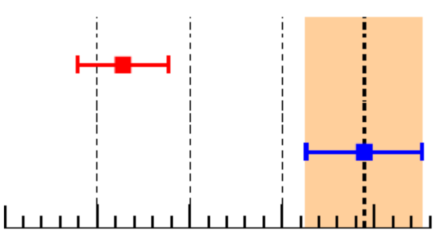

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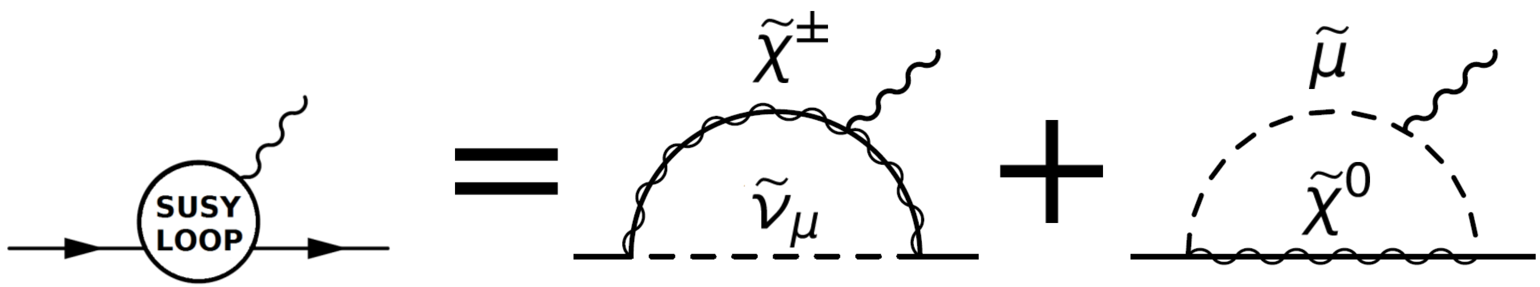

“chargino” diag. “neutralino” diag.

$\tan\beta = O(10)$ で、 $\left(\tilde{\chi}^0, \tilde{\chi}^\pm, \tilde{\mu}, \tilde{\nu}_\mu\right) = O(100)\,\mathrm{GeV}$ なら

SUSYの寄与がちょうどいいサイズ。

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

$(g-2)_\mu$ ⇨ SUSY粒子の一部が O(100)GeV ⇨ それらをLHCで見よう

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

1 TeV

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

100 GeV

- ✓ MSSM かつ R-parity 保存。
- ✓ Colored SUSY粒子は重い。（←126GeV Higgs）
  （Naturalness は無視！）

Overview

$(g-2)_\mu$ ⇨ $\widetilde{\mathrm{EW}} = \mathrm{O}(100)\,\mathrm{GeV}$ ⇨ EW直接生成で見える

こいつらを生成して
検出すればよい

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

1 TeV

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

100 GeV

- ✓ MSSM かつ R-parity 保存。
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①基礎知識

$(g-2)_\mu$ ⇒ $\widetilde{\mathrm{EW}} = \mathrm{O}(100)\,\mathrm{GeV}$ ⇒ EW直接生成で見える

もう一段階掘り下げて……

$(g-2)_\mu$

②パターン１（典型的）

③パターン２（ちょっと特殊）

1. 基礎知識

質量と mixing を決めるパラメータ

gaugino質量 | μ-term (Higgsino質量) | slepton質量 | $\langle H_\mathrm{u}\rangle/\langle H_\mathrm{d}\rangle$ =

$$M_1,\ M_2,\quad \mu,\quad m(l_\mathrm{L}),\ m(l_\mathrm{R}),\quad \underbrace{\tan\beta,\ \ A_l.}_{\text{Mixingを決める}}$$

$$\left(\tilde{B}, \widetilde{W}^0, \tilde{H}^0_\mathrm{u}, \tilde{H}^0_\mathrm{d}\right), \left(\widetilde{W}^\pm, \tilde{H}^\pm\right), \left(\tilde{l}_\mathrm{L}, \tilde{l}_\mathrm{R}\right), \tilde{\nu}$$ ：ゲージ固有状態

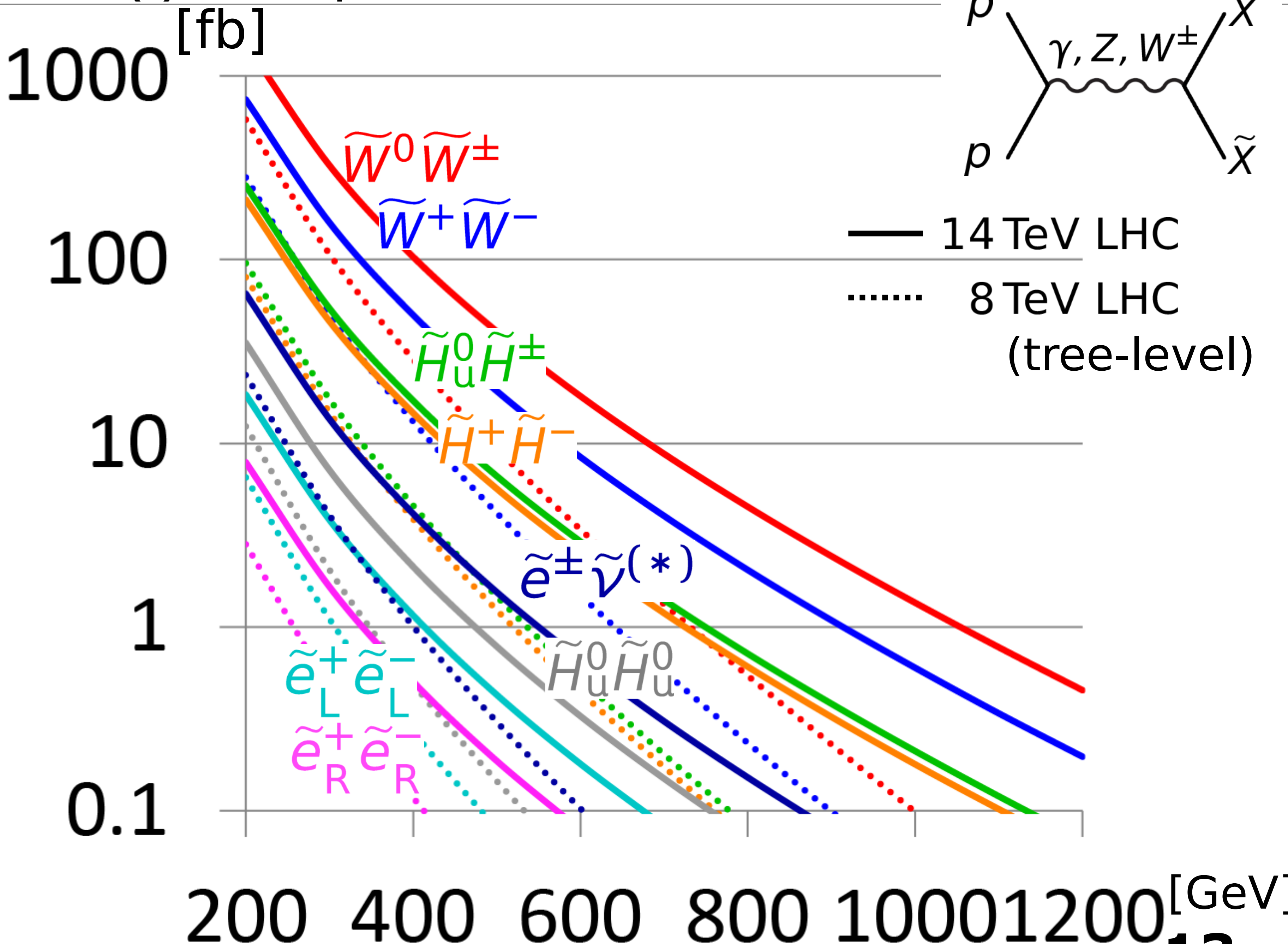
⇩

- Target: $$\left(\tilde{\chi}^0_1, \tilde{\chi}^0_2, \tilde{\chi}^0_3, \tilde{\chi}^0_4\right), \left(\tilde{\chi}^\pm_1, \tilde{\chi}^\pm_2\right), \left(\tilde{l}_1, \tilde{l}_2\right), \tilde{\nu}$$ ：質量固有状態

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -c_\beta s_\mathrm{W} m_Z & s_\beta s_\mathrm{W} m_Z \\ 0 & M_2 & c_\beta c_\mathrm{W} m_Z & -s_\beta c_\mathrm{W} m_Z \\ -c_\beta s_\mathrm{W} m_Z & c_\beta c_\mathrm{W} m_Z & 0 & -\mu \\ s_\beta s_\mathrm{W} m_Z & -s_\beta c_\mathrm{W} m_Z & -\mu & 0 \end{pmatrix};$$

$$M_{\tilde{\chi}^\pm} = \begin{pmatrix} M_2 & \sqrt{2} s_\beta m_W \\ \sqrt{2} c_\beta m_W & \mu \end{pmatrix};$$

$$M^2_{\tilde{\mu}} = \begin{pmatrix} m(l_\mathrm{L})^2 & m_\mu(A^*_\mu - \mu\tan\beta) \\ m_\mu(A^*_\mu - \mu\tan\beta) & m(l_\mathrm{R})^2 \end{pmatrix}.$$


[fb]
1000
100
10
1
0.1
$\widetilde{W}^0\widetilde{W}^\pm$
$\widetilde{W}^+\widetilde{W}^-$
$\widetilde{H}^0_u\widetilde{H}^\pm$
$\widetilde{H}^+\widetilde{H}^-$
$\widetilde{e}^\pm\widetilde{\nu}^{(*)}$
$\widetilde{H}^0_u\widetilde{H}^0_u$
$\widetilde{e}^+_L\widetilde{e}^-_L$
$\widetilde{e}^+_R\widetilde{e}^-_R$
200
400
600
800
1000
1200
[GeV]
p
p
$\gamma, Z, W^\pm$
$\tilde{\chi}$
$\tilde{\chi}$
14 TeV LHC
8 TeV LHC
(tree-level)

基礎知識(2) SUSY contribution to muon g-2

質量と mixing を決めるパラメータ

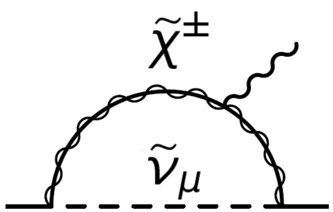
gaugino質量	μ-term (Higgsino質量)	slepton質量	$\langle H_\mathrm{u}\rangle / \langle H_\mathrm{d}\rangle$
$M_1, M_2,$	$\mu,$	$m(l_\mathrm{L}), m(l_\mathrm{R}),$	$\underbrace{\tan\beta, \ A_l.}_{\text{Mixingを決める}}$

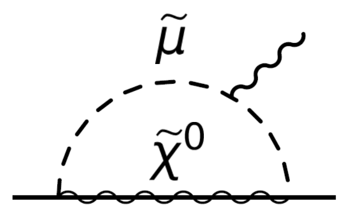
$$\left(\tilde{B}, \tilde{W}^0, \tilde{H}^0_\mathrm{u}, \tilde{H}^0_\mathrm{d}\right), \left(\tilde{W}^\pm, \tilde{H}^\pm\right), \left(\tilde{l}_\mathrm{L}, \tilde{l}_\mathrm{R}\right), \tilde{\nu} \quad \text{：ゲージ固有状態}$$

$$\Downarrow$$

◉ Target: $\left(\tilde{\chi}^0_1, \tilde{\chi}^0_2, \tilde{\chi}^0_3, \tilde{\chi}^0_4\right), \left(\tilde{\chi}^\pm_1, \tilde{\chi}^\pm_2\right), \left(\tilde{l}_1, \tilde{l}_2\right), \tilde{\nu}$ ：質量固有状態

$$\Downarrow$$

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

$+$ 

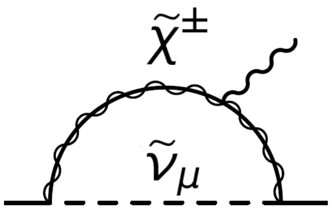
$$= a_\mu^\mathrm{SUSY}(M_1, M_2, \mu, m(\mu_\mathrm{L}), m(\mu_\mathrm{R}), \tan\beta, A_\mu)$$

基礎知識(2) SUSY contrib. (in mass-basis)

$$\left(\tilde\chi^0_1,\tilde\chi^0_2,\tilde\chi^0_3,\tilde\chi^0_4\right),\left(\tilde\chi^\pm_1,\tilde\chi^\pm_2\right),\left(\tilde l_1,\tilde l_2\right),\tilde\nu$$

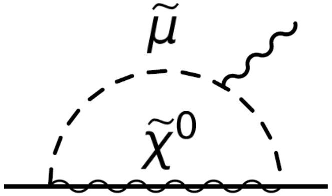
$$a_\mu^{\mathrm{SUSY}}(M_1, M_2, \mu, m(\mu_{\mathrm{L}}), m(\mu_{\mathrm{R}}), \tan\beta, A_\mu)$$

$=$



$$= f_{\mathrm{N}}\left(m_{\tilde\mu_a}, m_{\tilde\chi^0_i}, \frac{g_Y N^*_{1i}+g_2 N^*_{2i}}{\sqrt{2}}E^*_{1a} - Y_\mu N^*_{3i}E^*_{2a}, -Y_\mu N_{3i}E^*_{1a} - \sqrt{2}g_Y N_{1i}E^*_{2a}\right)$$

$+$



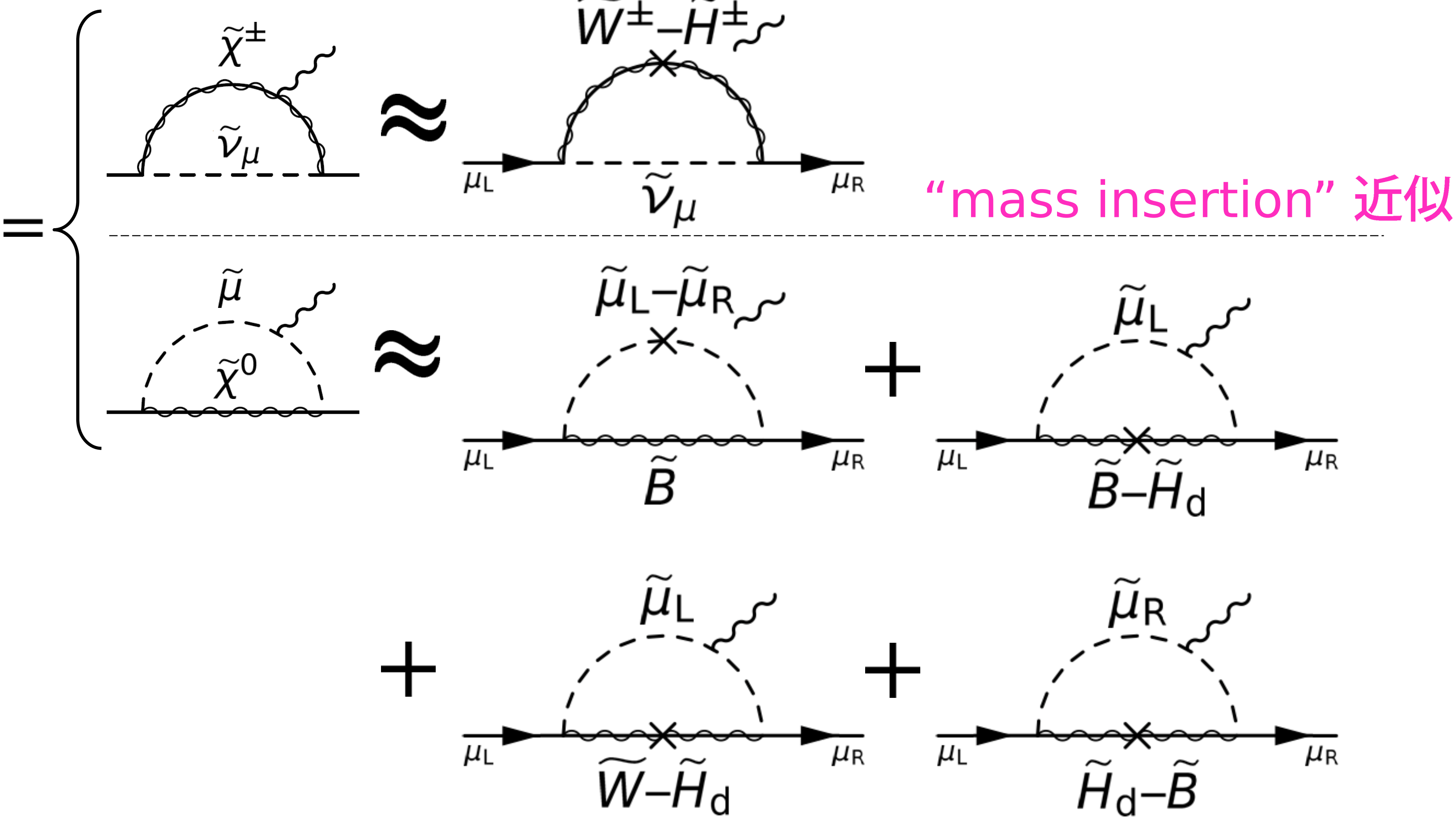
$$= f_{\mathrm{C}}\left(m_{\tilde\nu_\mu}, m_{\tilde\chi^\pm_i}, -g_2 D_{1i}, Y_\mu C_{2i}\right)$$

