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

Sho IWAMOTO（岩本　祥）

1 May 2018
Seminar @ KIAS

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.

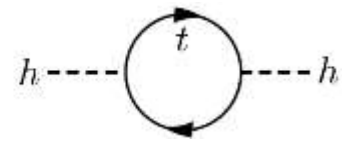
  - But also: **LHC physics until its last day.** ...high risk, high return.

■ 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)

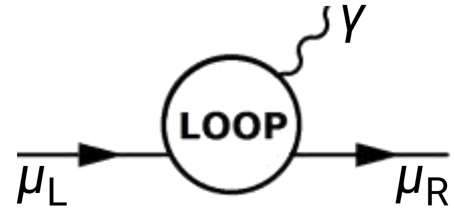
$$\langle \sigma v\rangle_{\text{DM DM}\to\text{any}} \sim 3\times 10^{-26}\,\text{cm}^3/\text{s} = \frac{\alpha_{\text{em}}^2}{(150\,\text{GeV})^2}.$$

→ DM @ ~100 GeV?

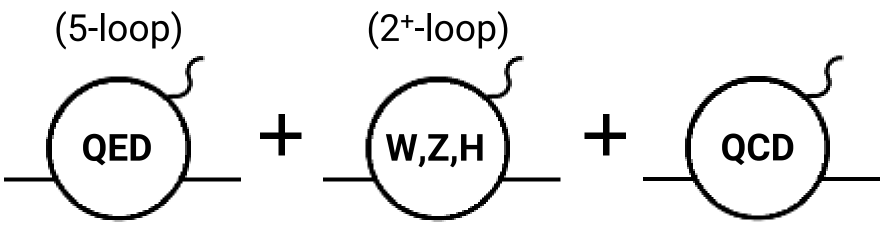
$$\Omega_{\text{DM}}h^2 \approx \frac{1.1\times 10^9\cdot x_{\text{f}}}{\sqrt{g_*}M_{\text{pl}}\langle\sigma v\rangle\cdot\text{GeV}} \approx 0.1\cdot\frac{15}{\sqrt{g_*}}\frac{x_{\text{f}}}{30}\frac{3\times 10^{-26}\,\text{cm}^3/\text{s}}{\langle\sigma v\rangle} \quad \text{with } x_{\text{f}} = m_{\text{DM}}/T_{\text{fo}}.$$

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

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



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



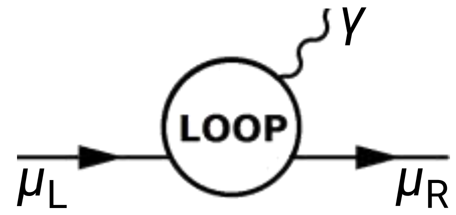
$$a_\mu(\mathrm{QED}) = (11\,658\,471.886 \pm 0.003) \times 10^{-10},$$
$$a_\mu(\mathrm{EW}) = (\qquad 15.36 \pm 0.11 \ ) \times 10^{-10},$$

SM combination according to Jegerlehner [1804.07409].
QED: Aoyama, Hayakawa, Kinoshita, Nio [1205.5370] (cf. [1712.06060]).
EW: Gnendiger, Stöckinger, Stöckinger-Kim [1306.5546].
QCD: Jegerlehner [1711.06089] [1705.00263].

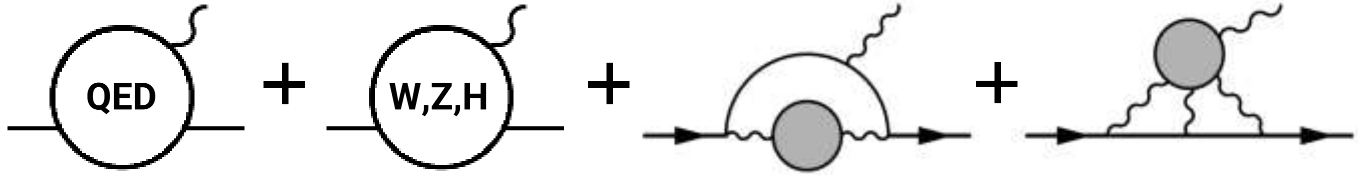
See also:
QED: Laporta [1704.06996], Marquard et al. [1708.07138].
HVP-LO: Keshavarzi, Nomura, Teubner [1802.02995]
HVP-HO: Kurz, Liu, Marquard, Steinhauser [1403.6400],
HLbL: Jegerlehner, Nyffeler [0902.3360],
Colangelo, Hoferichter, Nyffeler, Passera, Stoffer [1403.7512]

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

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

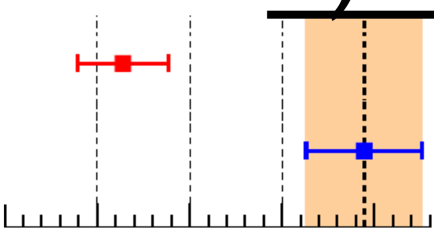


$$a_\mu^{SM} \simeq$$



$$a_\mu(\text{QED}) = (11\,658\,471.886 \pm 0.003) \times 10^{-10},$$
$$a_\mu(\text{EW}) = (15.36 \pm 0.11) \times 10^{-10},$$
$$a_\mu(\text{HVP-LO}) = (689.46 \pm 3.25) \times 10^{-10},$$
$$a_\mu(\text{HVP-HO}) = (-8.70 \pm 0.07) \times 10^{-10},$$
$$a_\mu(\text{HLbL}) = (10.34 \pm 2.88) \times 10^{-10}.$$

