MSSM in light of $(g\text{-}2)_\mu$ anomaly and dark matter

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Università degli Studi di Padova & INFN, Sezione di Padova

13 Dec. 2018
Seminar @ Uniwersytet Warszawski

Based on
- Endo, Hamaguchi, Iwamoto, Yanagi [1704.05287]
- Endo, Hamaguchi, Iwamoto, Yoshinaga [1303.4256]

and a few ongoing projects.

1. Introduction

- SUSY @ LHC
- $(g-2)_\mu$ anomaly

2. MSSM to solve $\Delta(g-2)_\mu$: Overview

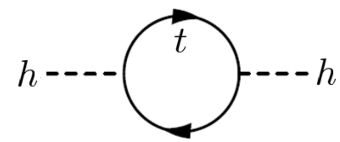
- Dark Matter
- LHC

3. MSSM to solve $\Delta(g-2)_\mu$: 4 solutions

- **"Chargino"**: multi-lepton = promising!
- **"Pure-bino"**: di-lepton (but not sufficient)
- **"BHR"** & **"BHL"**: multi-tau + direct detections.

* $g{-}2$ = anomalous magnetic moment

- LHC $\equiv$ to discover (0.1–1) TeV particles.
  - Higgs ✓
  - $(g{-}2)_\mu$ anomaly → next slides
  - Hierarchy problem



$$m_h^2 \sim m_{\text{bare}}^2 + \Delta m_h^2, \qquad \Delta m_h^2(\text{SM}) \sim -\frac{3|\lambda|^2}{8\pi^2}\Lambda_{\text{cutoff}}^2 + \text{finite}.$$

$$(100\,\text{GeV})^2 \sim \Lambda_{\text{cutoff}}^2 - \Lambda_{\text{cutoff}}^2 \qquad \to \Lambda_{\text{cutoff}} \sim 0.1\text{–}1\ \text{TeV} = \text{new physics?}$$

  - Dark matter "WIMP miracle"

simplest scenario = DM as a thermal relic, freezing out by pair-annihilation:

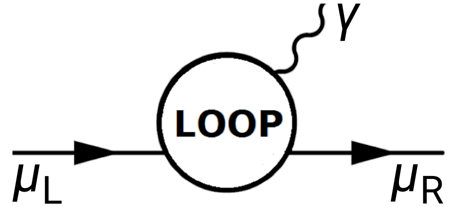
$$\langle\sigma v\rangle_{\text{DM DM}\to\text{any}} \text{ should be } \sim 3\times 10^{-26}\text{cm}^3/\text{s} = \frac{\alpha_{\text{em}}^2}{(150\,\text{GeV})^2}$$

→ DM @ ~100 GeV?

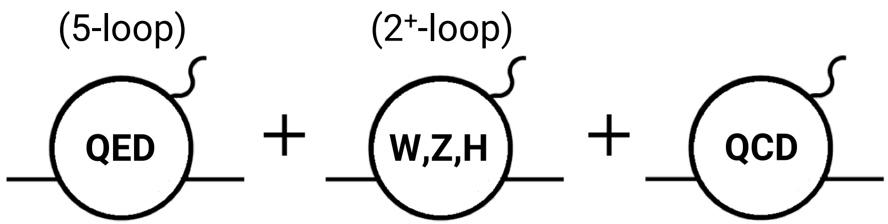
$$\boxed{\Omega_{\rm DM}h^2 \approx \frac{1.1\times 10^9\cdot x_{\rm f}}{\sqrt{g_*}M_{\rm pl}\langle\sigma v\rangle\cdot\text{GeV}} \approx 0.1\cdot\frac{15}{\sqrt{g_*}}\frac{x_{\rm f}}{30}\frac{3\times 10^{-26}\ \text{cm}^3/\text{s}}{\langle\sigma v\rangle} \quad \text{with } x_{\rm f} = m_{\rm DM}/T_{\rm fo}.}$$

Muon $g{-}2$ SM expectation : 3–4σ discrepancy!

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



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



$$a_\mu(\mathrm{QED}) = (11\,658\,471.886 \pm 0.003) \times 10^{-10},$$

$$a_\mu(\mathrm{EW}) = (\qquad 15.36 \pm 0.11\ ) \times 10^{-10},$$

SM combination according to Jegerlehner [1804.07409].
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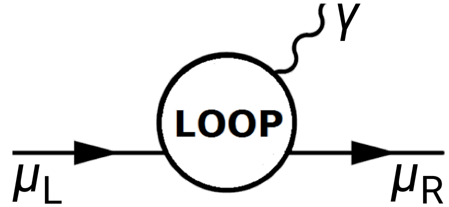

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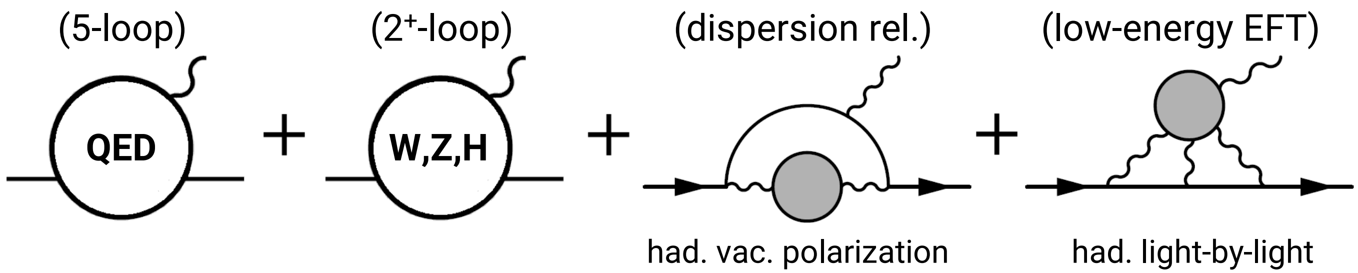

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[FermiLab: ±1.6]

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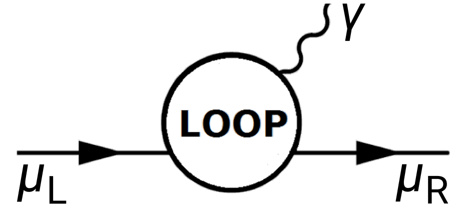

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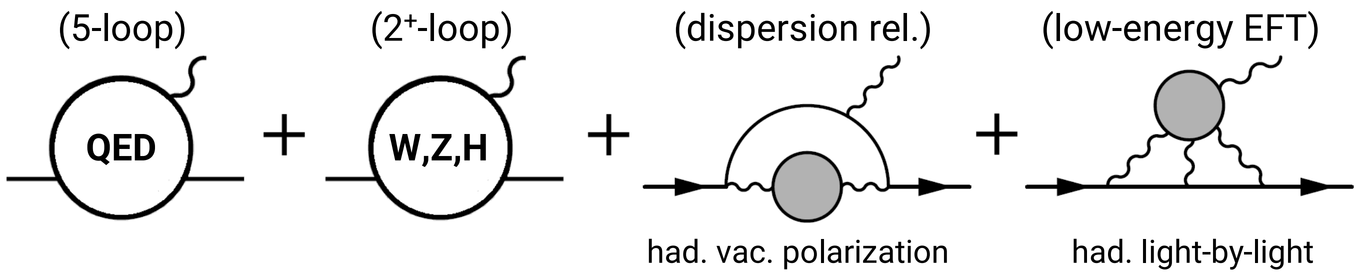

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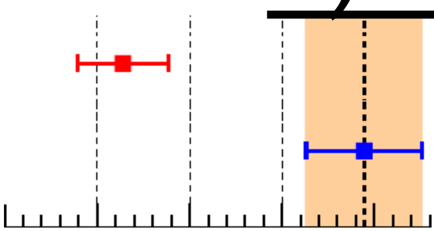

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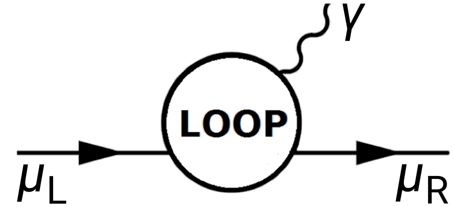

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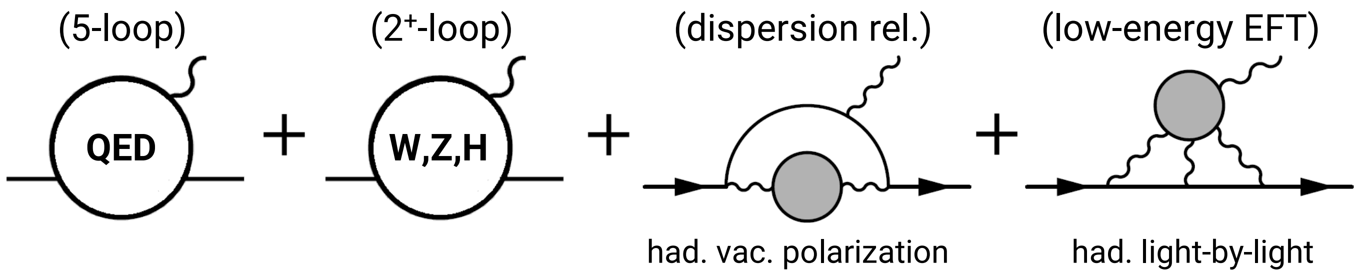

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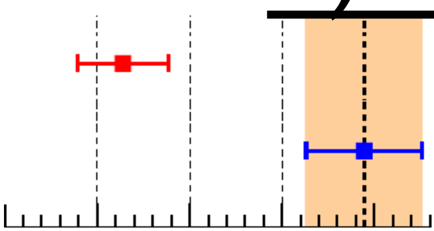

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  - $(g-2)_\mu$ anomaly → $\Delta a_\mu = 10\times 10^{-10} \approx \frac{\alpha_{\rm em}}{4\pi}\left(\frac{m_\mu}{\boxed{200\,\text{GeV}}}\right)^2$
  - Hierarchy problem

$$m_h^2 \sim m_{\rm bare}^2 + \Delta m_h^2, \qquad \Delta m_h^2(\text{SM}) \sim -\frac{3|\lambda|^2}{8\pi^2}\Lambda_{\rm cutoff}^2 + \text{finite.}$$

$$\boxed{(100\,\text{GeV})^2 \sim \Lambda_{\rm cutoff}^2 - \Lambda_{\rm cutoff}^2}$$

→ $\Lambda_{\rm cutoff} \sim$ 0.1−1 TeV = new physics?

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simplest scenario = DM as a thermal relic, freezing out by pair-annihilation:

$\langle\sigma v\rangle_{\rm DM\,DM\to any}$ should be $\sim 3\times 10^{-26}\text{cm}^3/\text{s} = \frac{\alpha_{\rm em}^2}{\boxed{(150\,\text{GeV})^2}}$

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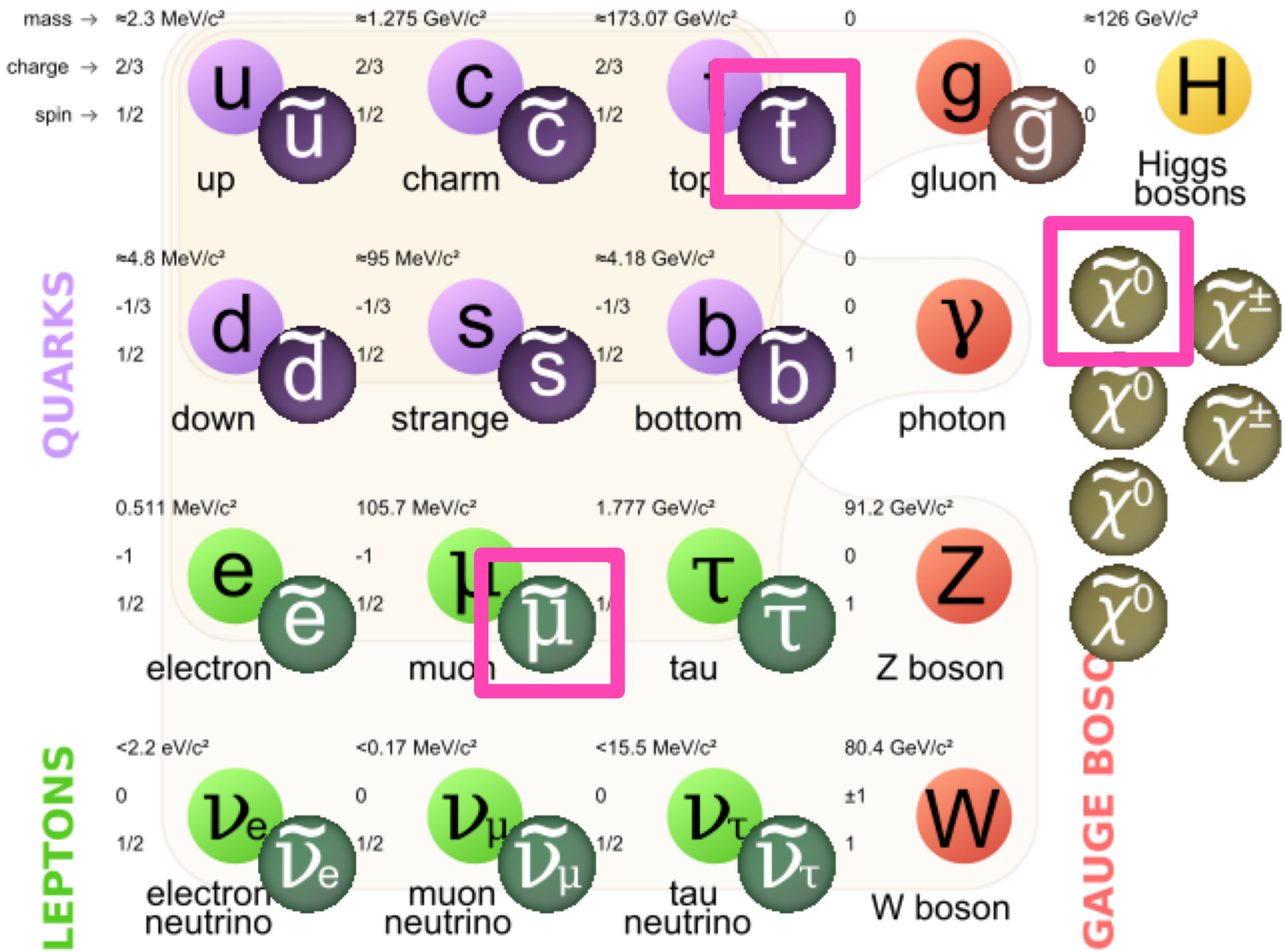
- MSSM = SUSY version of the Standard Model



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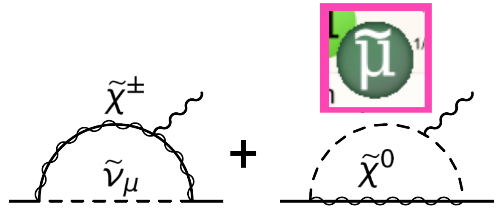
  - $(g-2)_\mu$ anomaly :  may explain the anomaly

if these particles are O(100) GeV.

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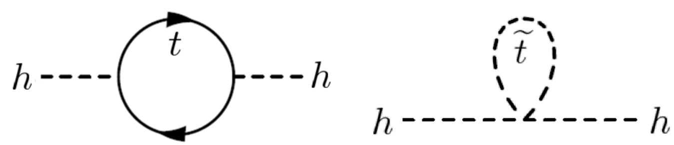

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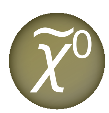
The lightest neutralino  may be stable.

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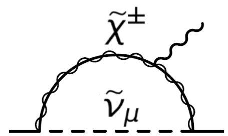
  - $(g-2)_\mu$ anomaly : 

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 $\lesssim 1\,\text{TeV}!$

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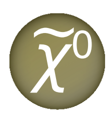
The lightest neutralino  may be stable.
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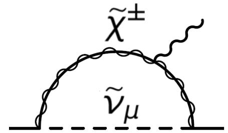
  - $(g-2)_\mu$ anomaly : 

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$\lesssim$ 1 TeV!