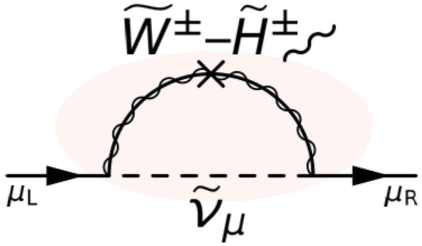
where
$$f_{\mathrm{N}}(M, M_{\tilde\chi}, g_{\mathrm{L}}, g_{\mathrm{R}}) = \frac{1}{16\pi^2}\left[-\frac{|g_{\mathrm{L}}|^2+|g_{\mathrm{R}}|^2}{6}\frac{m_\mu^2}{M^2}N_1\left(\frac{M_{\tilde\chi}^2}{M^2}\right) - \mathrm{Re}\,(g_{\mathrm{L}}^* g_{\mathrm{R}})\frac{m_\mu M_{\tilde\chi}}{M^2}N_2\left(\frac{M_{\tilde\chi}^2}{M^2}\right)\right],$$
$$f_{\mathrm{C}}(M, M_{\tilde\chi}, g_{\mathrm{L}}, g_{\mathrm{R}}) = \frac{1}{16\pi^2}\left[+\frac{|g_{\mathrm{L}}|^2+|g_{\mathrm{R}}|^2}{6}\frac{m_\mu^2}{M^2}C_1\left(\frac{M_{\tilde\chi}^2}{M^2}\right) - \mathrm{Re}\,(g_{\mathrm{L}}^* g_{\mathrm{R}})\frac{m_\mu M_{\tilde\chi}}{M^2}C_2\left(\frac{M_{\tilde\chi}^2}{M^2}\right)\right],$$

$$N_1(x) := \frac{1-6x+3x^2+2x^3-6x^2\log x}{(1-x)^4}, \qquad N_2(x) := \frac{1-x^2+2x\log x}{(1-x)^3},$$
$$C_1(x) := \frac{2+3x-6x^2+x^3+6x\log x}{(1-x)^4}, \qquad C_2(x) := \frac{3-4x+x^2+2\log x}{(1-x)^3}.$$

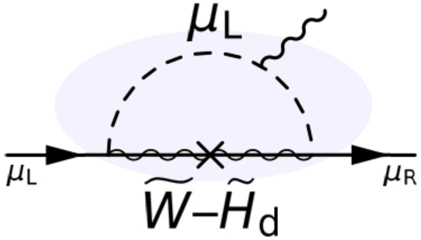
$\boxed{\left(\tilde{B}, \widetilde{W}^0, \tilde{H}^0_{\mathrm{u}}, \tilde{H}^0_{\mathrm{d}}\right), \left(\widetilde{W}^\pm, \tilde{H}^\pm\right), \left(\tilde{l}_{\mathrm{L}}, \tilde{l}_{\mathrm{R}}\right), \tilde{\nu}}$

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

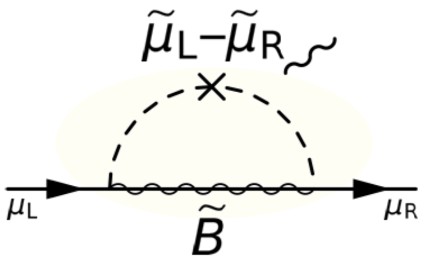




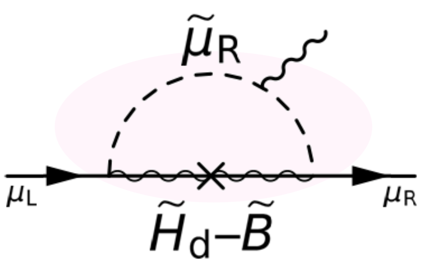
$$\frac{g_2^2 m_\mu^2}{8\pi^2}\,\frac{M_2\mu\tan\beta}{m_{\tilde{\nu}_\mu}^4}\cdot F_a\left(\frac{M_2}{m_{\tilde{\nu}_\mu}},\frac{\mu}{m_{\tilde{\nu}_\mu}}\right)$$



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



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



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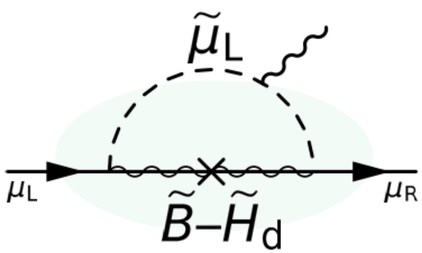


$$\frac{g_Y^2 m_\mu^2}{16\pi^2}\,\frac{M_1\mu\tan\beta}{m_{\tilde{\mu}_\mathrm{L}}^4}\cdot F_b\left(\frac{M_1}{m_{\tilde{\mu}_\mathrm{L}}},\frac{\mu}{m_{\tilde{\mu}_\mathrm{L}}}\right)$$

（※ F_a, F_b は loop 関数 (>0)。）

$$\left(\begin{aligned} F_a(x,y) &= \frac{1}{2}\frac{C_1(x^2)-C_1(y^2)}{x^2-y^2}, & F_b(x,y) &= -\frac{1}{2}\frac{N_2(x^2)-N_2(y^2)}{x^2-y^2}; \\ C_1(x) &= \frac{3-4x+x^2+2\log x}{(1-x)^3}, & N_2(x) &= \frac{1-x^2+2x\log x}{(1-x)^3}. \end{aligned}\right)$$

注目点

◉ すべて $\dfrac{m_\mu^2}{M_{\rm SUSY}^2}\tan\beta$ の構造。

- SUSYは軽い方が良い。
- tanβ に比例！
- $(g-2)_e^{\rm SUSY}$ は小さい。

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

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

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

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

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

（※ F_a, F_b は loop 関数 (>0)。）

$$\left(\begin{aligned} F_a(x,y) &= \frac{1}{2}\frac{C_1(x^2)-C_1(y^2)}{x^2-y^2}, & F_b(x,y) &= -\frac{1}{2}\frac{N_2(x^2)-N_2(y^2)}{x^2-y^2}; \\ C_1(x) &= \frac{3-4x+x^2+2\log x}{(1-x)^3}, & N_2(x) &= \frac{1-x^2+2x\log x}{(1-x)^3}. \end{aligned}\right)$$

$(g-2)_\mu$ → $\widetilde{\mathrm{EW}} = \mathcal{O}(100)\,\mathrm{GeV}$ → EW直接生成で見える

①基礎知識

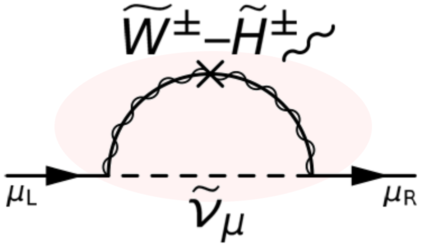
もう一段階掘り下げて......

$(g-2)_\mu$

②パターン１（典型的）

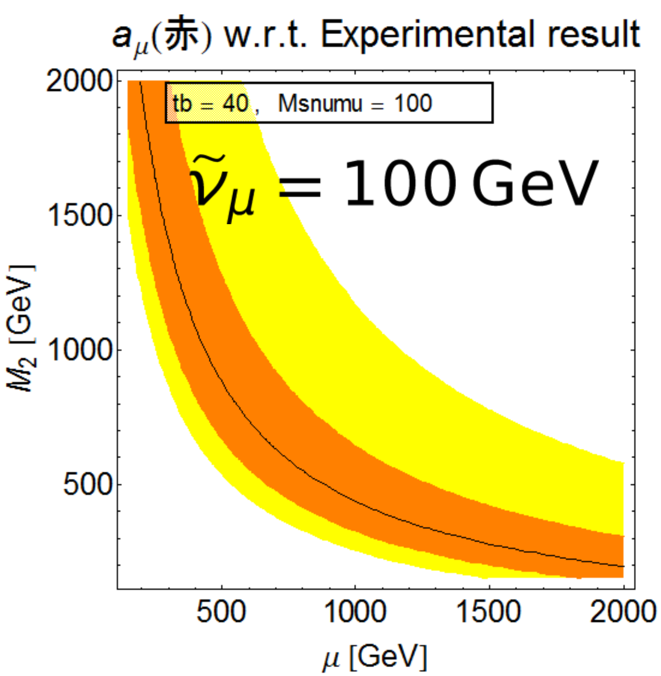
③パターン２（ちょっと特殊）

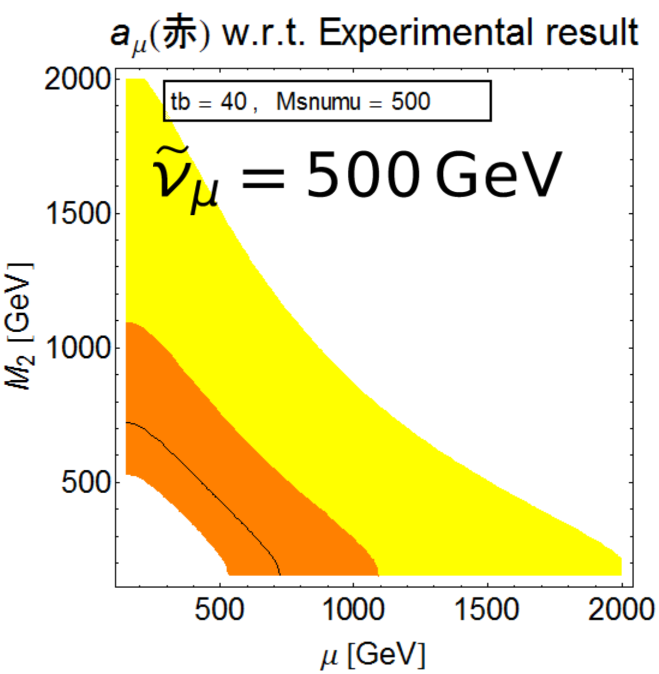
2. Chargino dominance



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

- 通称：chargino contribution
- 特徴：唯一の “chargino”。 tan β に比例。

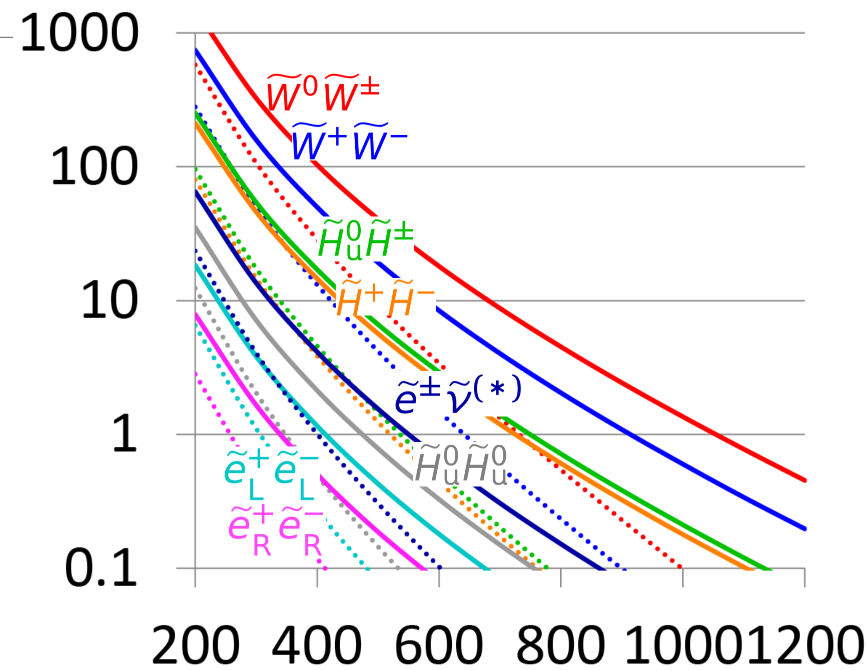


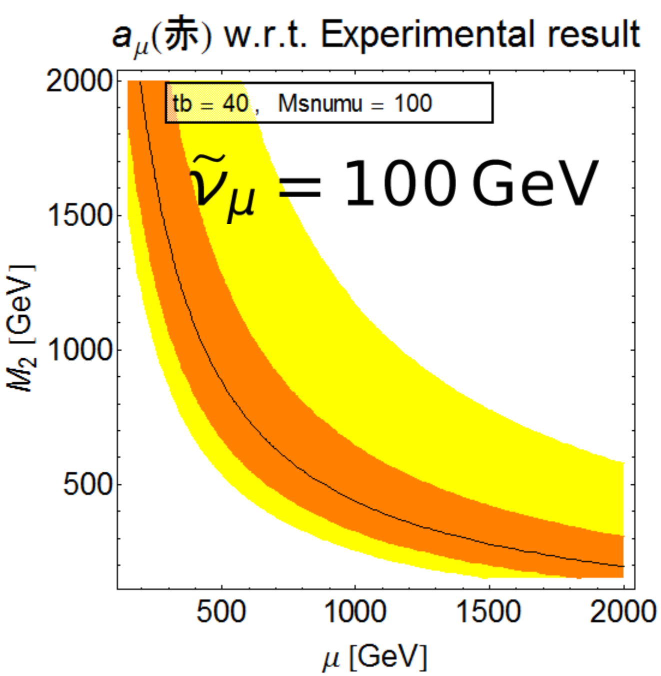


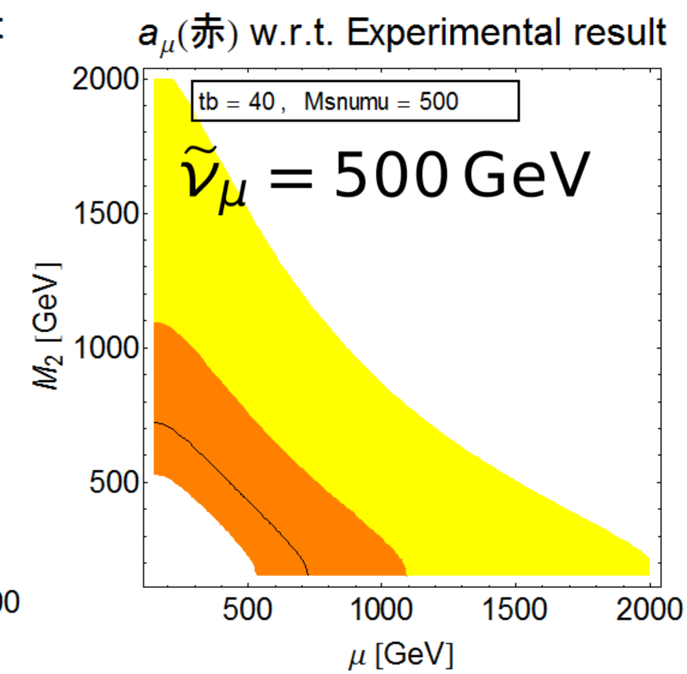
Chargino diagram が効くパターン（典型的）

$\tilde{\chi}^0\tilde{\chi}^\pm$

$\tilde{\chi}^+\tilde{\chi}^-$







Chargino diagram が効くパターン（典型的）

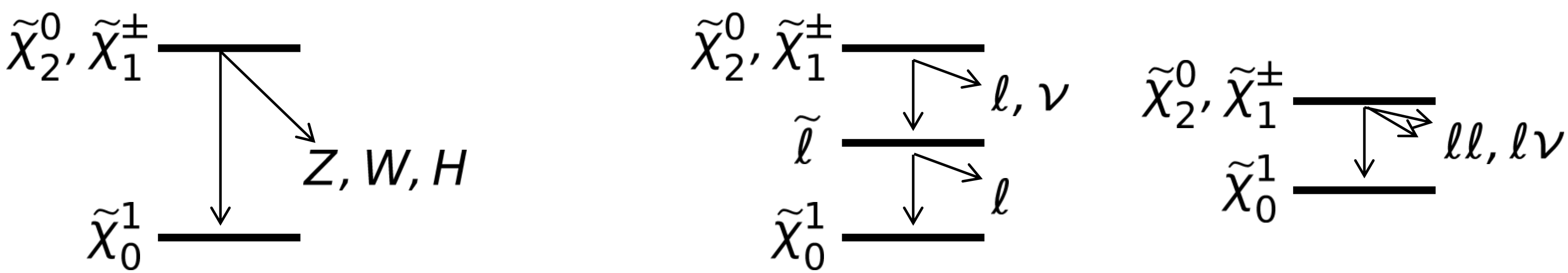
（τ もあるが，やや見えにくい。）

$$\tilde{\chi}^0\tilde{\chi}^\pm \rightarrow (WZ, Wh) + \not{E}_T \quad \text{or} \quad 3\ell + \not{E}_T$$

$$\tilde{\chi}^+\tilde{\chi}^- \rightarrow WW + \not{E}_T \quad \text{or} \quad 2\ell + \not{E}_T$$

途中に $\tilde{\ell}$ or 縮退

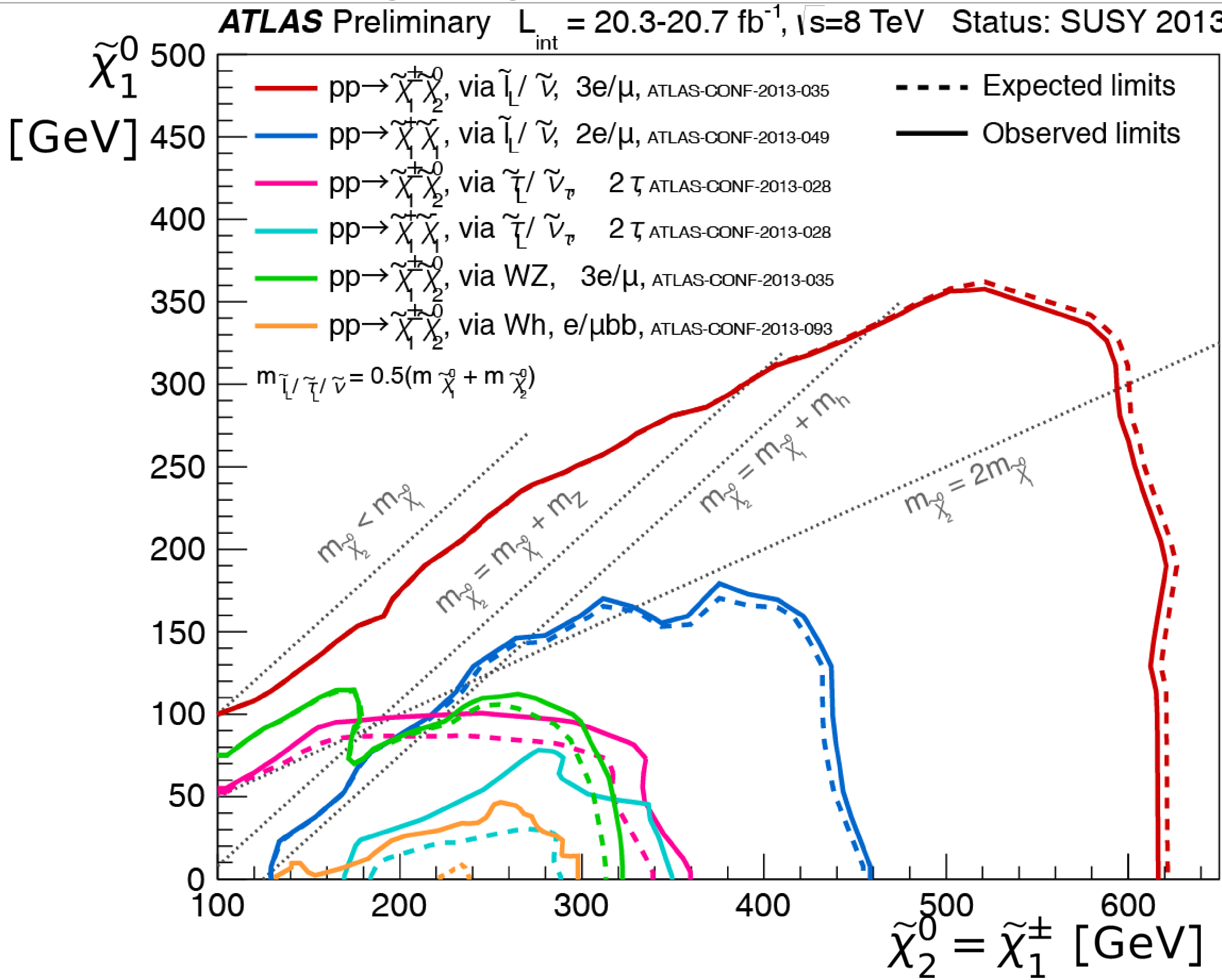
$W, Z \rightarrow$ leptonic decay
$h \rightarrow b\bar{b}$
のモードで見る