+)



$$a_\mu^{SM} = (11\,659\,178.3 \pm 4.3) \times 10^{-10}$$

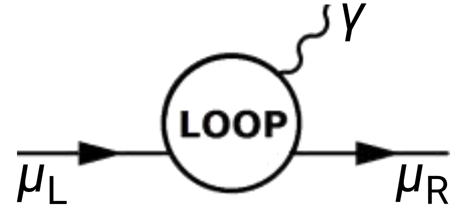
$$a_\mu^{SM} = (11\,659\,209.2 \pm 6.3) \times 10^{-10}$$ (BNL '04+CODATA '14)

SM combination according to Jegerlehner [1804.07409].
QED: Aoyama, Hayakawa, Kinoshita, Nio [1205.5370] (cf. [1712.06060]).
EW: Gnendiger, Stöckinger, Stöckinger-Kim [1306.5546].
QCD: Jegerlehner [1711.06089] [1705.00263].

See also:
QED: Laporta [1704.06996], Marquard et al. [1708.07138].
HVP-LO: Keshavarzi, Nomura, Teubner [1802.02995]
HVP-HO: Kurz, Liu, Marquard, Steinhauser [1403.6400],
HLbL: Jegerlehner, Nyffeler [0902.3360],
Colangelo, Hoferichter, Nyffeler, Passera, Stoffer [1403.7512]

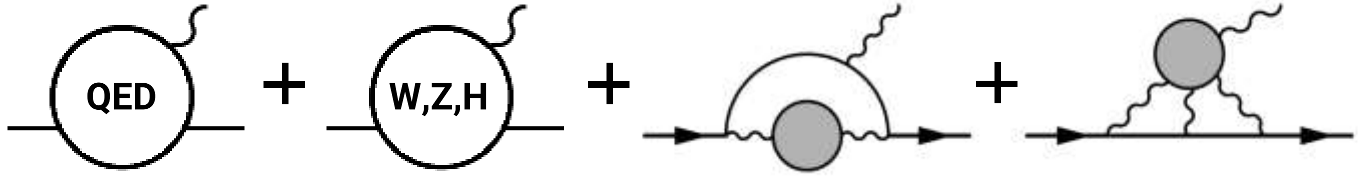
[FermiLab: ±1.6]

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



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

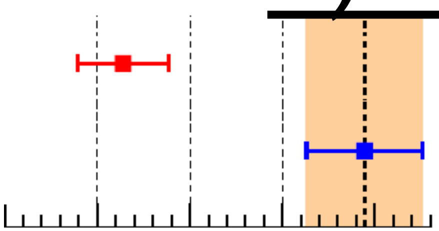
$$a_\mu^{SM} \simeq$$



had. vac. polarization — had. light-by-light

$$a_\mu(\text{QED}) = (11\,658\,471.886 \pm 0.003) \times 10^{-10},$$
$$a_\mu(\text{EW}) = (15.36 \pm 0.11) \times 10^{-10},$$
$$a_\mu(\text{HVP-LO}) = (689.46 \pm 3.25) \times 10^{-10},$$
$$a_\mu(\text{HVP-HO}) = (-8.70 \pm 0.07) \times 10^{-10},$$
$$a_\mu(\text{HLbL}) = (10.34 \pm 2.88) \times 10^{-10}.$$

+) $a_\mu(\text{NP})? \;\ldots\; 10 \times 10^{-10} \approx \frac{\alpha_{em}}{4\pi}\left(\frac{m_\mu}{200\,\text{GeV}}\right)^2$



$$a_\mu^{SM} = (11\,659\,178.3 \pm 4.3) \times 10^{-10}$$

$$a_\mu^{SM} = (11\,659\,209.2 \pm 6.3) \times 10^{-10}$$ (BNL ’04+CODATA ’14)

SM combination according to Jegerlehner [1804.07409].
QED: Aoyama, Hayakawa, Kinoshita, Nio [1205.5370] (cf. [1712.06060]).
EW: Gnendiger, Stöckinger, Stöckinger-Kim [1306.5546].
QCD: Jegerlehner [1711.06089] [1705.00263].

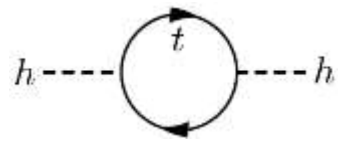
See also:
QED: Laporta [1704.06996], Marquard et al. [1708.07138].
HVP-LO: Keshavarzi, Nomura, Teubner [1802.02995]
HVP-HO: Kurz, Liu, Marquard, Steinhauser [1403.6400],
HLbL: Jegerlehner, Nyffeler [0902.3360],
Colangelo, Hoferichter, Nyffeler, Passera, Stoffer [1403.7512]

[FermiLab: ±1.6]

