MSSM in the light of $(g-2)_\mu$ and DM

Sho IWAMOTO（岩本　祥）

30 Apr. 2018
Seminar @ Korea University

Based on

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

and a few ongoing projects.

N.B. partially overlapped with my plenary talk @ Gwangju (18–19 Oct. 2016)

1. Introduction

- Why did we expect new physics @ LHC?
- $(g-2)_\mu$ anomaly

2. Four scenarios of MSSM as the solution of $(g-2)_\mu$ anomaly

- Overview
- Collider physics
- Dark Matter

3. Discussion for each scenario

- "Chargino" scenario: multi-lepton signature is promising.
- "Pure-bino" scenario: di-lepton, but production not sufficient.
- "BHR" or "BHL": multi-tau, combined with direct detections.

- LHC found a Higgs boson, and nothing else.
  - *"Crisis is no longer a whispered word, but it's openly discussed"* from "Resonaances".
  - But we need new physics.

- Three directions (proposed in the blog post)
  - Astrophysics — for DM, baryogenesis, inflation,
  - Precision physics — for neutrino mass, Higgs sector, *B*-anomalies(?),
  - Formal theoretical developments.

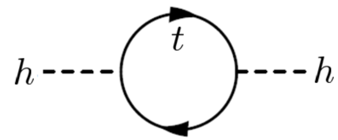
  - But also: **LHC physics until its last day.** ...high risk, high return.

- Motivation for LHC? (i.e., for students in ATLAS/CMS groups)

  $\equiv$ for 0.1–1 TeV new particles.

  - $(g-2)_\mu$ anomaly → next slides [g−2 = anomalous magnetic moment]
  - Hierarchy problem

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



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

→ New physics @ 0.1–1 TeV?

  - Dark matter "WIMP miracle"

simplest scenario predicts (DM as a thermal relic, freezing out by pair-annihilation)

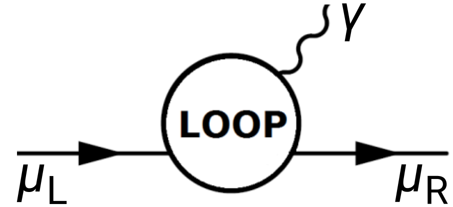
$$\langle\sigma v\rangle_{\text{DM DM}\to\text{any}} \sim 3\times10^{-26}\,\text{cm}^3/\text{s} = \frac{\alpha_{\text{em}}^2}{(150\,\text{GeV})^2}.$$

→ DM @ ~100 GeV?

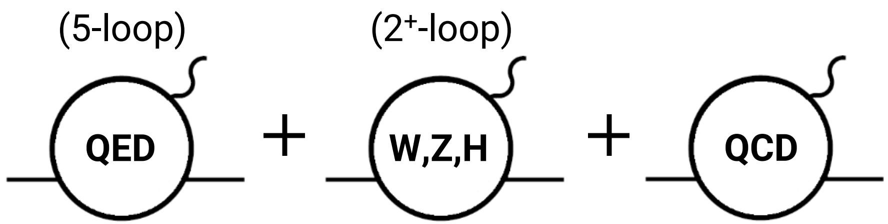
$$\Omega_{\text{DM}}h^2 \approx \frac{1.1\times10^9\cdot x_{\text{f}}}{\sqrt{g_*}M_{\text{pl}}\langle\sigma v\rangle\cdot\text{GeV}} \approx 0.1\cdot\frac{15}{\sqrt{g_*}}\frac{x_{\text{f}}}{30}\frac{3\times10^{-26}\,\text{cm}^3/\text{s}}{\langle\sigma v\rangle} \quad \text{with } x_{\text{f}} = m_{\text{DM}}/T_{\text{fo}}.$$

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

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



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



$$a_\mu(\text{QED}) = (11\,658\,471.886 \pm 0.003) \times 10^{-10},$$
$$a_\mu(\text{EW}) = (\quad 15.36 \pm 0.11 \quad) \times 10^{-10},$$

SM combination according to Jegerlehner [1804.07409].
QED: Aoyama, Hayakawa, Kinoshita, Nio [1205.5370] (cf. [1712.06060]).
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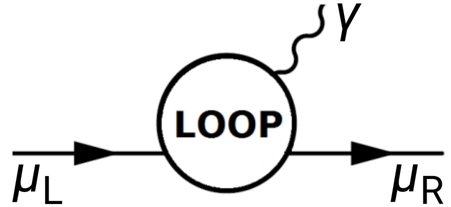

(5-loop) (2⁺-loop) (dispersion rel.) (low-energy EFT)

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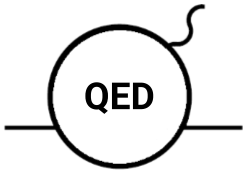

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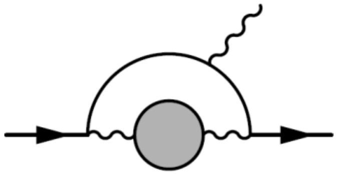

had. vac. polarization

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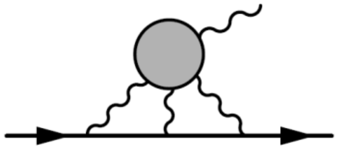

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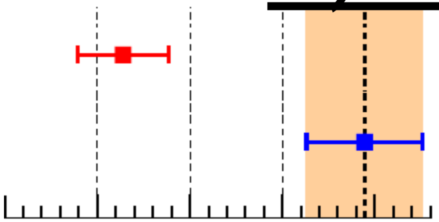

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[FermiLab: ±1.6]

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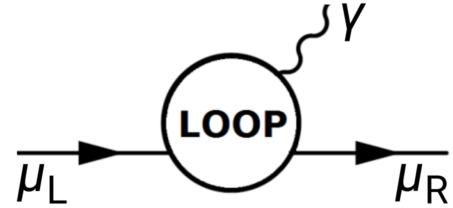

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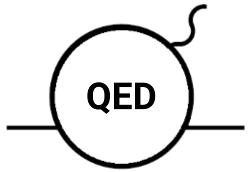

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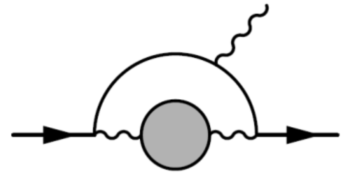

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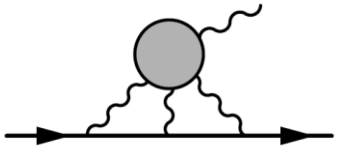

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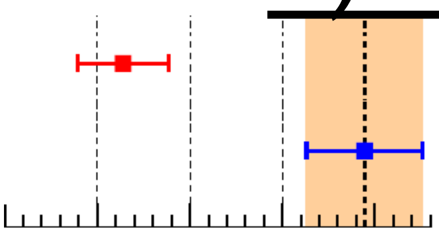

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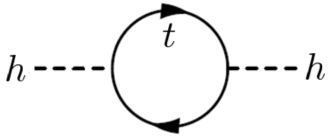
Motivation for LHC? (i.e., for students in ATLAS/CMS groups)

- $(g-2)_\mu$ anomaly $\Delta a_\mu = 10\times10^{-10} \approx \frac{\alpha_{\rm em}}{4\pi}\left(\frac{m_\mu}{200\,\mathrm{GeV}}\right)^2$
- Hierarchy problem

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



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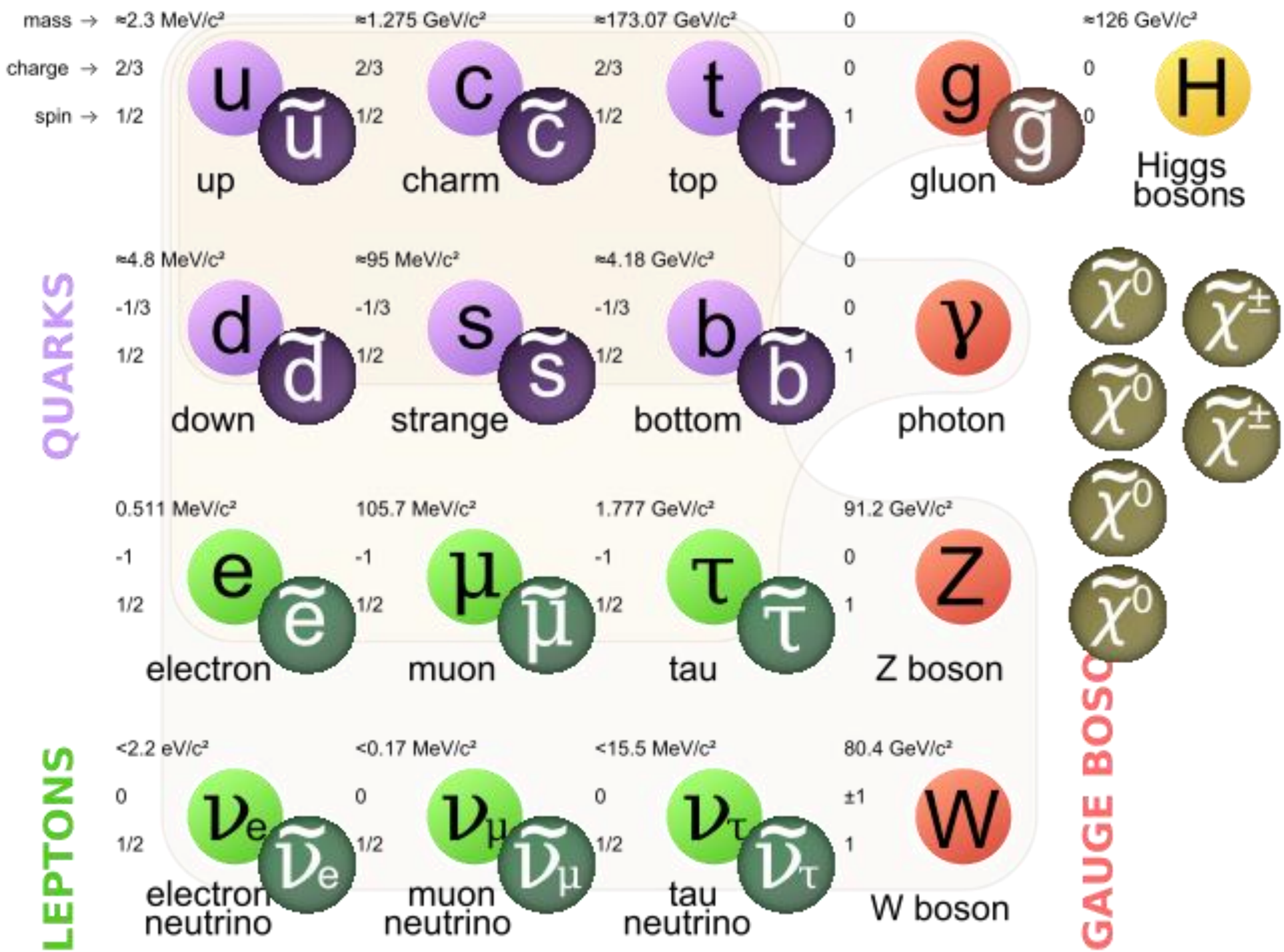
- MSSM = SUSY version of the Standard Model



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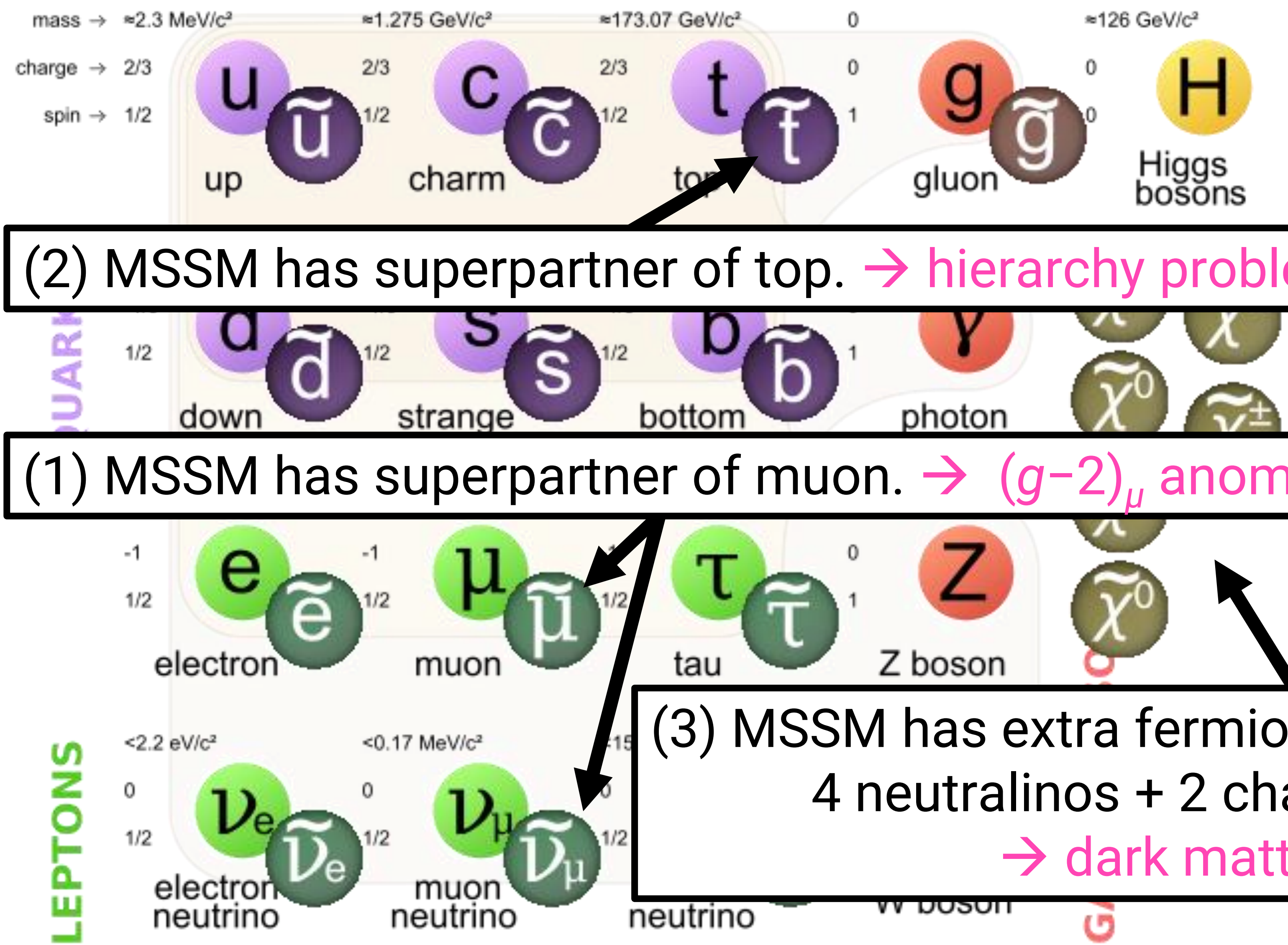
$$\tilde{\chi}^0_{1-4} = \tilde{B} \oplus \tilde{W}^0 \oplus \tilde{H}_d \oplus \tilde{H}_u, \quad \tilde{\chi}^{\pm}_{1,2} = \tilde{W}^{\pm} \oplus \tilde{H}^{\pm}.$$



(2) MSSM has superpartner of top. → hierarchy problem?