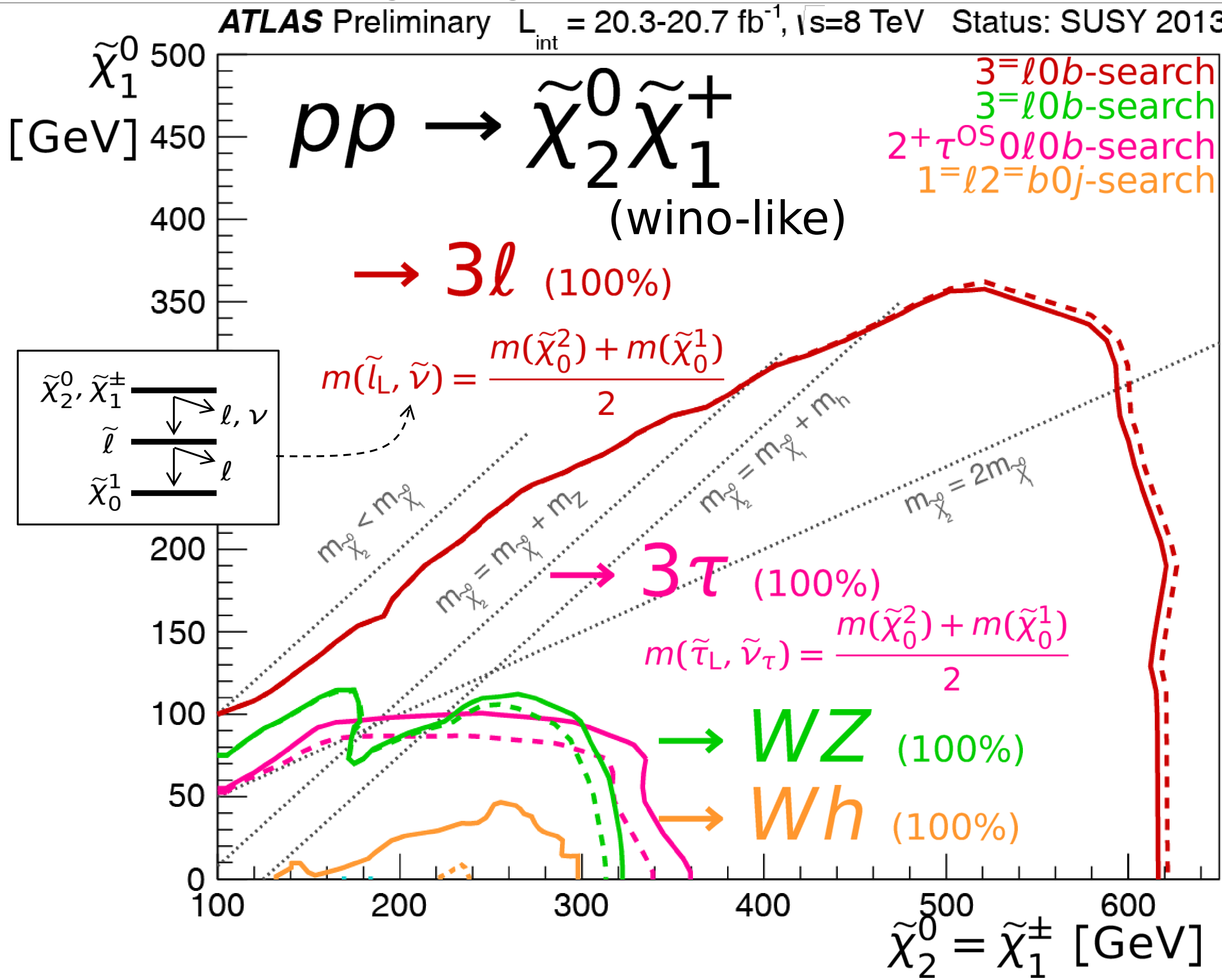
SM bkg 多い (di-boson)
↓
large $\not{E}_T$ が欲しい

SM bkg 少ない （見やすい）
※縮退して soft ℓ だと難？

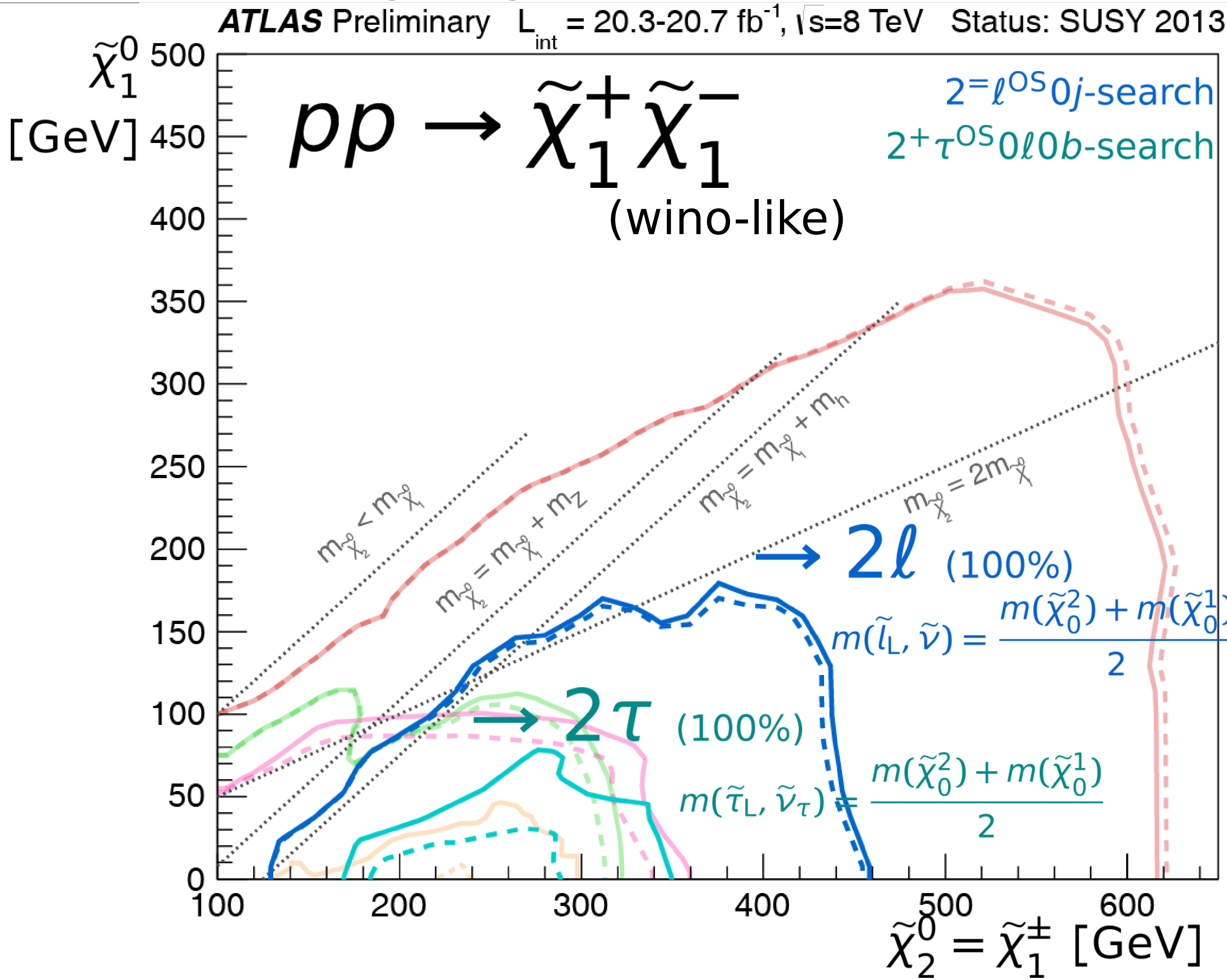
Current status : chargino diagram が効く場合



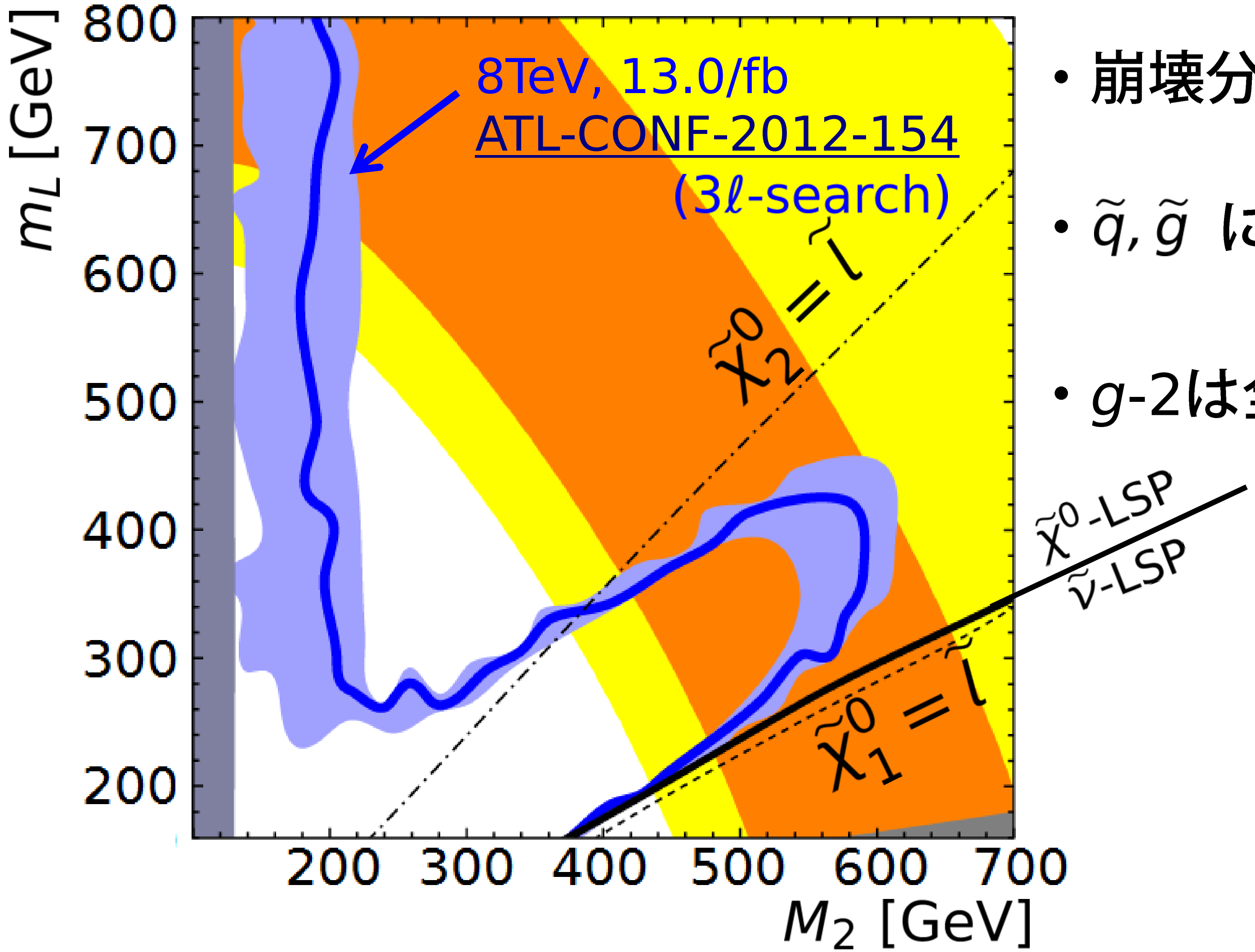
Current status : chargino diagram が効く場合



Current status : chargino diagram が効く場合



 Endo, Hamaguchi, SI, Yoshinaga [1303.4256]

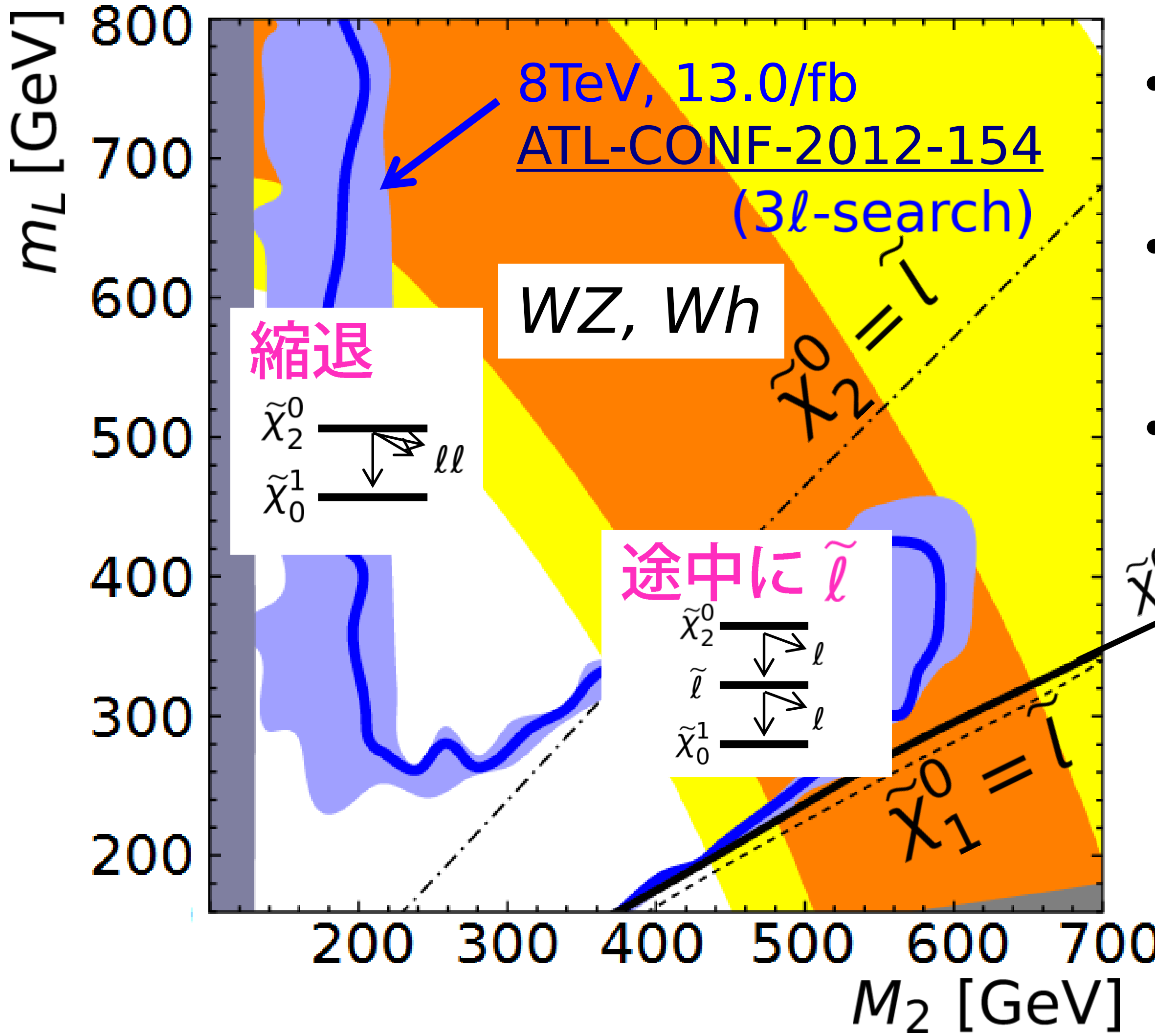


- 崩壊分岐比の仮定なし。（模型そのまま）
- $\tilde{q}, \tilde{g}$ に加え，$\tilde{\tau}, \tilde{\nu}_\tau$ もdecoupled。
- g-2は全て含む。

$$M_1, M_2, \quad \mu, \quad m(l_L), m(l_R), \quad \tan\beta.$$

$$M_1 = M_2/2, \quad \mu = M_2, \quad m(l_R) = 3\,\mathrm{TeV}, \quad \tan\beta = 40$$

Endo, Hamaguchi, SI, Yoshinaga [1303.4256]