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

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

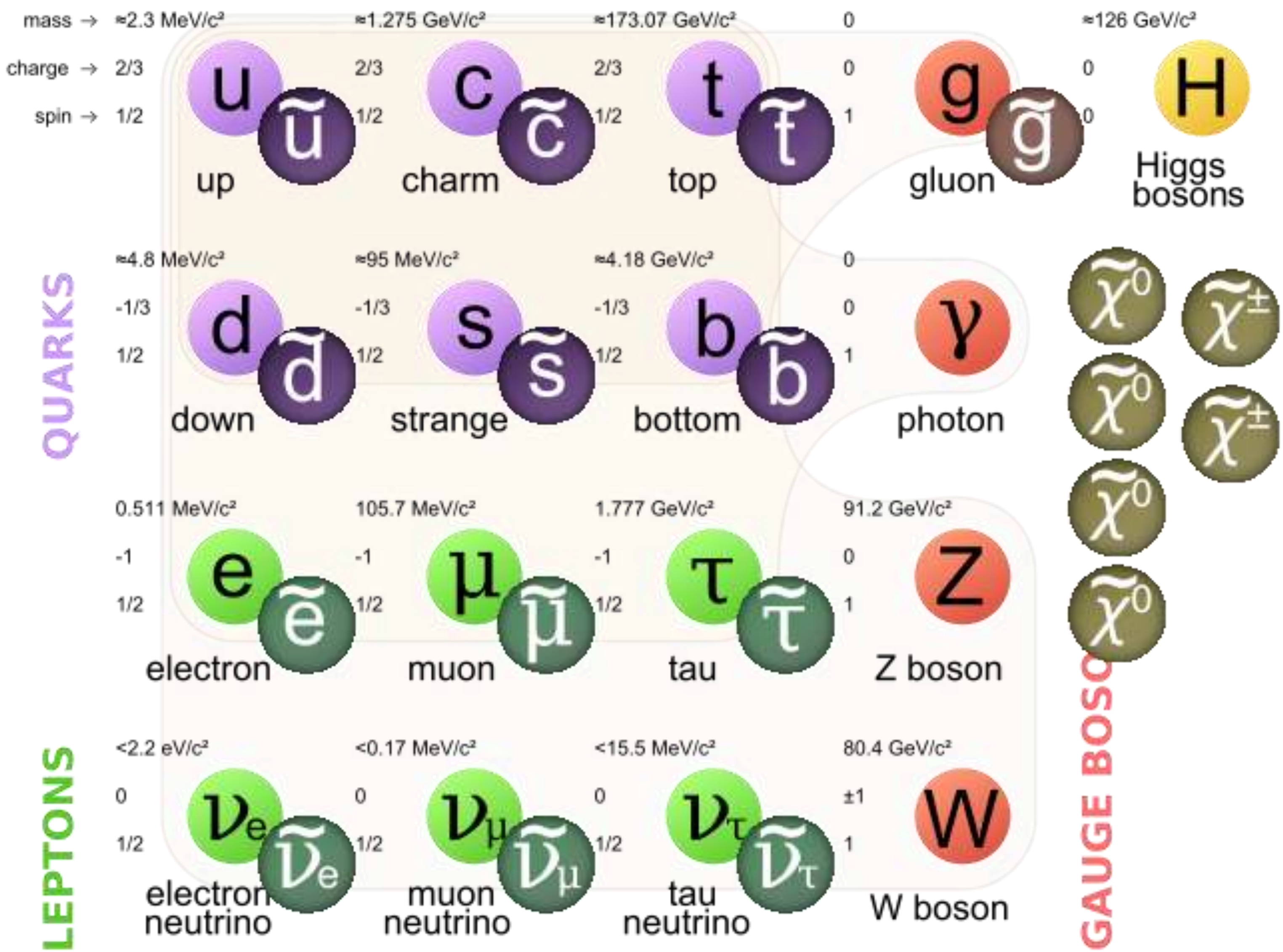
simplest scenario predicts (DM as a thermal relic, freezing out by pair-annihilation)

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

→ DM @ ~100 GeV?