= colored particle
→ easier @ LHC
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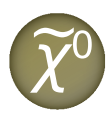
    The lightest neutralino 

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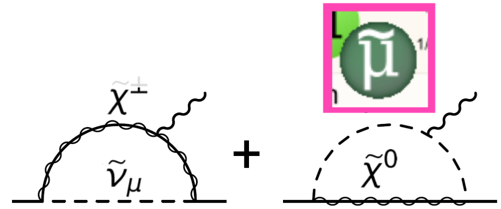
  - $(g-2)_\mu$ anomaly : 

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Electroweakino searches motivated by DM + $(g-2)_\mu$
= Good target @ Run2/3/HL-LHC

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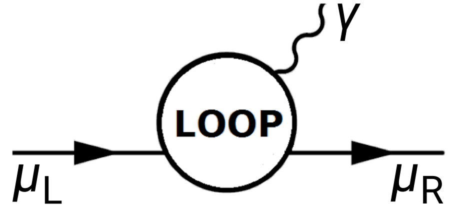

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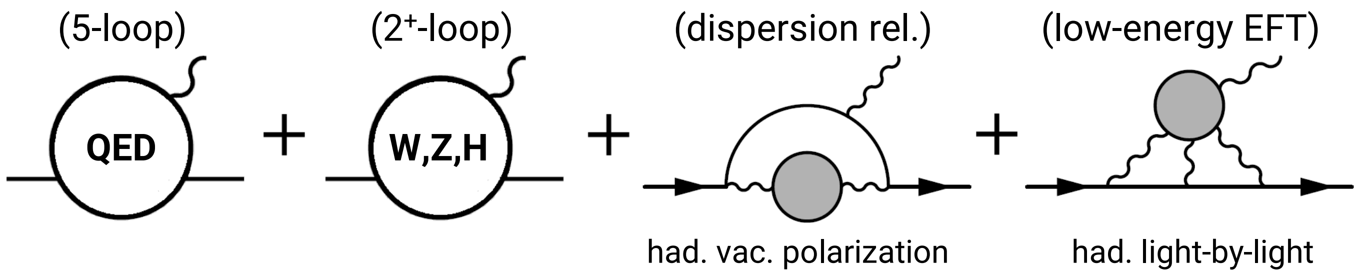

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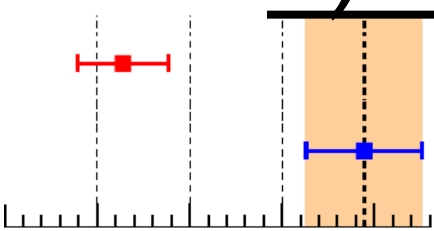

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[FermiLab: ±1.6]

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  - Just a statistical fluctuation.
  - Just an issue in the experiment.
  - $O(100)$ GeV particles with $O(0.1)$ couplings $10\times10^{-10} \approx \frac{\alpha_{em}}{4\pi}\left(\frac{m_\mu}{m_{new}}\right)^2$
    - MSSM

~200GeV

  - keV−MeV particles with tiny couplings. $10\times10^{-10} \approx \frac{(\varepsilon^2/4\pi)}{4\pi}\left(\frac{m_\mu}{m_{new}}\right)^2$
    - dark photon (extra U(1) gauge boson)
    - extra $L_\mu - L_\tau$ gauge boson

keV−MeV

Gninenko, Krasnikov [ph/0102222],
Baek, Deshpande, He, Ko [ph/0104141]

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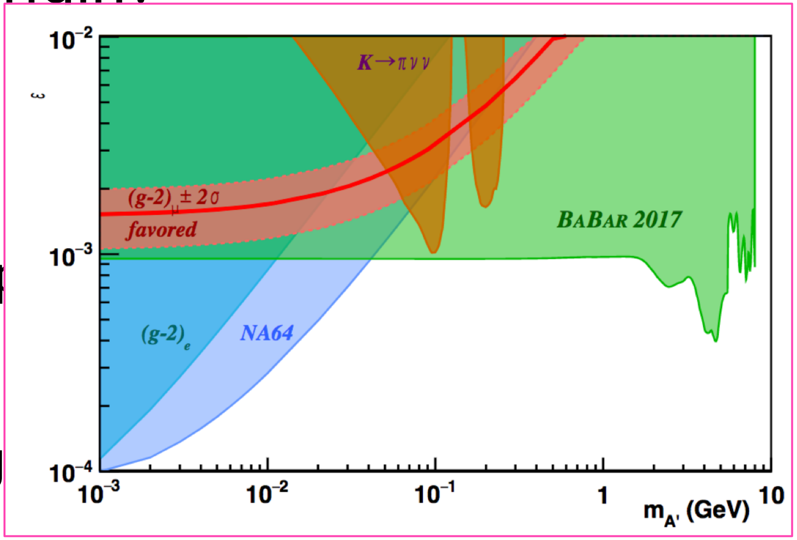

$e^+e^- \to \gamma A', \ A' \to$ invisible

BaBar [1702.03327]

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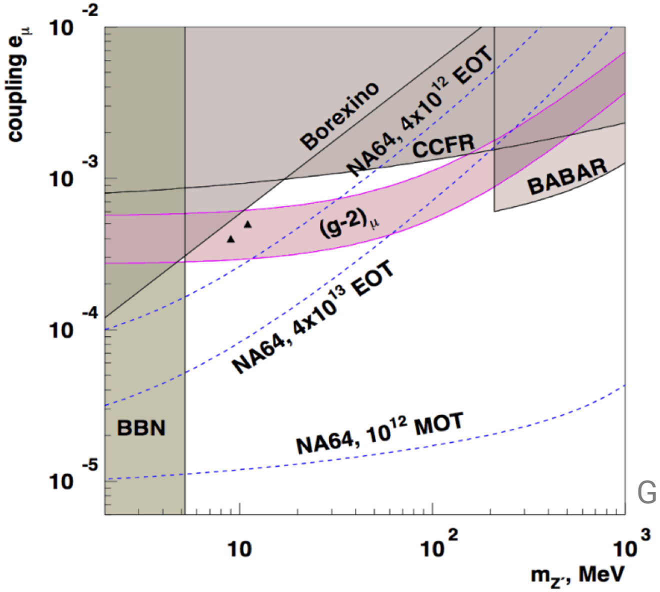


Gninenko, Krasnikov [1801.10448]

$$L_{Z'} = e_\mu Z'_\nu [\bar{\mu}\gamma^\nu \mu - \bar{\tau}\gamma^\nu \tau + \bar{\nu}_\mu \gamma^\nu \nu_\mu - \bar{\nu}_\tau \gamma^\nu \nu_\tau]$$

1. Introduction

- SUSY @ LHC
- $(g-2)_\mu$ anomaly

2. MSSM to solve $\Delta(g-2)_\mu$: Overview

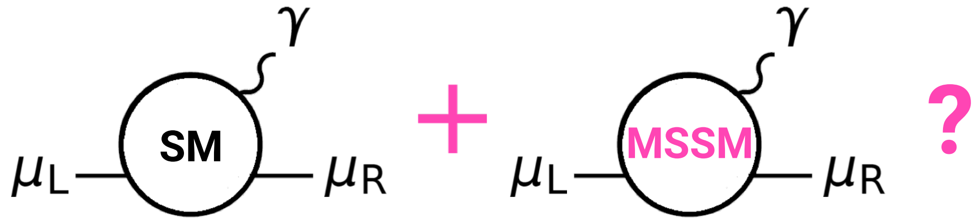
- Dark Matter
- LHC

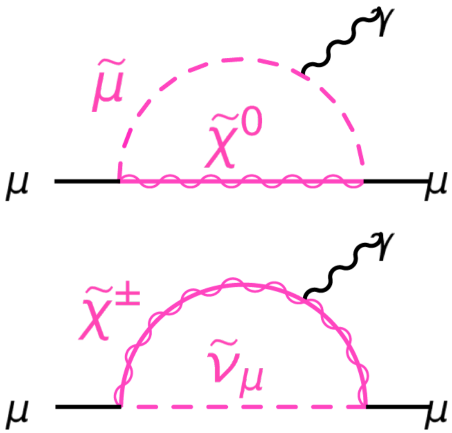
3. MSSM to solve $\Delta(g-2)_\mu$: 4 solutions

- **"Chargino"**: multi-lepton = promising!
- **"Pure-bino"**: di-lepton (but not sufficient)
- **"BHR"** & **"BHL"**: multi-tau + direct detections.

Muon $g-2$ anomaly can be solved by MSSM.

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





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

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

- lighter SUSY-particles
- larger tan β

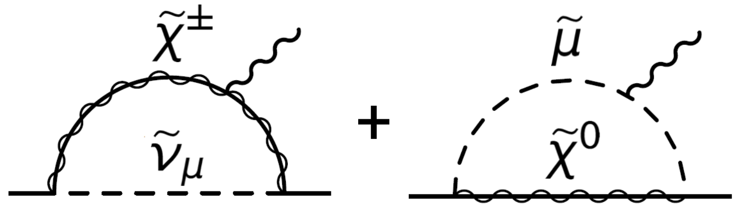
$\Rightarrow$ larger a_μ^{SUSY}

$W \ni \mu H_{\mathrm{u}} H_{\mathrm{d}}$ (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.

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

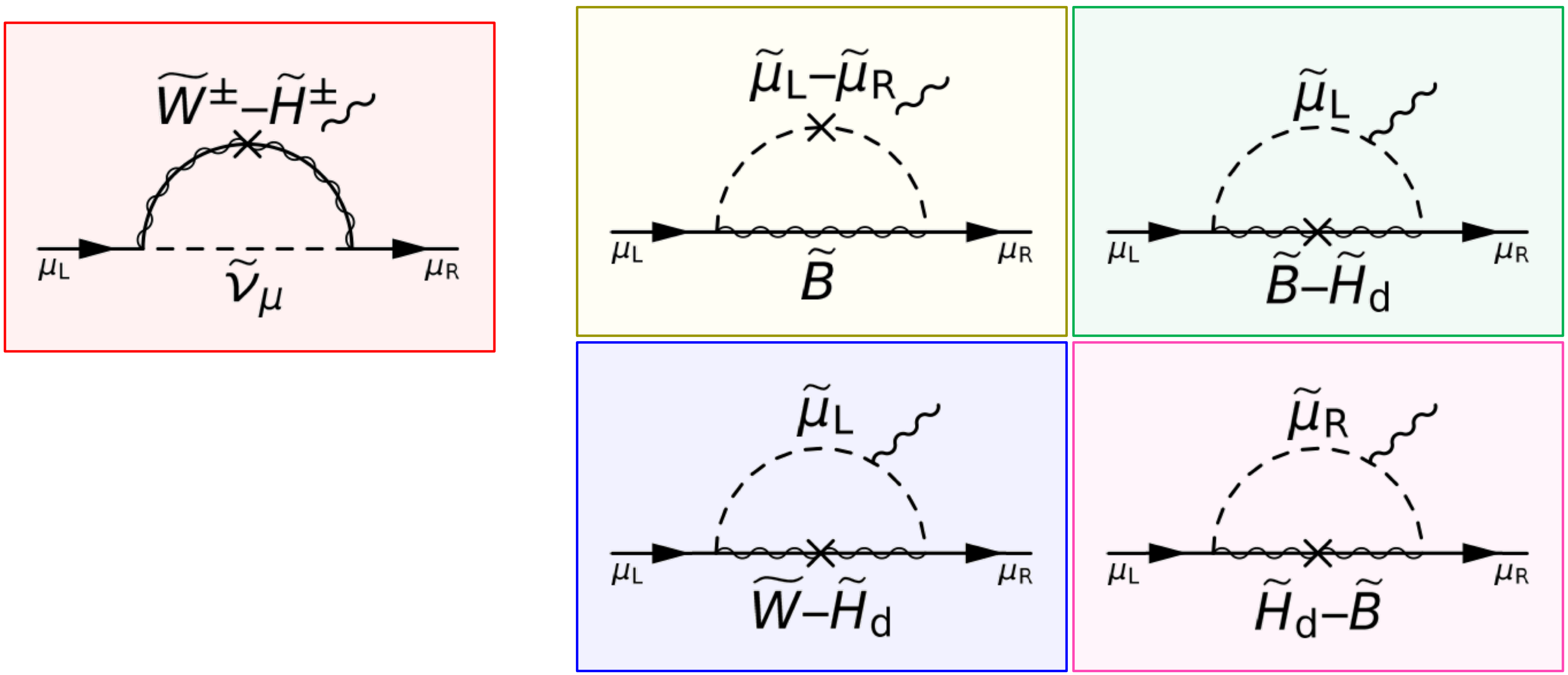
mass eigenstates

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

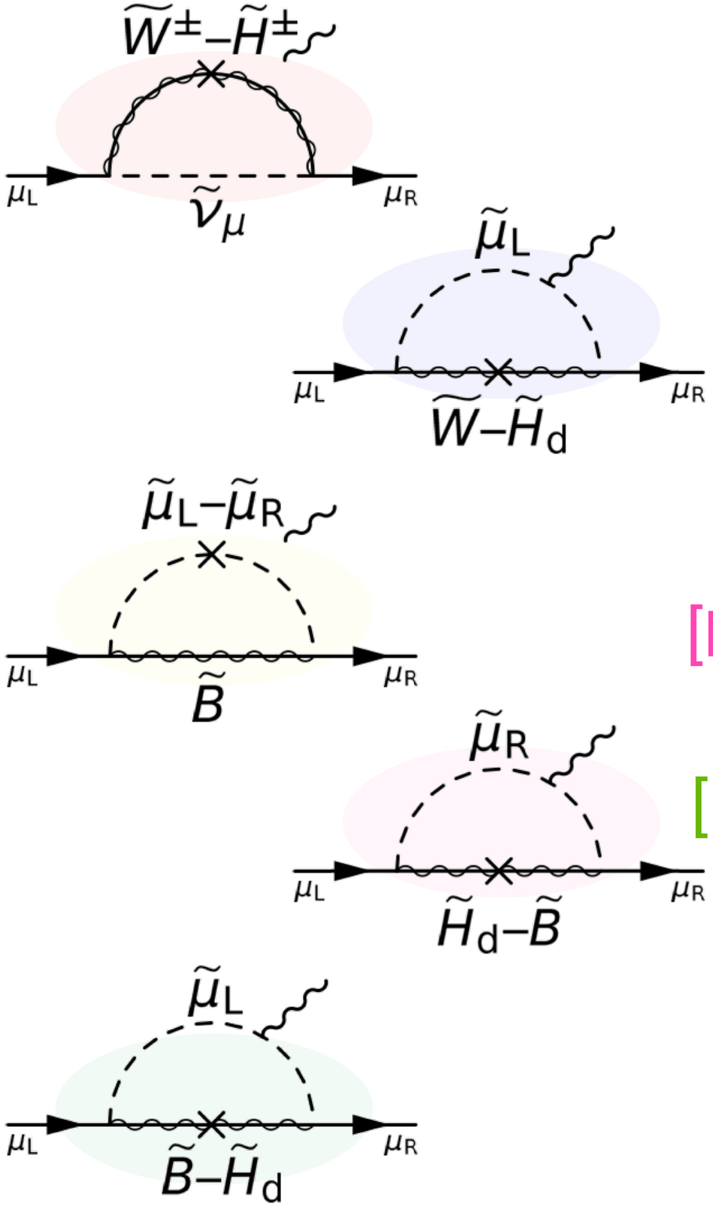


$$\boxed{\tilde{\chi}^0_{1-4} = \tilde{B} \oplus \tilde{W}^0 \oplus \tilde{H}_{\mathrm{d}} \oplus \tilde{H}_{\mathrm{u}}, \quad \tilde{\chi}^{\pm}_{1,2} = \tilde{W}^{\pm} \oplus \tilde{H}^{\pm}.}$$

gauge eigenstates



(“mass insertion” technique)



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

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

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

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

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

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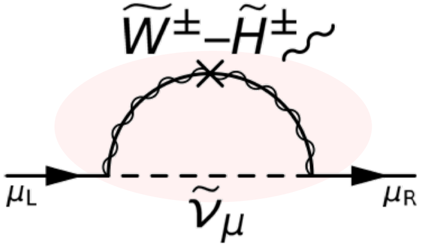
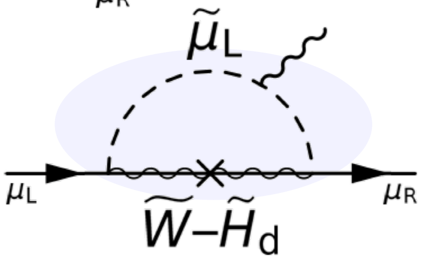
SUSY contribution to muon $g-2$: (1) "Chargino" contributions





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

[C'] $$-\frac{g_2^2 m_\mu^2}{16\pi^2}\frac{M_2\mu\tan\beta}{m_{\widetilde{\mu}_L}^4}\cdot F_b\left(\frac{M_2}{m_{\widetilde{\mu}_L}},\frac{\mu}{m_{\widetilde{\mu}_L}}\right)$$

- "Chargino contribution"
- $\propto g_2^2$ (not g_Y^2) → tends to be the dominant contribution.
- SU(2) pair → [C'] $\simeq -0.5$[C] → $\mu > 0$ to be positive.
- Higgsino, Wino, and $\widetilde{\mu}_L$ must be $O(100)$GeV.

F_a, F_b are loop functions and positive.

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

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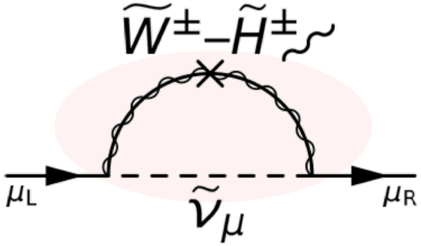

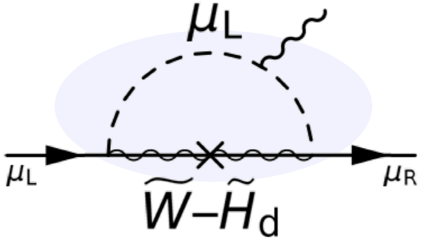

[C] $$\frac{g_2^2 m_\mu^2}{8\pi^2}\frac{M_2 \mu \tan\beta}{m_{\tilde{\nu}_\mu}^4}\cdot F_a\left(\frac{M_2}{m_{\tilde{\nu}_\mu}}, \frac{\mu}{m_{\tilde{\nu}_\mu}}\right)$$