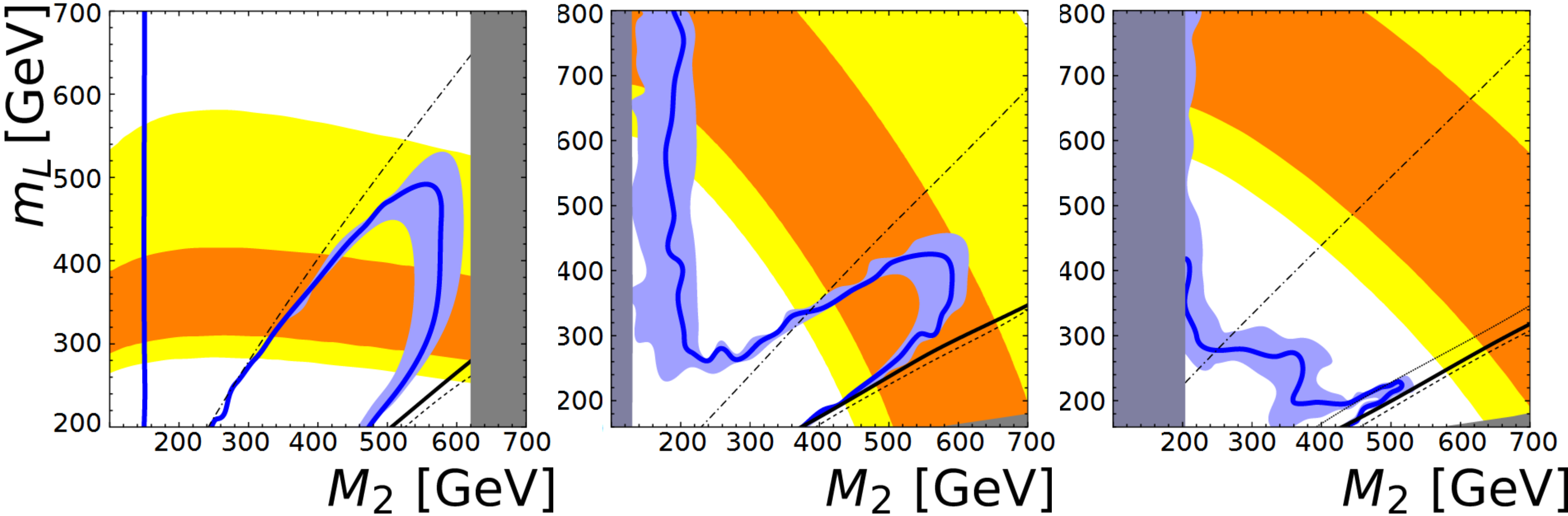


- 崩壊分岐比の仮定なし。（模型そのまま）
- $\tilde{q}, \tilde{g}$ に加え，$\tilde{\tau}, \tilde{\nu}_\tau$ もdecoupled。
- g-2は全て含む。

➢*WZ, Wh* 領域
➢soft lepton 領域が残っている。

$$M_1, M_2, \quad \mu, \quad m(l_L), m(l_R), \quad \tan\beta.$$

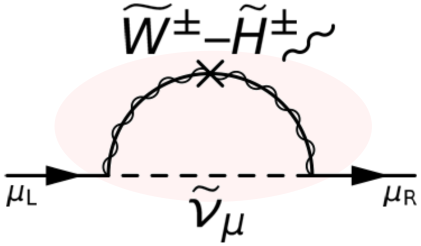
$$M_1 = M_2/2, \quad \mu = M_2, \quad m(l_R) = 3\,\mathrm{TeV}, \quad \tan\beta = 40$$



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

$\tilde{H}$ いない
↓
生成した $\widetilde{W}$ が
素直に 3-lepton

$\tilde{H}$ が軽い
↓
$\widetilde{W}$ は $\tilde{H}$ 経由でも崩壊
↓
全体は軽いけど制限弱

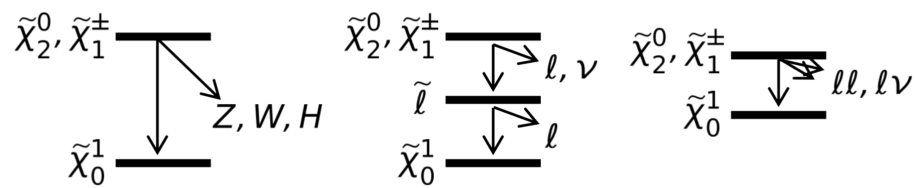


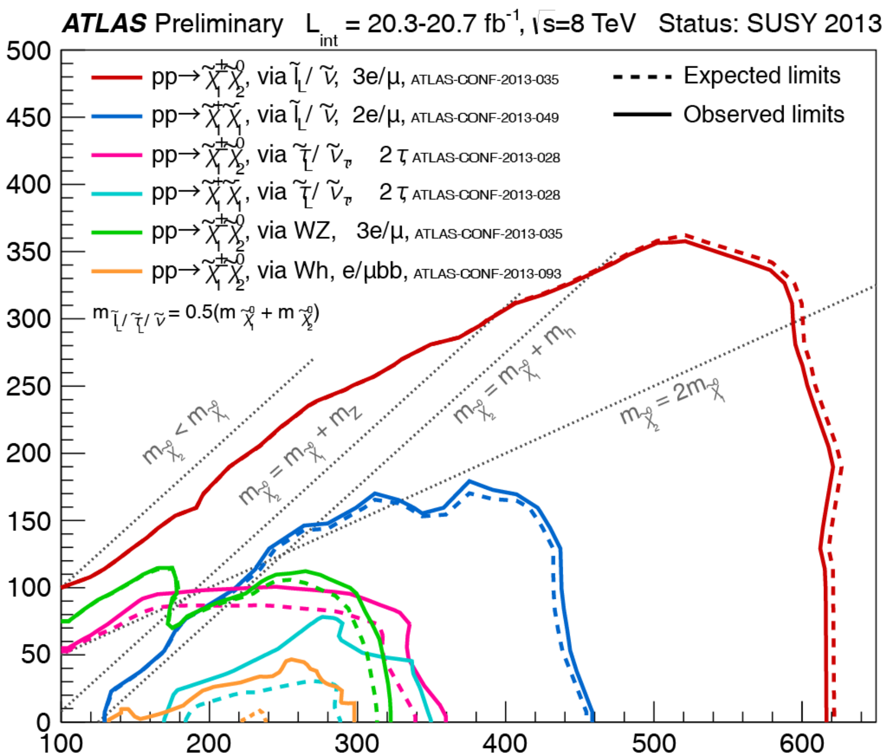
⇨ $\widetilde{W}, \widetilde{H}$ が比較的軽い

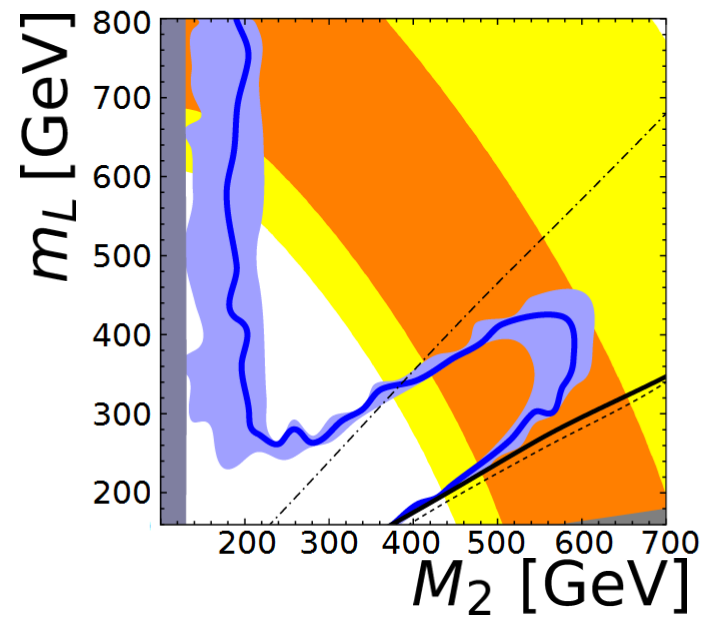
⇨ 基本的には $\tilde{\chi}^0 \tilde{\chi}^{\pm}$ 作って **3-lepton search**

- M_2 と μ の関係
- slepton の質量関係

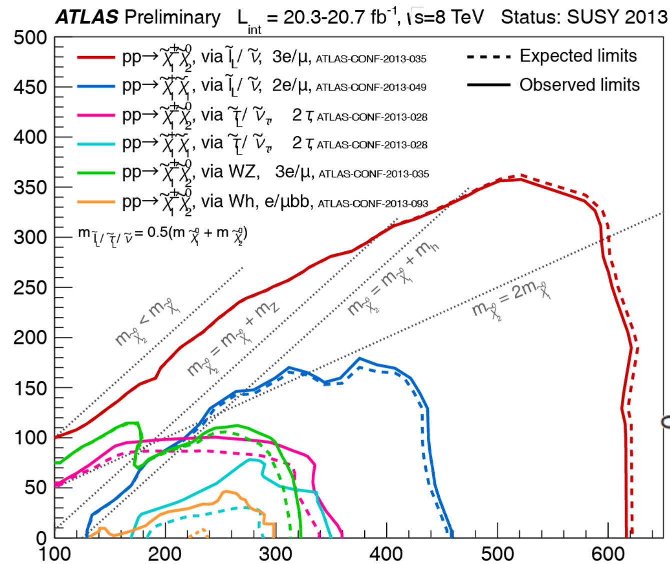
} に激しく依存







Future Prospect?



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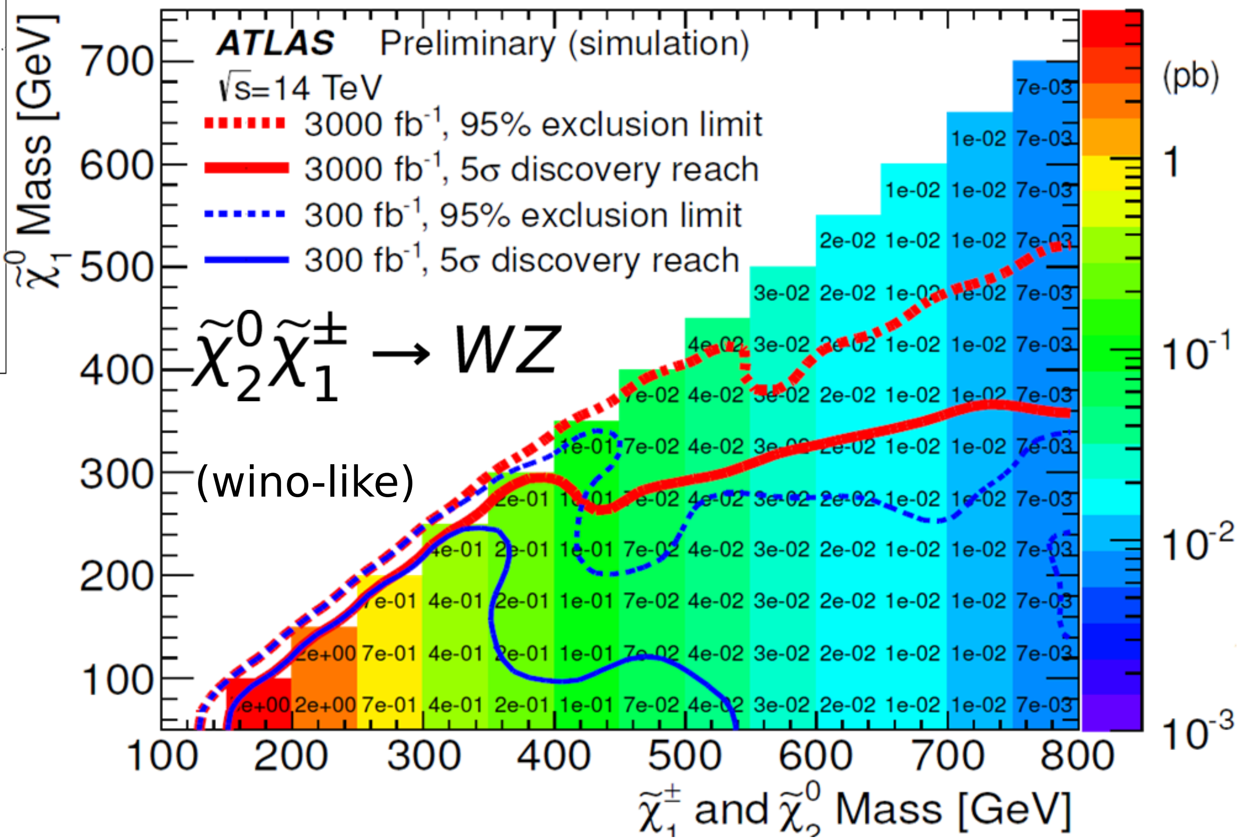


※ $\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to Wh$ なら $m_{\widetilde{W}} \sim 450\,(950)$ GeV に届く@0.3(3) ab^{-1}

(mSUGRA-like, large mu, large m0) [Baer et al., 1207.4846]

$(g-2)_\mu$ ⇒ $\widetilde{\mathrm{EW}} = \mathrm{O}(100)\,\mathrm{GeV}$ ⇒ ①基礎知識 EW直接生成で見える

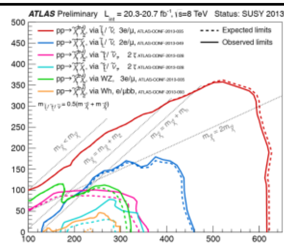
もう一段階掘り下げて……

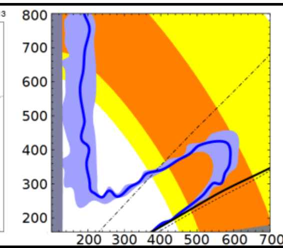
$(g-2)_\mu$

② $\widetilde{W}, \widetilde{H}$ が比較的軽い（M_2, μ が小さい）場合

$\tilde{\chi}^0\tilde{\chi}^\pm \to$ 3-lep. 探索

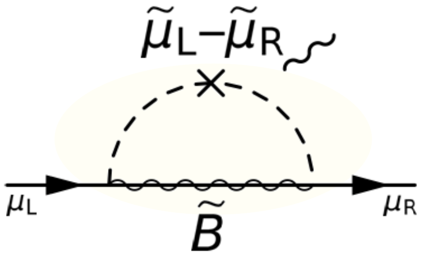
（3ℓ, WZ, Wh）





③ パターン２（ちょっと特殊）

3. Pure-bino dominance



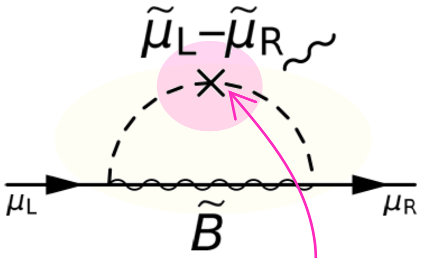
$$\boxed{\frac{g_Y^2 m_\mu^2}{8\pi^2}\frac{\mu\tan\beta}{M_1^3}\cdot F_b\left(\frac{m_{\tilde{\mu}_L}}{M_1},\frac{m_{\tilde{\mu}_R}}{M_1}\right)}$$

- 通称：pure-bino contribution
- 特徴：μ tanβ に比例する。

- slepton LR-mixing
  $= m_\mu \cdot \mu \tan\beta$
- なのにHiggsinoが
  loopを回らない。

⇒ 寄与が μ（Higgsino質量）に比例！

Pure-bino diagram が効くパターン（μ がとてもおおきい特殊な場合）



$$\boxed{\frac{g_Y^2 m_\mu^2}{8\pi^2}\frac{\mu\tan\beta}{M_1^3}\cdot F_b\left(\frac{m_{\tilde{\mu}_{\rm L}}}{M_1},\frac{m_{\tilde{\mu}_{\rm R}}}{M_1}\right)}$$

◎ 通称：pure-bino contribution

◎ 特徴：μ tanβ に比例する。

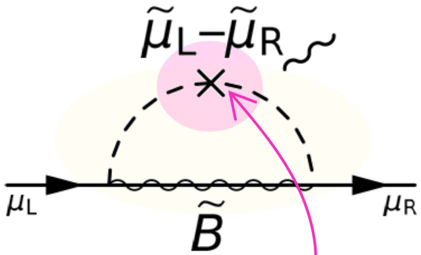
- slepton LR-mixing

$$= m_\mu \cdot \mu \tan\beta$$

- なのにHiggsinoが loopを回らない。

⇨ 寄与が μ（Higgsino質量）に比例！

$$M_{\tilde{\mu}}^2 = \begin{pmatrix} m(l_{\rm L})^2 & m_\mu(A_\mu^* - \mu\tan\beta) \\ m_\mu(A_\mu^* - \mu\tan\beta) & m(l_{\rm R})^2 \end{pmatrix}.$$



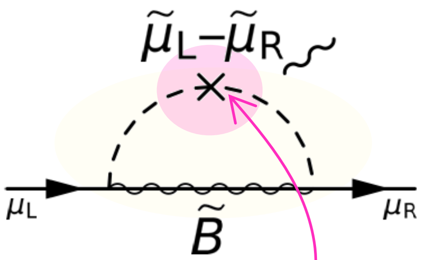
$$\boxed{\frac{g_Y^2 m_\mu^2}{8\pi^2}\frac{\mu\tan\beta}{M_1^3}\cdot F_b\left(\frac{m_{\tilde{\mu}_L}}{M_1},\frac{m_{\tilde{\mu}_R}}{M_1}\right)}$$

- 通称：pure-bino contribution
- 特徴：μ tanβ に比例する。

- slepton LR-mixing
  $= m_\mu \cdot \mu\tan\beta$
- なのにHiggsinoが loopを回らない。

⇒ **寄与が μ（Higgsino質量）に比例！**

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



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

◎ 通称：pure-bino cont

◎ 特徴：μ tanβ に比例す

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

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

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

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

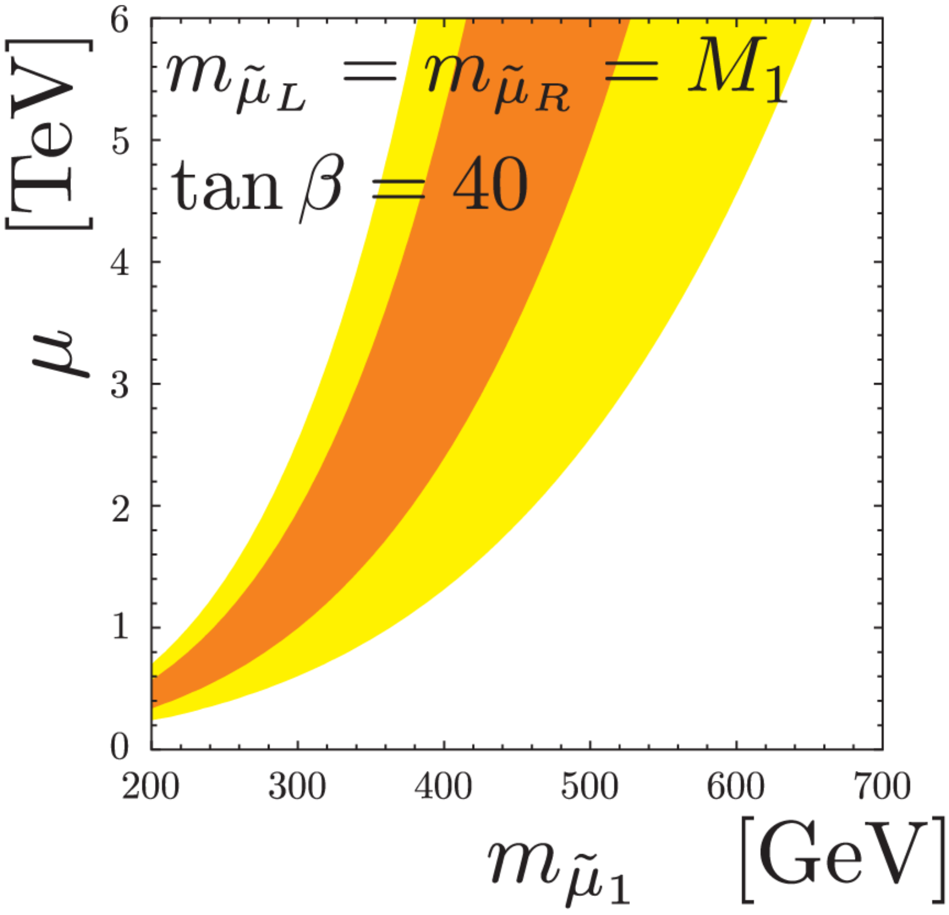
$$\frac{g_Y^2 m_\mu^2}{16\pi^2}\,\frac{M_1\mu\tan\beta}{m_{\tilde\mu_L}^4}\cdot F_b\left(\frac{M_1}{m_{\tilde\mu_L}},\frac{\mu}{m_{\tilde\mu_L}}\right)$$