(1) MSSM has superpartner of muon. → $(g-2)_\mu$ anomaly?

(3) MSSM has extra fermions: 4 neutralinos + 2 charginos. → dark matter?

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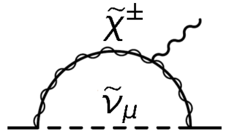
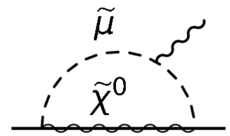
- ➢ $(g-2)_\mu$ anomaly : 

 + 

 may explain the anomaly

  if these particles are O(100) GeV.

  (we'll discuss later.)

- ➢ Hierarchy problem

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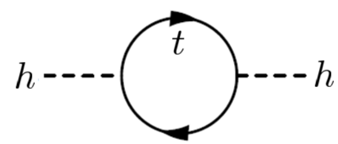

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  The lightest neutralino $\tilde{\chi}^0$ may be stable. → DM?

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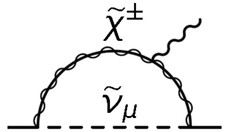
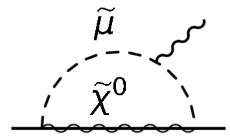
- $(g-2)_\mu$ anomaly : 

 + 

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  → top partner ("scalar top") should be $\lesssim$ 1 TeV!

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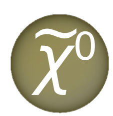
  The lightest neutralino 

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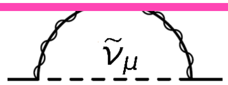
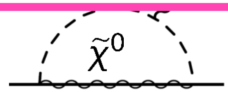
just 3−4σ from single experiment

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

 + 

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Not found yet.

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  - Dark matter "WIMP miracle" **depends on history of the universe**

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difficult to capture at the LHC

and we are about to be lost.

- MSSM = SUS[…] of the Standard Model

~~**just [...] single experiment**~~

- $(g-2)_\mu$ anom[…] + […] may explain the anomaly

  g−2 anomaly is actual!

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Muon g−2 anomaly: What is the origin?

- Just a statistical fluctuation.
- Just an issue in the experiment.
- $O(100)$ GeV particles with $O(0.1)$ couplings
  - MSSM
- keV−MeV particles with tiny couplings.
  - dark photon (extra U(1) gauge boson)

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$m_{\rm new}$ ~200GeV

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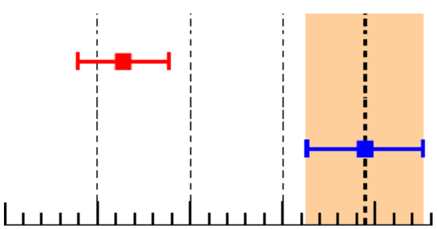

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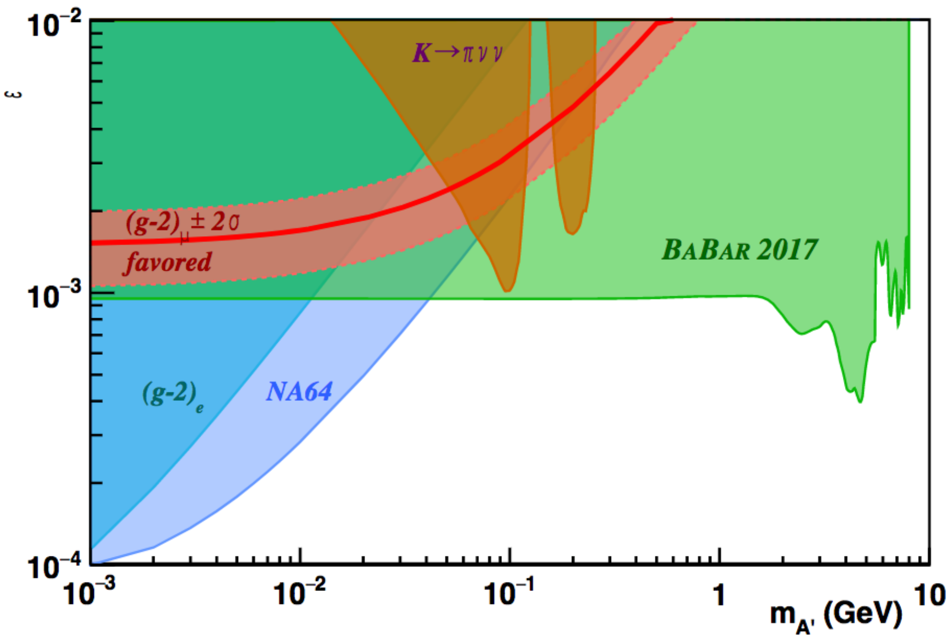

$e^+e^-\to\gamma A',\ A'\to$ invisible

BaBar [1702.03327]

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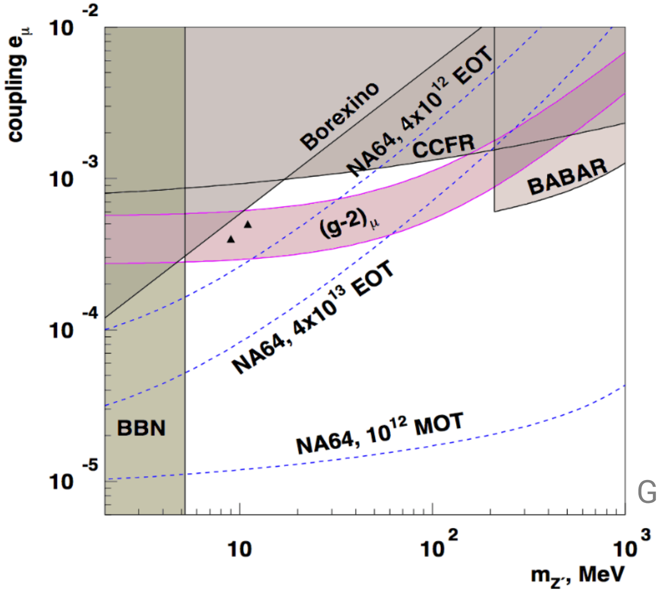
Gninenko, Krasnikov [ph/0102222],
Baek, Deshpande, He, Ko [ph/0104141]



Gninenko, Krasnikov [1801.10448]

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

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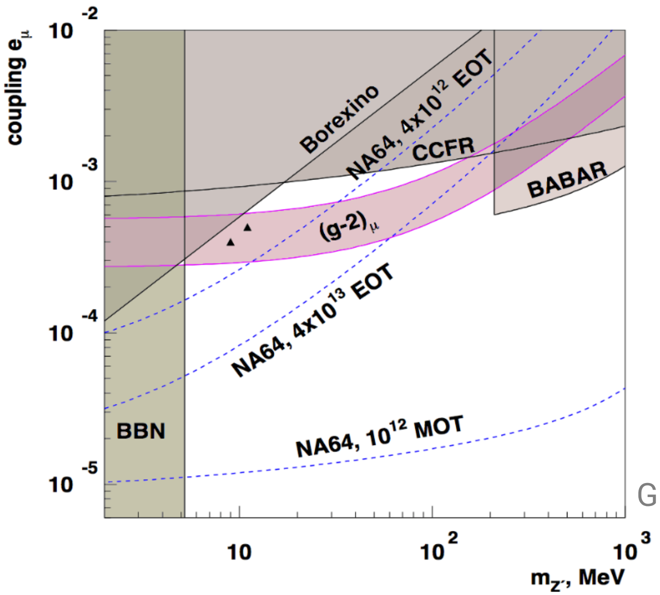

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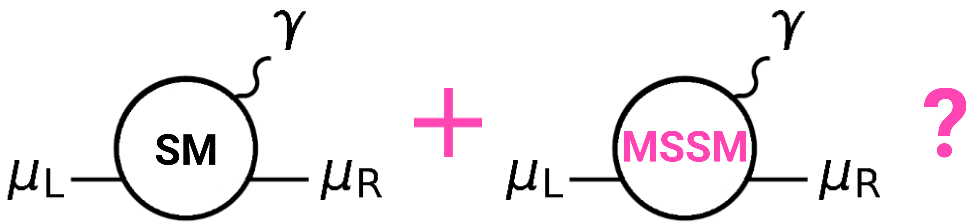
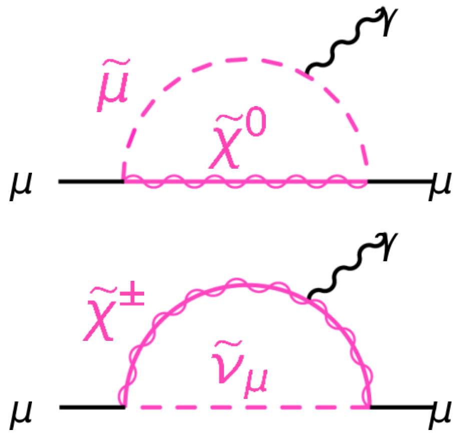
   - Collider physics
   - Dark Matter
3. **Discussion for each scenario**
   - "Chargino" scenario: multi-lepton signature is promising.
   - "Pure-bino" scenario: di-lepton, but production not sufficient.
   - "BHR" or "BHL": multi-tau, combined with direct detections.

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





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

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

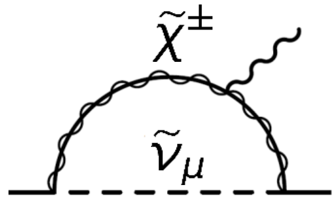
- lighter SUSY-particles
- larger tan β

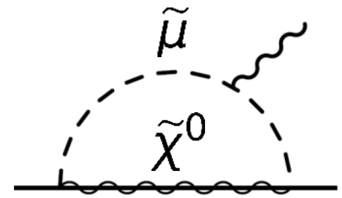
⇨ larger $a_\mu^{\rm SUSY}$

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

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

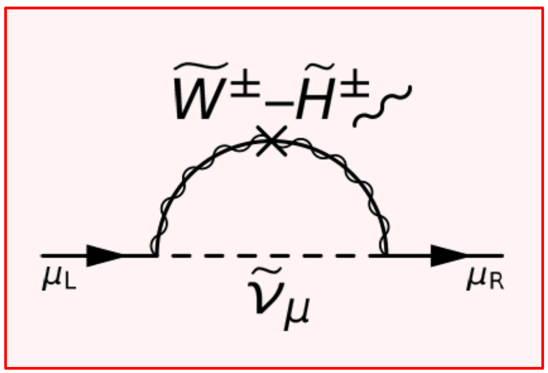
mass eigenstates

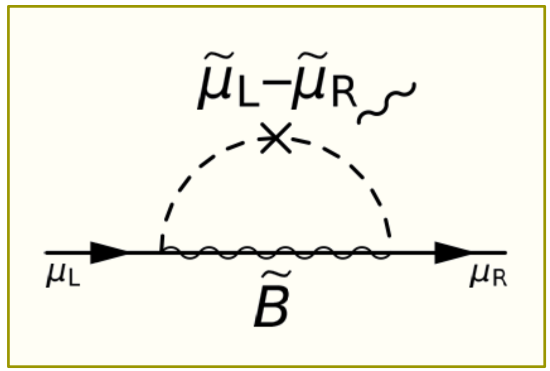
$a_\mu^{\mathrm{SUSY}} \simeq$ 

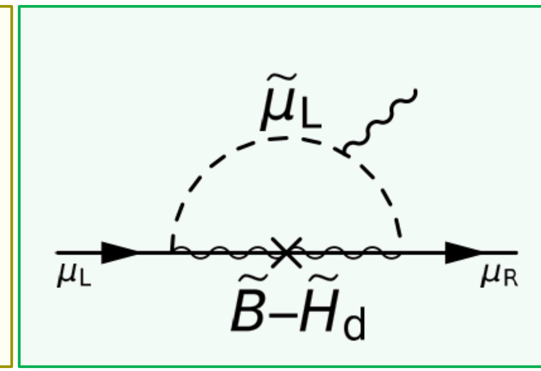
+ 

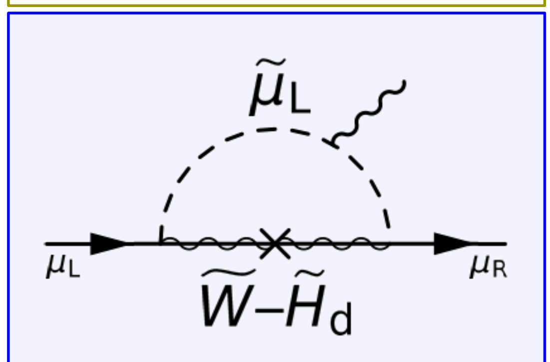
$$\tilde\chi^0_{1-4} = \tilde B \oplus \tilde W^0 \oplus \tilde H_{\mathrm d} \oplus \tilde H_{\mathrm u}, \quad \tilde\chi^\pm_{1,2} = \tilde W^\pm \oplus \tilde H^\pm.$$