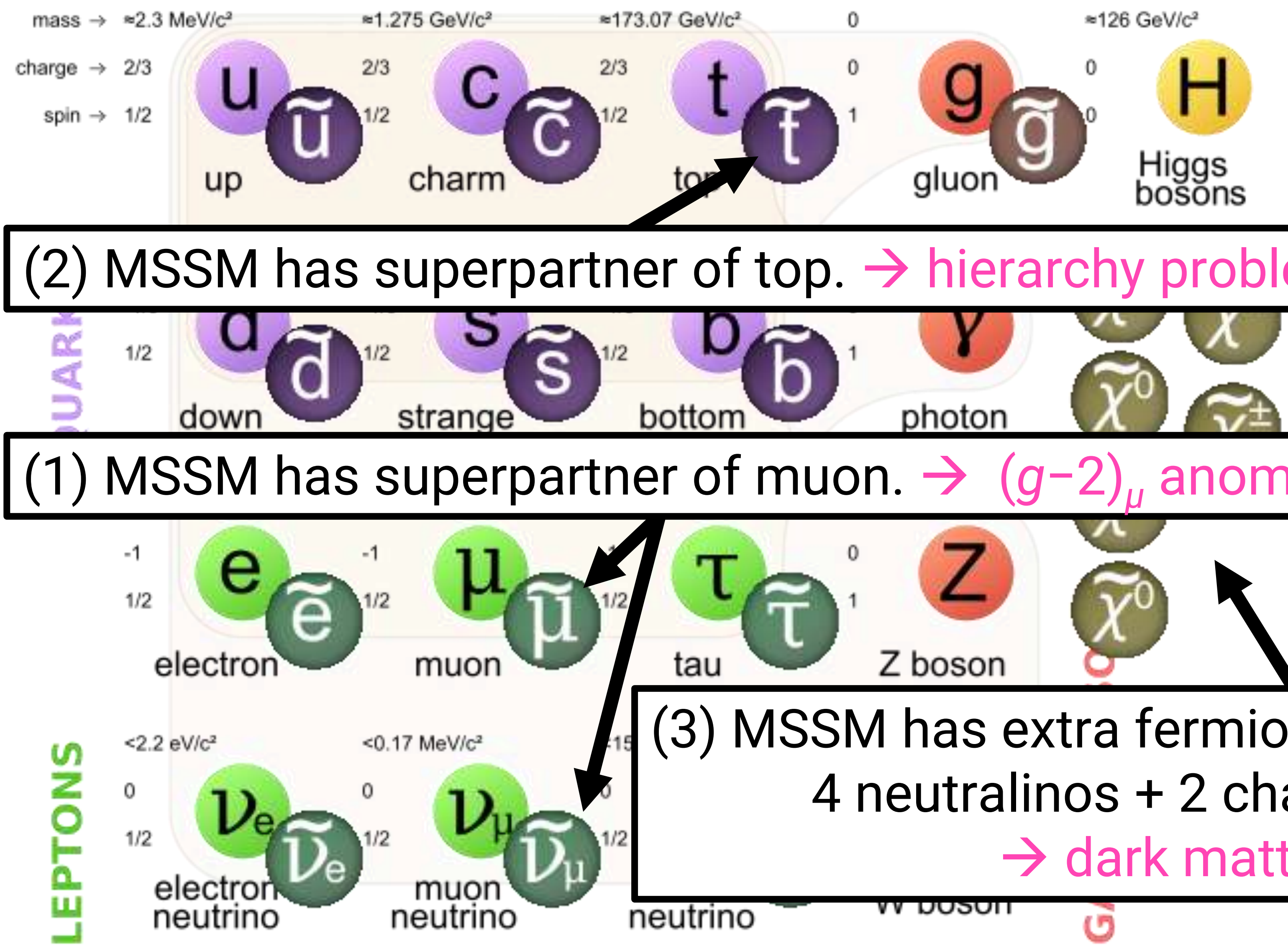
$$\Omega_{\rm DM}h^2 \approx \frac{1.1\times 10^9\cdot x_{\rm f}}{\sqrt{g_*}M_{\rm pl}\langle\sigma v\rangle\cdot \text{GeV}} \approx 0.1\cdot\frac{15}{\sqrt{g_*}}\frac{x_{\rm f}}{30}\frac{3\times 10^{-26}\,\text{cm}^3/\text{s}}{\langle\sigma v\rangle} \quad \text{with } x_{\rm f} = m_{\rm DM}/T_{\rm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

- MSSM = SUSY version of the Standard Model



- MSSM = SUSY versi

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

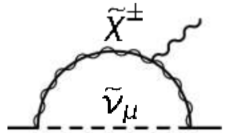


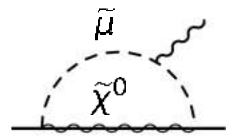
(2) MSSM has superpartner of top. → hierarchy problem?

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

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

■ MSSM = SUSY version of the Standard Model

- ➢ $(g-2)_\mu$ anomaly : 

+ 

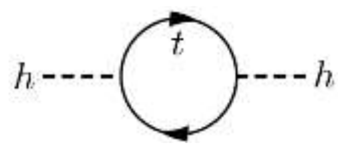
may explain the anomaly

  if these particles are O(100) GeV.

  (we'll discuss later.)

- ➢ Hierarchy problem

$$m_h^2 \sim m_{\rm bare}^2 + \Delta m_h^2, \qquad \Delta m_h^2(\text{MSSM}) \sim -\frac{3|\lambda|^2}{8\pi^2}\Lambda_{\rm cutoff}^2 + \left(2 \times \frac{3|\lambda|^2}{16\pi^2}\Lambda_{\rm cutoff}^2\right) + O(\log \Lambda_{\rm cutoff}).$$

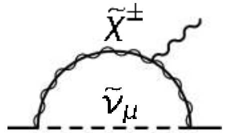


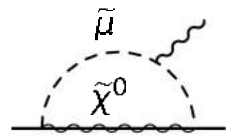
- ➢ Dark matter "WIMP miracle"

  The lightest neutralino 

may be stable. → DM?

■ MSSM = SUSY version of the Standard Model

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

 + 

 may explain the anomaly

  if these particles are O(100) GeV.

  (we'll discuss later.)

- Hierarchy problem

$$m_h^2 \sim m_{\text{bare}}^2 + \Delta m_h^2, \qquad \Delta m_h^2(\text{MSSM}) \sim -\frac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 \log \frac{\Lambda_{\text{cutoff}}}{m_{\tilde{t}}}$$

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

- Dark matter "WIMP miracle"

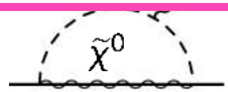
  The lightest neutralino 

 may be stable. → DM?

■ MSSM = SUSY version of the Standard Model

just 3–4σ from single experiment

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

 + 

 may explain the anomaly

  Not found yet.

  if these particles are O(100) GeV.

  (we'll discuss later.)

- Hierarchy problem

$$m_h^2 \sim m_{\text{bare}}^2 + \Delta m_h^2, \qquad \Delta m_h^2(\text{MSSM}) \sim -\frac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 \log \frac{\Lambda_{\text{cutoff}}}{m_{\tilde{t}}}$$

"natural" is subjective and unnecessary **Not found yet.**

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

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

  The lightest neutralino 

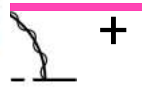
 may be stable. → DM **Not found yet.**

  difficult to capture at the LHC

and we are about to be lost.

- MSSM = SUS  of the Standard Model

~~**just** … **n single experiment**~~

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

g−2 anomaly is actual!

if these particles are O(100) GeV.