- slepton LR-mixing
  $= m_\mu\cdot\mu\tan\beta$
- なのにHiggsinoが
  loopを回らない。

⇨ **寄与が μ（Higgsino質量）に比例！**

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

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

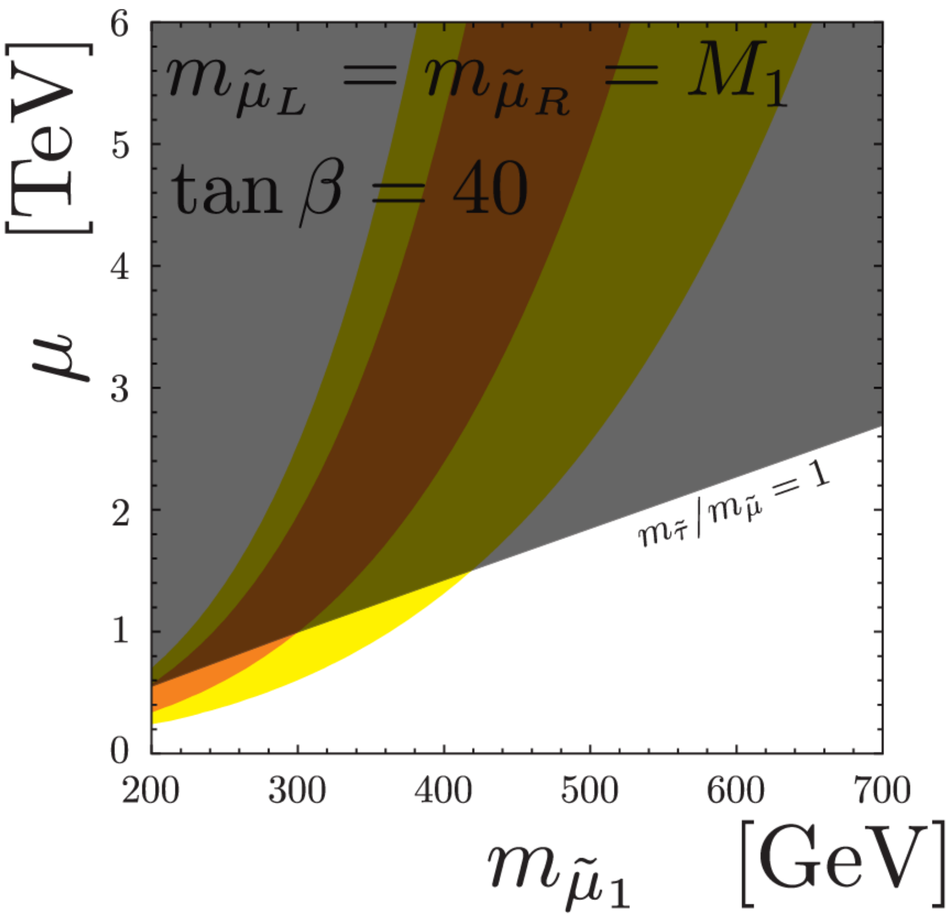


ただし μ tanβ には上限

（Higgs potentialの安定性）

$$V_\mathrm{Higgs} \supset - m_\tau\, \mu \tan\beta \cdot \widetilde{\tau}_\mathrm{L}^* \widetilde{\tau}_\mathrm{R} h$$

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



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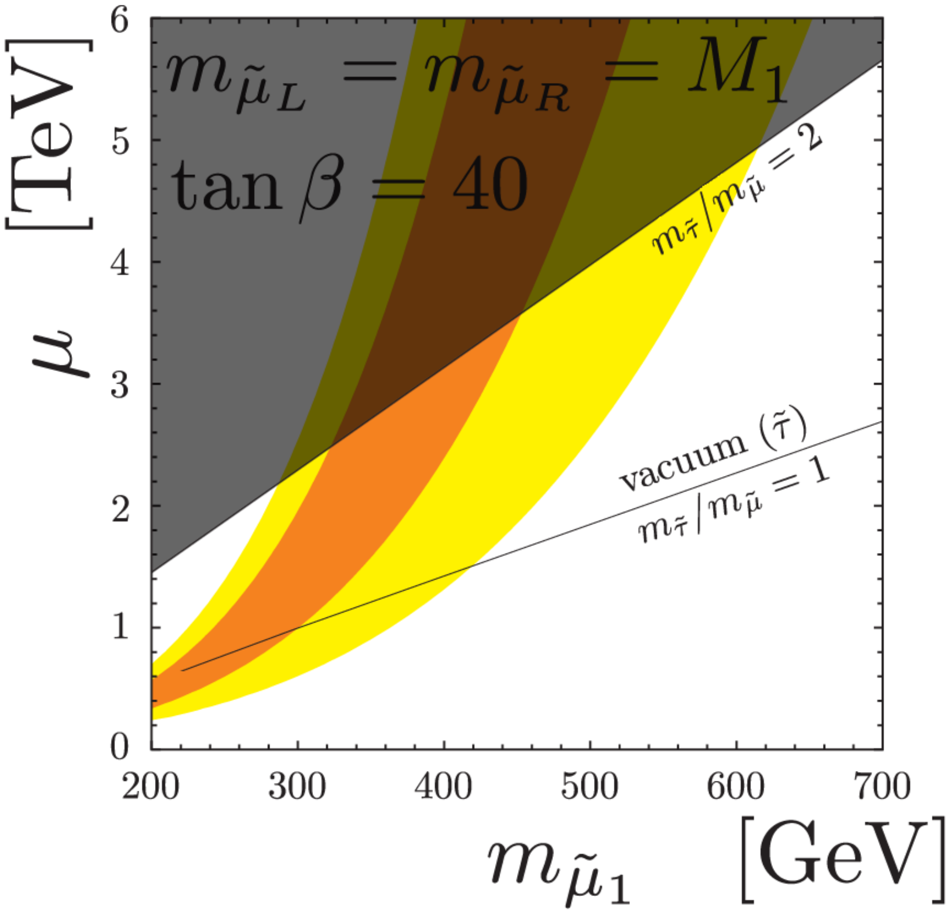
$$V_\mathrm{Higgs} \supset -m_\tau\,\mu\tan\beta\cdot\tilde{\tau}_\mathrm{L}^*\tilde{\tau}_\mathrm{R}h$$

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

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

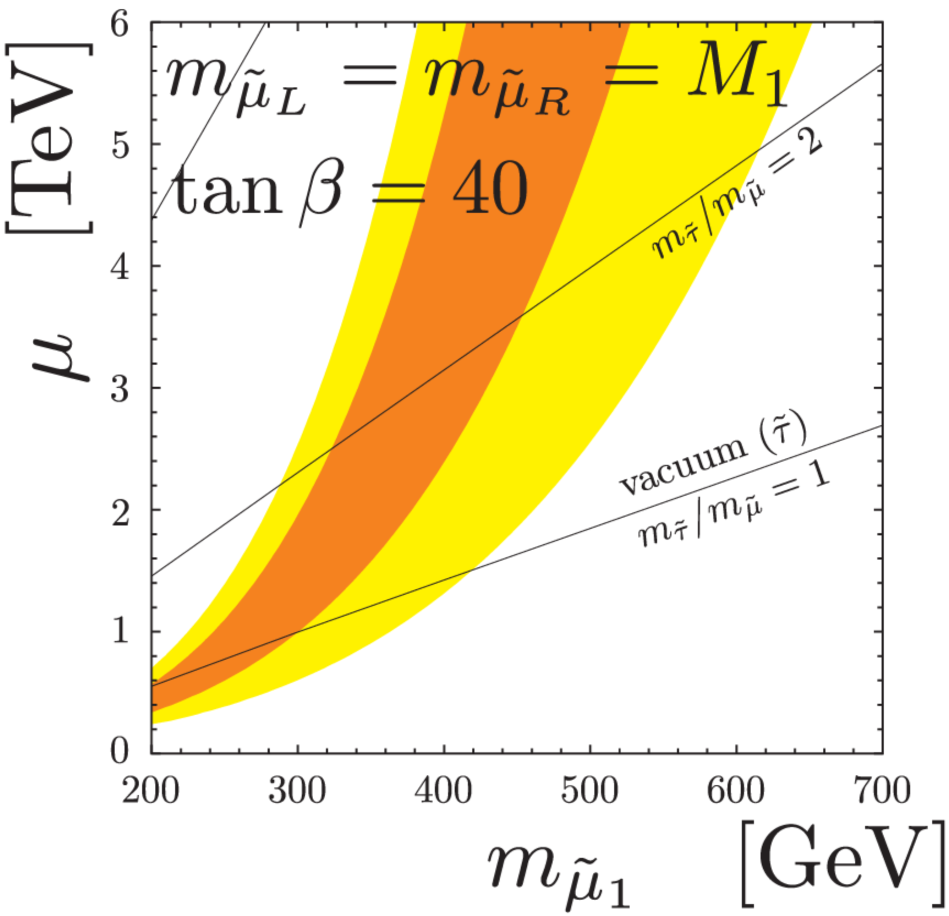


ただし μ tanβ には上限
（Higgs potentialの安定性）

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

$m_{\tilde{\tau}}/m_{\tilde{\mu}}$
$= 1 \Rightarrow m_{\tilde{\mu}} \lesssim 300(420)\,\text{GeV}$
$= 2 \Rightarrow \quad\quad \lesssim 440(620)\,\text{GeV}$

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



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（Higgs potentialの安定性）

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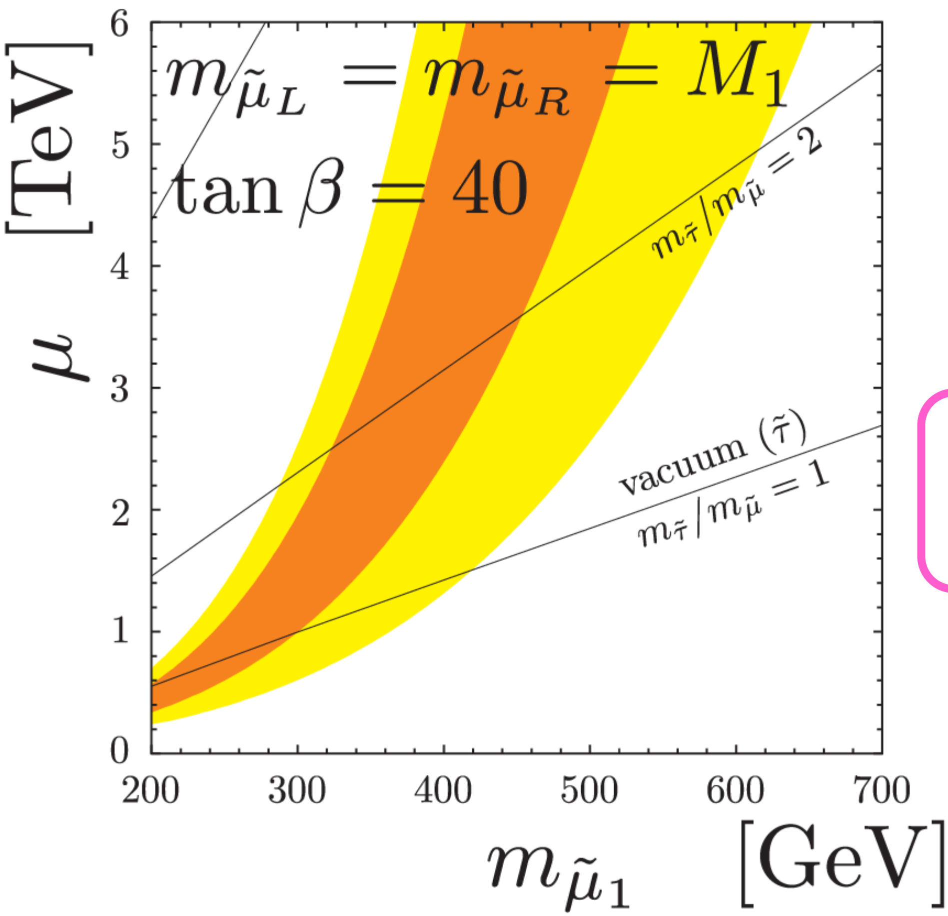
$m_{\tilde{\tau}}/m_{\tilde{\mu}}$

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

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

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

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



ただし μ tanβ には上限

（Higgs potentialの安定性）

$$V_{\text{Higgs}} \supset -m_\tau\,\mu\tan\beta\cdot\tilde{\tau}_L^*\tilde{\tau}_R h$$