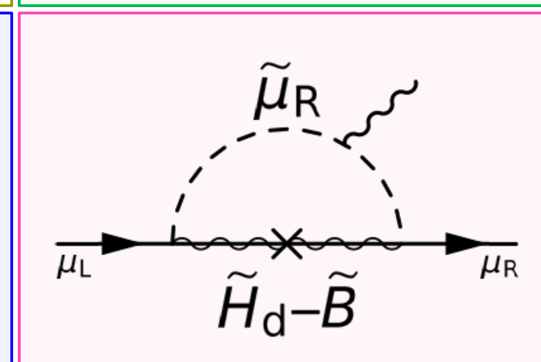
gauge eigenstates



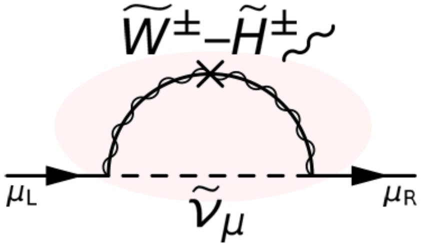




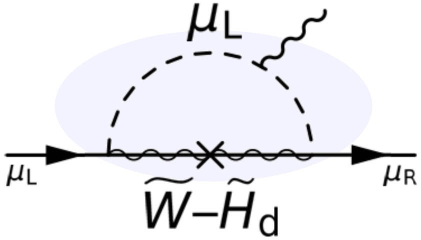




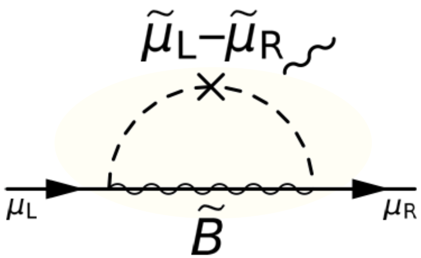
(“mass insertion” technique)



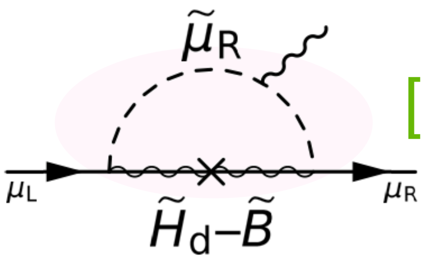
[C] $$\frac{g_2^2 m_\mu^2}{8\pi^2}\frac{M_2\mu\tan\beta}{m_{\tilde{\nu}_\mu}^4}\cdot F_a\left(\frac{M_2}{m_{\tilde{\nu}_\mu}},\frac{\mu}{m_{\tilde{\nu}_\mu}}\right)$$



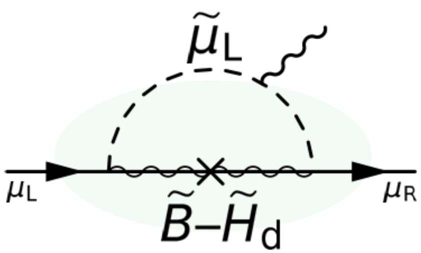
[C'] $$-\frac{g_2^2 m_\mu^2}{16\pi^2}\frac{M_2\mu\tan\beta}{m_{\tilde{\mu}_L}^4}\cdot F_b\left(\frac{M_2}{m_{\tilde{\mu}_L}},\frac{\mu}{m_{\tilde{\mu}_L}}\right)$$



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



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

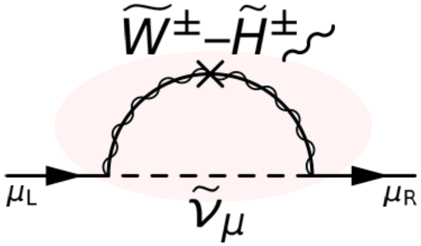


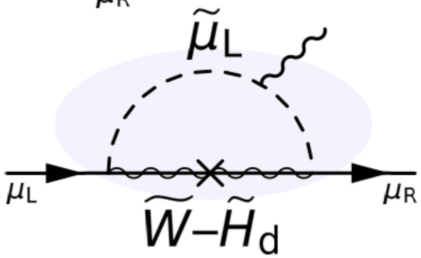
[BHL] $$\frac{g_Y^2 m_\mu^2}{16\pi^2}\frac{M_1\mu\tan\beta}{m_{\tilde{\mu}_L}^4}\cdot F_b\left(\frac{M_1}{m_{\tilde{\mu}_L}},\frac{\mu}{m_{\tilde{\mu}_L}}\right)$$

F_a, F_b are loop functions and positive.

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

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





[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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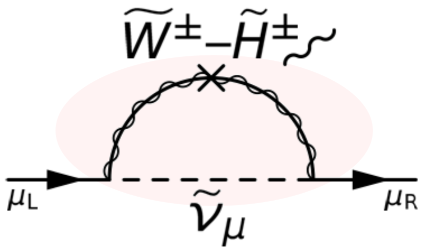
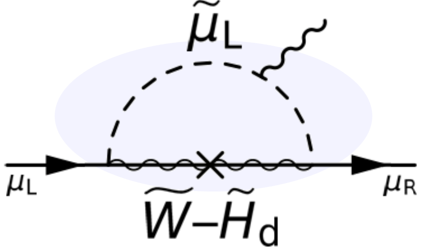
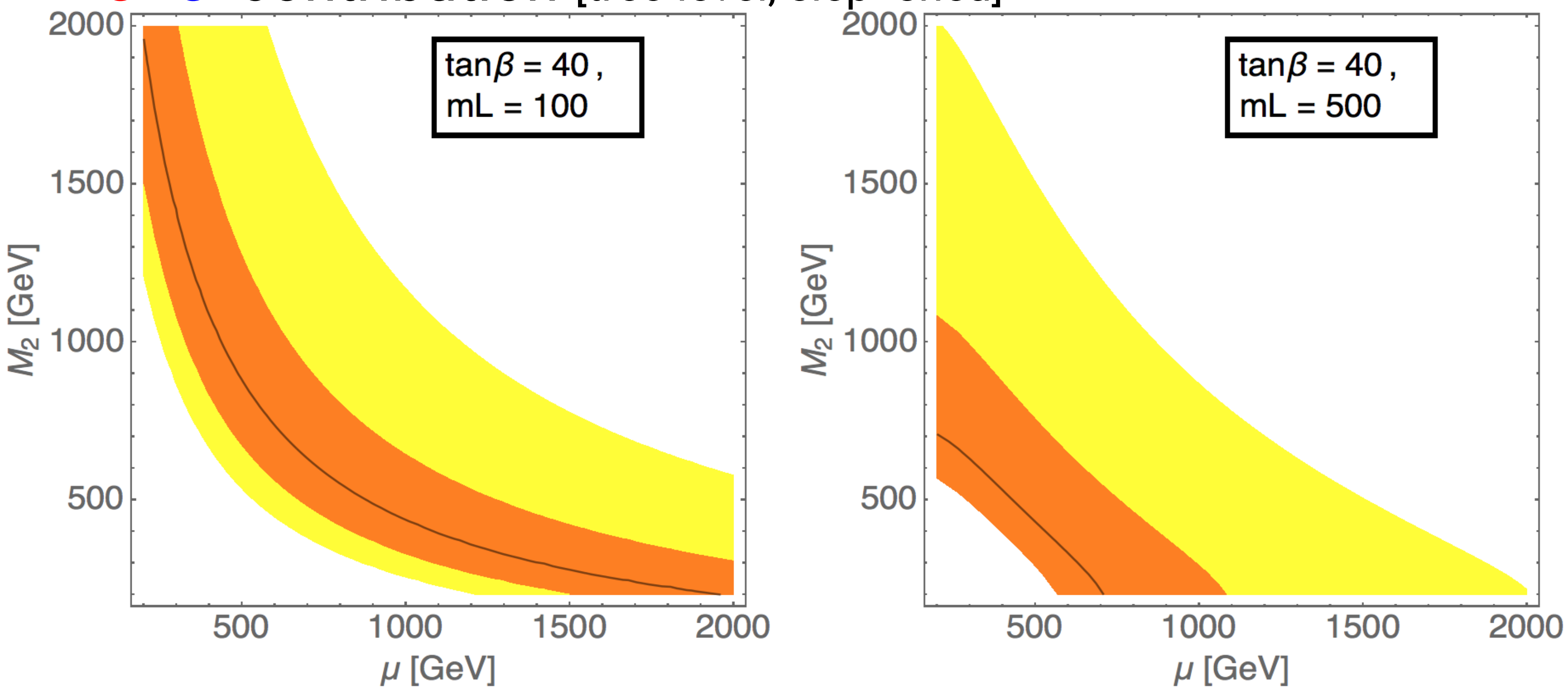


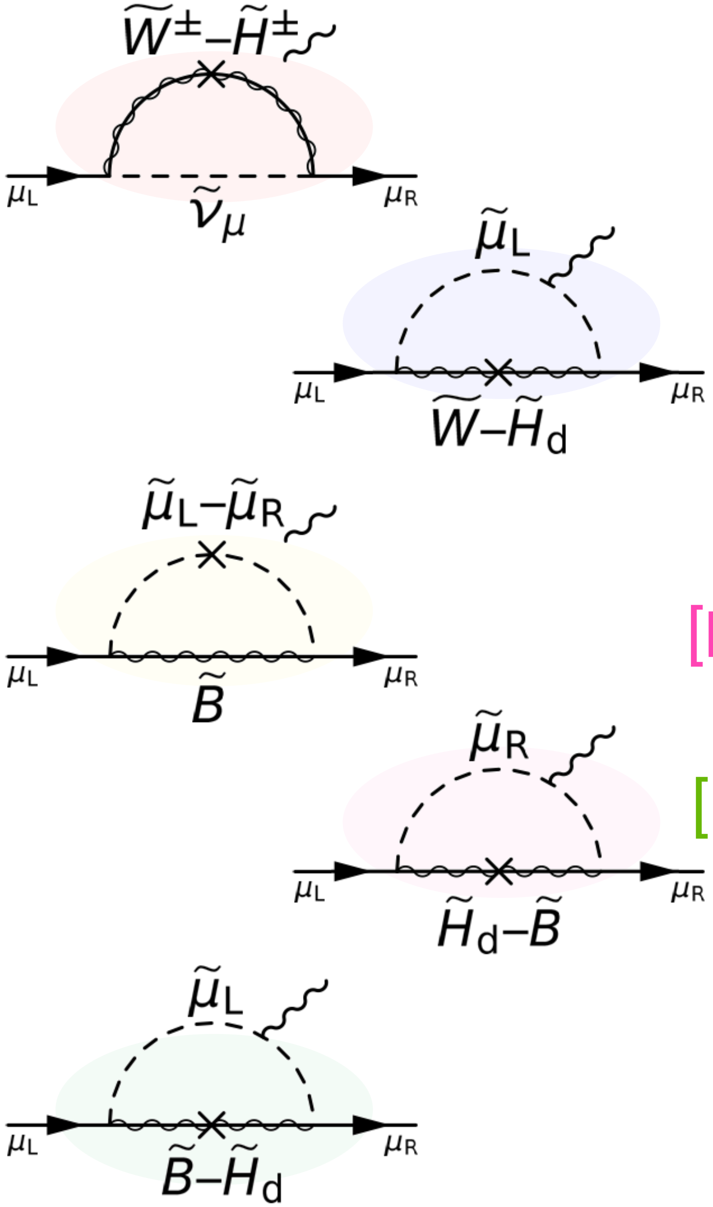


[C]
$$\frac{g_2^2 m_\mu^2}{8\pi^2}\frac{M_2\mu\tan\beta}{m_{\tilde{\nu}_\mu}^4}\cdot F_a\left(\frac{M_2}{m_{\tilde{\nu}_\mu}},\frac{\mu}{m_{\tilde{\nu}_\mu}}\right)$$

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

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





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

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

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

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

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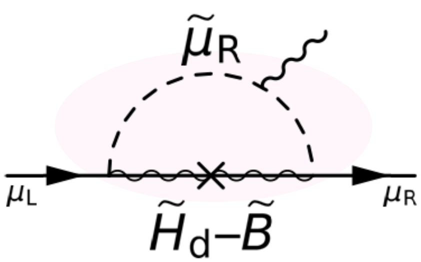
$$C_1(x) = \frac{3 - 4x + x^2 + 2\log x}{(1-x)^3}, \qquad N_2(x) = \frac{1 - x^2 + 2x\log x}{(1-x)^3}.$$

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



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

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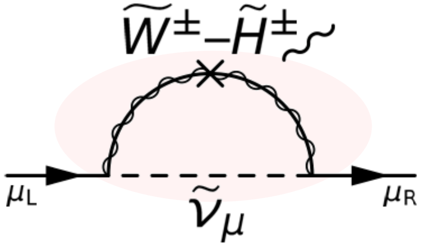

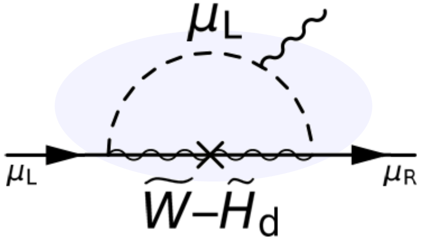

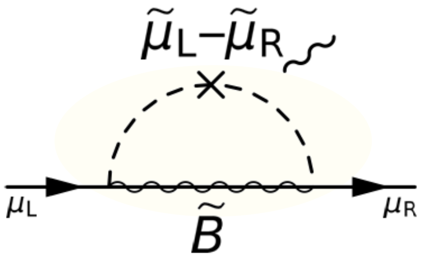

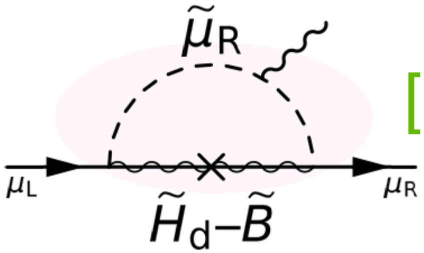

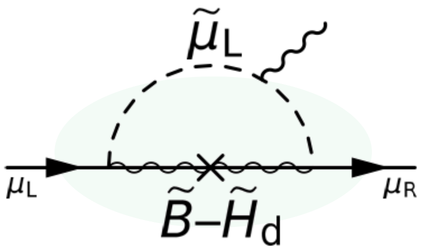

[C]
$$\frac{g_2^2 m_\mu^2}{8\pi^2}\frac{M_2\mu\tan\beta}{m_{\tilde{\nu}_\mu}^4}\cdot F_a\left(\frac{M_2}{m_{\tilde{\nu}_\mu}},\frac{\mu}{m_{\tilde{\nu}_\mu}}\right)$$

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

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

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

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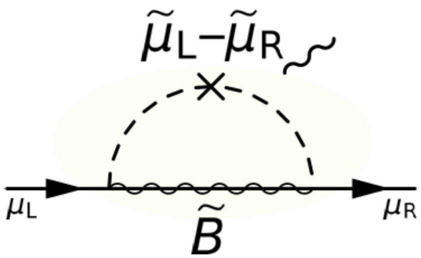
$$C_1(x)=\frac{3-4x+x^2+2\log x}{(1-x)^3},\qquad N_2(x)=\frac{1-x^2+2x\log x}{(1-x)^3}.$$