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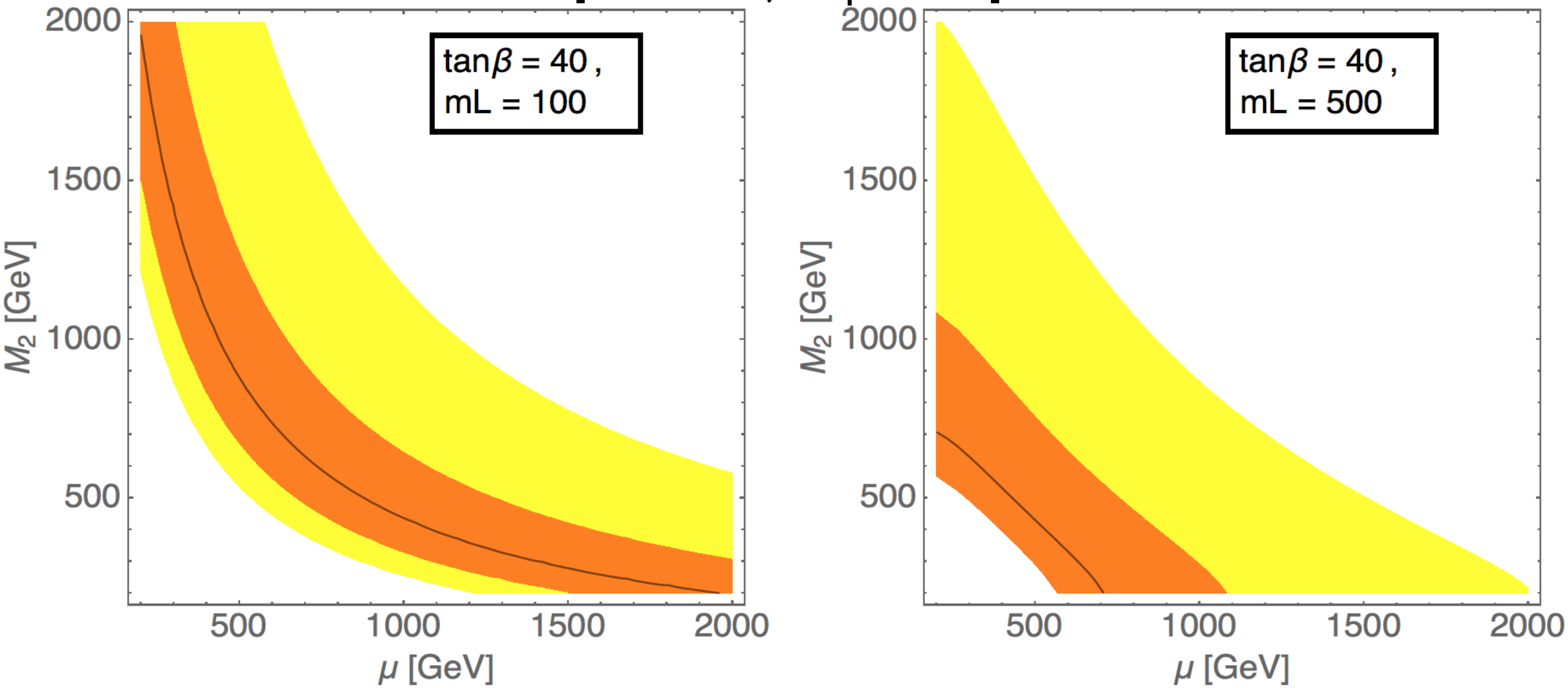
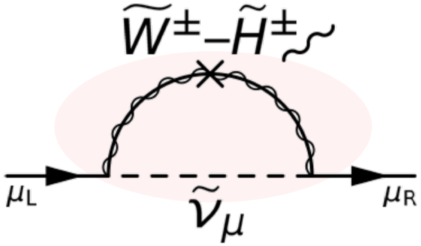
C+C'-contribution [tree-level; slep=sneu]





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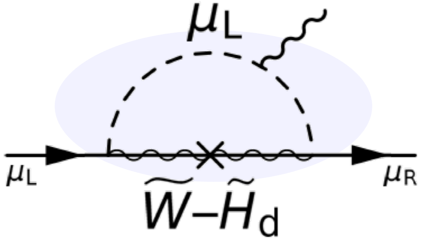
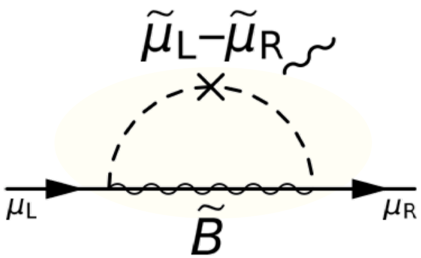
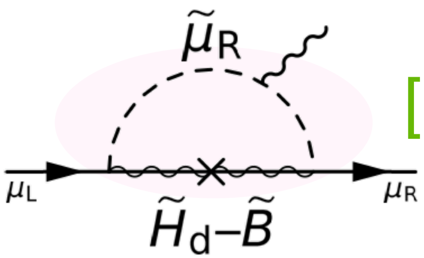


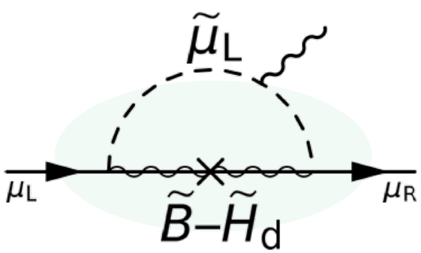
[C'] $$-\frac{g_2^2 m_\mu^2}{16\pi^2}\frac{M_2\mu\tan\beta}{m_{\widetilde{\mu}_L}^4}\cdot F_b\left(\frac{M_2}{m_{\widetilde{\mu}_L}},\frac{\mu}{m_{\widetilde{\mu}_L}}\right)$$



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



[BHR] $$-\frac{g_Y^2 m_\mu^2}{8\pi^2}\frac{M_1\mu\tan\beta}{m_{\widetilde{\mu}_R}^4}\cdot F_b\left(\frac{M_1}{m_{\widetilde{\mu}_R}},\frac{\mu}{m_{\widetilde{\mu}_R}}\right)$$



[BHL] $$\frac{g_Y^2 m_\mu^2}{16\pi^2}\frac{M_1\mu\tan\beta}{m_{\widetilde{\mu}_L}^4}\cdot F_b\left(\frac{M_1}{m_{\widetilde{\mu}_L}},\frac{\mu}{m_{\widetilde{\mu}_L}}\right)$$

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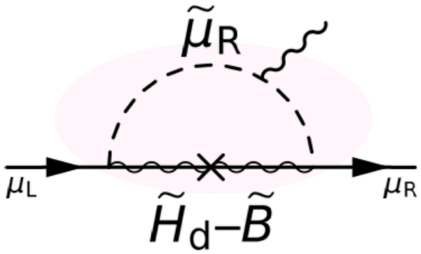
- "BHR contribution" (Bino, Higgsino, $\tilde{\mu}_{\mathrm{R}}$ must be $O(100)$GeV)
- If μ-parameter < 0, this is the only viable contribution.
  (Higgsino-mass parameter)
- $\propto g_Y^2$



[BHR] $$\boxed{-\frac{g_Y^2 m_\mu^2}{8\pi^2}\frac{M_1\mu\tan\beta}{m_{\tilde{\mu}_{\mathrm{R}}}^4}\cdot F_b\left(\frac{M_1}{m_{\tilde{\mu}_{\mathrm{R}}}},\frac{\mu}{m_{\tilde{\mu}_{\mathrm{R}}}}\right)}$$

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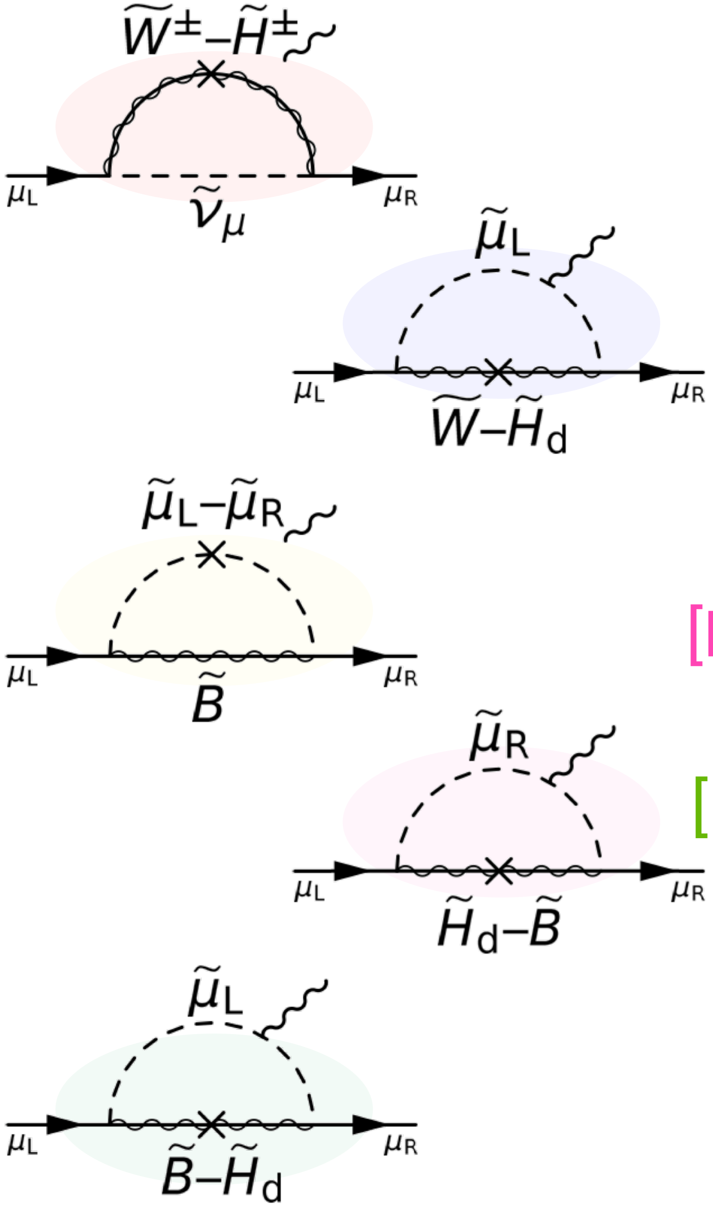

[C] $$\frac{g_2^2 m_\mu^2}{8\pi^2}\frac{M_2\mu\tan\beta}{m_{\widetilde{\nu}_\mu}^4}\cdot F_a\left(\frac{M_2}{m_{\widetilde{\nu}_\mu}},\frac{\mu}{m_{\widetilde{\nu}_\mu}}\right)$$

[C'] $$-\frac{g_2^2 m_\mu^2}{16\pi^2}\frac{M_2\mu\tan\beta}{m_{\widetilde{\mu}_L}^4}\cdot F_b\left(\frac{M_2}{m_{\widetilde{\mu}_L}},\frac{\mu}{m_{\widetilde{\mu}_L}}\right)$$

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

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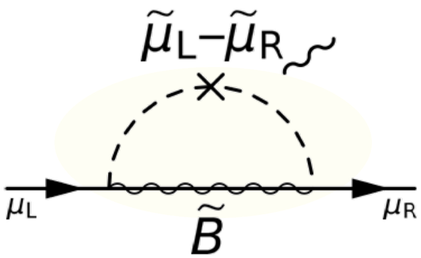
$$C_1(x)=\frac{3-4x+x^2+2\log x}{(1-x)^3},\qquad N_2(x)=\frac{1-x^2+2x\log x}{(1-x)^3}.$$

- "pure-Bino contribution": Bino and $\tilde{\mu}_{\mathrm{L}}, \tilde{\mu}_{\mathrm{R}}$ must be $O(100)$GeV.
  - Higgsino and Wino can be any heavy.
- $\propto \mu \tan\beta$ → heavier Higgsino gives larger contribution.



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

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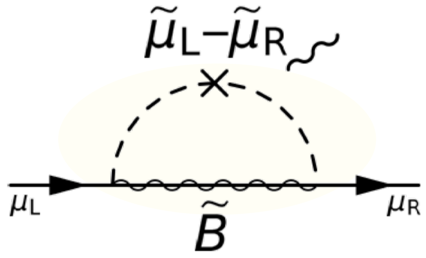
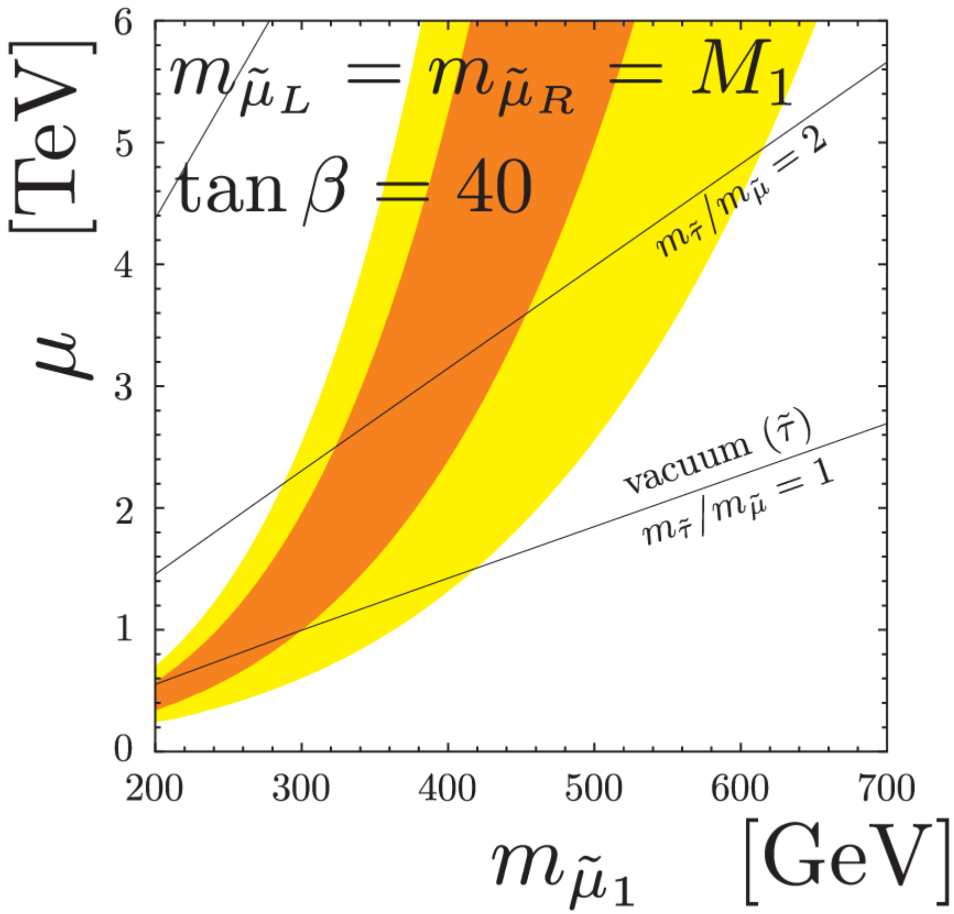
Endo, Hamaguchi, Kitahara, Yoshinaga [1309.3065]



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

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



***μ* tan*β* has upper bounds:**

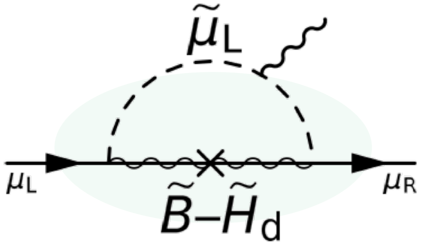
$$V_{\rm Higgs} \supset -\left(m_\tau\,\mu\tan\beta\cdot\tilde\tau_L^*\tilde\tau_R h + m_\mu\,\mu\tan\beta\cdot\tilde\mu_L^*\tilde\mu_R h\right)$$

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

$$\begin{aligned} &= 1 &&\Rightarrow m_{\tilde\mu} \lesssim 300(420)\ \text{GeV} \\ &= 2 &&\Rightarrow \phantom{m_{\tilde\mu}} \lesssim 440(620)\ \text{GeV} \\ &= \infty &&\Rightarrow \phantom{m_{\tilde\mu}} \lesssim 1.4(1.9)\ \text{TeV} \end{aligned}$$

- "BHL contribution" (Bino, Higgsino, $\tilde{\mu}_{\mathrm{L}}$ must be $O(100)$GeV)
- nothing special.

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



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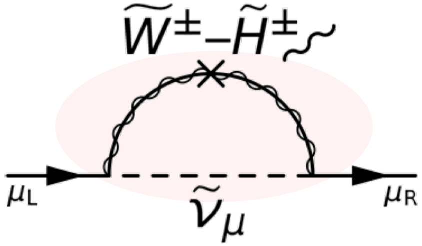

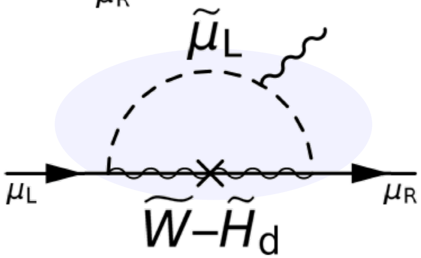

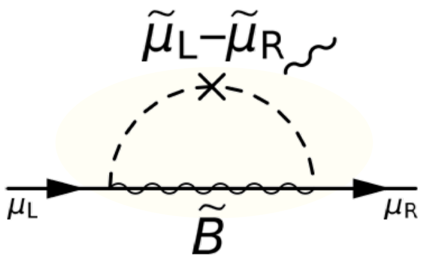

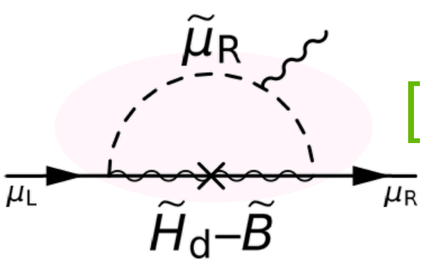

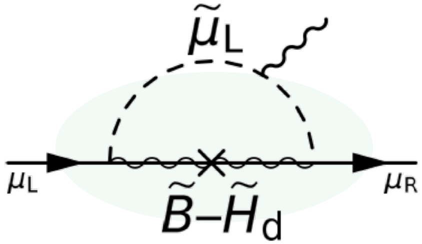

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tend to be large/dominant

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

μ-enhancement

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

negative

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

nothing special

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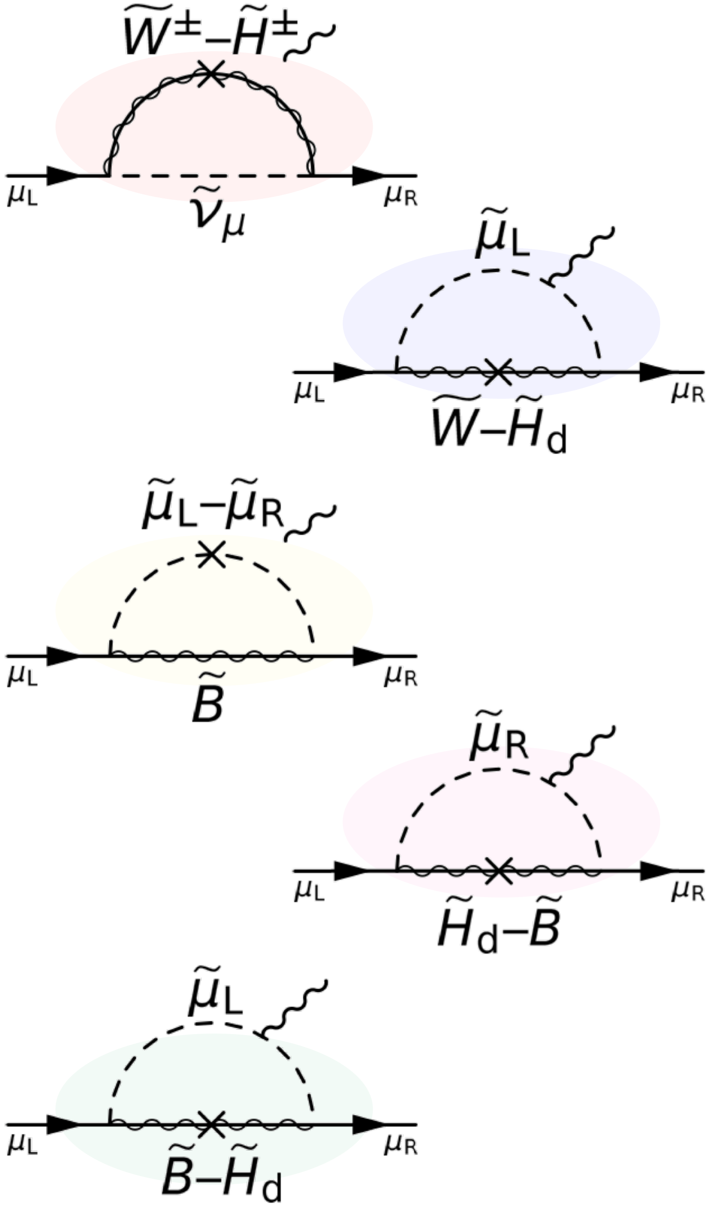
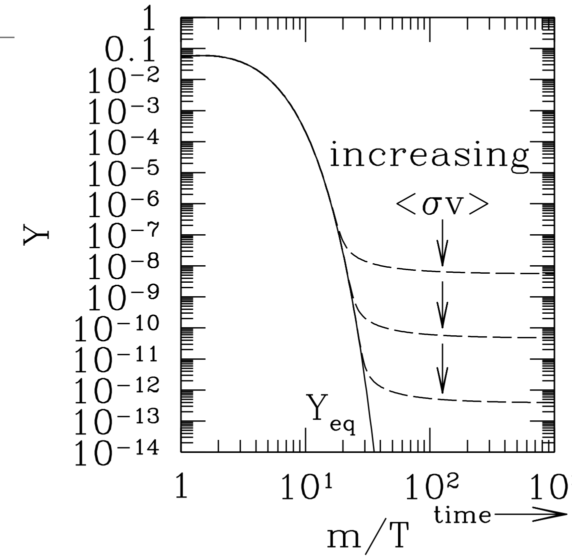


- $(g-2)_\mu$ always requires $\widetilde{\chi}^0$
  → good DM candidate!