とりあえず楽観的に……。

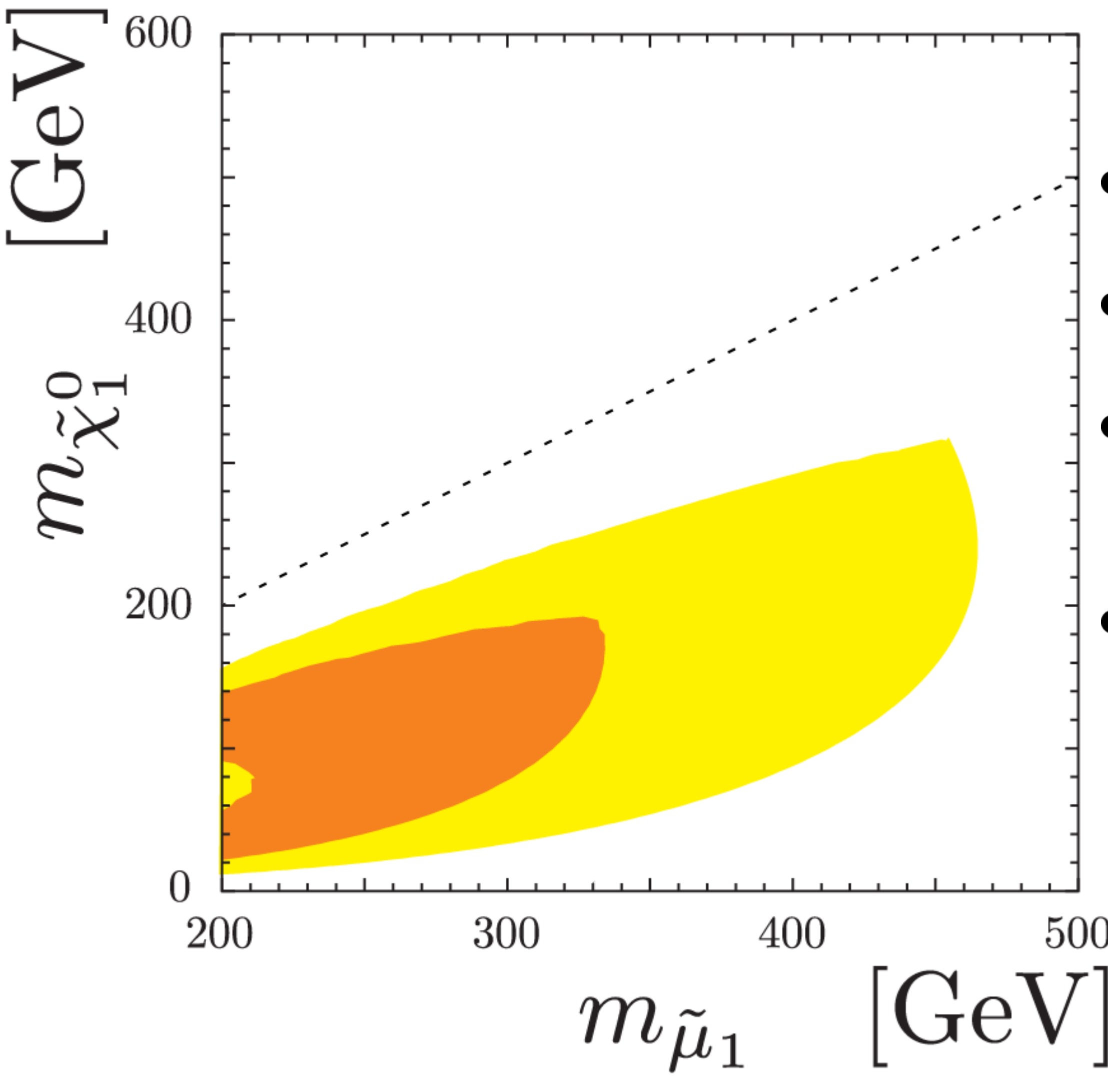
$m_{\tilde{\tau}}/m_{\tilde{\mu}}$

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

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

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

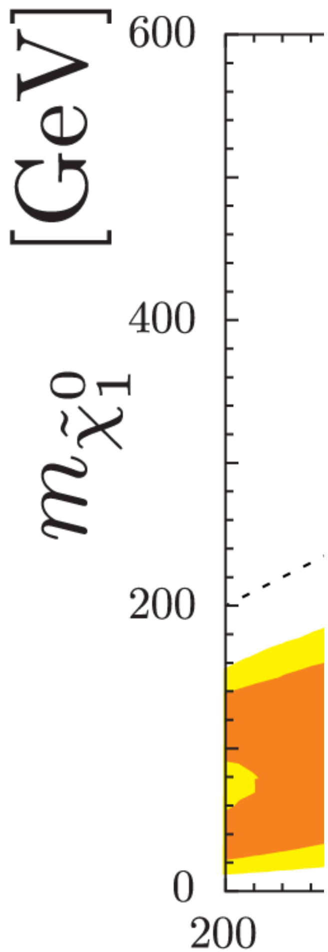
Flavor / CP の破れから
アプローチ可能

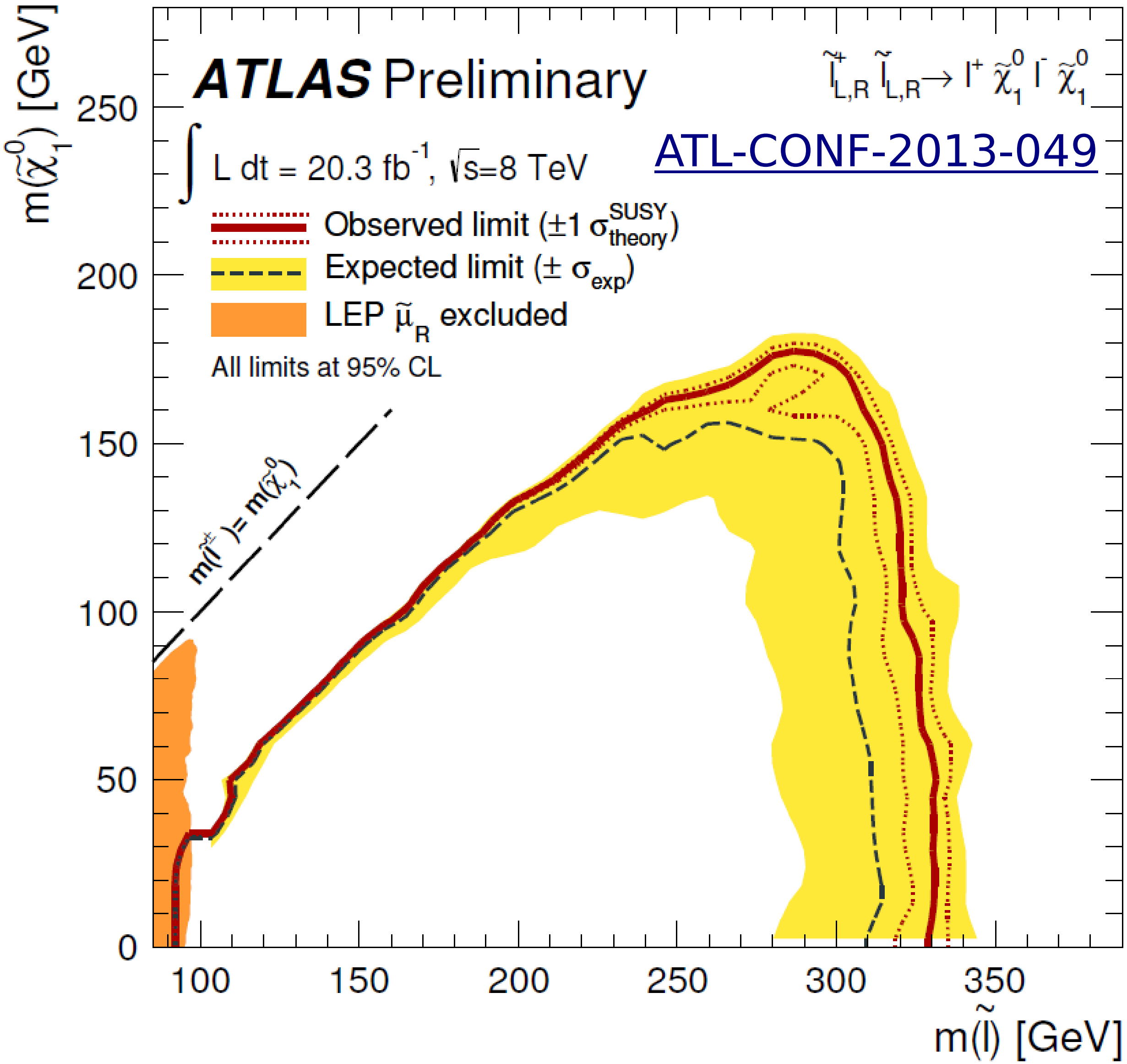


Assumptions

- Neutralino LSP ($m_{\tilde{\tau}} > m_{\tilde{\chi}_1^0}$)
- $\tan\beta = 40$
- $m_{\tilde{\tau}}/m_{\tilde{\mu}} = 1$
  (severe vac. bound)
- $m_{\tilde{\mu}_L} = m_{\tilde{\mu}_R}$
  ($\Rightarrow (g-2)_\mu$ maximized.)

LHC探索： $\tilde{B}, \tilde{l}_L, \tilde{l}_R$ しかいない $\to pp \to \tilde{l}^+\tilde{l}^- \to 2\ell + \not{E}_T$



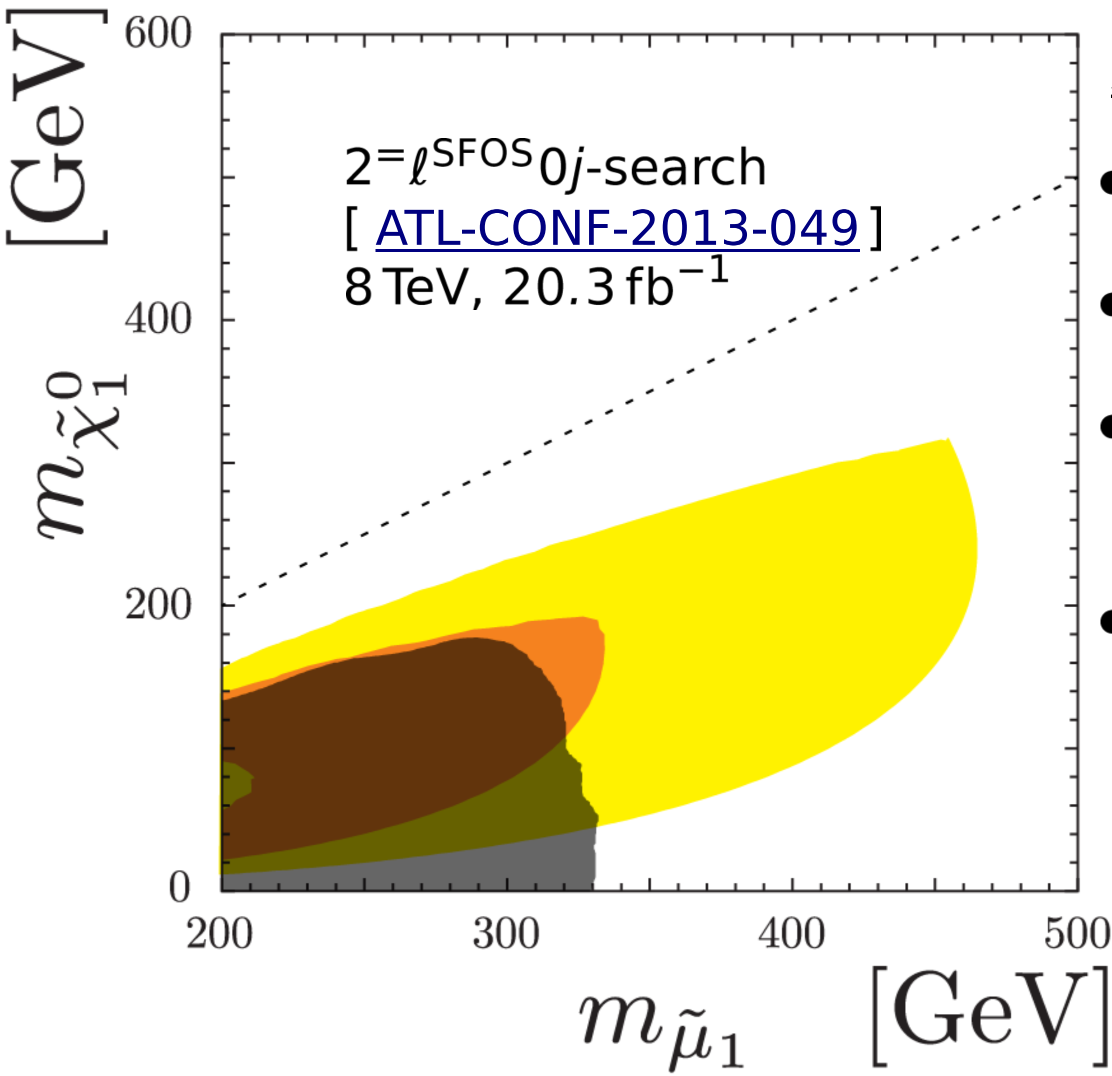


P ($m_{\tilde\tau} > m_{\tilde\chi_1^0}$)

bound)

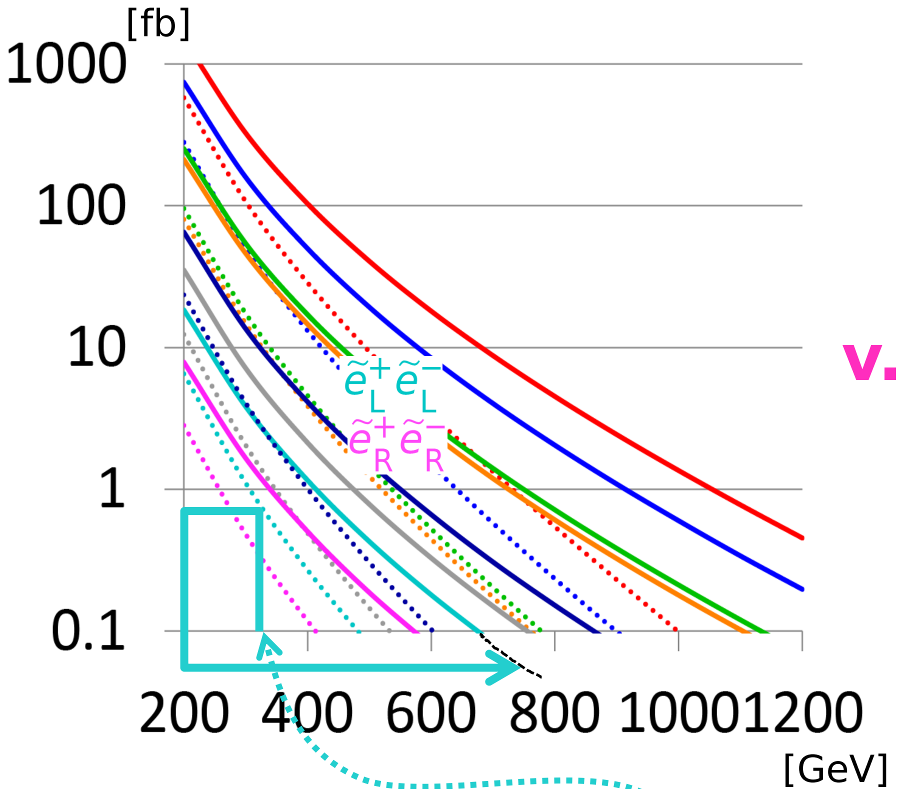
aximized.)

LHC探索： $\tilde{B}, \tilde{l}_\mathrm{L}, \tilde{l}_\mathrm{R}$ しかいない $\to pp \to \tilde{l}^+\tilde{l}^- \to 2\ell + \not{E}_\mathrm{T}$

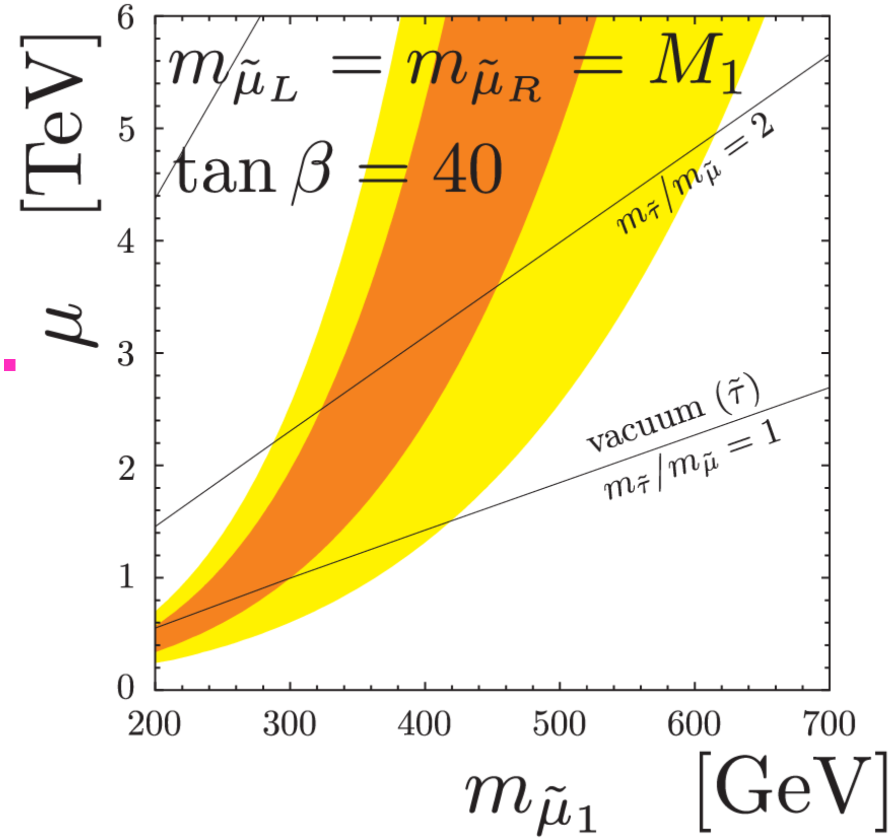


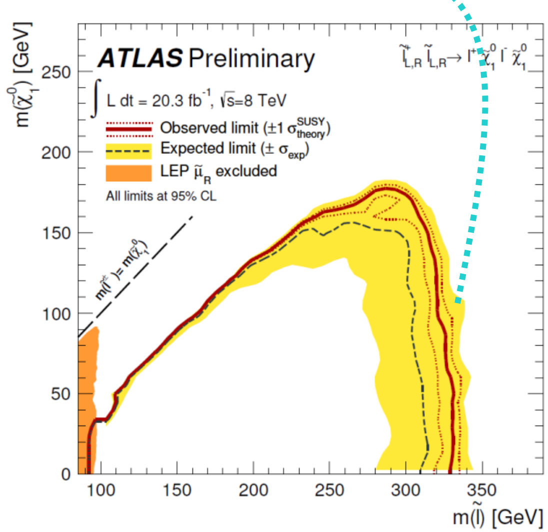
Assumptions

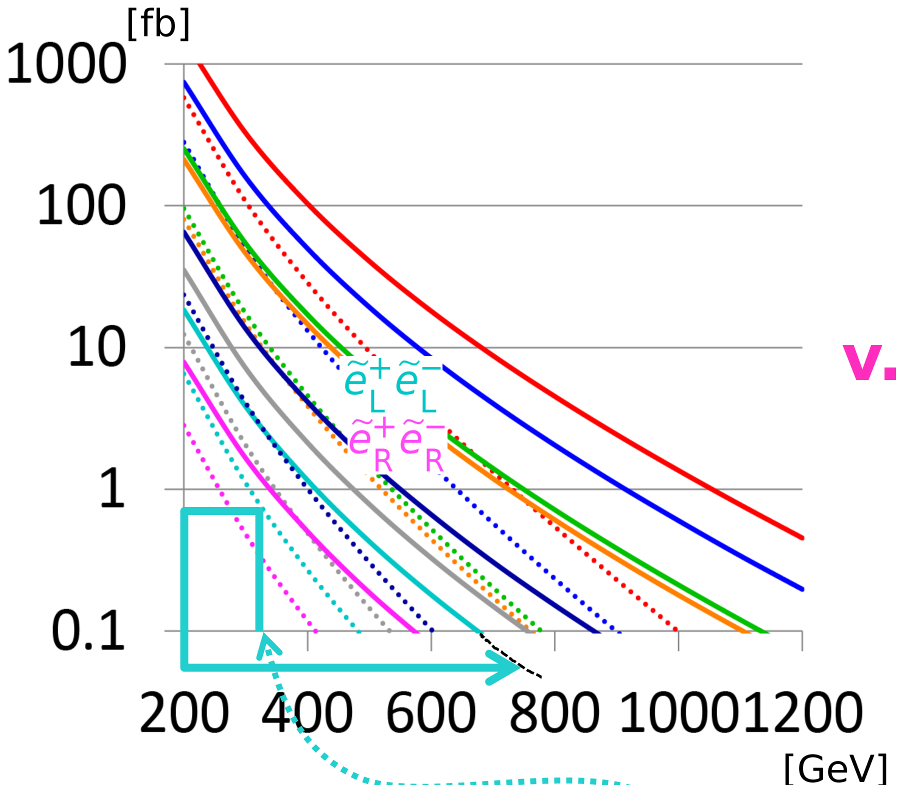
- Neutralino LSP ($m_{\tilde{\tau}} > m_{\tilde{\chi}_1^0}$)
- $\tan\beta = 40$
- $m_{\tilde{\tau}}/m_{\tilde{\mu}} = 1$ (severe vac. bound)
- $m_{\tilde{\mu}_\mathrm{L}} = m_{\tilde{\mu}_\mathrm{R}}$ ($\Rightarrow (g-2)_\mu$ maximized.)