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



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

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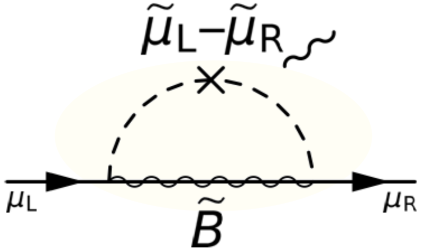
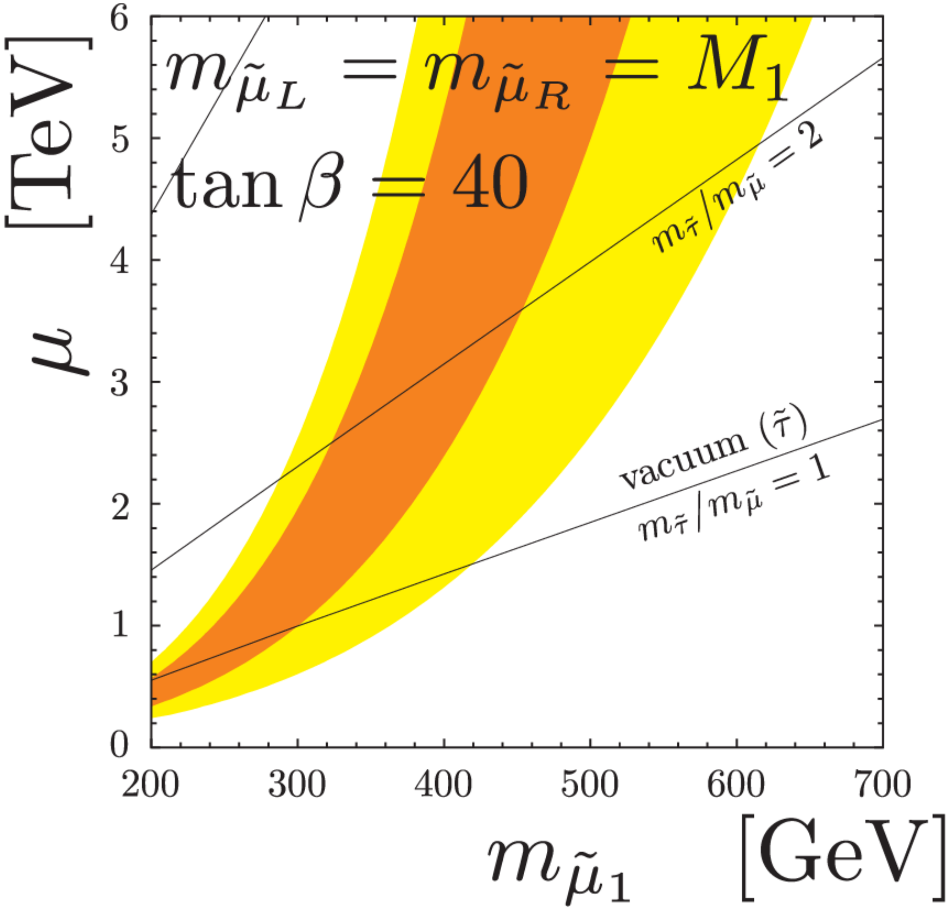
Endo, Hamaguchi, Kitahara, Yoshinaga [1309.3065]



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

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:

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

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

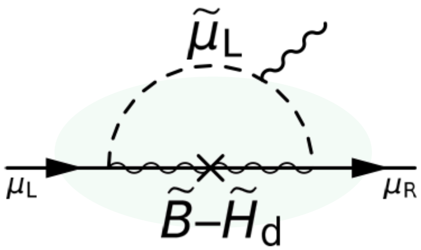
$= 1 \Rightarrow m_{\tilde{\mu}} \lesssim 300(420)$ GeV

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

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

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

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



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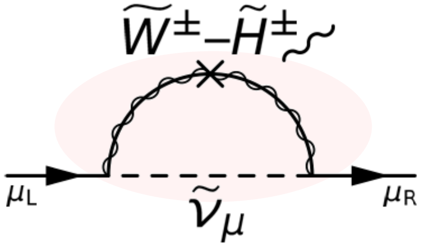
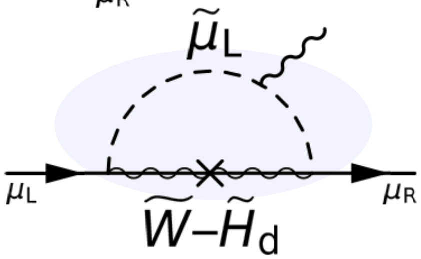
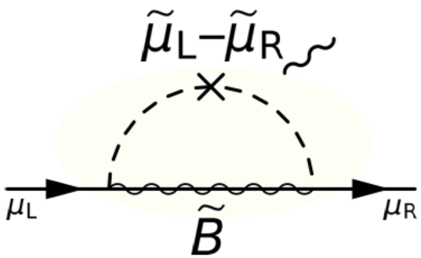


[C] $\frac{g_2^2 m_\mu^2}{8\pi^2}\,\frac{M_2\mu\tan\beta}{m^4}\cdot F_a\left(\frac{M_2}{m},\frac{\mu}{m}\right)$

tend to be large/dominant

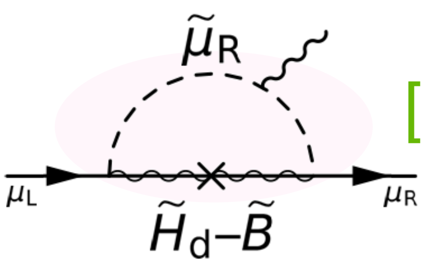


[C'] $-\frac{g_2^2 m_\mu^2}{16\pi^2}\,\frac{M_2\mu\tan\beta}{m_{\tilde\mu_L}^4}\cdot F_b\left(\frac{M_2}{m_{\tilde\mu_L}},\frac{\mu}{m_{\tilde\mu_L}}\right)$



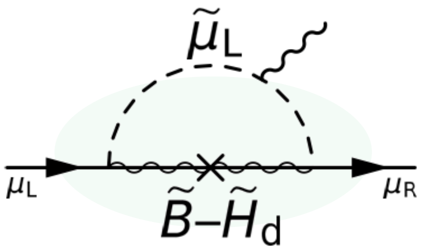
[B] $\frac{g_Y^2 m_\mu^2}{8\pi^2}\,\frac{\cdots}{M_1}\left(\cdots,\frac{m_{\tilde\mu_R}}{M_1}\right)$

μ-enhancement



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

negative



[BHL] $\frac{g_Y^2 m_\mu^2}{16\pi^2}\,\frac{\cdots}{m_{\tilde\mu_L}^{\cdots}}\left(\cdots,\frac{\mu}{m_{\tilde\mu_L}}\right)$

nothing special

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

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)

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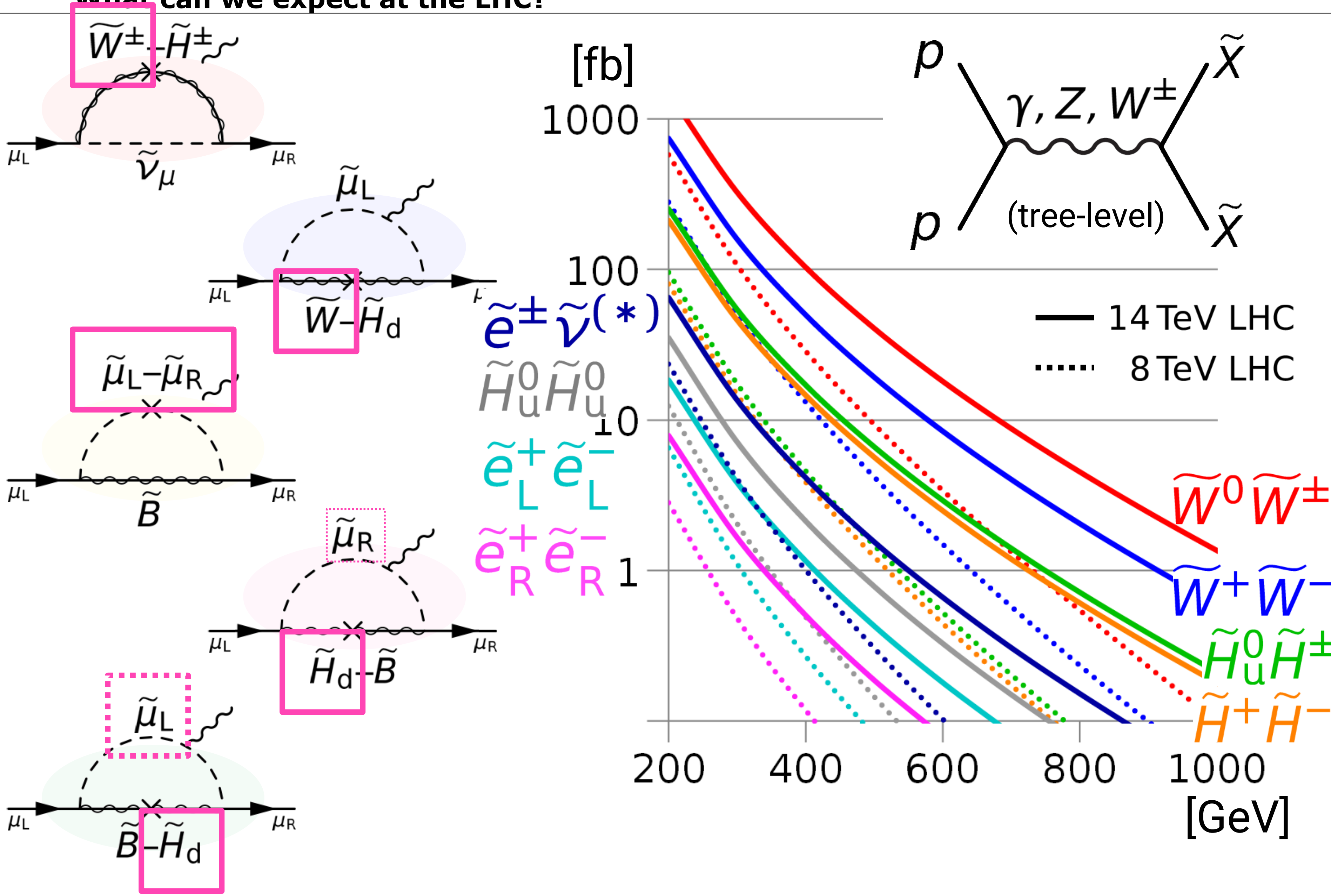

[fb]
1000
100
10
1
200
400
600
800
1000
[GeV]
p
p
γ, Z, W±
(tree-level)
14 TeV LHC
8 TeV LHC

1. **Introduction**
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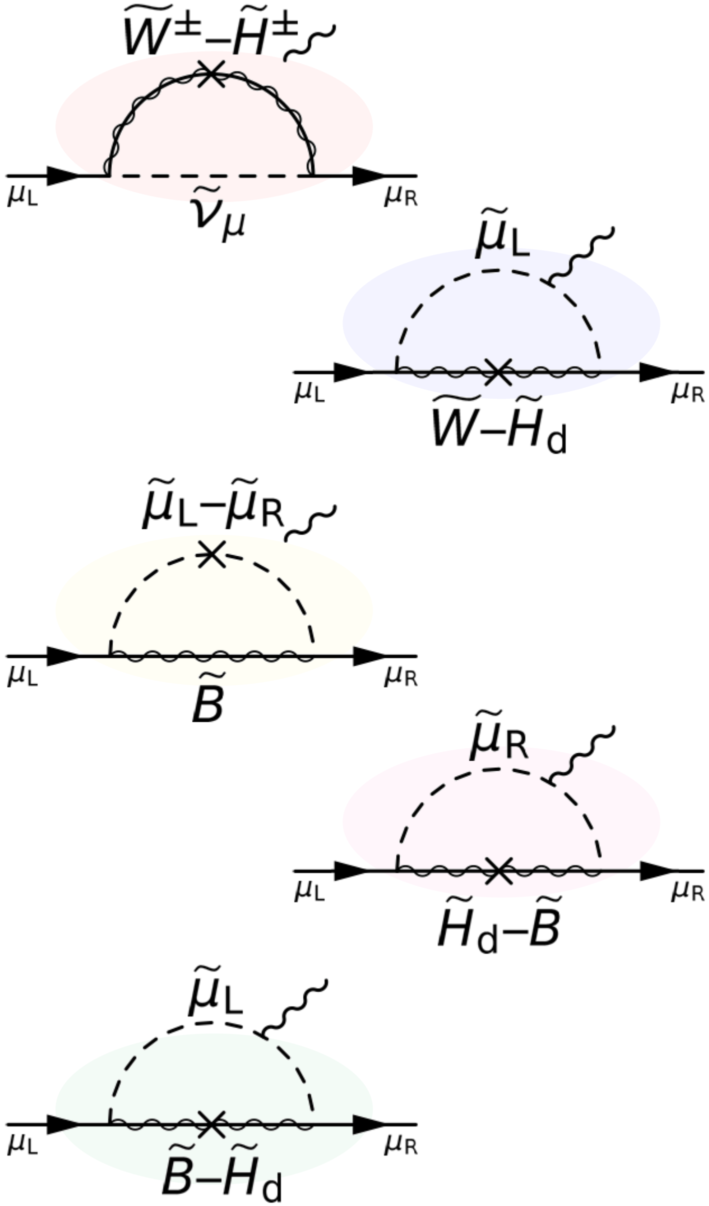
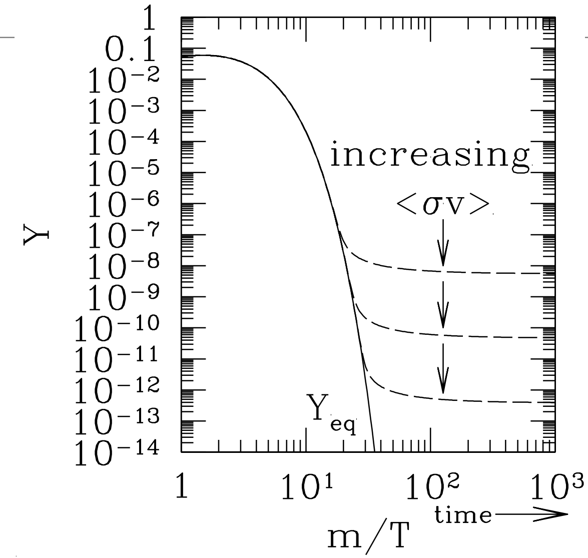


- $(g-2)_\mu$ always requires $\tilde{\chi}^0$
  → good DM candidate!