(we'll discuss later.)

➢ Hierarchy problem

$$m_h^2 \sim m_{\text{bare}}^2 + \Delta m_h^2, \qquad \Delta m_h^2(\text{MSSM}) \sim -\frac{3y_t^2}{4\pi^2} m_{\tilde t}^2 \log \frac{\Lambda_{\text{cutoff}}}{m_{\tilde t}}$$

"natural" is subjective and unnecessary

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

Not found yet.

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

The lightest neutralino $\tilde\chi^0$ may be stable. → DM **Not found yet.**

difficult to capture at the LHC

and we are about to be lost.

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.

- 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)

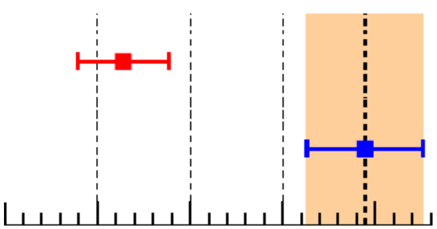
$$10 \times 10^{-10} \approx \frac{\alpha_{em}}{4\pi}\left(\frac{m_\mu}{m_{new}}\right)^2$$

m_{new}: ~200GeV

$$10 \times 10^{-10} \approx \frac{(\varepsilon^2/4\pi)}{4\pi}\left(\frac{m_\mu}{m_{new}}\right)^2$$

m_{new}: keV−MeV

$$a_\mu(\mathrm{NP})? \;\ldots\; 10 \times 10^{-10} \approx \frac{\alpha_{em}}{4\pi}\left(\frac{m_\mu}{200\,\mathrm{GeV}}\right)^2$$



$$a_\mu^{SM} = (11\,659\,178.3 \pm 4.3) \times 10^{-10}$$

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

- Muon g−2 anomaly: What is the origin?
  - ~~Just a statistical fluctuation.~~
  - ~~Just an issue in the experiment.~~

we assume it is "actual".

  - $O(100)$ GeV particles with $O(0.1)$ couplings
    - MSSM

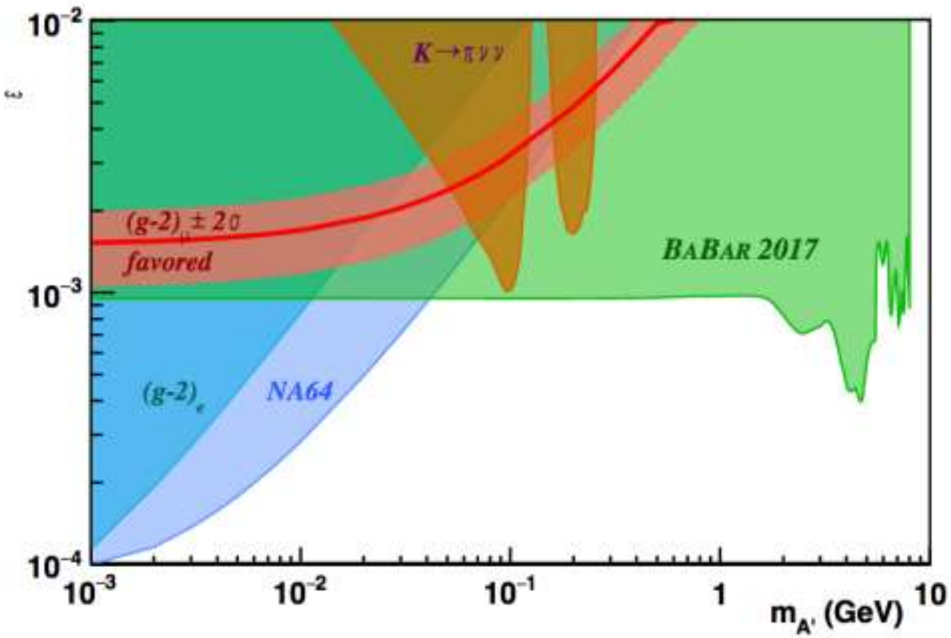
$$10\times10^{-10}\approx\frac{\alpha_{\rm em}}{4\pi}\left(\frac{m_\mu}{m_{\rm new}}\right)^2$$

~200GeV

  - keV−MeV particles with tiny couplings.
    - ~~dark photon (extra U(1) gauge boson)~~

$$10\times10^{-10}\approx\frac{(\varepsilon^2/4\pi)}{4\pi}\left(\frac{m_\mu}{m_{\rm new}}\right)^2$$

keV−MeV



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

BaBar [1702.03327]

- Muon g−2 anomaly: What is the origin?
  - ~~Just a statistical fluctuation.~~
  - ~~Just an issue in the experiment.~~

we assume it is "actual".