- Relic Density?
  → depends on thermal history of Univ.
  - too much → some mechanism to reduce.
  - too little → late production or other DM.

→ Let's discuss simplest case!



- Simplest $\tilde{\chi}^0$-DM scenario
  - DM was in thermal equilibrium → freeze-out.

    $\cdots\ \langle\sigma v\rangle_{\mathrm{DM\,DM}\to\mathrm{any}} \sim 3\times10^{-26}\,\mathrm{cm}^3/\mathrm{s}$
  - No other component of DM.
- If $\tilde{\chi}^0$ is almost...
  - pure-Bino → almost no interaction → over-abundant.
  - pure-Higgsino → m_{LSP} ~ 1TeV for correct abundance.
  - pure-Wino → m_{LSP} ~ 2.5TeV for correct abundance.
- Possibilities:
  - Bino-like + some mechanism to reduce the relic density
    (100−500GeV)
  - Higgsino DM, or Bino−Higgsino mixed DM ("well-tempered scenario")
    (~1TeV) (100−1TeV)
  - Bino−Wino mixed DM.
    (100−2.5TeV)

Figure from Gelmini and Gondolo, 1009.3690

- Simplest $\tilde{\chi}^0$-DM scenario

> ➢ **Bino−slepton co-annihilation**
> ($m_{\tilde{B}} \simeq m_{\tilde{l}}$)
>
> ➢ *H*- or *Z*-resonance ("funnel")
> ($m_{\tilde{B}} = m_H/2$ or $m_Z/2$)
>
> ➢ MSSM4G
> Abdullah, Feng [1510.06089],
> Abdullah, Feng, SI, Lillard [1608.00283]

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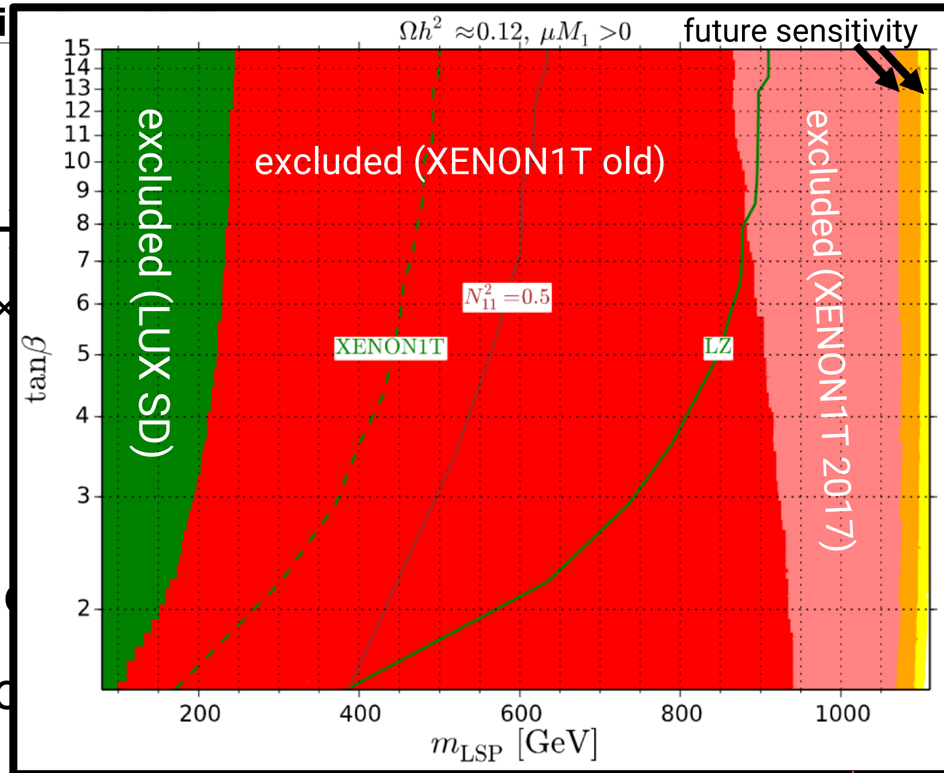
➢ pure-Wino → m_{LS} 5TeV for correct abundance.



- Possibilities:

➢ Bino-like + some mechanism to reduce the relic density
(100−500GeV)

➢ Higgsino DM, or Bino−Higgsino mixed DM ("well-tempered scenario")
(~1TeV)

➢ Bino−Wino mixed DM.

theoretically not nice

almost excluded by XENON1T

Badziak, Olechowski, Szczerbiak [1701.05869]

Figure from Gelmini and Gondolo, 1009.3690

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- SUSY @ LHC
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2. MSSM to solve $\Delta(g-2)_\mu$: Overview

- Dark Matter
- LHC

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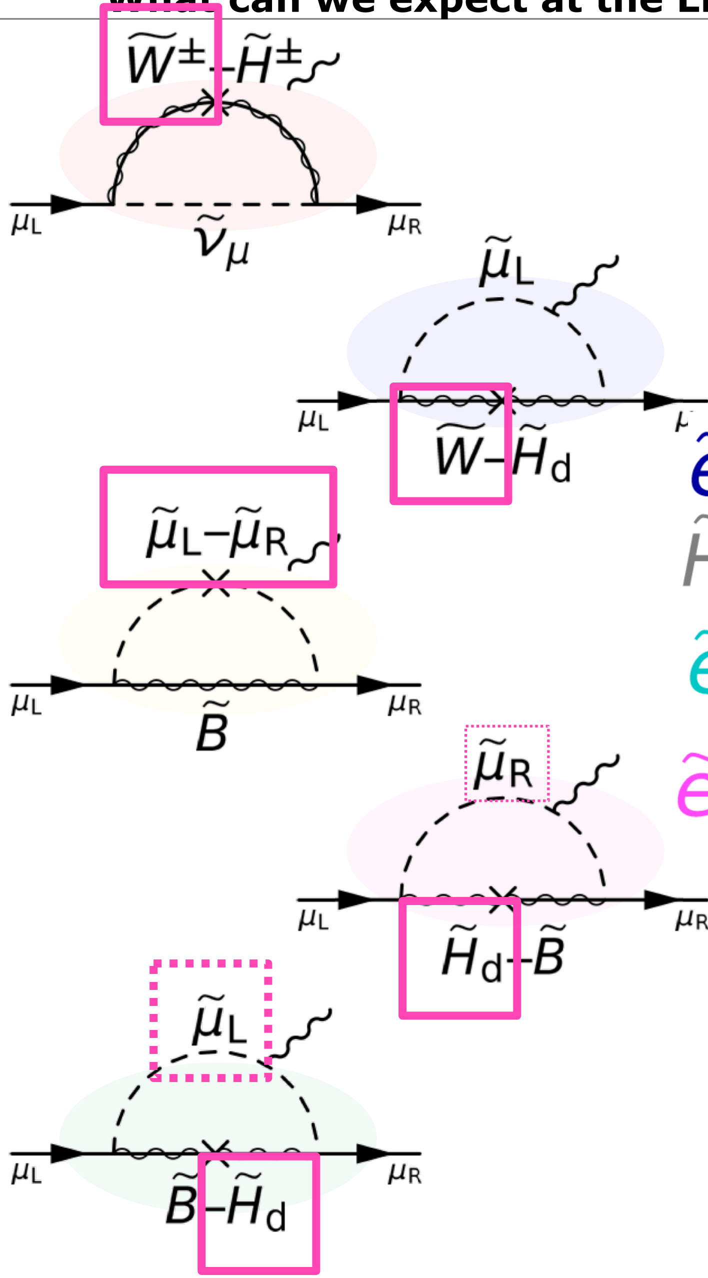
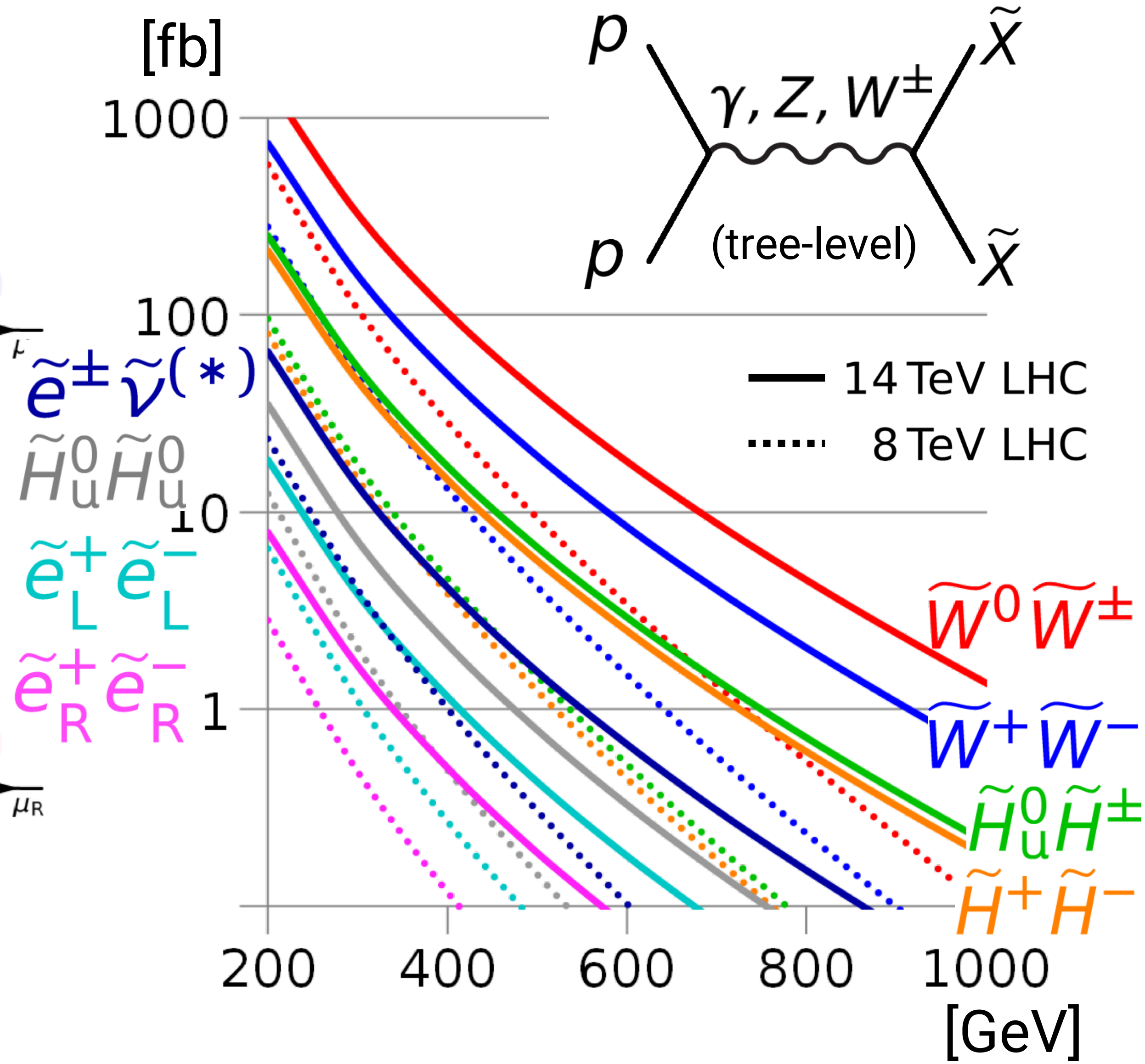
- **"Chargino"**: multi-lepton = promising!
- **"Pure-bino"**: di-lepton (but not sufficient)
- **"BHR"** & **"BHL"**: multi-tau + direct detections.

What can we expect at the LHC?





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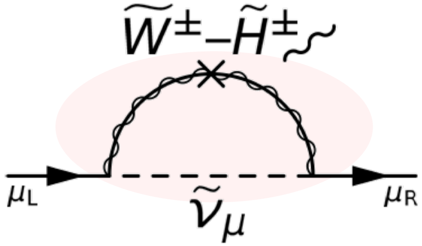
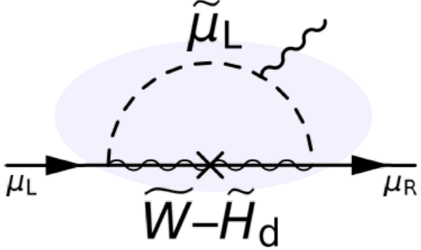
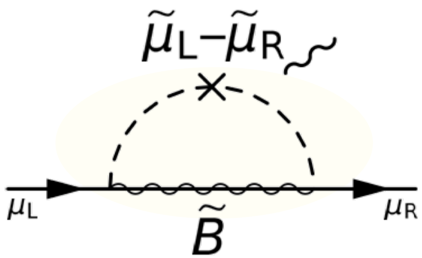
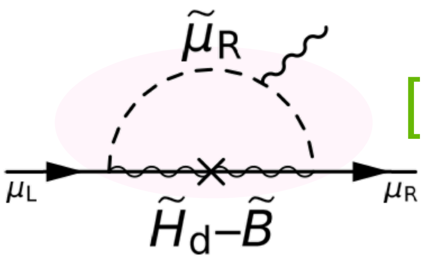
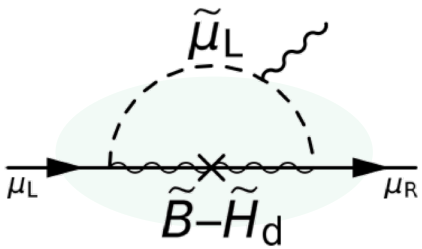










[C] $\frac{g_2^2 m_\mu^2}{8\pi^2}\frac{M_2\mu\tan\beta}{m^4}\cdot F_a\left(\frac{M_2}{m},\frac{\mu}{m}\right)$

tend to be large/dominant

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

[B] $\frac{g_Y^2 m_\mu^2}{8\pi^2}$ … $\frac{m_{\tilde\mu_R}}{M_1}\Big)$

μ-enhancement

[BHR] $-\frac{g_Y^2 m_\mu^2}{8\pi^2}\frac{M_1\mu}{m}$ … $\frac{M_1}{m_{\tilde\mu_R}},\frac{\mu}{m_{\tilde\mu_R}}\Big)$

negative

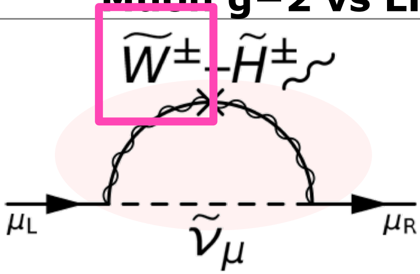
[BHL] $\frac{g_Y^2 m_\mu^2}{16\pi^2}$ … $,\frac{\mu}{m_{\tilde\mu_L}}\Big)$

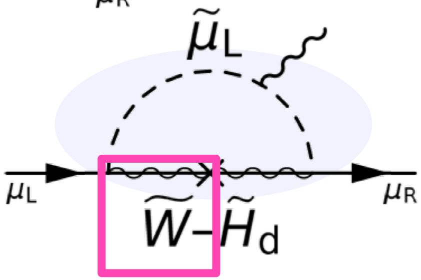
nothing special

F_a, F_b are loop functions and positive.