[fb]
1000
100
10
1
0.1
$\tilde{e}^+_L \tilde{e}^-_L$
$\tilde{e}^+_R \tilde{e}^-_R$
200
400
600
800
1000
1200
[GeV]

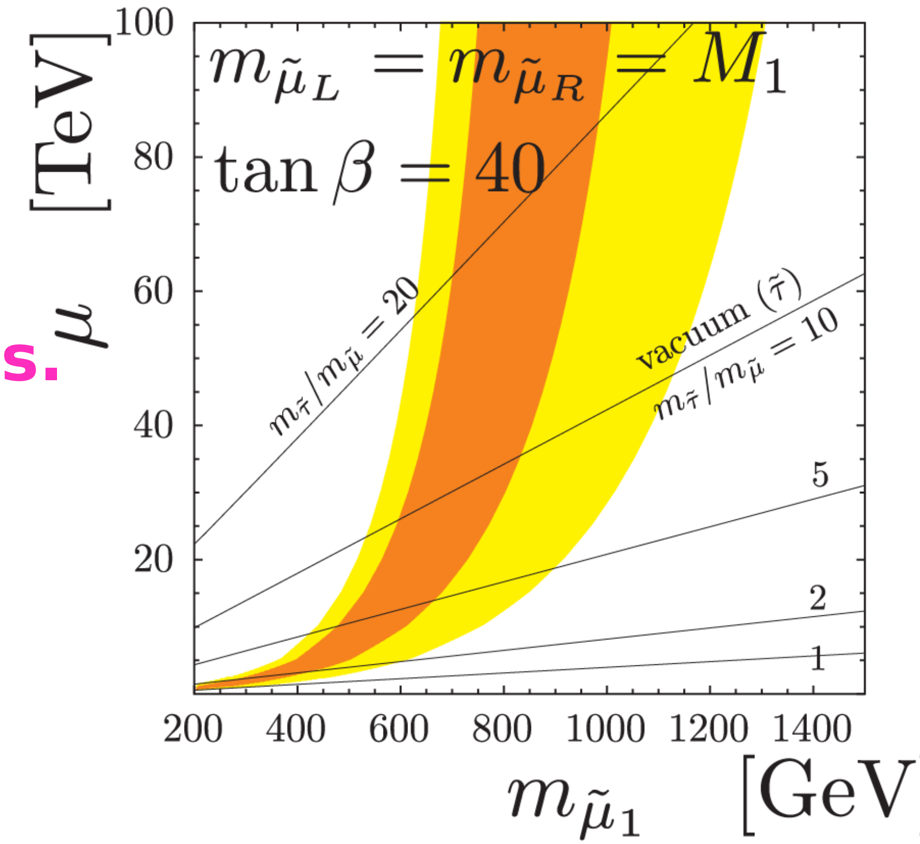
v.s.

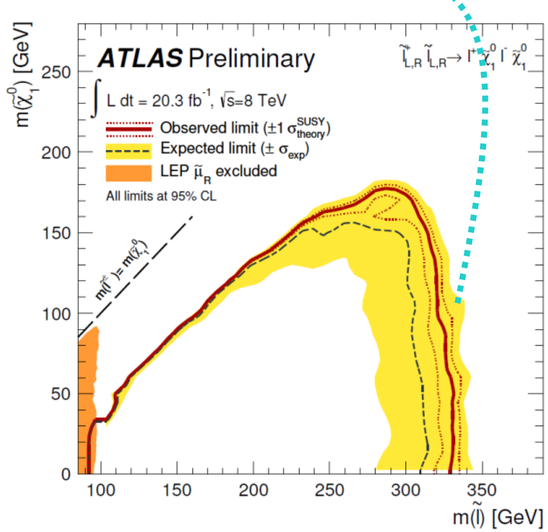

$m_{\tilde{\mu}_L} = m_{\tilde{\mu}_R} = M_1$
$\tan\beta = 40$
$m_{\tilde{\tau}}/m_{\tilde{\mu}} = 2$
vacuum ($\tilde{\tau}$)
$m_{\tilde{\tau}}/m_{\tilde{\mu}} = 1$
μ [TeV]
0
1
2
3
4
5
6
200
300
400
500
600
700
$m_{\tilde{\mu}_1}$ [GeV]


ATLAS Preliminary
$\tilde{l}_{L,R}\tilde{l}_{L,R} \rightarrow l^+\tilde{\chi}^0_1 l^-\tilde{\chi}^0_1$
$\int L\,dt = 20.3\ \mathrm{fb}^{-1}$, $\sqrt{s}$=8 TeV
Observed limit ($\pm1\ \sigma^{SUSY}_{theory}$)
Expected limit ($\pm\ \sigma_{exp}$)
LEP $\tilde{\mu}_R$ excluded
All limits at 95% CL
$m(\tilde{l}) = m(\tilde{\chi}^0_1)$
$m(\tilde{\chi}^0_1)$ [GeV]
$m(\tilde{l})$ [GeV]
0
50
100
150
200
250
100
150
200
250
300
350

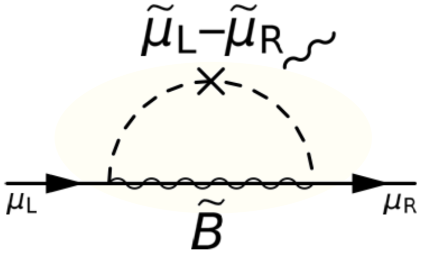


v.s.

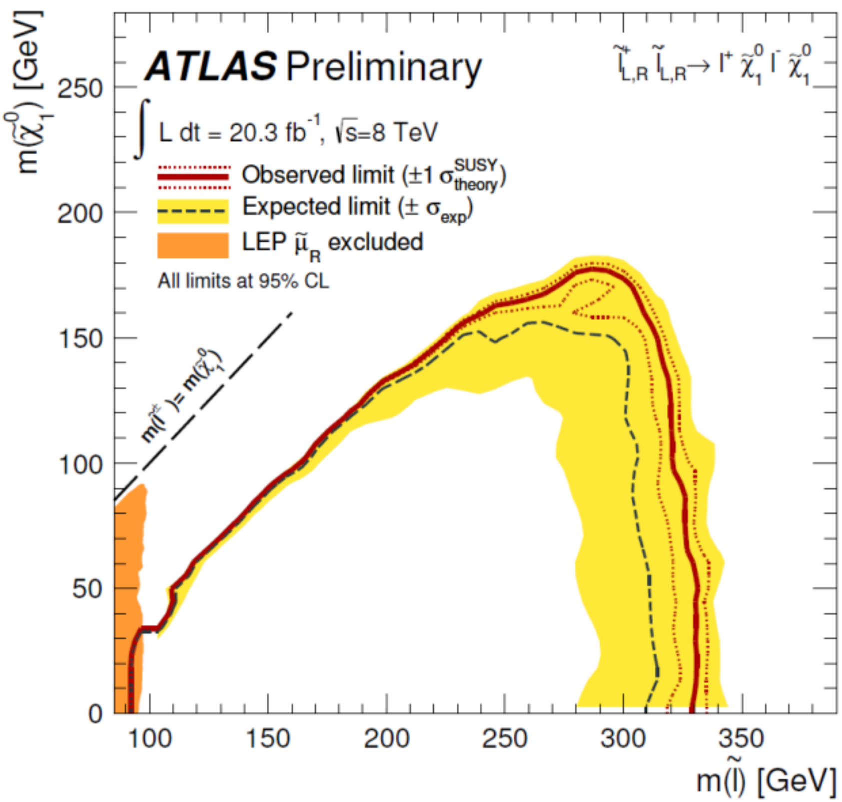




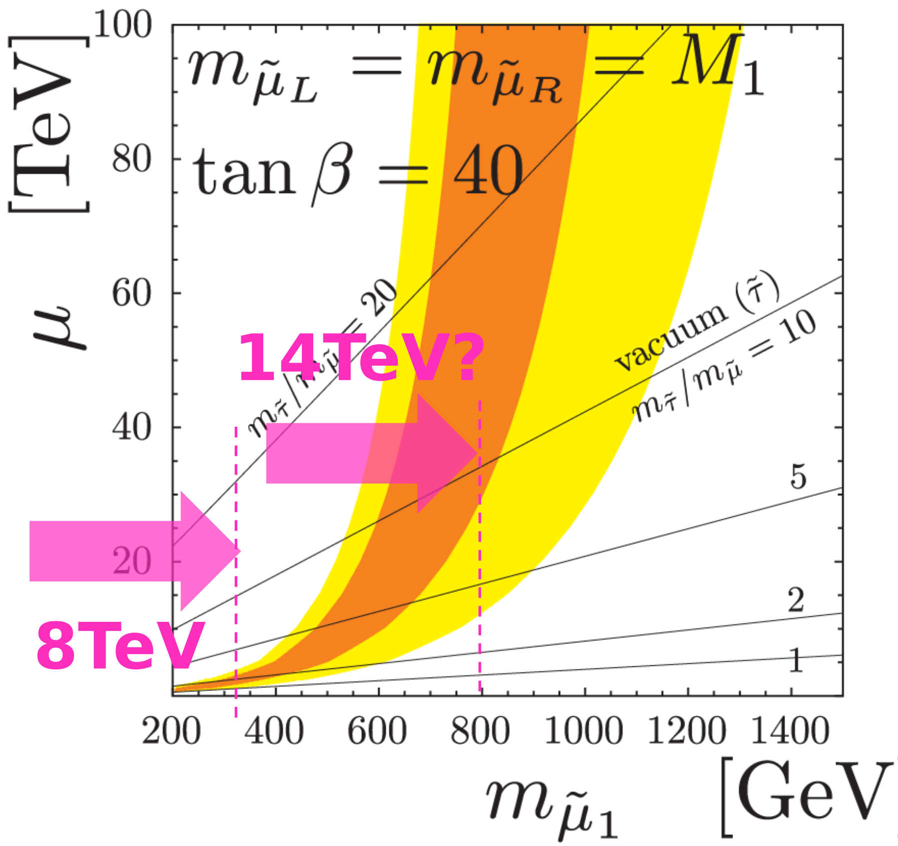
- どこまで行ける？
- 縮退領域……



- **μ tanβ に比例** （$\tilde{B}, \tilde{l}_L, \tilde{l}_R$ だけあればよい。）
- Vacuum の安定性から
  $m_{\tilde{\tau}}$ に強く依存した制限
- 探索は $pp \to \tilde{l}^+\tilde{l}^- \to 2\ell^{\mathrm{SFOS}} + \not{E}_T$



v.s.



$(g-2)_\mu$ ⇒ $\widetilde{\mathrm{EW}} = \mathrm{O}(100)\,\mathrm{GeV}$ ⇒ ①基礎知識 EW直接生成で見える

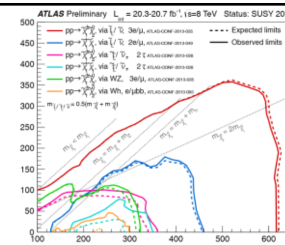
もう一段階掘り下げて……

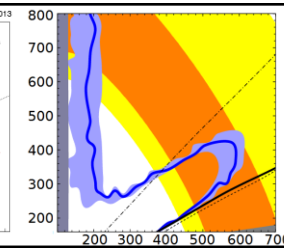
$(g-2)_\mu$

② $\widetilde{W}, \widetilde{H}$ が比較的軽い（M_2, μ が小さい）場合

$\tilde{\chi}^0\tilde{\chi}^\pm \to$ 3-lep. 探索

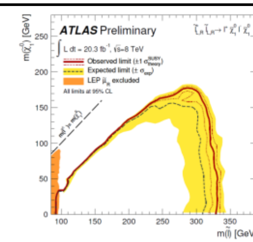
（3ℓ, WZ, Wh）

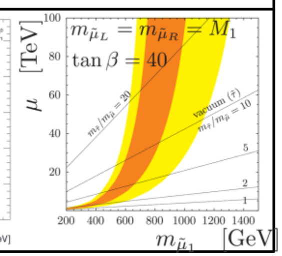




③ μ がとても大きい場合（$\widetilde{B}, \tilde{l}_\mathrm{L}, \tilde{l}_\mathrm{R}$ だけで十分）

$\tilde{l}^+\tilde{l}^- \to$ 2-lep.$^{\mathrm{SFOS}}$ 探索





4. 議論

$(g-2)_\mu$ ⇒ $\widetilde{\mathrm{EW}} = \mathrm{O}(100)\,\mathrm{GeV}$ ⇒ EW直接生成で見える

ILC，DM探索，
背後の SUSY 模型…。

$(g-2)_\mu$

⇒ $\widetilde{W}, \widetilde{H}$ が
比較的軽い

→ $\tilde{\chi}^0\tilde{\chi}^\pm \to 3\ell$ OK!

→ $\tilde{\chi}^0\tilde{\chi}^\pm \to WZ, Wh$ がんばる

→ 縮退の場合？

→ Wino LSP なら長寿命 $\widetilde{W}$

（$\tilde{H} < \widetilde{W}$ の場合どれもやや難）

⇒ μ が大きく
$\tilde{B}, \tilde{l}_{\mathrm{L}}, \tilde{l}_{\mathrm{R}}$が軽い

→ $\tilde{l}^+\tilde{l}^- \to 2\ell$ どこまで行ける？

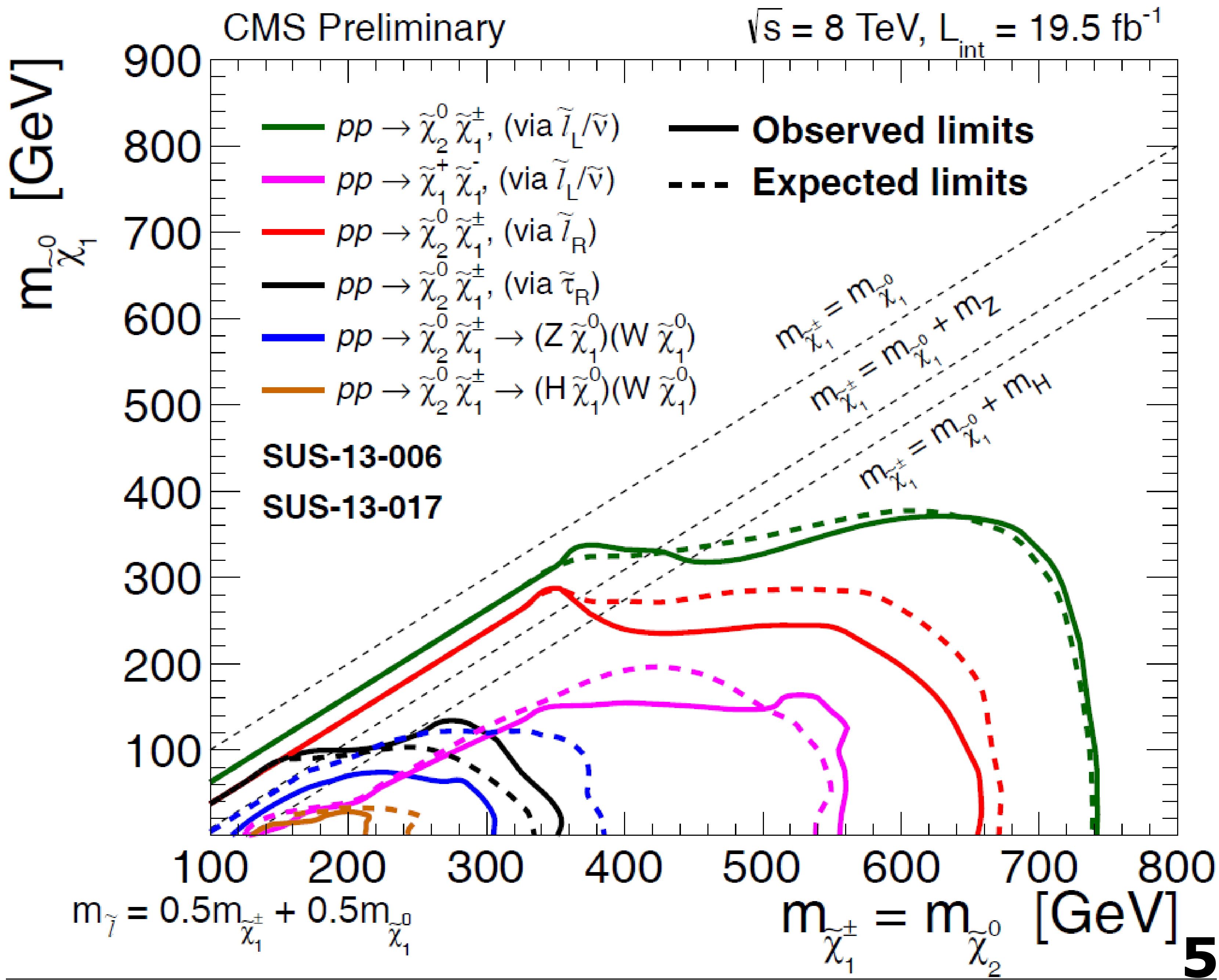
→ Gravitino LSPの場合？
（基本的には同じ？）

⇒ 更に特殊な場合？
（μ<0とか）

↓ 全空間scan？

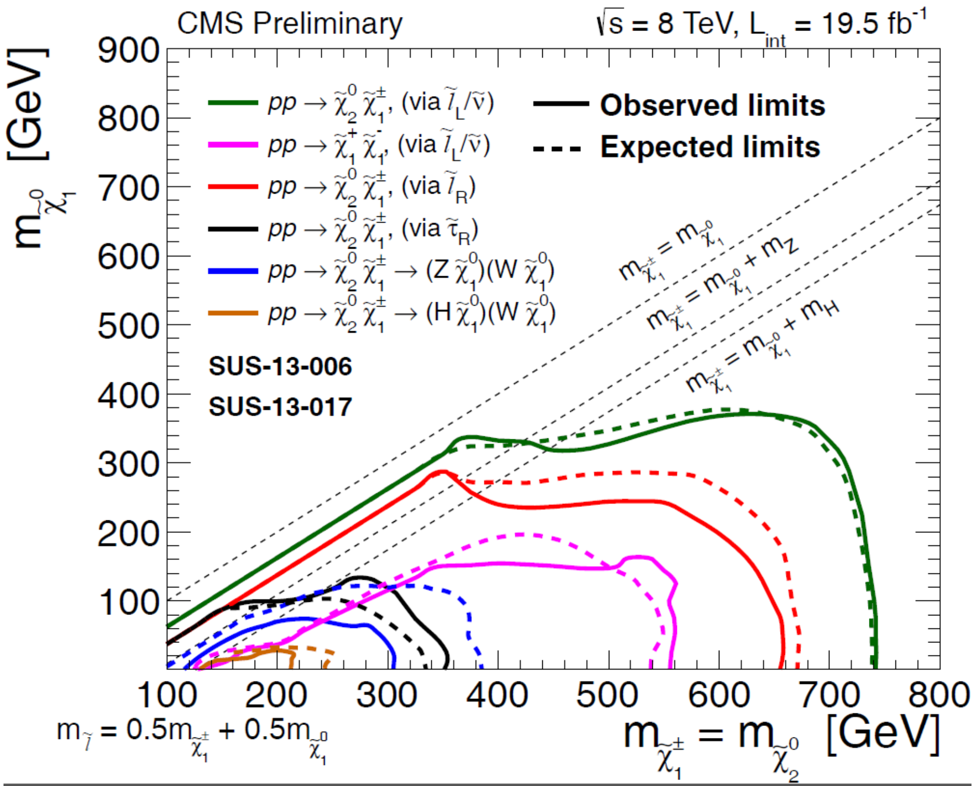
他に有効なLHC探索手法？
(multi SM-boson:
Baer et al., 1310.4858)