  - $O(100)$ GeV particles with $O(0.1)$ couplings
    - MSSM

$$10\times10^{-10}\approx\frac{\alpha_{em}}{4\pi}\left(\frac{m_\mu}{m_{new}}\right)^2$$

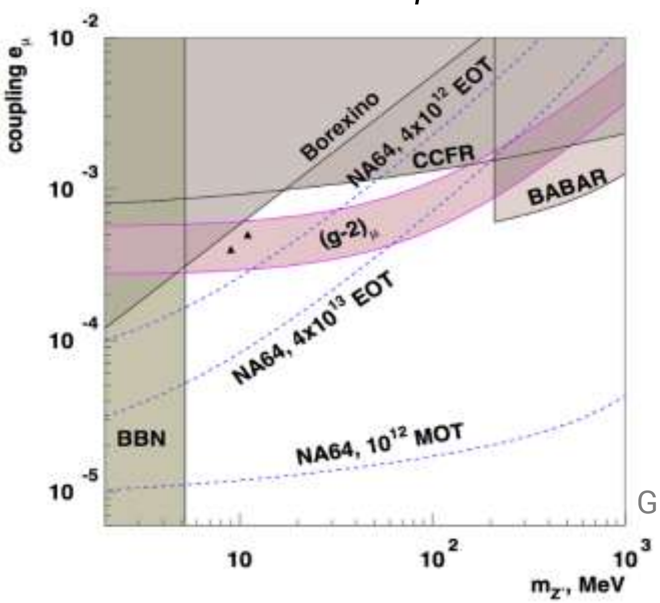
~200GeV

  - keV−MeV particles with tiny couplings.
    - ~~dark photon (extra U(1) gauge boson)~~
    - extra $L_\mu - L_\tau$ gauge boson

$$10\times10^{-10}\approx\frac{(\varepsilon^2/4\pi)}{4\pi}\left(\frac{m_\mu}{m_{new}}\right)^2$$

keV−MeV

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



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

Gninenko, Krasnikov [1801.10448]

- Muon g−2 anomaly: What is the origin?

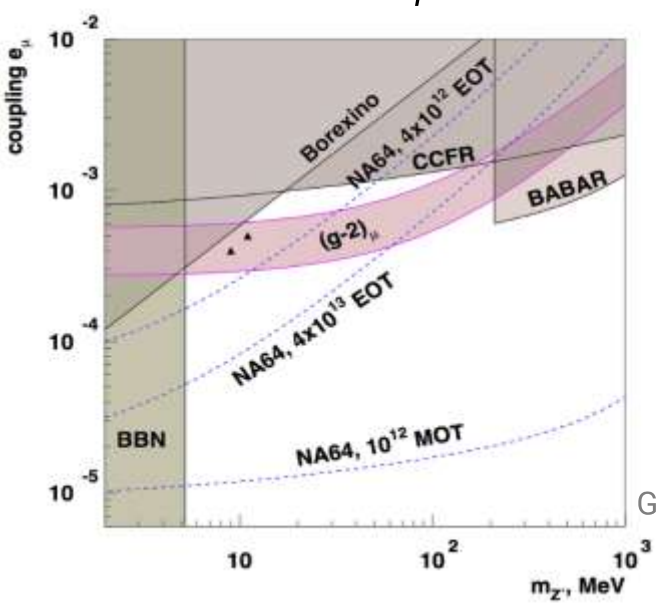
~~ust a statistical fluctuation.~~

~~ust an issue in the experiment.~~

we assume it is "actual".

- (100) GeV particles with $O(0.1)$ couplings $10\times10^{-10} \approx \frac{\alpha_{em}}{4\pi}\left(\frac{m_\mu}{m_{new}}\right)^2$ (m_{new} ~200GeV)
  - MSSM
- ➢ keV−MeV particles with tiny couplings. $10\times10^{-10} \approx \frac{(\varepsilon^2/4\pi)}{4\pi}\left(\frac{m_\mu}{m_{new}}\right)^2$ (m_{new}: keV−MeV)
  - ~~dark photon (extra U(1) gauge boson)~~
  - extra $L_\mu - L_\tau$ gauge boson

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



Gninenko, Krasnikov [1801.10448]

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

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

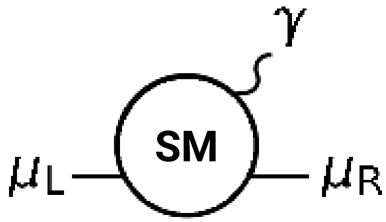
- Overview
- Collider physics
- Dark Matter

3. Discussion for each scenario

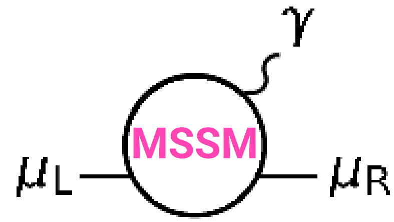
- "Chargino" scenario: multi-lepton signature is promising.
- "Pure-bino" scenario: di-lepton, but production not sufficient.
- "BHR" or "BHL": multi-tau, combined with direct detections.

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

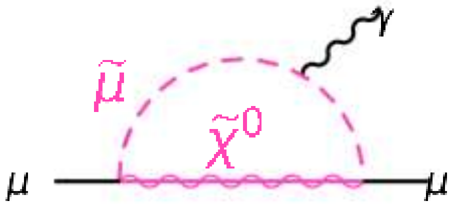
$a_\mu \equiv \frac{(g-2)_\mu}{2} =$



+



?