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

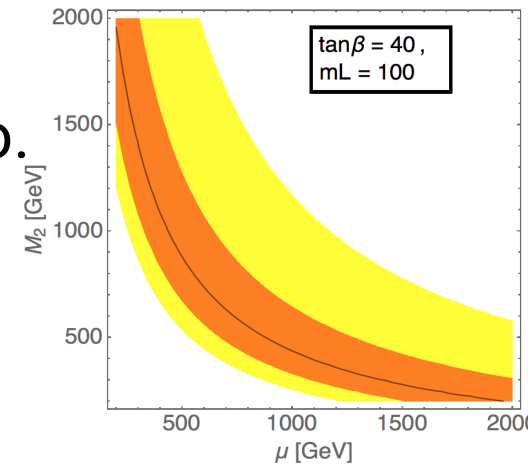
$$C_1(x)=\frac{3-4x+x^2+2\log x}{(1-x)^3},\qquad N_2(x)=\frac{1-x^2+2x\log x}{(1-x)^3}.$$





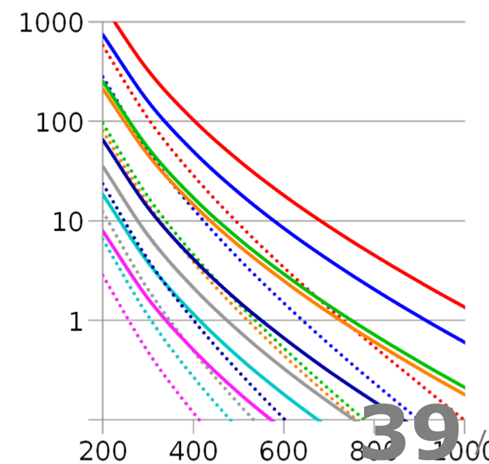
$$\frac{g_2^2 m_\mu^2}{8\pi^2}\frac{M_2 \mu \tan\beta}{m_{\tilde{\nu}_\mu}^4}\cdot F_a\left(\frac{M_2}{m_{\tilde{\nu}_\mu}},\frac{\mu}{m_{\tilde{\nu}_\mu}}\right)$$

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

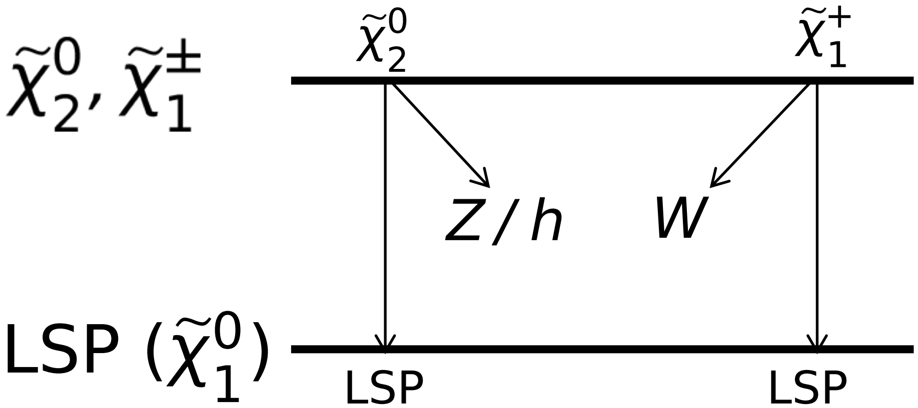


- Wino&Higgsino < TeV → chargino scenario.
  - $\propto g_2^2$ → relevant particles $\lesssim$ 1 TeV
  - DM: not considered here
    - $(g-2)_\mu \Leftarrow (\widetilde{W},\widetilde{H},\tilde{\mu}_L)$;   DM $\Leftarrow (\tilde{l}_L,\widetilde{B})$ ... "orthogonal"
    - co-annihilation or resonance may work.
      $(m_{\widetilde{B}} \simeq m_{\tilde{l}})$ $(m_{\widetilde{B}} \simeq m_Z/2$ or $m_h/2)$
  - LHC: Wino pair-production

$$\sigma(pp \to \widetilde{W}\widetilde{W})_{14\,\mathrm{TeV}} \sim 50\,\mathrm{fb} \quad @\ m_{\widetilde{W}} = 500\,\mathrm{GeV}$$
$$1.5\,\mathrm{fb} \qquad 1\,\mathrm{TeV}$$



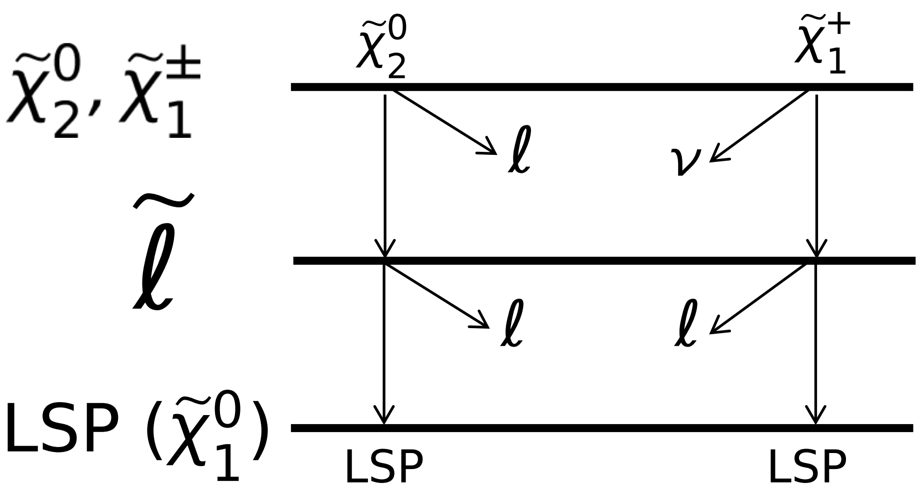
$pp \to \tilde{\chi}^0 \tilde{\chi}^+ \;\; (\widetilde{W}^0 \widetilde{W}^+$ or $\widetilde{H}^0 \widetilde{H}^+)$; then?



$\tilde{\chi}_2^0 \tilde{\chi}_1^+ \to ZW/hW + \text{mET}$

$(\to 3\ell + \text{mET})$

but Z-like leptons

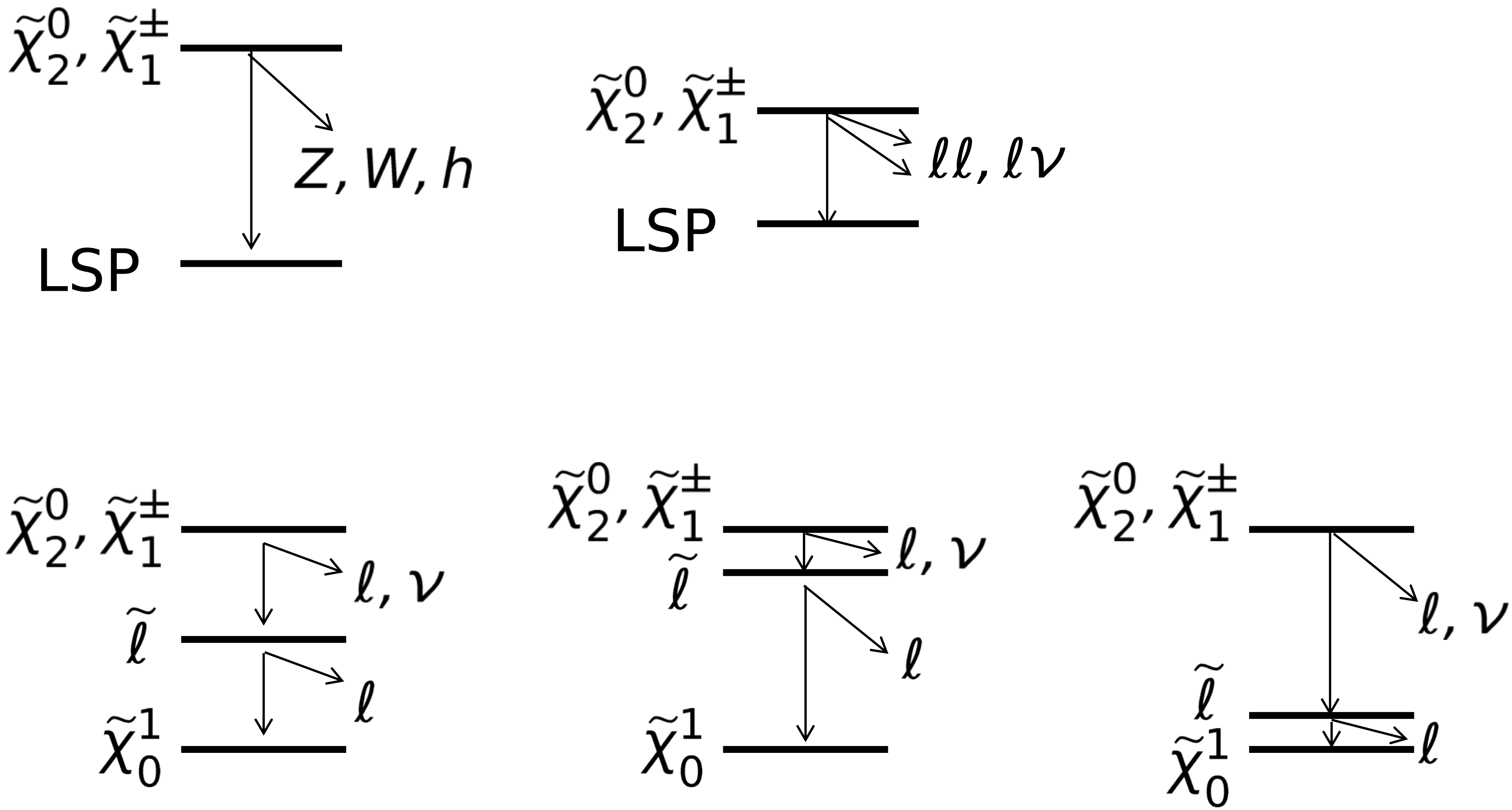


$\tilde{\chi}_2^0 \tilde{\chi}_1^+ \to 3\ell + \text{mET}$

Z-unlike

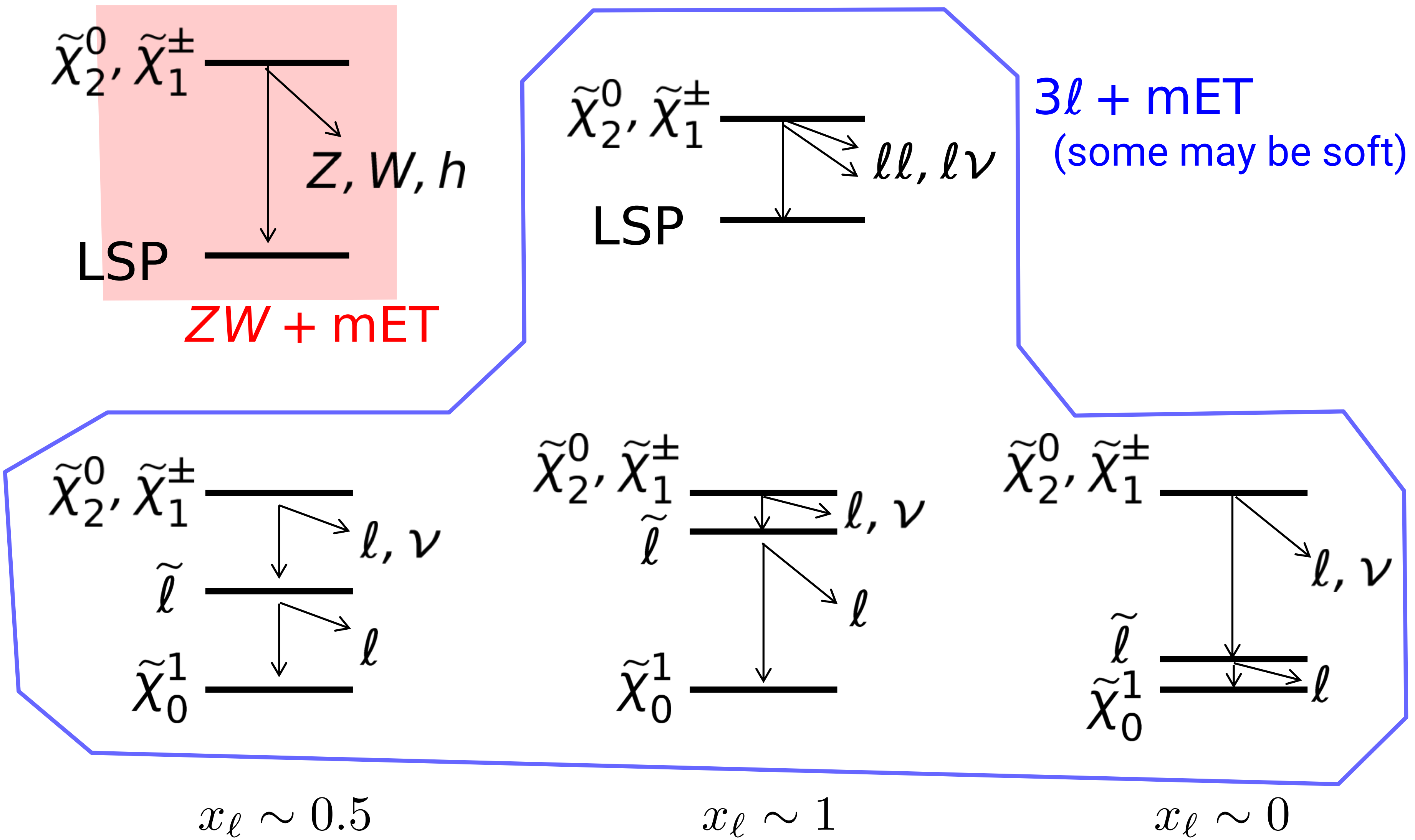
"Chargino" scenario may give multi-lepton signature. Endo, Hamaguchi, SI, Yoshinaga [1303.4256]

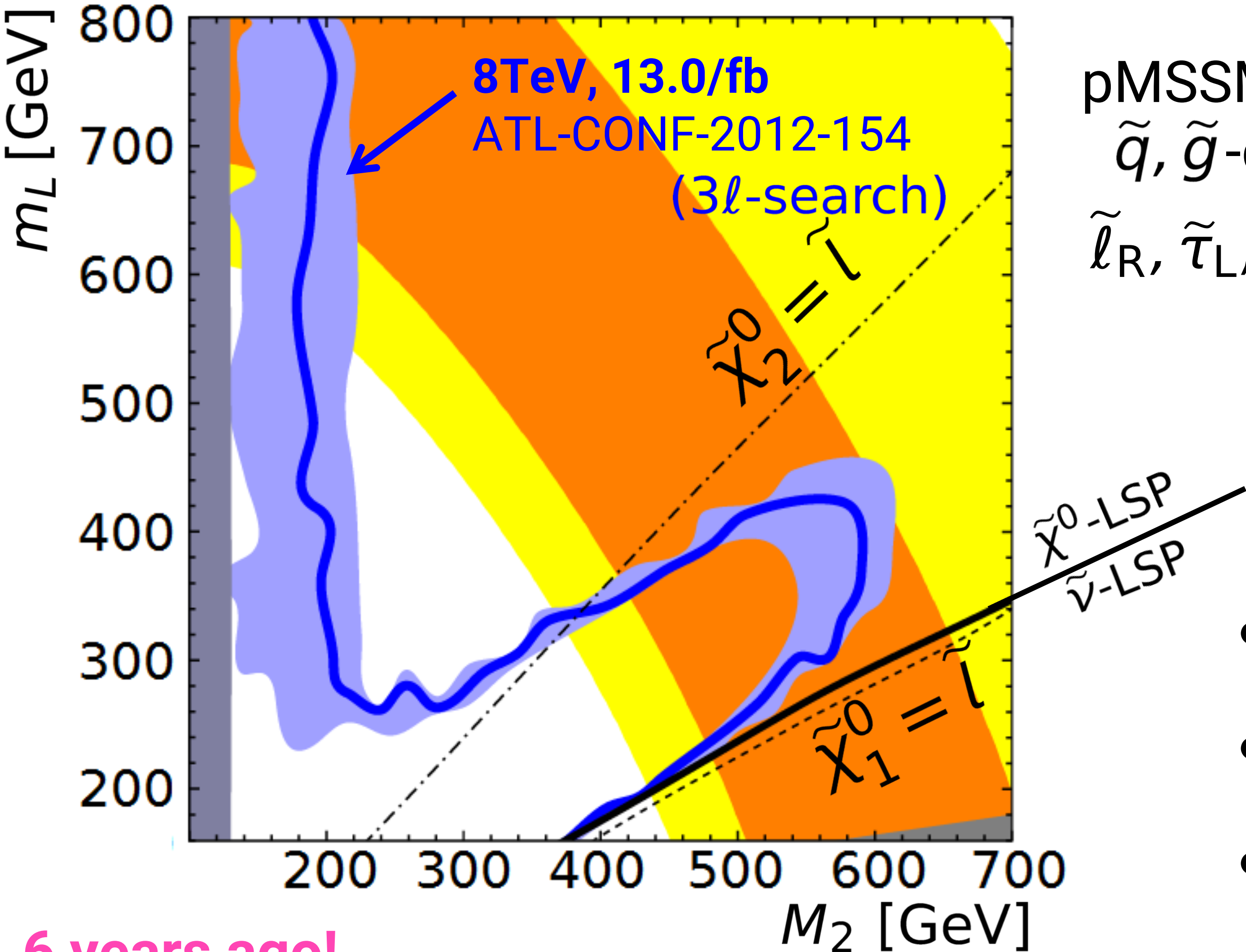
$pp \to \tilde{\chi}^0 \tilde{\chi}^+ \ (\widetilde{W}^0 \widetilde{W}^+$ or $\tilde{H}^0 \tilde{H}^+)$; then?



$x_\ell \sim 0.5$ $x_\ell \sim 1$ $x_\ell \sim 0$

$pp \to \tilde{\chi}^0 \tilde{\chi}^+$ $(\widetilde{W}^0 \widetilde{W}^+$ or $\widetilde{H}^0 \widetilde{H}^+)$; then?