- 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!

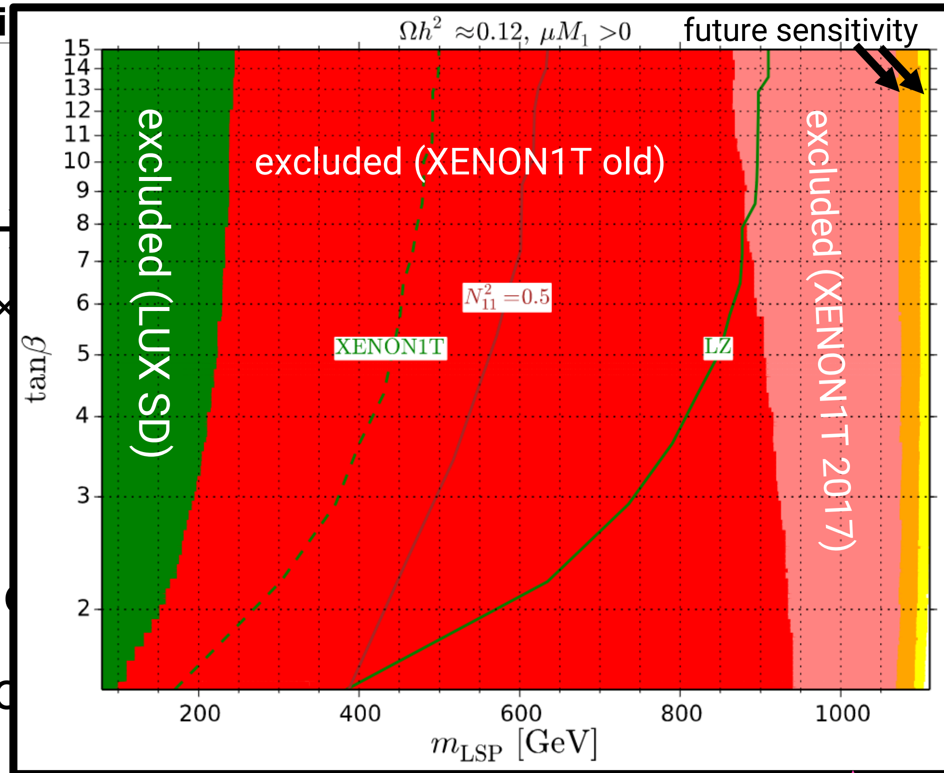


- Simplest $\tilde{\chi}^0$-DM scenario
  - DM was in thermal equilibrium → freeze-out.

    $\cdots \langle\sigma v\rangle_{\mathrm{DM\,DM}\to\mathrm{any}} \sim 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$
  - No other component of DM.
- If $\tilde{\chi}^0$ is almost...
  - pure-Bino → almost no interaction → over-abundant.
  - pure-Higgsino → $m_{\mathrm{LSP}} \sim$ 1TeV for correct abundance.
  - pure-Wino → $m_{\mathrm{LSP}} \sim$ 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
  - DM was in thermal equilibrium –
    $\cdots \langle \sigma v \rangle_{\text{DM DM} \to \text{any}} \sim 3 \times$
  - No other component of DM.
- If $\tilde{\chi}^0$ is almost...
  - pure Bino → almost no interacti
  - y fo
  - or correct abundance.



- Bino–slepton co-annihilation
- MSSM4G
  Abdullah, Feng [1510.06089],
  Abdullah, Feng, SI, Lillard [1608.00283]

- 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.

almost excluded by XENON1T

theoretically not nice

Figure from Gelmini and Gondolo, 1009.3690

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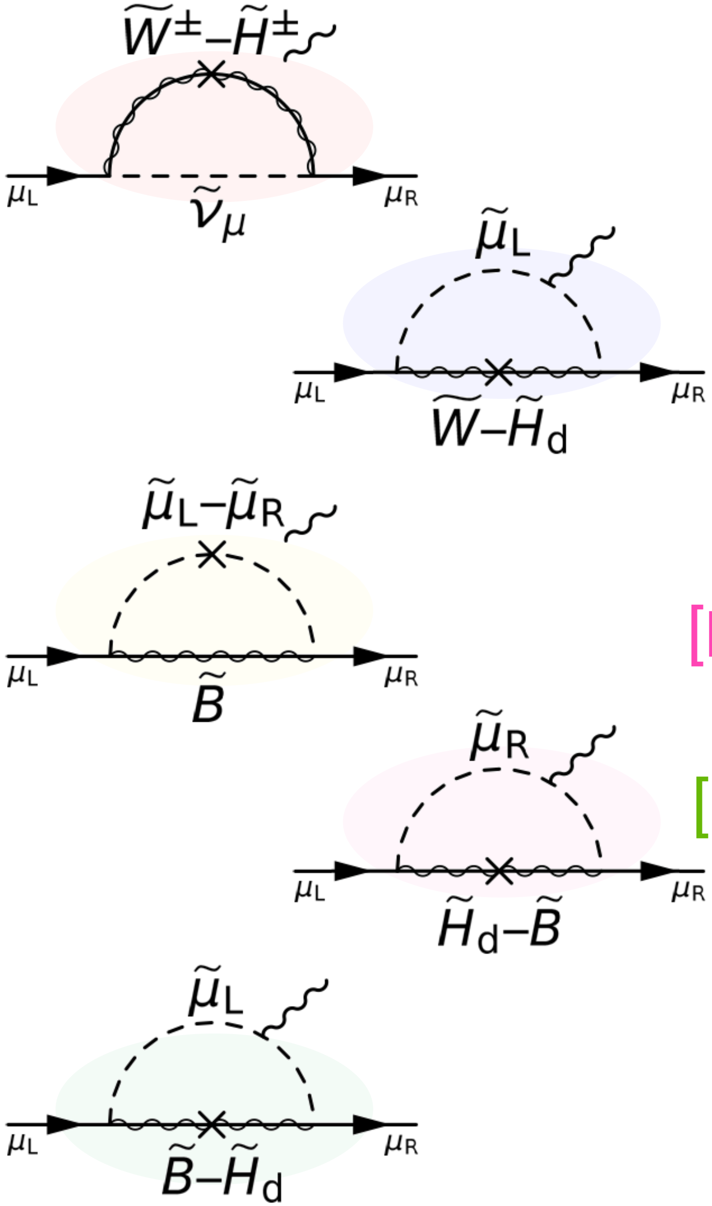

[C] $$\frac{g_2^2 m_\mu^2}{8\pi^2}\frac{M_2\mu\tan\beta}{m_{\tilde\nu}^4}\cdot F_a\left(\frac{M_2}{m_{\tilde\nu}},\frac{\mu}{m_{\tilde\nu}}\right)$$

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] $$\frac{g_Y^2 m_\mu^2}{8\pi^2}\ldots\left(\ldots,\frac{m_{\tilde\mu_R}}{M_1}\right)$$

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

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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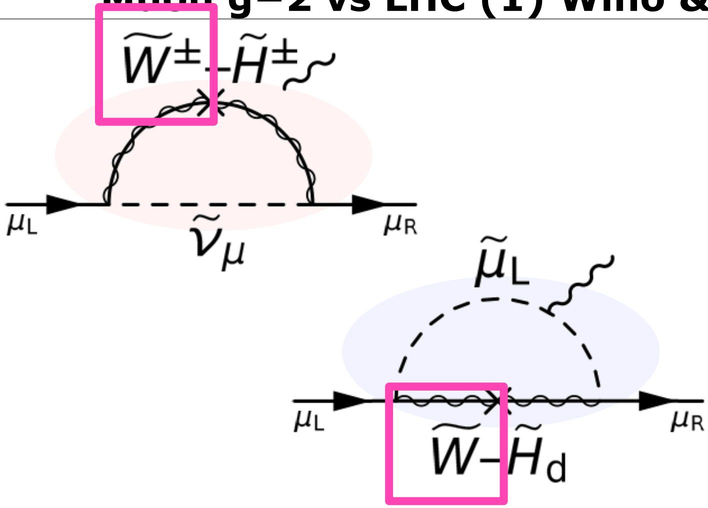
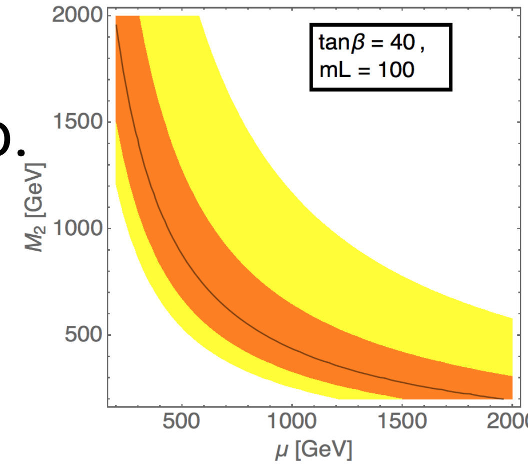
Muon g−2 vs LHC (1) Wino & Higgsino < 1TeV → "Chargino" scenario



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

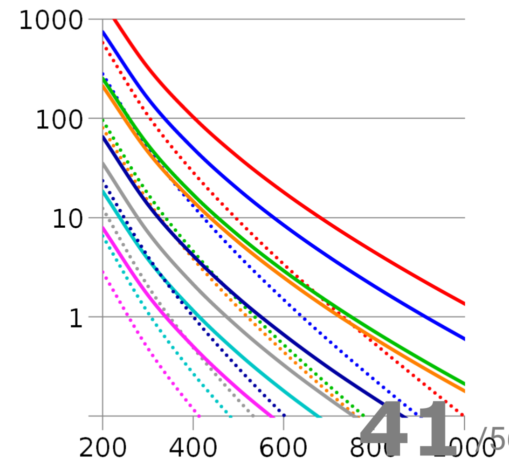
$$-\frac{g_2^2 m_\mu^2}{16\pi^2} \frac{M_2 \mu \tan\beta}{m_{\widetilde{\mu}_L}^4} \cdot F_b\left(\frac{M_2}{m_{\widetilde{\mu}_L}}, \frac{\mu}{m_{\widetilde{\mu}_L}}\right)$$



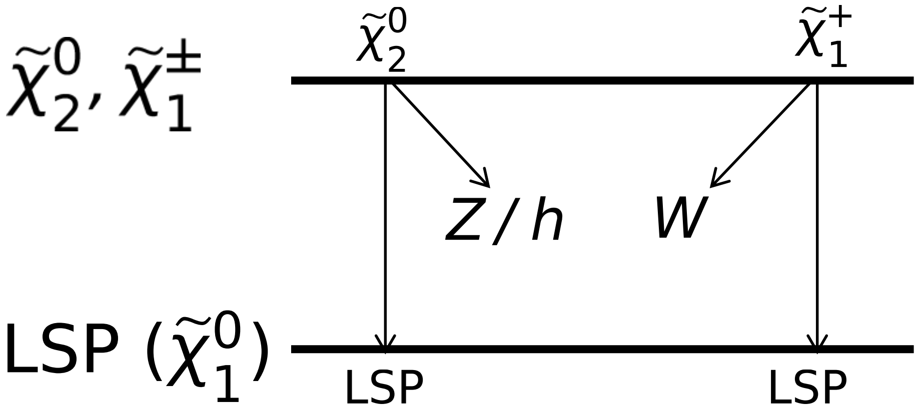
- Wino&Higgsino < TeV → chargino scenario.
  - $\propto g_2^2$ → relevant particles $\lesssim 1\,\mathrm{TeV}$
  - DM: not considered here
    - $(g-2)_\mu \Leftarrow (\widetilde{W}, \widetilde{H}, \widetilde{\mu}_L)$; DM $\Leftarrow (\widetilde{l}_L, \widetilde{B})$ ... "orthogonal"
    - co-annihilation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

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

$$1.5\,\mathrm{fb} \qquad\qquad 1\,\mathrm{TeV}$$



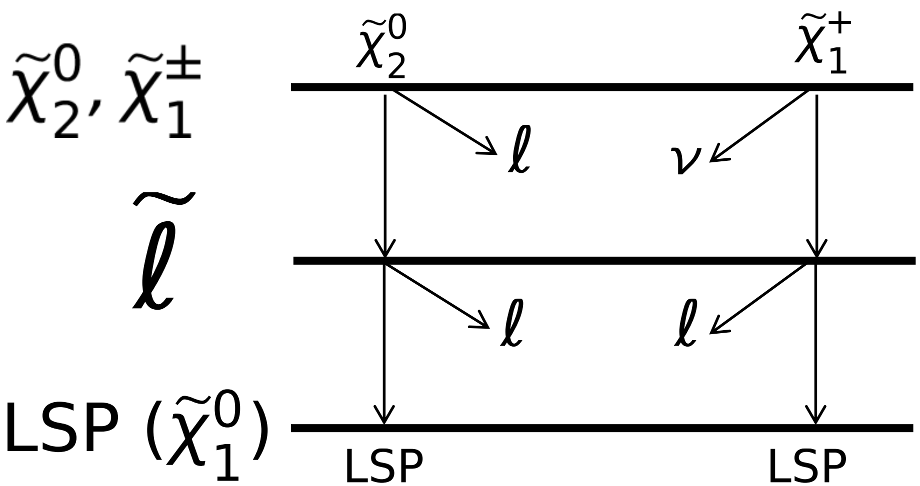
$pp \to \tilde{\chi}^0 \tilde{\chi}^+$ $(\widetilde{W}^0 \widetilde{W}^+$ or $\widetilde{H}^0 \widetilde{H}^+)$; then?