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

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

- lighter SUSY-particles
- larger $\tan\beta$

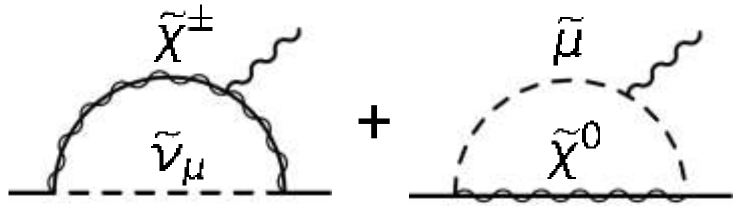
⇨ larger $a_\mu^{\rm SUSY}$

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

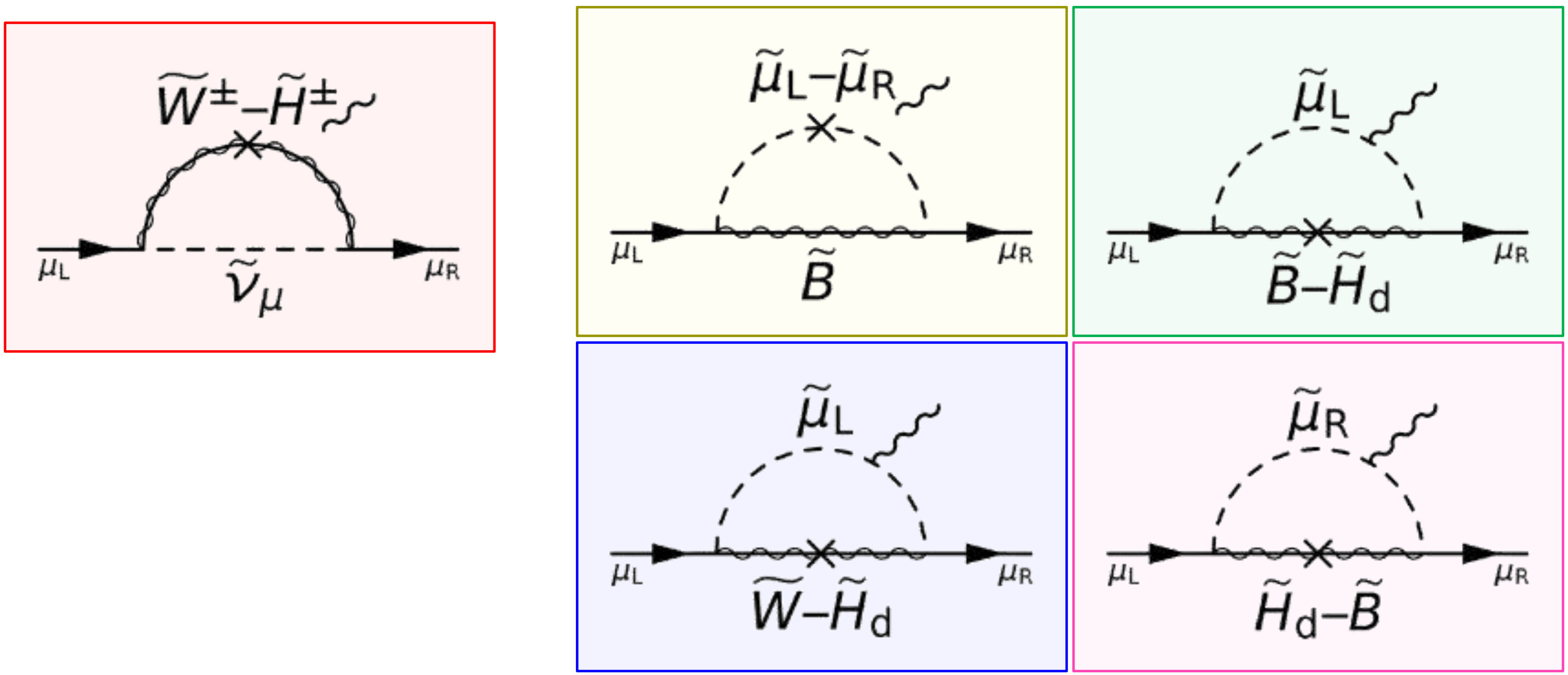
mass eigenstates

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

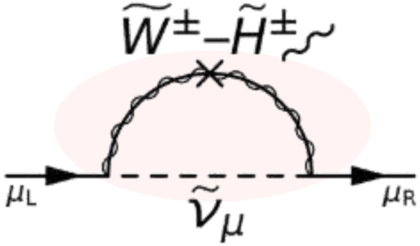


$$\tilde\chi^0_{1-4} = \tilde B \oplus \tilde W^0 \oplus \tilde H_{\rm d} \oplus \tilde H_{\rm u}, \quad \tilde\chi^\pm_{1,2} = \tilde W^\pm \oplus \tilde H^\pm .$$

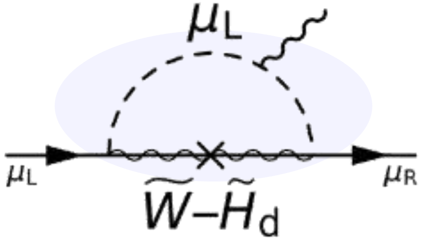
gauge eigenstates



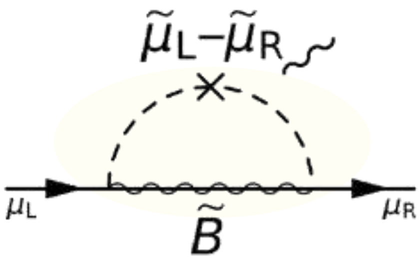
(“mass insertion” technique)



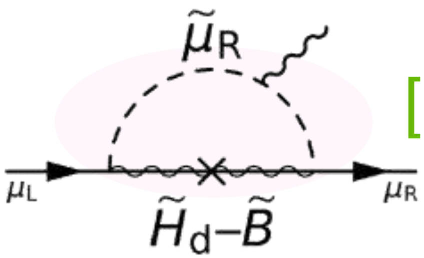
[C] $$\frac{g_2^2 m_\mu^2}{8\pi^2}\frac{M_2 \mu \tan\beta}{m_{\tilde{\nu}_\mu}^4}\cdot F_a\left(\frac{M_2}{m_{\tilde{\nu}_\mu}},\frac{\mu}{m_{\tilde{\nu}_\mu}}\right)$$