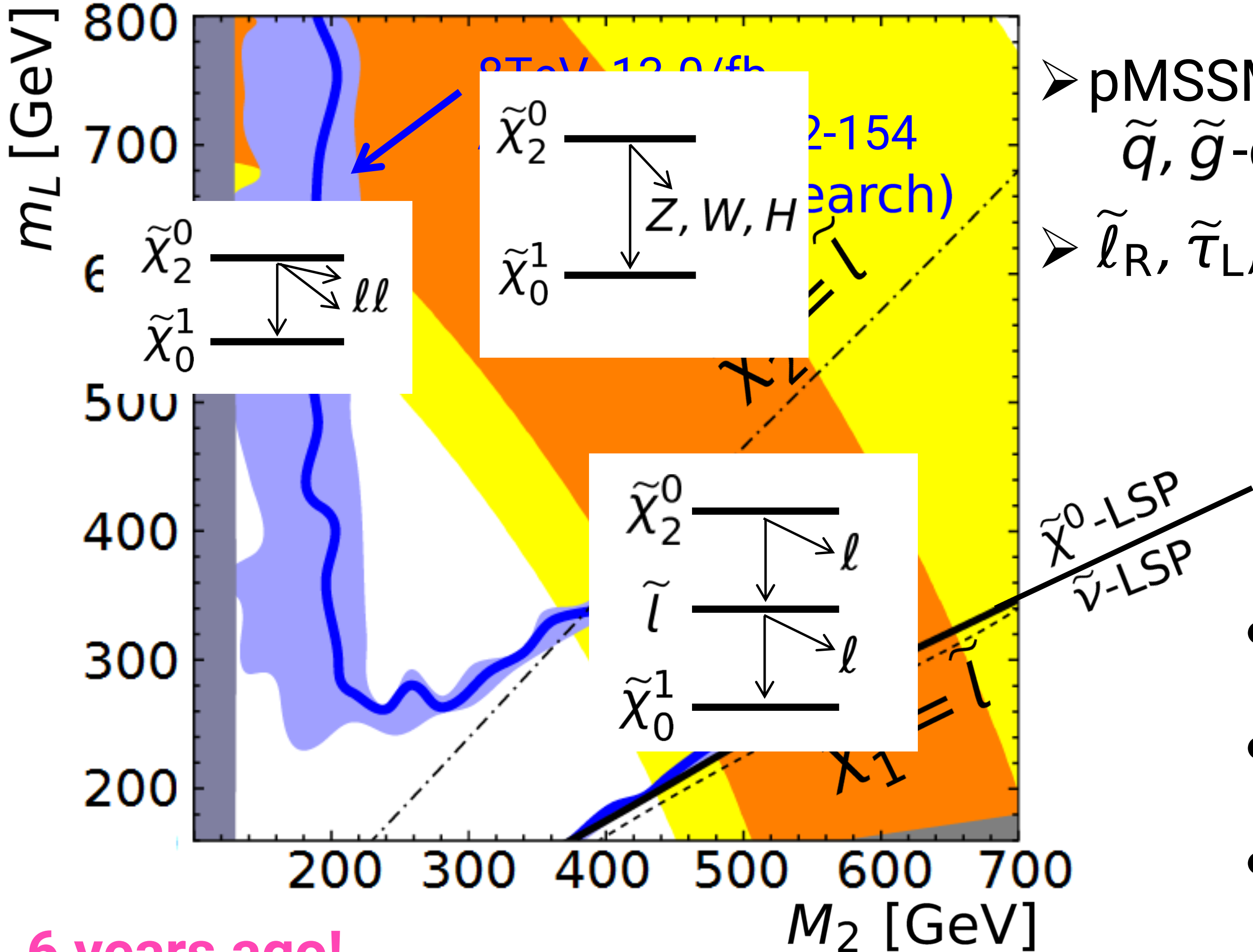




pMSSM w.
$\tilde{q}, \tilde{g}$-decoupled.
$\tilde{\ell}_R, \tilde{\tau}_L, \tilde{\tau}_R$ also decoupled.

- $\tan\beta = 40$
- $M_1 = M_2/2$
- $\mu = M_2$

6 years ago!



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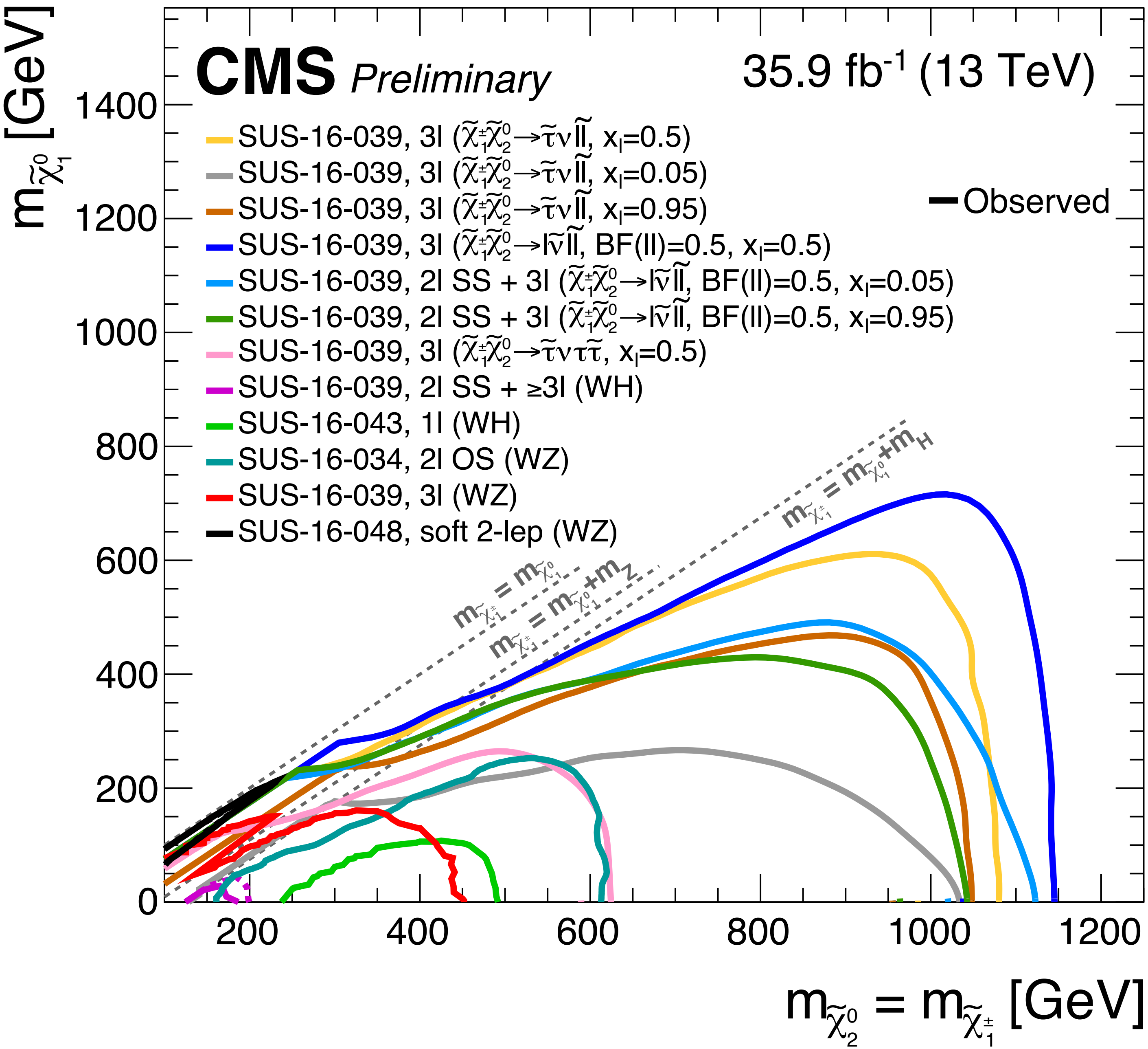
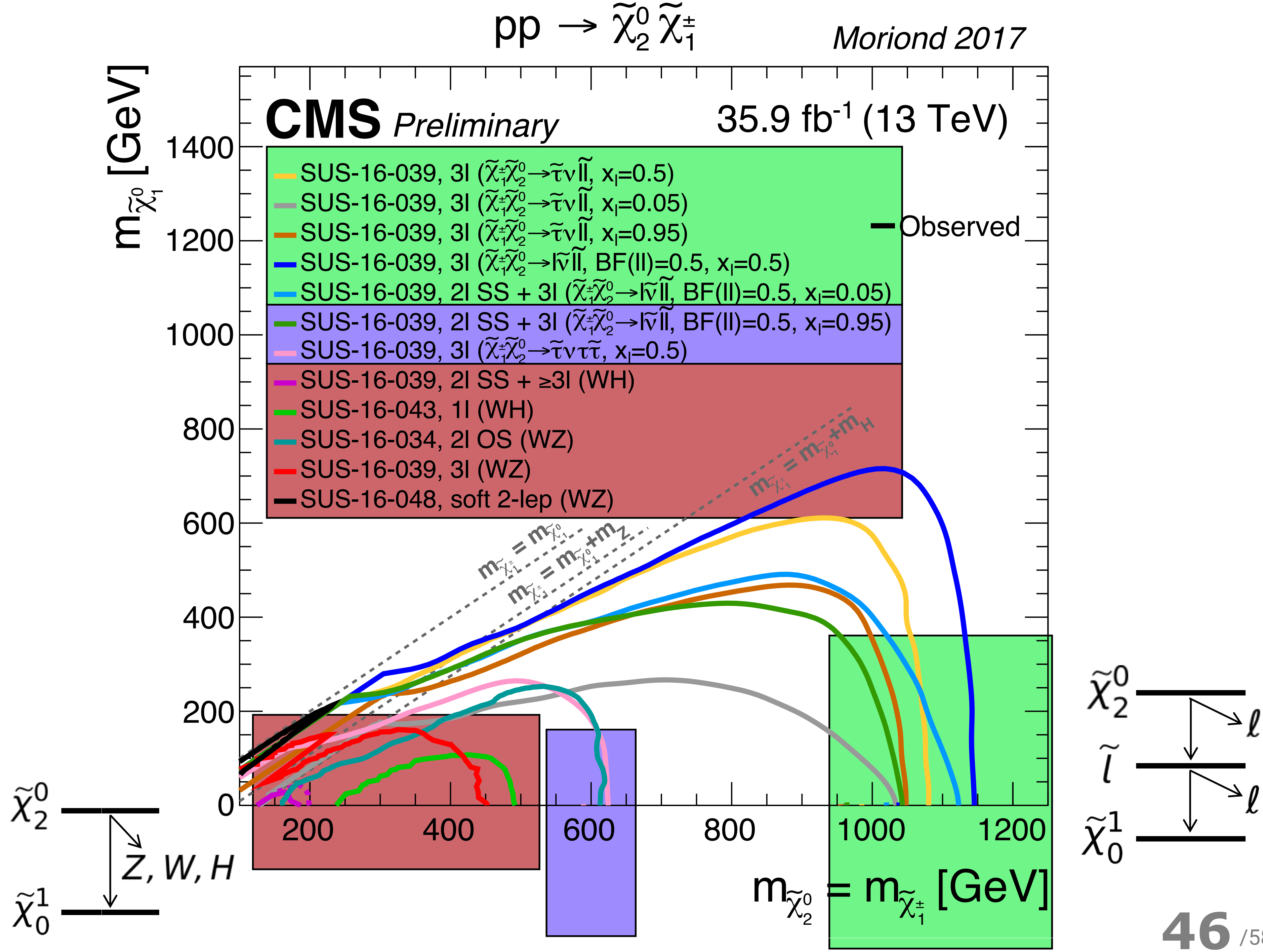
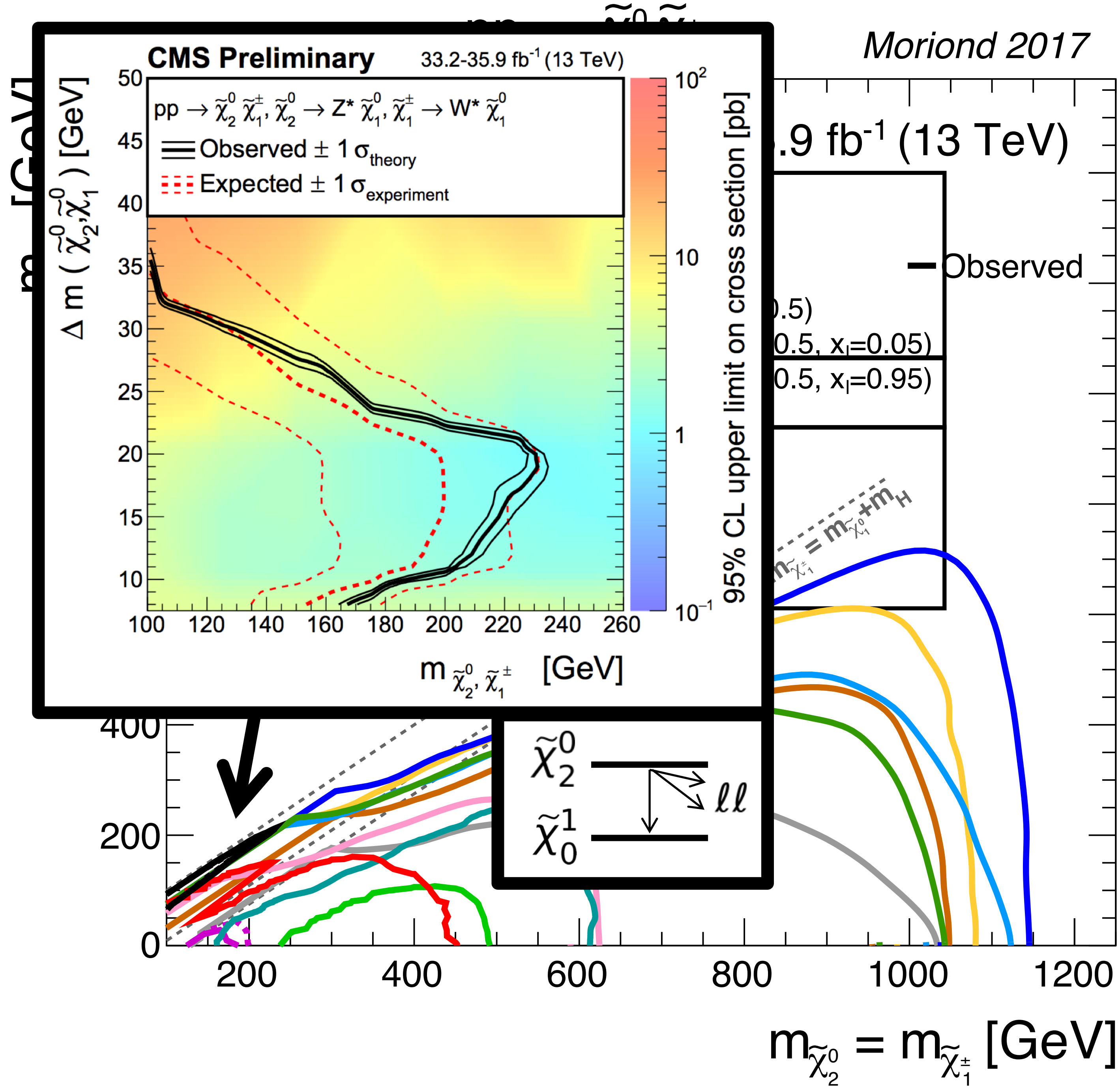
6 years ago!

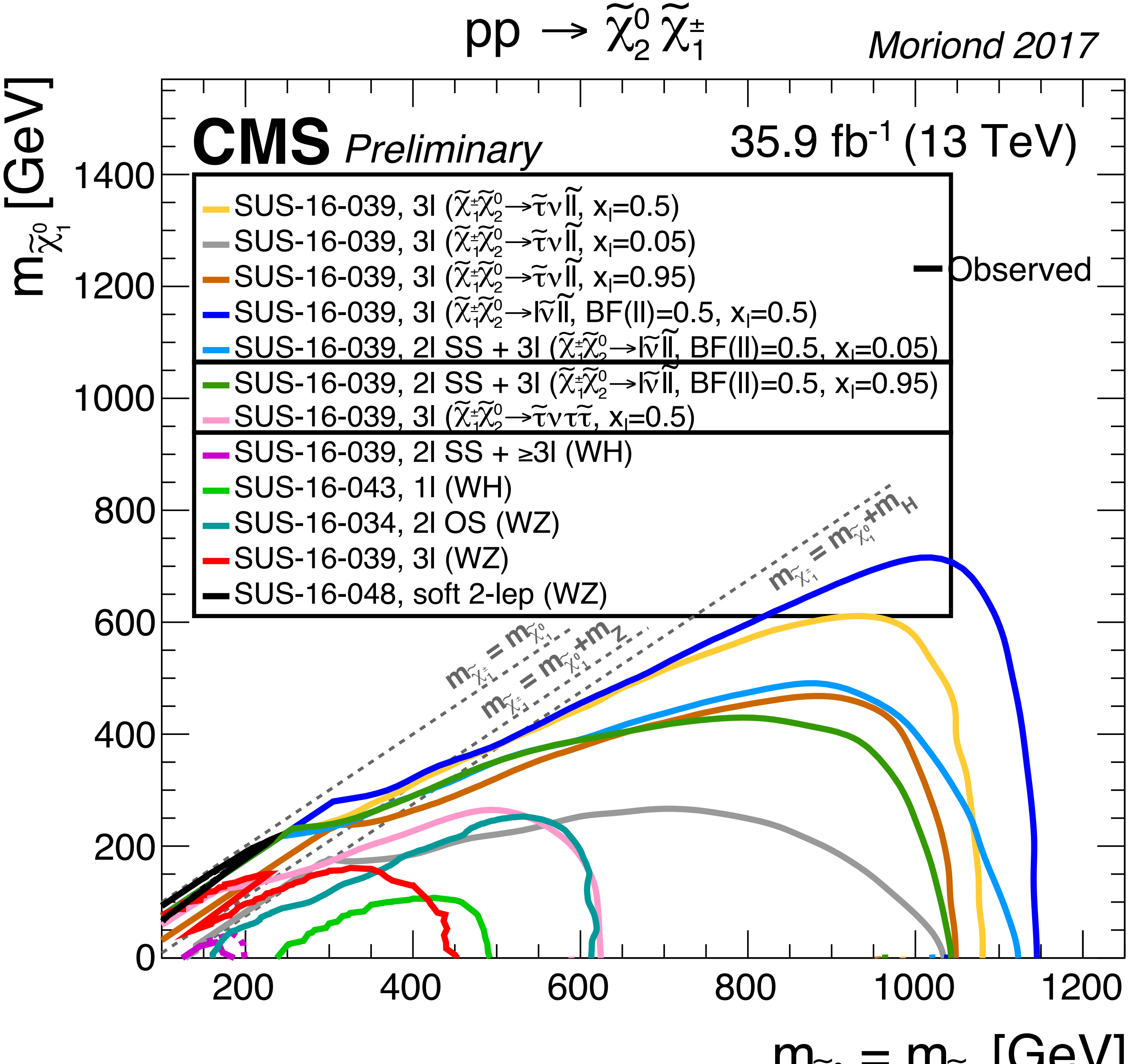
$pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ *Moriond 2017*





$pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$
Moriond 2017
CMS Preliminary
35.9 fb^{-1} (13 TeV)
SUS-16-039, 3l ($\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow \tilde{\tau}\nu\tilde{l}l$, x_l=0.5)
SUS-16-039, 3l ($\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow \tilde{\tau}\nu\tilde{l}l$, x_l=0.05)
SUS-16-039, 3l ($\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow \tilde{\tau}\nu\tilde{l}l$, x_l=0.95)
SUS-16-039, 3l ($\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow l\tilde{\nu}\tilde{l}l$, BF(ll)=0.5, x_l=0.5)
SUS-16-039, 2l SS + 3l ($\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow l\tilde{\nu}\tilde{l}l$, BF(ll)=0.5, x_l=0.05)
SUS-16-039, 2l SS + 3l ($\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow l\tilde{\nu}\tilde{l}l$, BF(ll)=0.5, x_l=0.95)
SUS-16-039, 3l ($\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow \tilde{\tau}\nu\tau\tilde{\tau}$, x_l=0.5)
SUS-16-039, 2l SS + ≥3l (WH)
SUS-16-043, 1l (WH)
SUS-16-034, 2l OS (WZ)
SUS-16-039, 3l (WZ)
SUS-16-048, soft 2-lep (WZ)
Observed
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}+m_H$
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}+m_Z$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm}$ [GeV]
0
200
400
600
800
1000
1200
1400
$\tilde{\chi}_2^0$
$\tilde{\chi}_0^1$
Z, W, H
$\tilde{l}$
ℓ
ℓ


Moriond 2017
CMS Preliminary
33.2-35.9 fb^{-1} (13 TeV)
pp → $\tilde{\chi}^0_2 \tilde{\chi}^\pm_1$, $\tilde{\chi}^0_2$ → Z* $\tilde{\chi}^0_1$, $\tilde{\chi}^\pm_1$ → W* $\tilde{\chi}^0_1$
Observed ± 1 σ_{theory}
Expected ± 1 $\sigma_{experiment}$
Δ m ($\tilde{\chi}^0_2,\tilde{\chi}^0_1$) [GeV]
$m_{\tilde{\chi}^0_2, \tilde{\chi}^\pm_1}$ [GeV]
95% CL upper limit on cross section [pb]
.9 fb^{-1} (13 TeV)
Observed
.5)
0.5, x_l=0.05)
0.5, x_l=0.95)
$m_{\tilde{\chi}^\pm_1} = m_{\tilde{\chi}^0_1} + m_H$
$\tilde{\chi}^0_2$
$\tilde{\chi}^1_0$
$\ell\ell$
$m_{\tilde{\chi}^0_2} = m_{\tilde{\chi}^\pm_1}$ [GeV]



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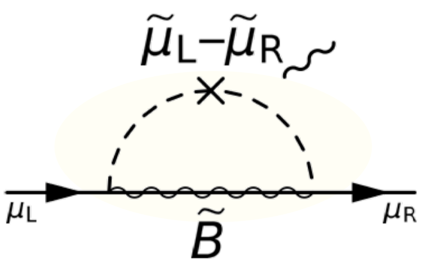
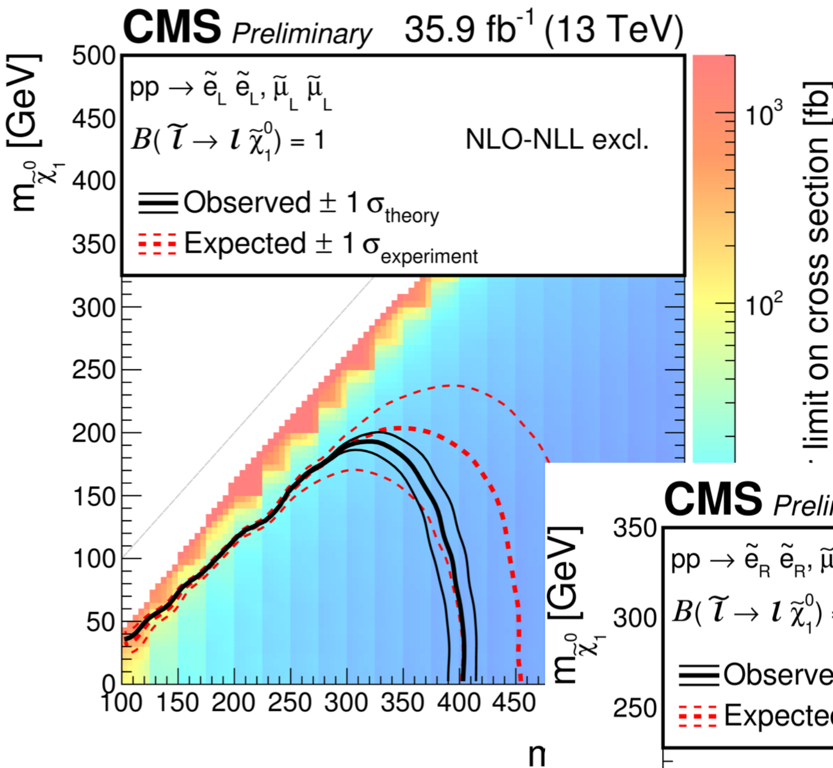


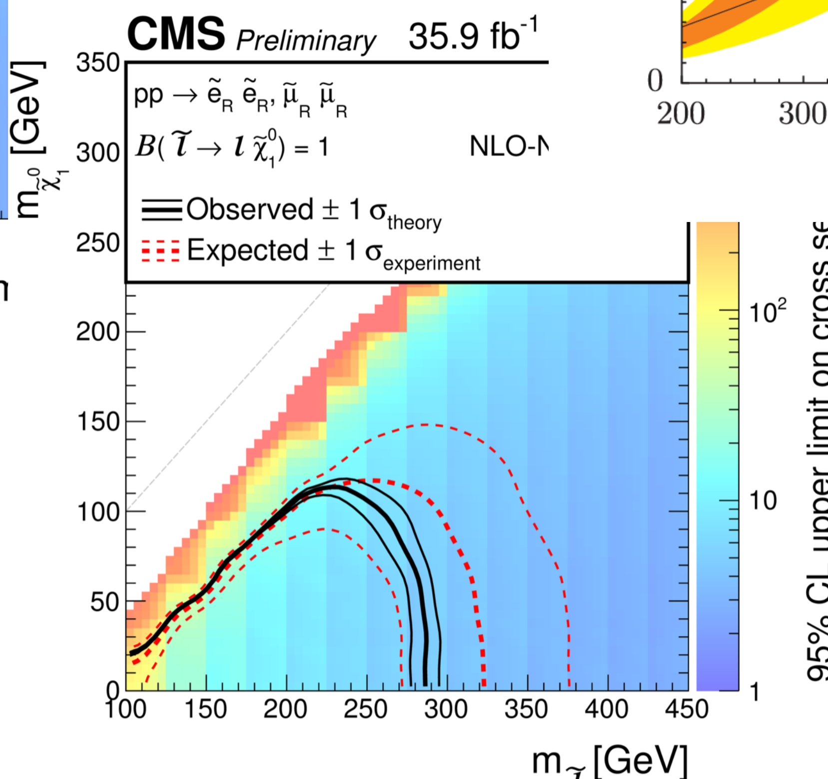
[B] $$\frac{g_Y^2 m_\mu^2}{8\pi^2} \ldots , \frac{m_{\tilde\mu_R}}{M_1}\Big)$$

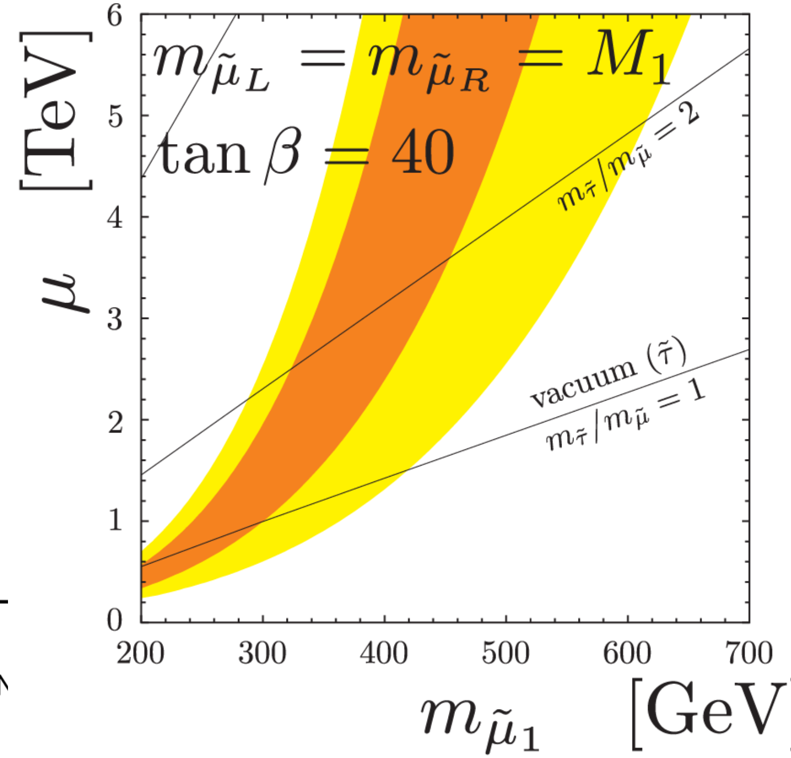
μ-enhancement

  - LHC: only slepton pair-production
    - small cross section: 0.47 (0.18) fb for 500 GeV $\tilde\ell_L$ ($\tilde\ell_R$)
    - "di-lepton + missing" signature ... not easy.

Muon $g-2$ vs LHC (2) Pure-bino contribution results in slepton pair-production







top-right figure from Endo, Hamaguchi, Kitahara, Yoshinaga [1309.3065]

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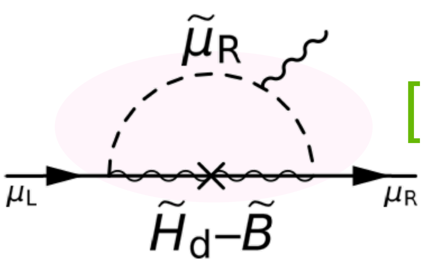
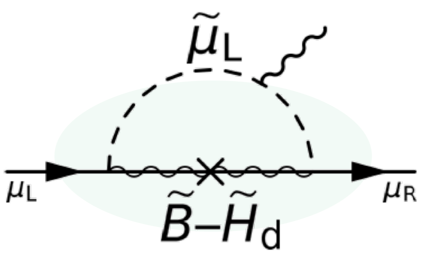
- Wino >> TeV & Higgsino < TeV → BHL or BHR scenario.
  $(\mu > 0)$ $(\mu < 0)$
  - $\propto g_Y^2$ → relevant particles $\lesssim 500\,\mathrm{GeV}$
  - LHC: $pp \to \widetilde{H}^+\widetilde{H}^0,\ \widetilde{H}^+\widetilde{H}^-$ "not much, but enough"
  - excl. by XENON1T
    DM: ~~Bino−Higgsino mixing~~, bino−slepton co-annihilation.





[BHR]
$$-\frac{g_Y^2 m_\mu^2}{8\pi^2}\frac{M_1\mu\tan\beta}{m_{\widetilde{\mu}_\mathrm{R}}^4}\cdot F_b\left(\frac{M_1}{m_{\widetilde{\mu}_\mathrm{R}}},\frac{\mu}{m_{\widetilde{\mu}_\mathrm{R}}}\right)$$

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

F_a, F_b are loop functions and positive.

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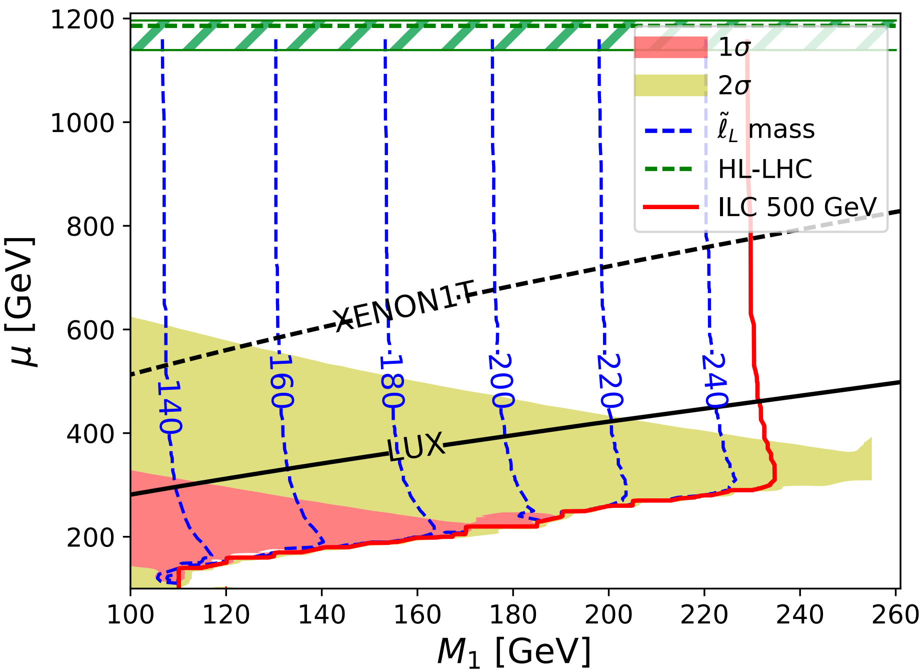
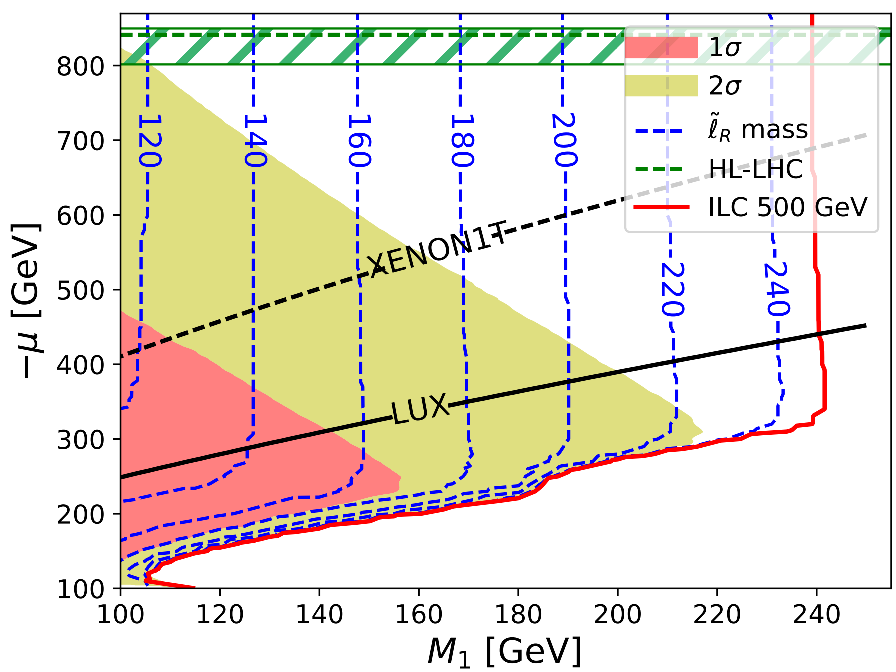
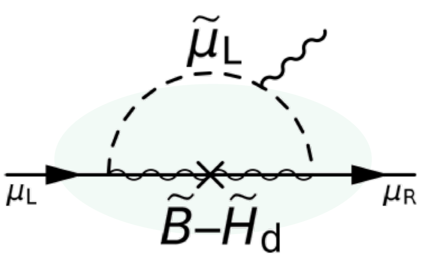
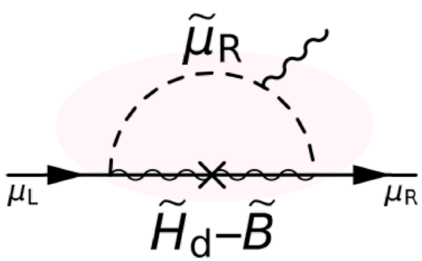
  - DM: ~~Bino−Higgsino mixing~~ excl. by XENON1T, bino−slepton co-annihilation.