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

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

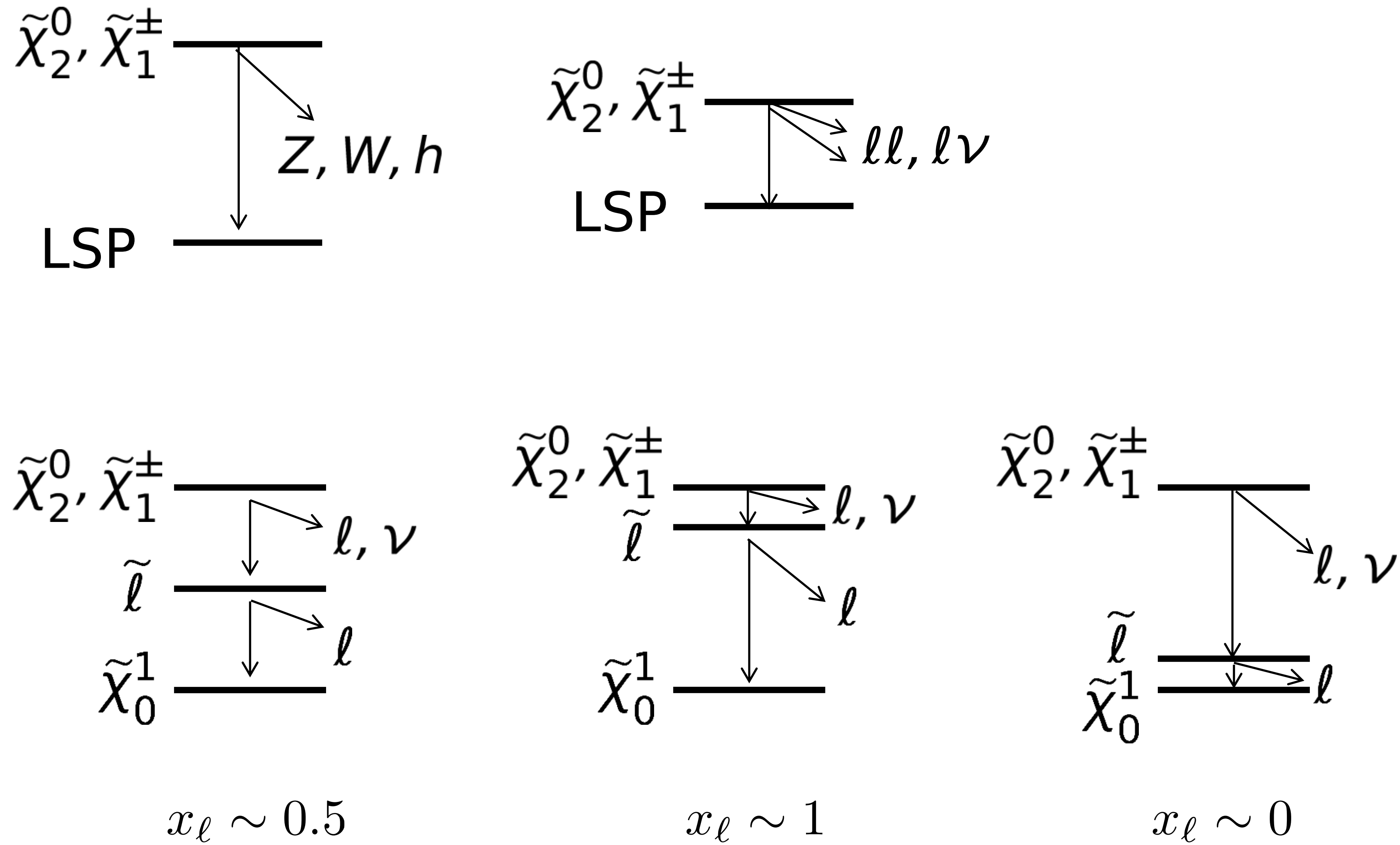
but Z-like leptons



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

Z-unlike

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



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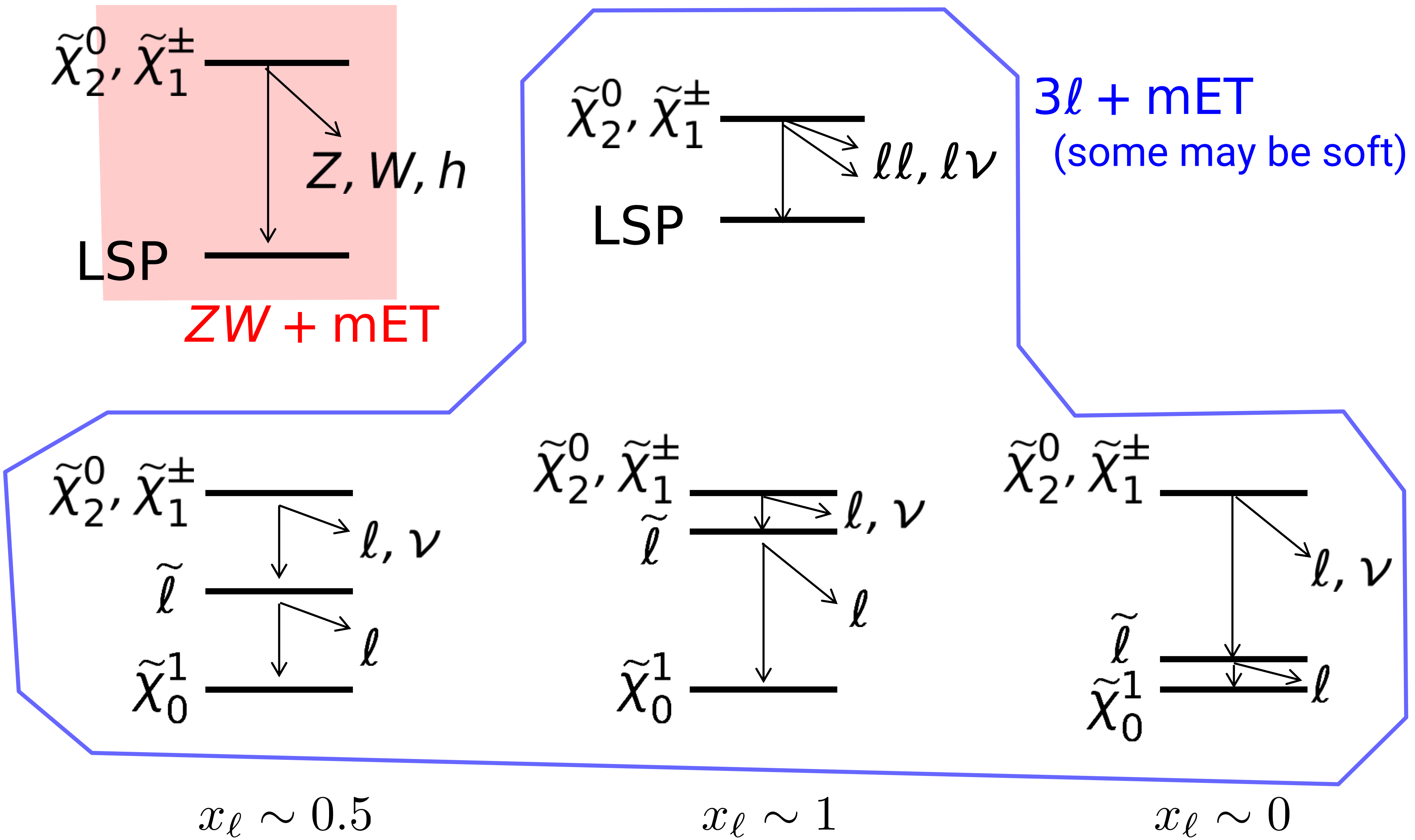
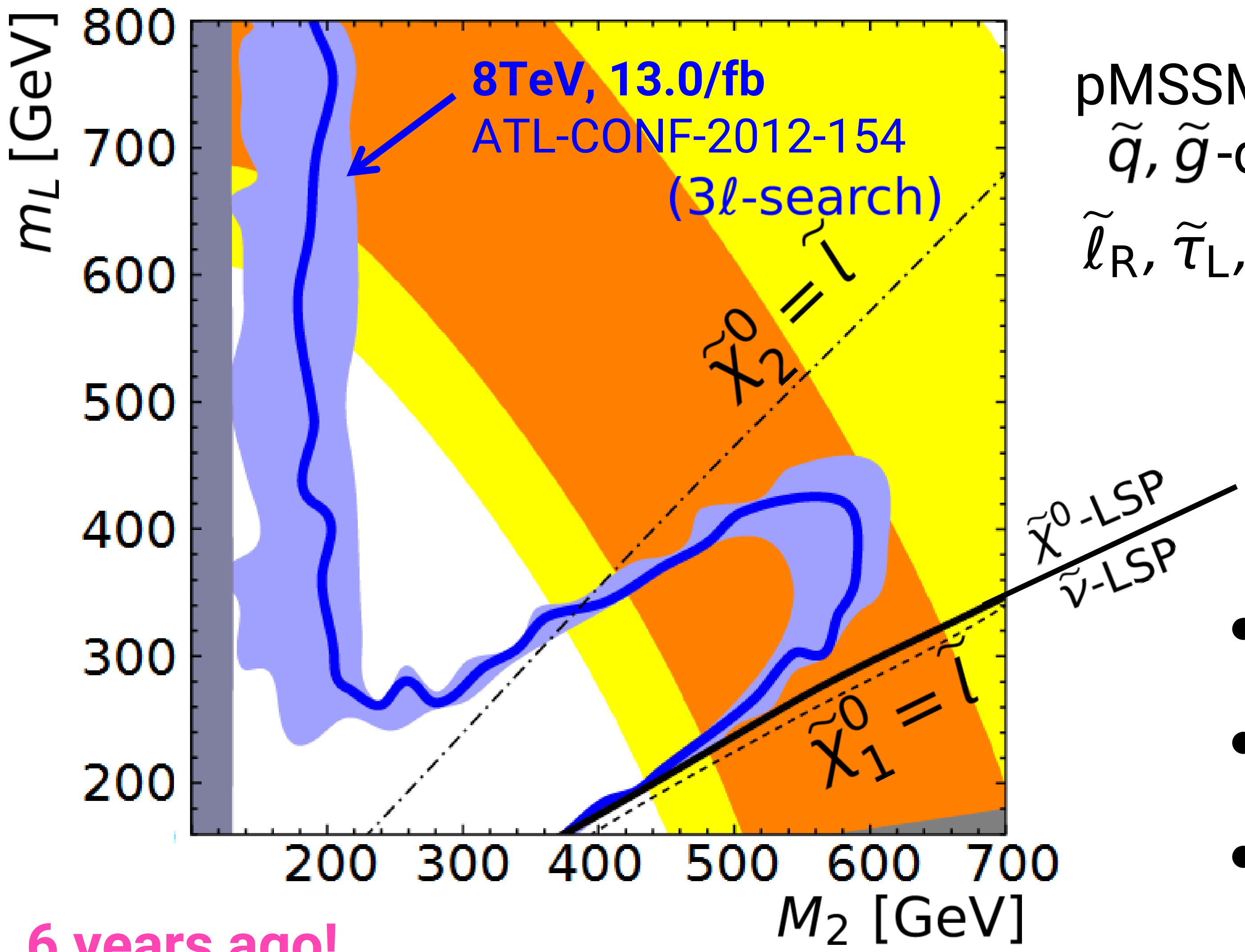
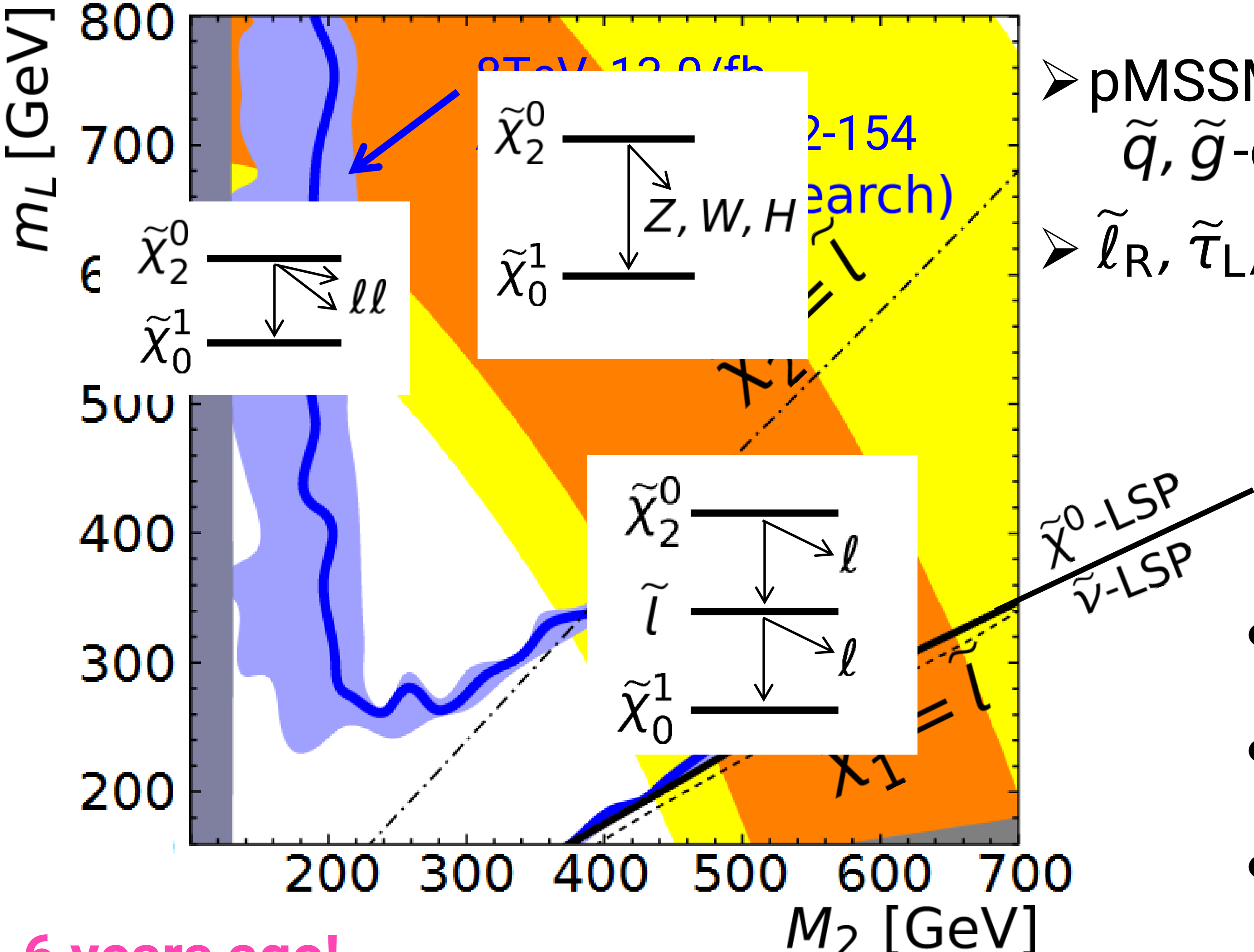




6 years ago!