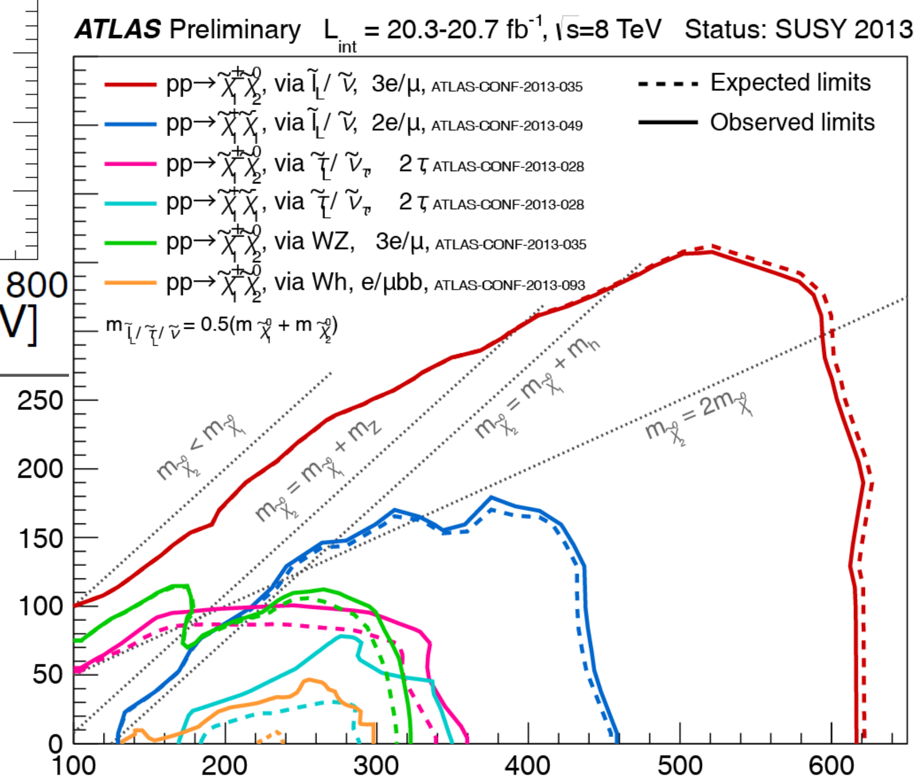
Backup

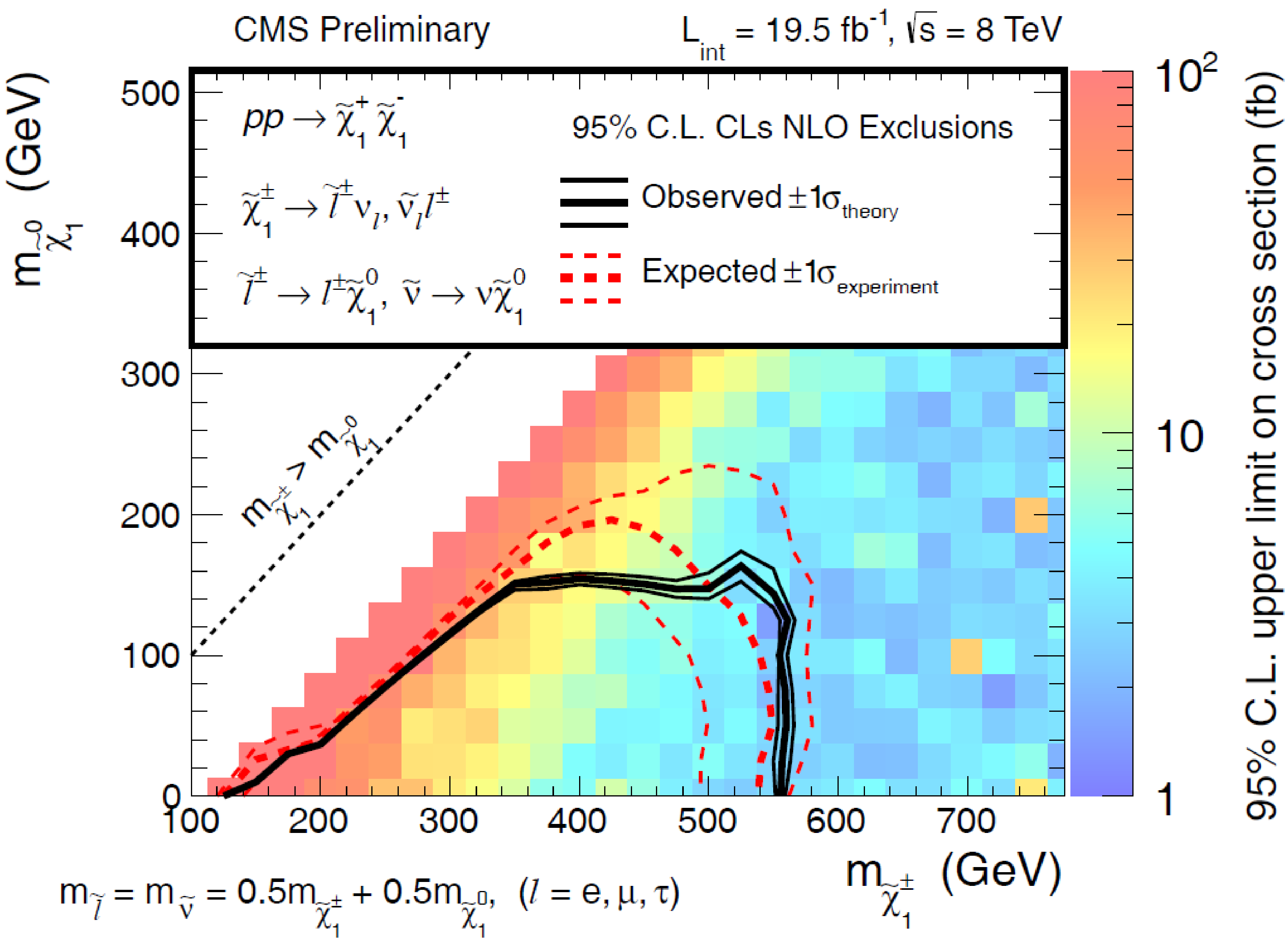


CMS Preliminary
$\sqrt{s}$ = 8 TeV, L_{int} = 19.5 fb^{-1}
$pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$, (via $\tilde{l}_L/\tilde{\nu}$)
$pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$, (via $\tilde{l}_L/\tilde{\nu}$)
$pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$, (via $\tilde{l}_R$)
$pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$, (via $\tilde{\tau}_R$)
$pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow (Z\,\tilde{\chi}_1^0)(W\,\tilde{\chi}_1^0)$
$pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow (H\,\tilde{\chi}_1^0)(W\,\tilde{\chi}_1^0)$
Observed limits
Expected limits
SUS-13-006
SUS-13-017
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + m_Z$
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + m_H$
$m_{\tilde{\chi}_1^0}$ [GeV]
900
800
700
600
500
400
300
200
100
100
200
300
400
500
600
700
800
$m_{\tilde{l}} = 0.5m_{\tilde{\chi}_1^\pm} + 0.5m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0}$ [GeV]

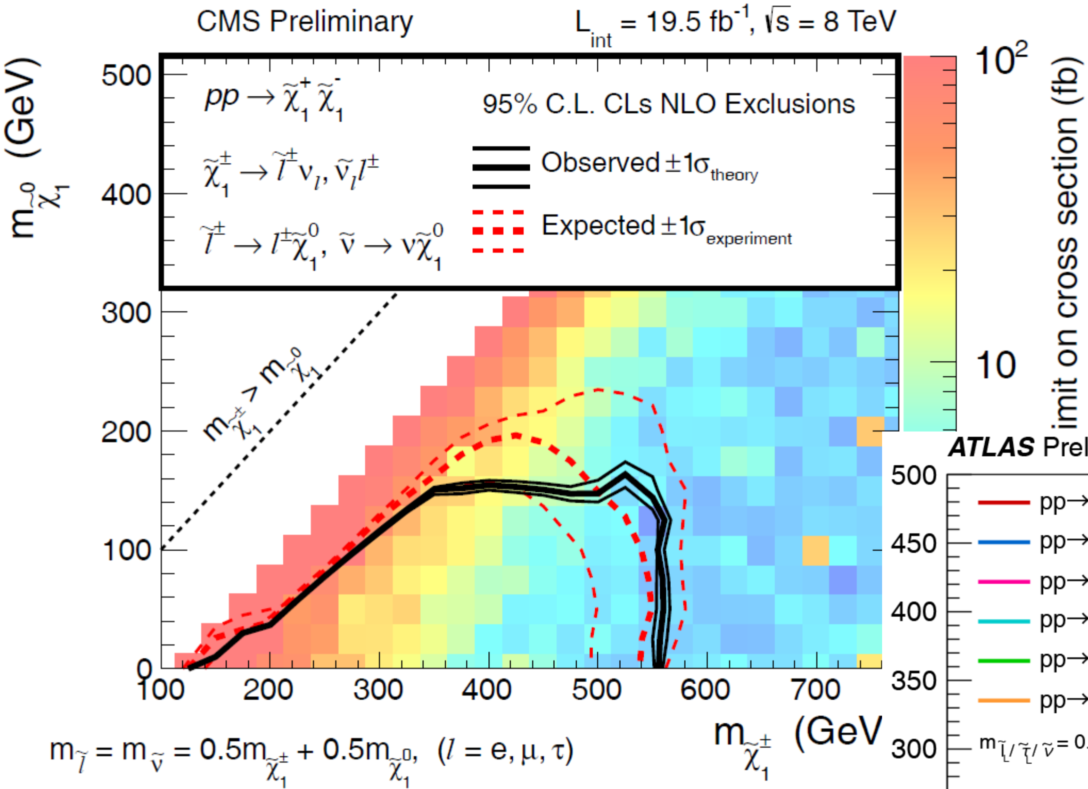
CMS electroweakino search (Golden channel)

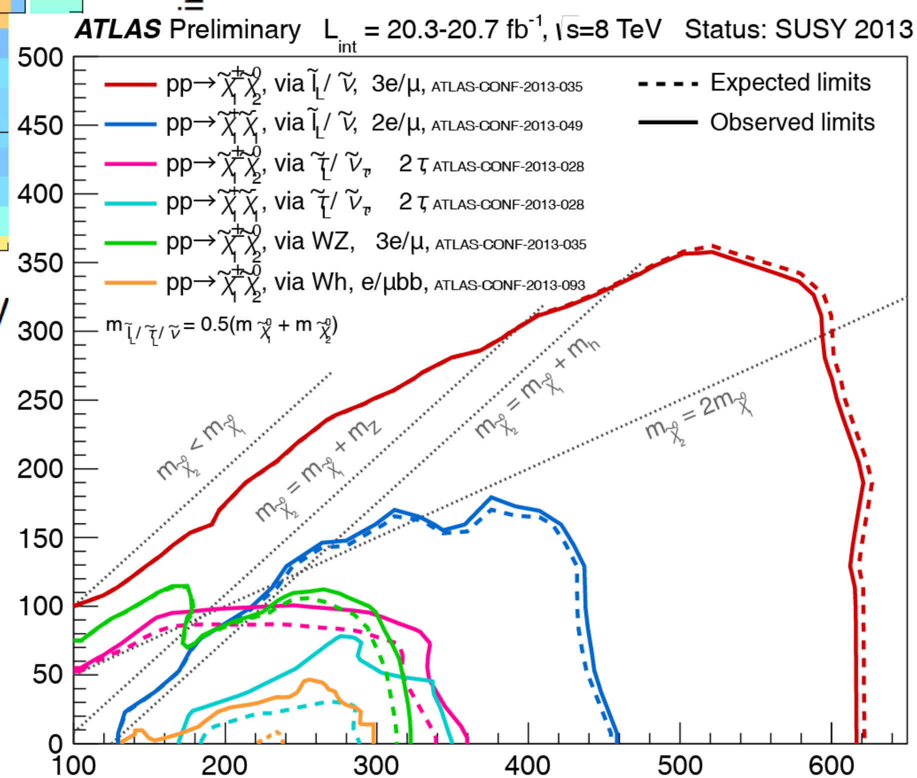


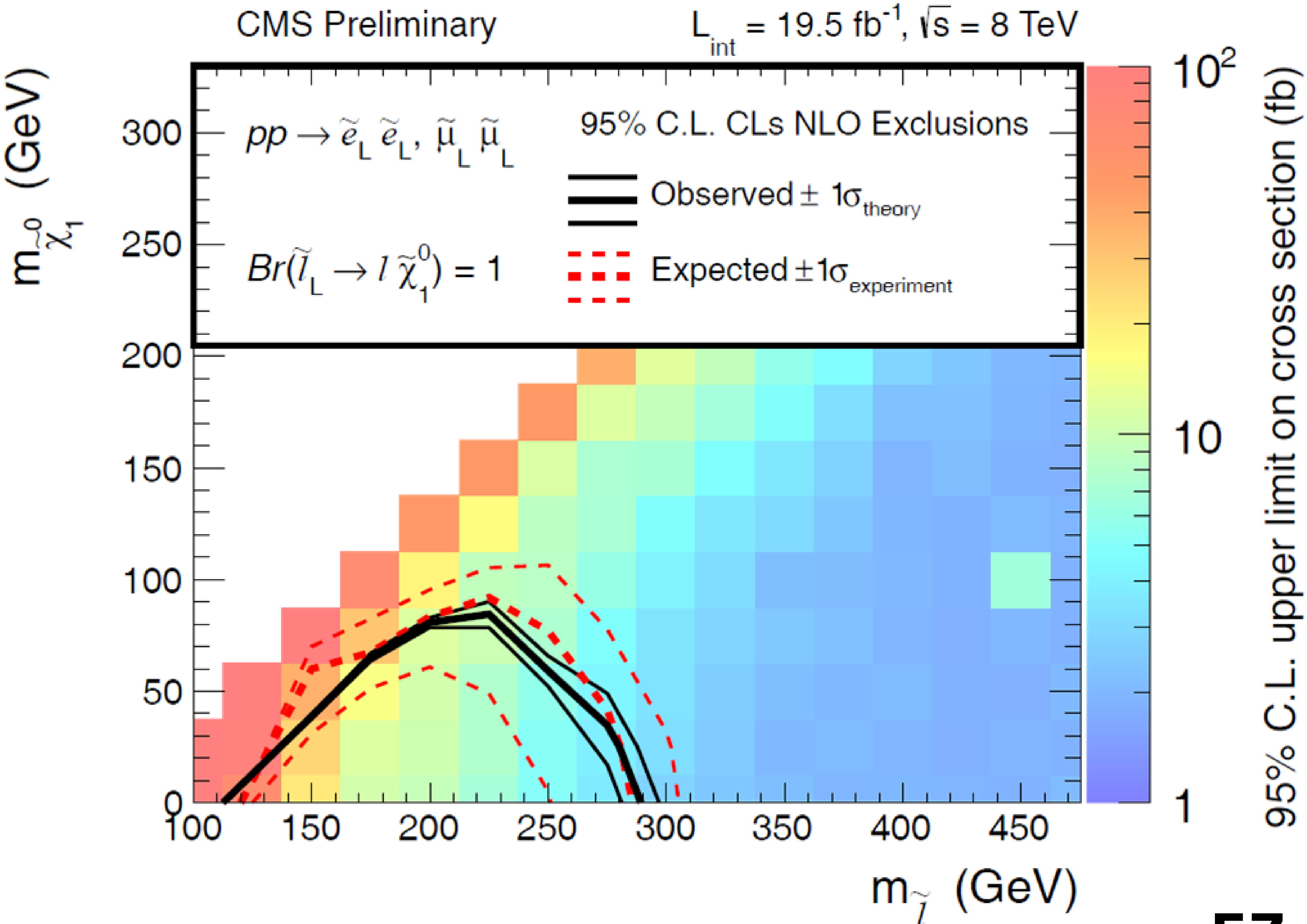



CMS Preliminary
$L_{int} = 19.5\ fb^{-1}, \sqrt{s} = 8$ TeV
$pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$
$\tilde{\chi}_1^\pm \to \tilde{l}^\pm \nu_l, \tilde{\nu}_l l^\pm$
$\tilde{l}^\pm \to l^\pm \tilde{\chi}_1^0,\ \tilde{\nu} \to \nu \tilde{\chi}_1^0$
95% C.L. CLs NLO Exclusions
Observed $\pm 1\sigma_{theory}$
Expected $\pm 1\sigma_{experiment}$
$m_{\tilde{\chi}_1^\pm} > m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^0}$ (GeV)
$m_{\tilde{\chi}_1^\pm}$ (GeV)
95% C.L. upper limit on cross section (fb)
$m_{\tilde{l}} = m_{\tilde{\nu}} = 0.5 m_{\tilde{\chi}_1^\pm} + 0.5 m_{\tilde{\chi}_1^0}$, ($l = e, \mu, \tau$)

CMS electroweakino search (Chargino pair-production)






CMS Preliminary
L_{int} = 19.5 fb^{-1}, $\sqrt{s}$ = 8 TeV
$pp \rightarrow \tilde{e}_L \tilde{e}_L, \tilde{\mu}_L \tilde{\mu}_L$
$Br(\tilde{l}_L \rightarrow l \tilde{\chi}^0_1) = 1$
95% C.L. CLs NLO Exclusions
Observed ± $1\sigma_{theory}$
Expected ± $1\sigma_{experiment}$
$m_{\tilde{\chi}^0_1}$ (GeV)
$m_{\tilde{l}}$ (GeV)
95% C.L. upper limit on cross section (fb)
0
50
100
150
200
250
300
100
150
200
250
300
350
400
450
1
10
10^2

CMS electroweakino search (Slepton pair-production)