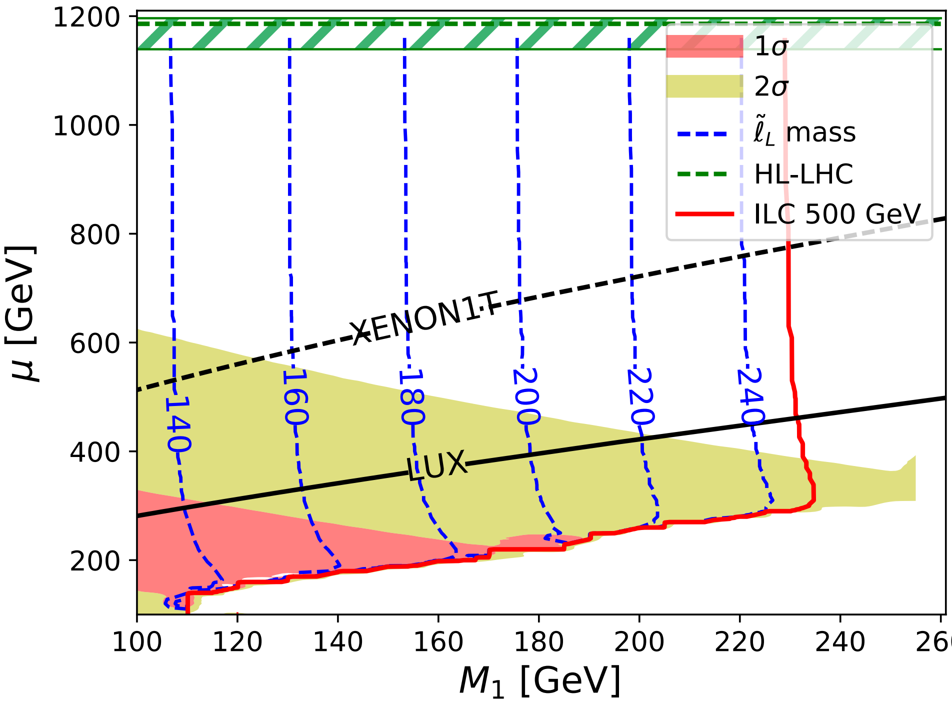






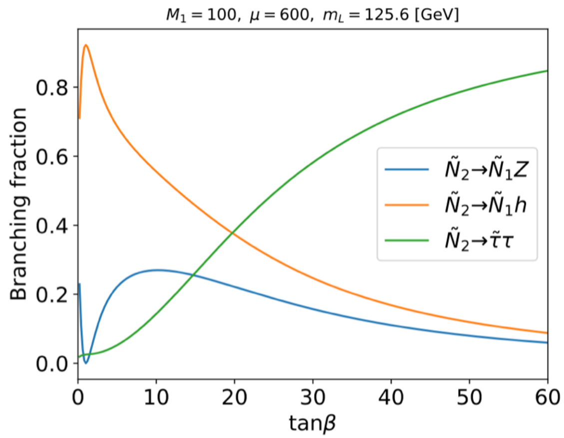
- Bino−slepton (stau) co-annihilation → $m_{\tilde{\nu}_\tau}$ (or $m_{\tilde{\tau}_R}$) $\simeq m_{\tilde{B}}$.
- We assumed:
  - slepton universality,
  - DM density is realized at each point in the plots.

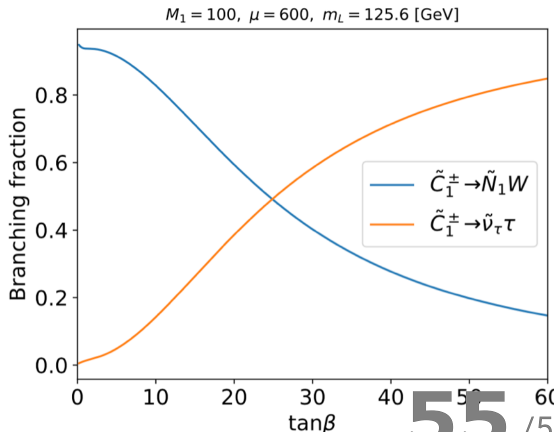
  → $m_{\tilde{B}} \lesssim m_{\tilde{\mu}} < m_{\tilde{H}}$
  $(\sim M_1)$ $(\sim \mu)$

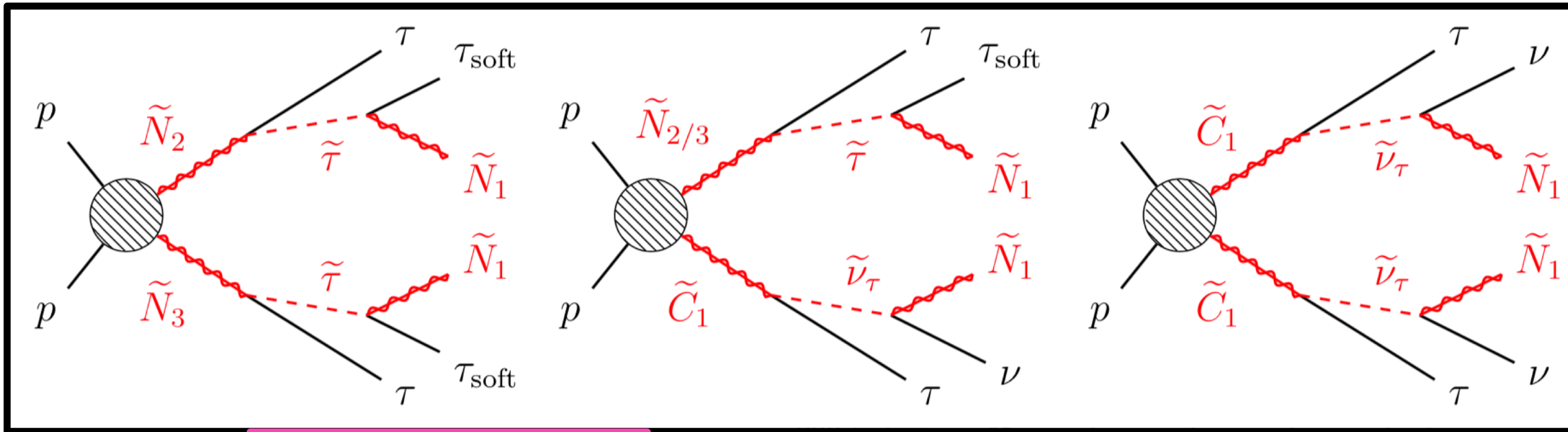


- HL-LHC?
  - $pp \to \tilde{H}^+\tilde{H}^0,\ \tilde{H}^+\tilde{H}^-$
  - $\tilde{H}^0 \to \tau\tilde{\tau},\ \ \tilde{H}^+ \to \tau\tilde{\nu}_\tau$ because of tanβ

  → multi-tau signature

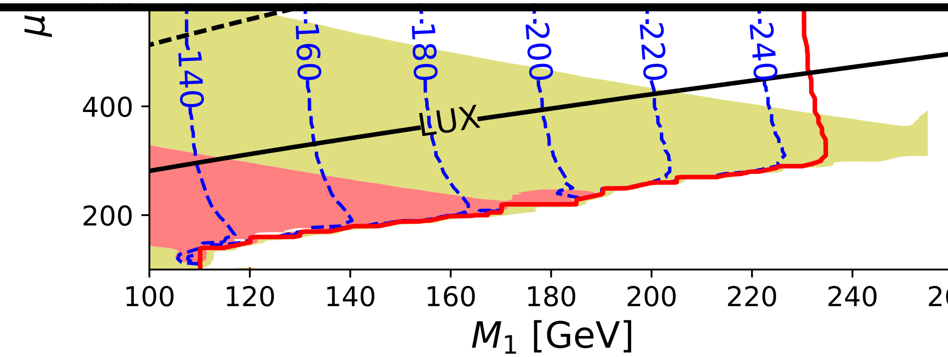






→ $\boxed{m_{\widetilde{B}} \lesssim m_{\widetilde{\mu}} < m_{\widetilde{H}}}$

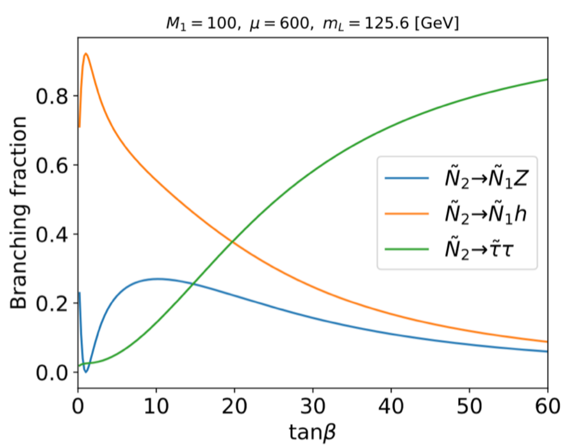
($\sim M_1$) ($\sim\mu$)

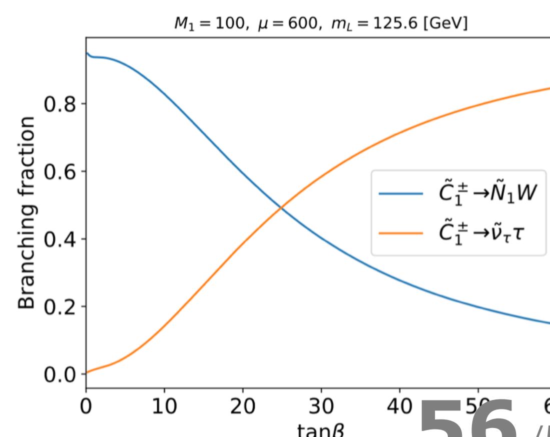


- HL-LHC?
  - $pp \to \widetilde{H}^+\widetilde{H}^0,\ \widetilde{H}^+\widetilde{H}^-$
  - $\widetilde{H}^0 \to \tau\widetilde{\tau},\ \ \widetilde{H}^+ \to \tau\widetilde{\nu}_\tau$ because of tanβ

→ multi-tau signature

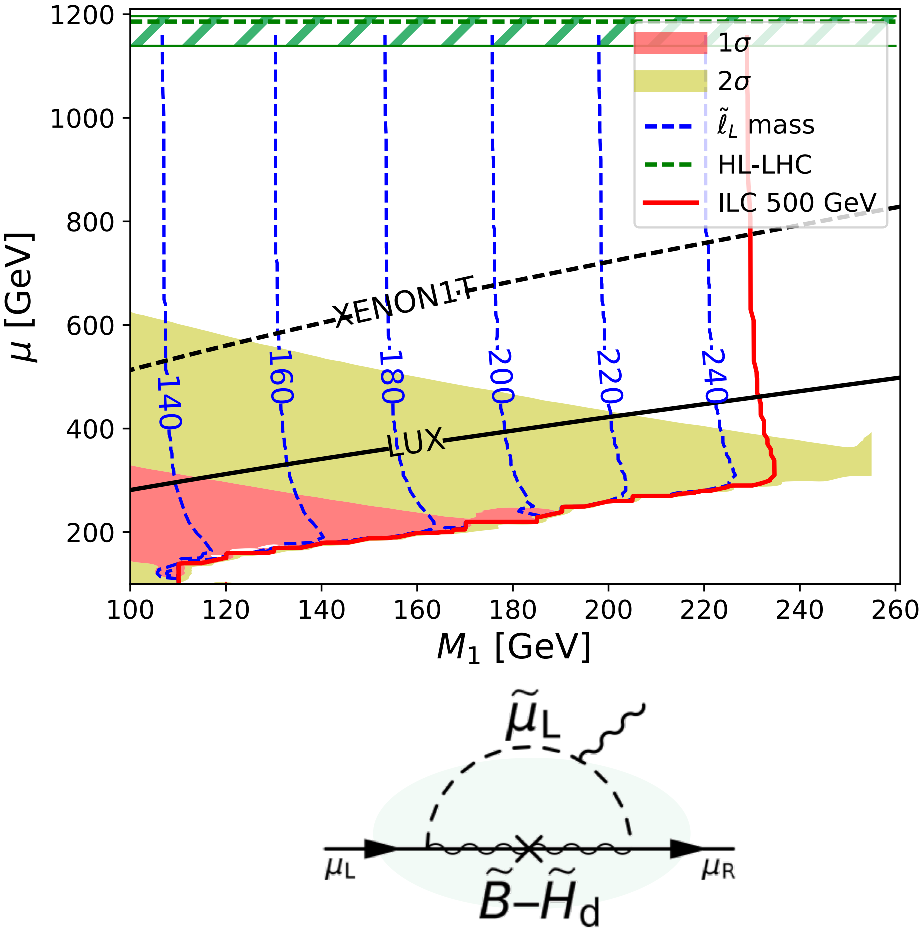
"2τ (+ soft) **+ missing"**

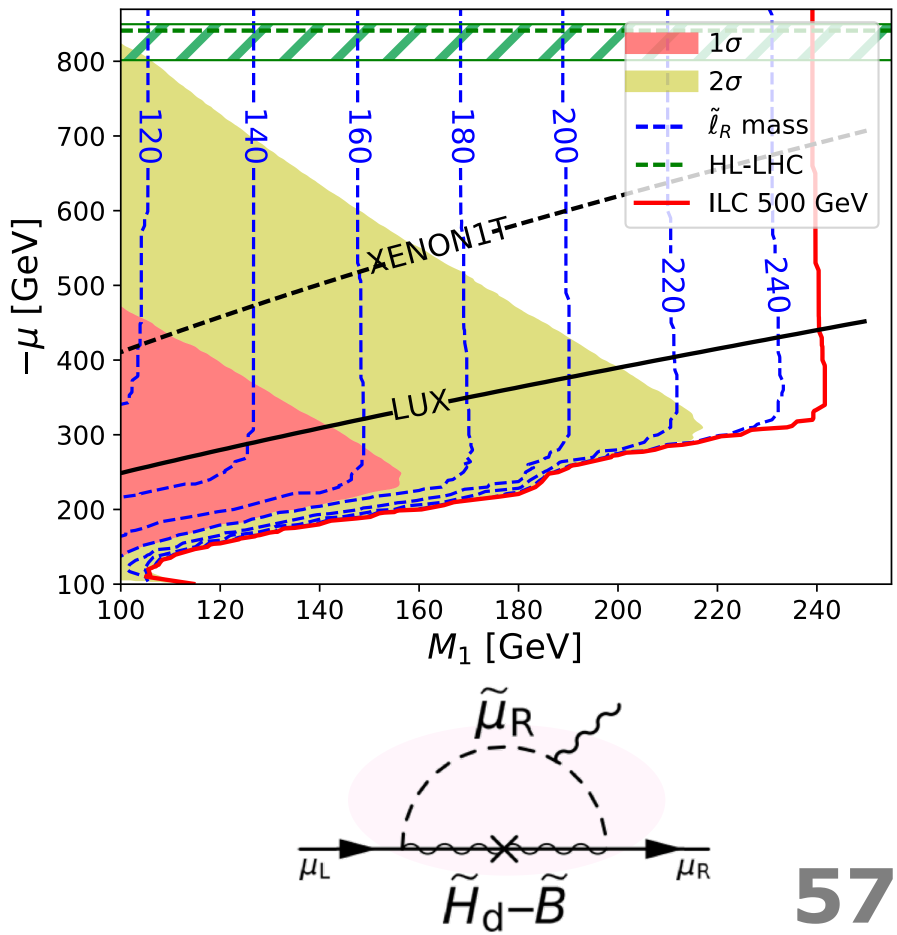




($\mu > 0$) ($\mu < 0$)

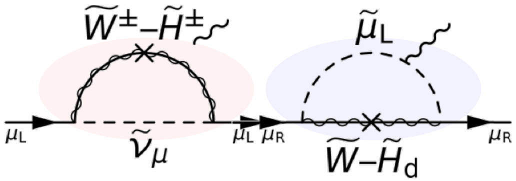
- Wino >> TeV & Higgsino < TeV → BHL or BHR scenario.
  - DM: Bino−stau co-annihilation → $m_{\tilde{B}} \simeq (m_{\tilde{\tau}_R}$ or $m_{\tilde{\nu}_\tau}) \lesssim m_{\tilde{\mu}} < m_{\tilde{H}}$
  - DM has small Higgsino component → **LUX/XENON1T** constraint.
  - LHC: $pp \to \tilde{H}^+\tilde{H}^0,\ \tilde{H}^+\tilde{H}^-;\ \ \tilde{H} \to \tau + \cdots$ **"2τ+missing"** signature

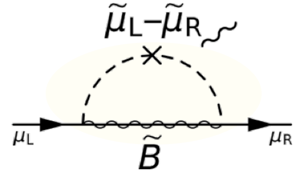


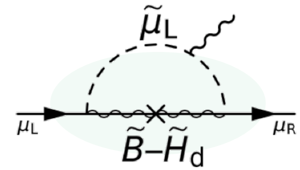


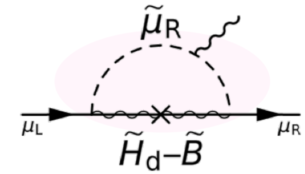
Scenario:

"chargino" | "pure-Bino" | BHL / BHR









$\widetilde{W}, \widetilde{H} \lesssim$ TeV | $\widetilde{H} >$ TeV | $\widetilde{H} <$ TeV

DM:

"orthogonal" (determined by $m_{\widetilde{B}}$)

... coannihilation / resonance

($m_{\widetilde{B}} \simeq m_{\tilde{l}}$) ($m_{\widetilde{B}} \simeq m_Z/2$ or $m_h/2$)

coannihilation / resonance

we discussed

future work

Collider:

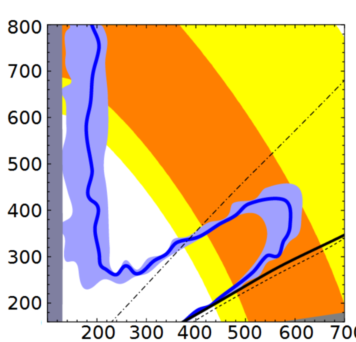
multi-lepton
→ promising

("stay tuned!")

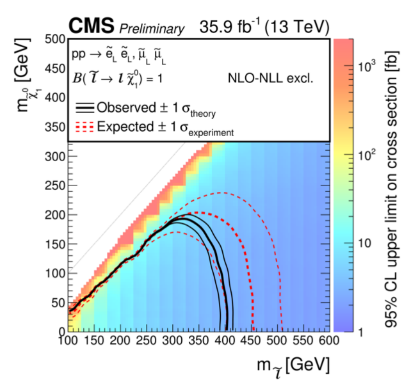
di-lepton
→ **difficult @LHC**

Higgsino → multi-tau

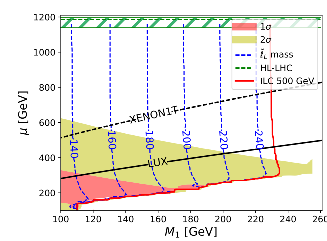
"**covered@HL-LHC**
if we seriously consider
the relic density"

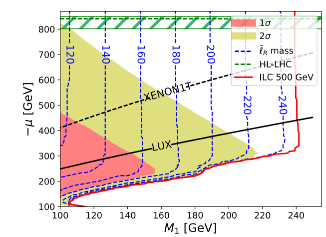


Endo, Hamaguchi, ***SI***, Yoshinaga [1303.4256]



(cf. Endo, Hamaguchi, Kitahara, Yoshinaga [1309.3065])





Endo, Hamaguchi, ***SI***, Yanagi [1704.05287]