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

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



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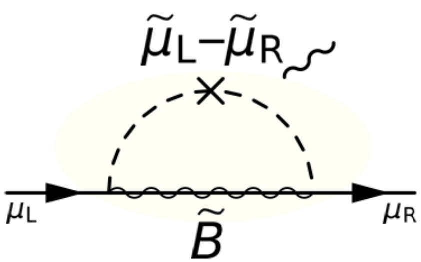
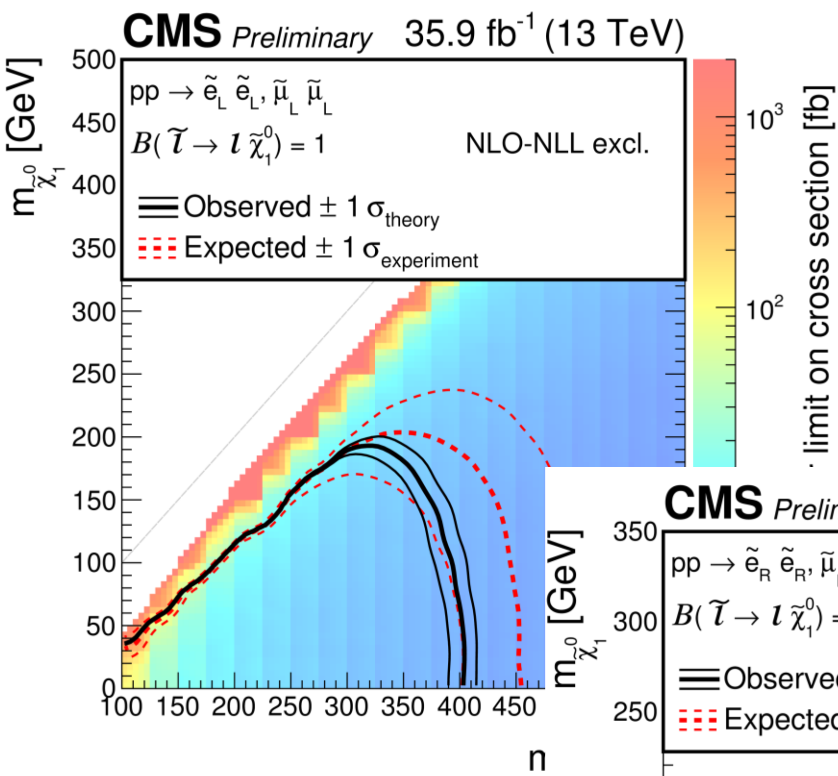
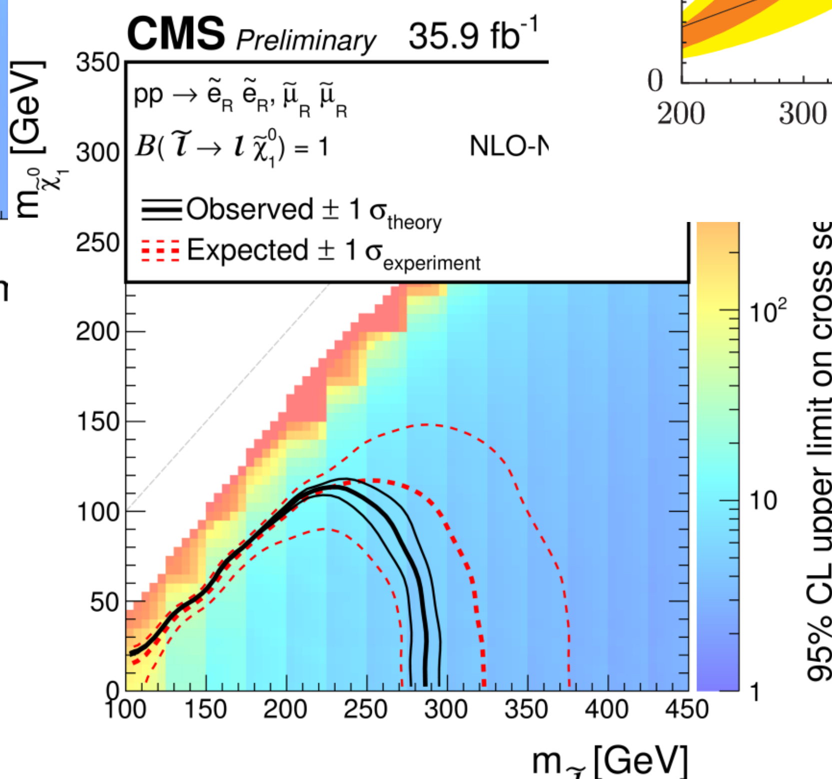


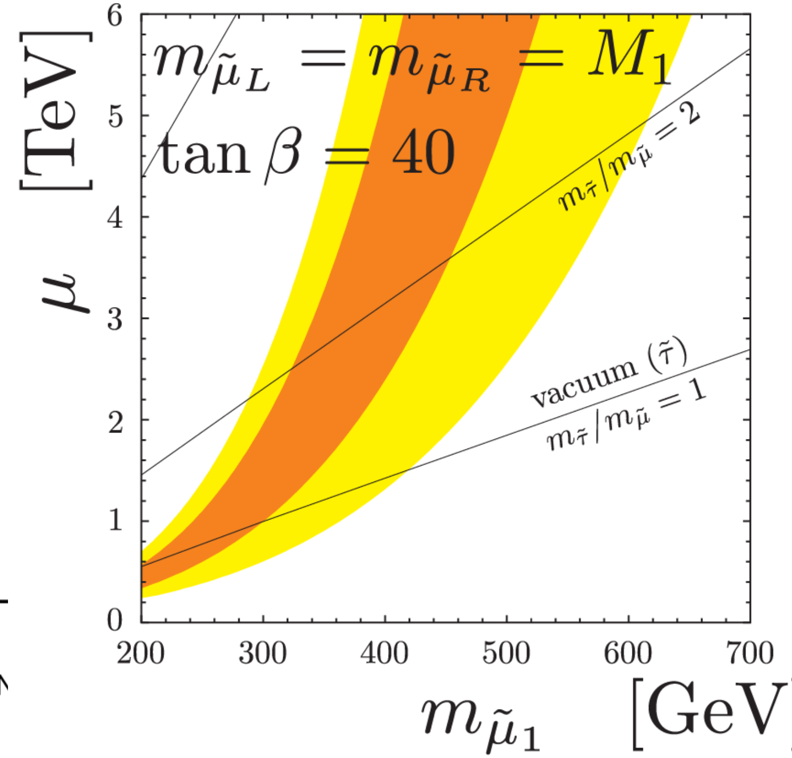
[B] $\frac{g_Y^2 m_\mu^2}{8\pi^2}$ **μ-enhancement** , $\frac{m_{\tilde\mu_R}}{M_1}\Big)$

  - 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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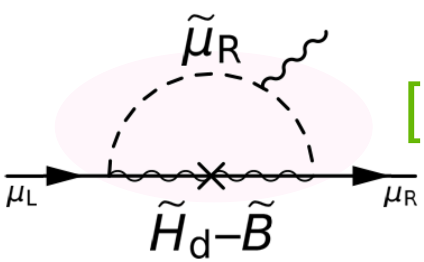

[BHR]
$$-\frac{g_Y^2 m_\mu^2}{8\pi^2}\frac{M_1\mu\tan\beta}{m_{\widetilde{\mu}_R}^4}\cdot F_b\left(\frac{M_1}{m_{\widetilde{\mu}_R}},\frac{\mu}{m_{\widetilde{\mu}_R}}\right)$$

[BHL]
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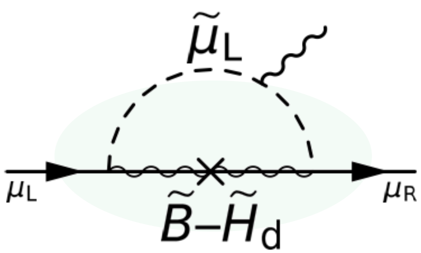

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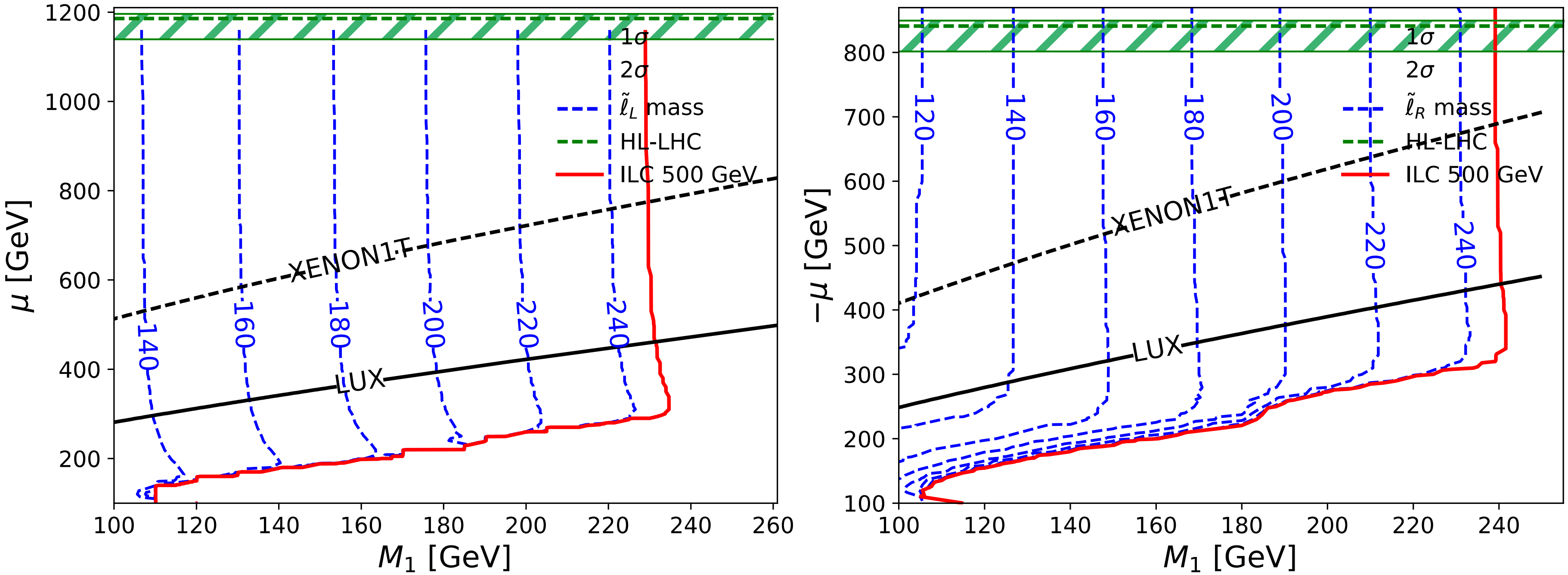
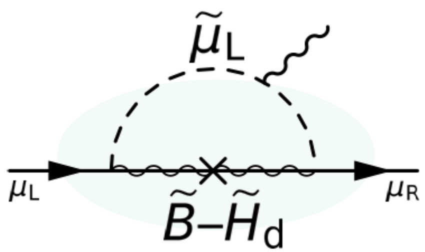
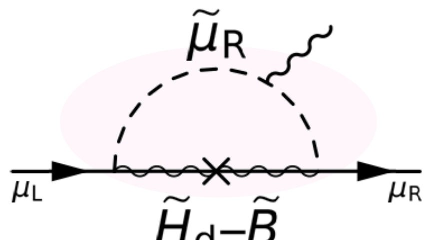
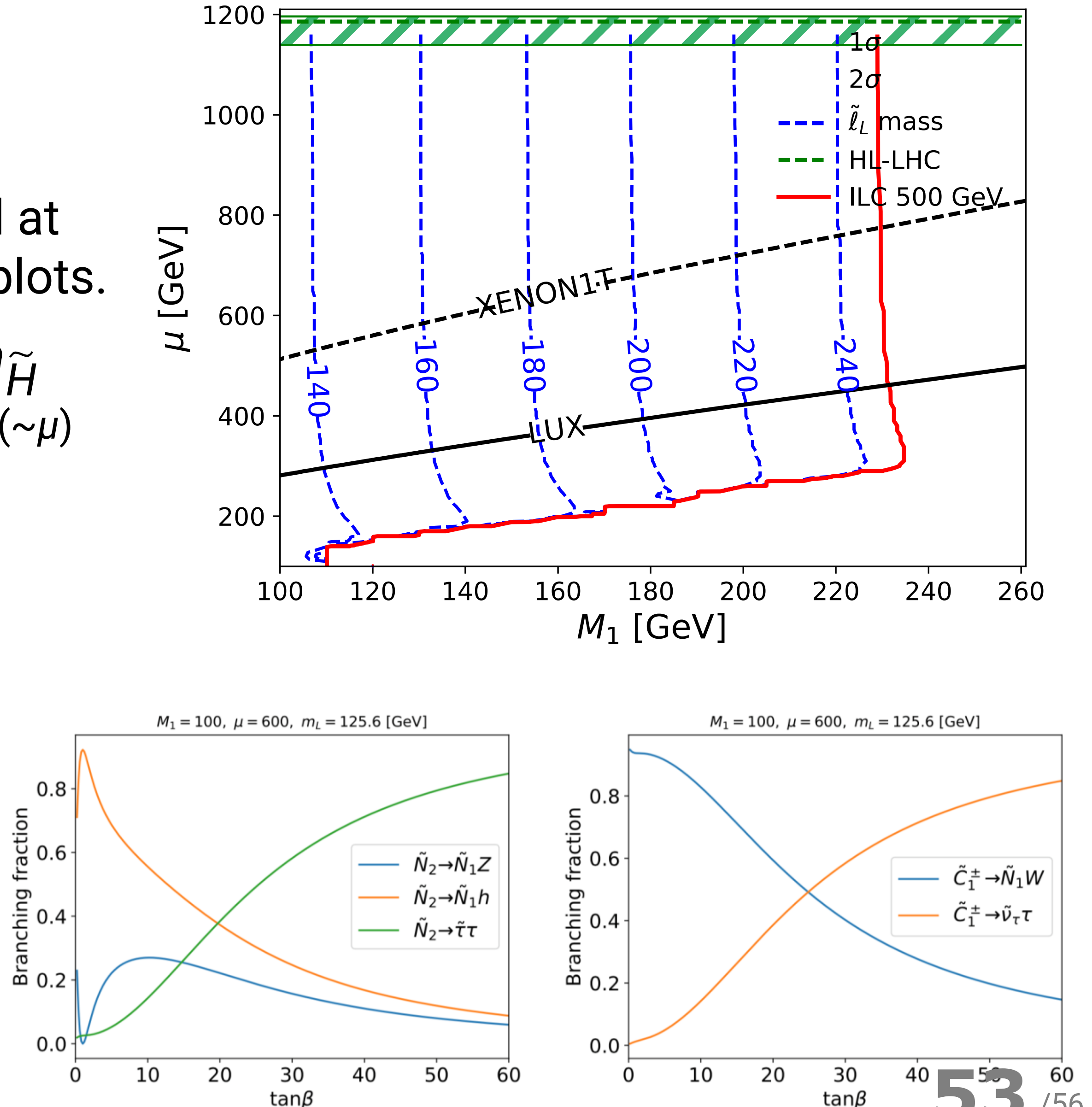






- Bino−slepton (stau) co-annihilation → $m_{\tilde{\nu}_\tau}$ (or $m_{\tilde{\tau}_R}$) $\simeq m_{\tilde{B}}$.
- We assumed:
  - slepton universality,
  - DM density is realized at each point in the plots.

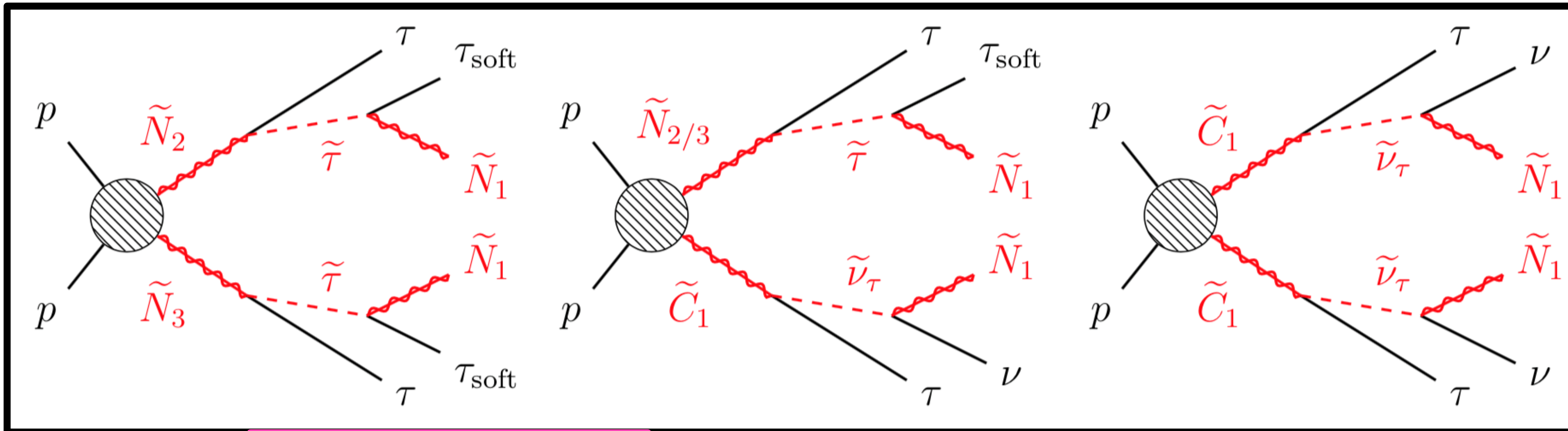
  → $m_{\tilde{B}} \lesssim m_{\tilde{\mu}} < m_{\tilde{H}}$
  $(\sim M_1)$ $(\sim \mu)$



- 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

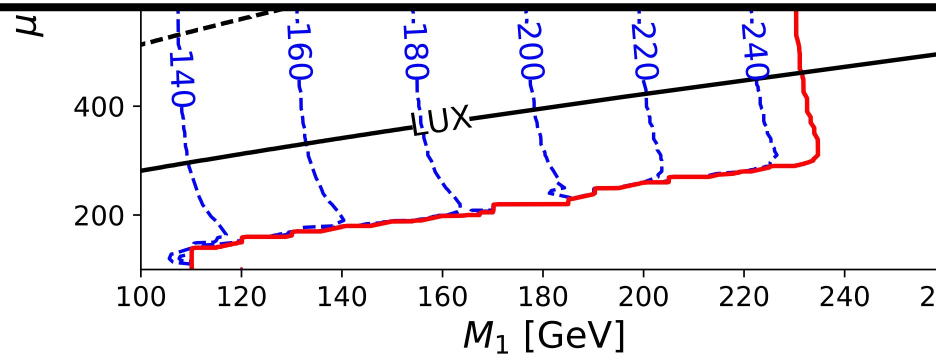
  → multi-tau signature

Endo, Hamaguchi, SI, Yanagi [1704.05287]



→ $m_{\tilde B} \lesssim m_{\tilde\mu} < m_{\tilde H}$

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

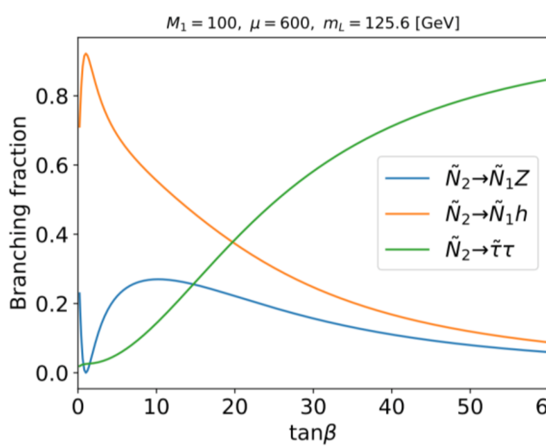


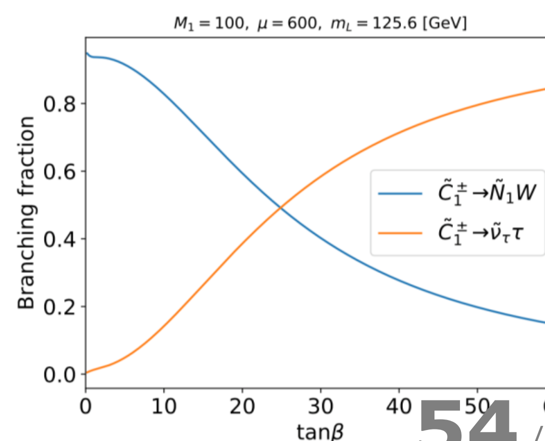
■ HL-LHC?

- $pp \to \tilde H^+ \tilde H^0,\ \tilde H^+ \tilde H^-$
- $\tilde H^0 \to \tau\tilde\tau,\ \ \tilde H^+ \to \tau\tilde\nu_\tau$ because of $\tan\beta$

→ multi-tau signature

"2τ (+ soft) **+ missing"**

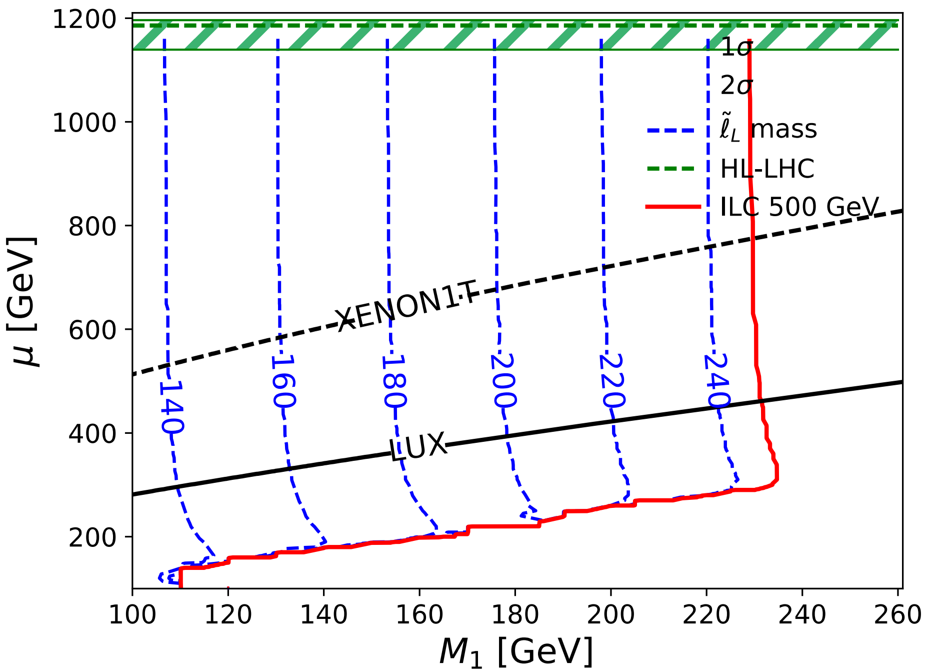


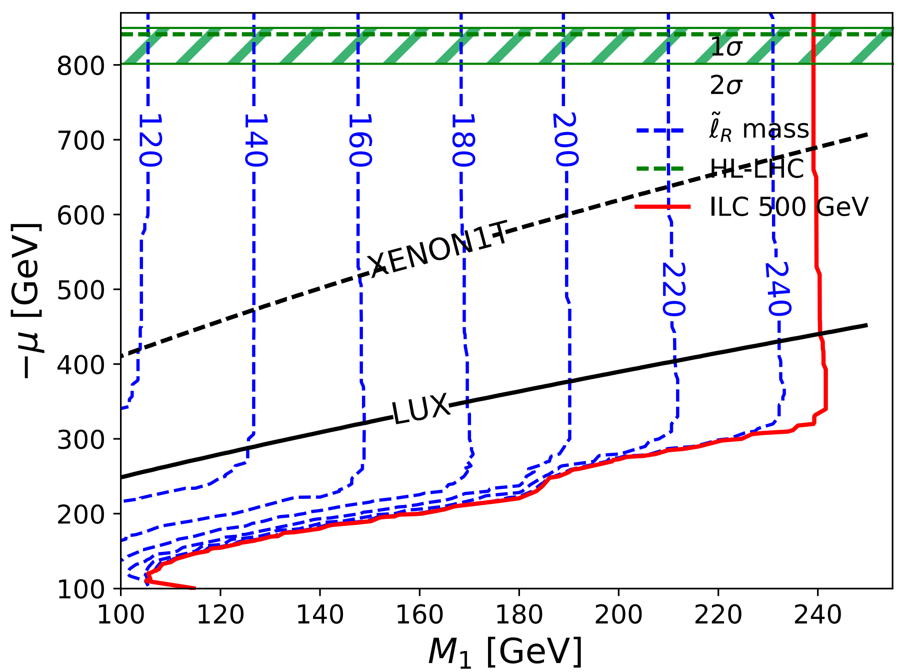


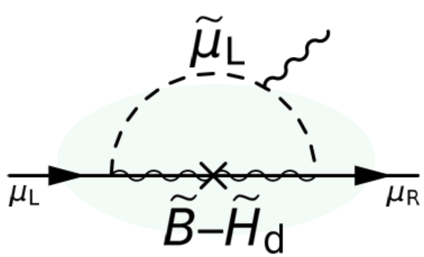
 Endo, Hamaguchi, SI, Yanagi [1704.05287]

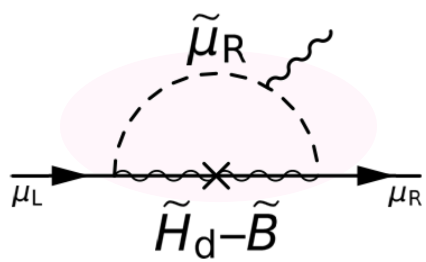
($\mu > 0$) ($\mu < 0$)

- Wino >> TeV & Higgsino < TeV → BHL or BHR scenario.
  - DM: Bino−stau co-annihilation → $m_{\tilde{B}} \simeq (m_{\tilde{\tau}_R} \text{ or } m_{\tilde{\nu}_\tau}) \lesssim m_{\tilde{\mu}} < m_{\tilde{H}}$
  - 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



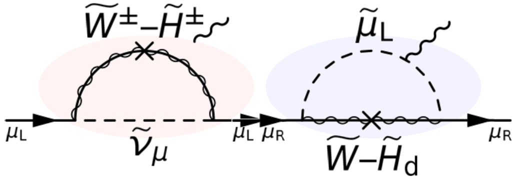


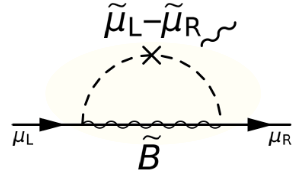


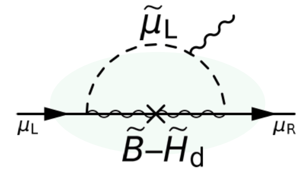


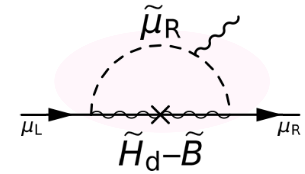
Scenario:

"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:

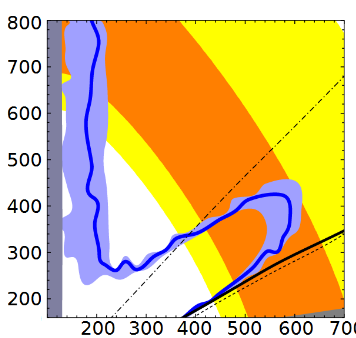
multi-lepton
→ promising

("stay tuned!")

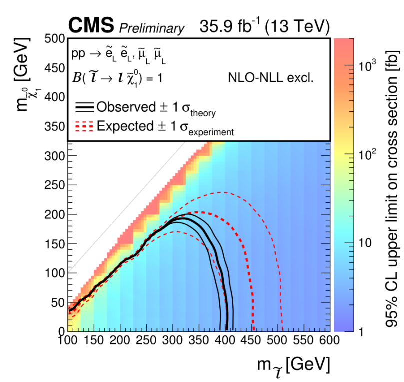
di-lepton
→ **difficult @LHC**

Higgsino → multi-tau

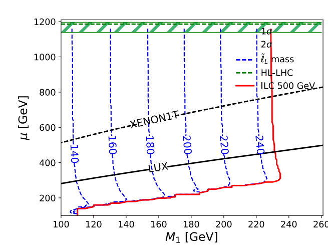
"covered@HL-LHC
if we seriously consider
the relic density"

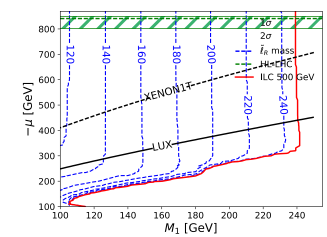


Endo, Hamaguchi, ***SI***, Yoshinaga [1303.4256]



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





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