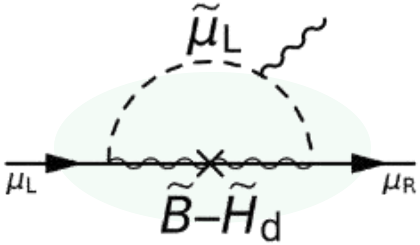
[C'] $$-\frac{g_2^2 m_\mu^2}{16\pi^2}\frac{M_2 \mu \tan\beta}{m_{\tilde{\mu}_L}^4}\cdot F_b\left(\frac{M_2}{m_{\tilde{\mu}_L}},\frac{\mu}{m_{\tilde{\mu}_L}}\right)$$



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

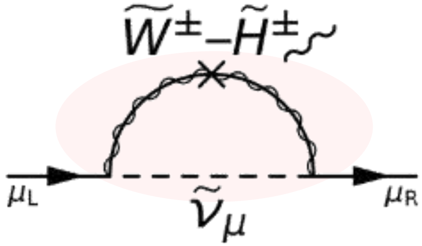


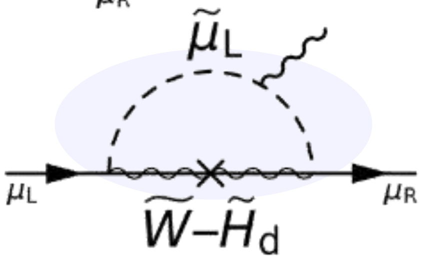
[BHL] $$\frac{g_Y^2 m_\mu^2}{16\pi^2}\frac{M_1 \mu \tan\beta}{m_{\tilde{\mu}_L}^4}\cdot F_b\left(\frac{M_1}{m_{\tilde{\mu}_L}},\frac{\mu}{m_{\tilde{\mu}_L}}\right)$$

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

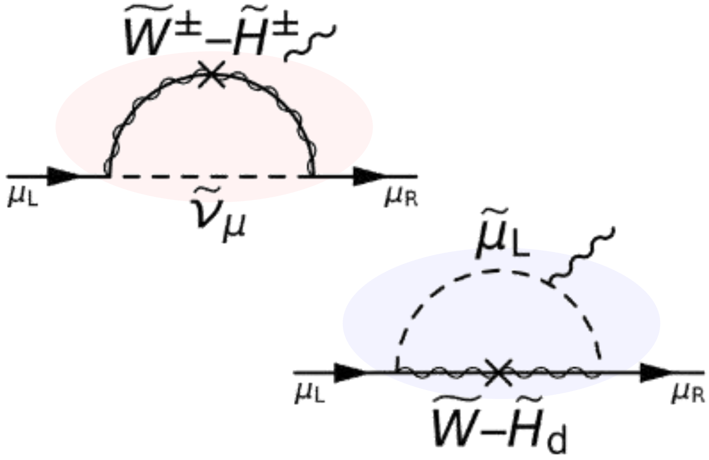
[C'] $$-\frac{g_2^2 m_\mu^2}{16\pi^2}\frac{M_2\mu\tan\beta}{m_{\widetilde{\mu}_L}^4}\cdot F_b\left(\frac{M_2}{m_{\widetilde{\mu}_L}},\frac{\mu}{m_{\widetilde{\mu}_L}}\right)$$

- "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.

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

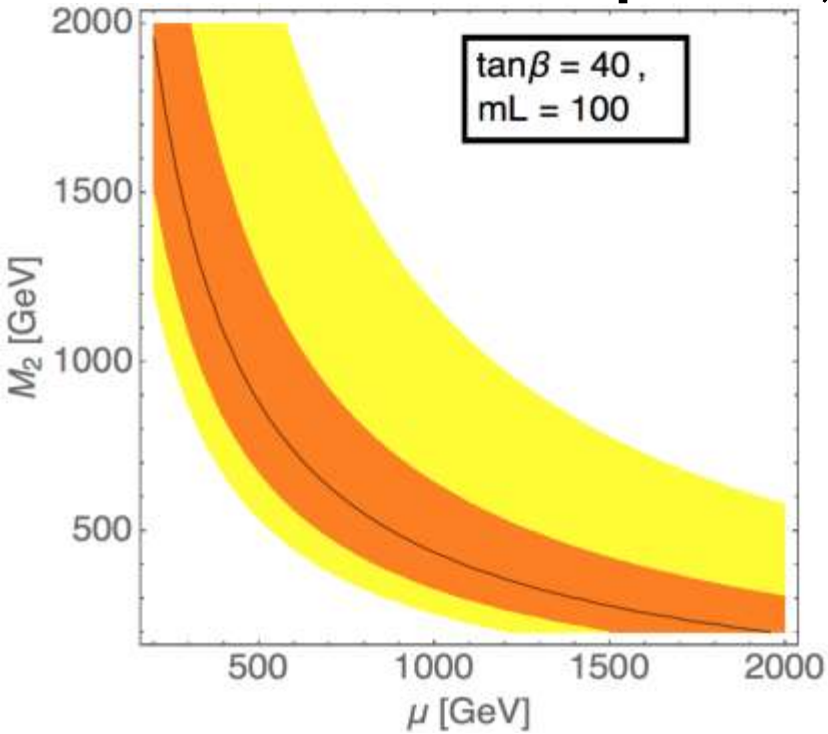
$$C_1(x)=\frac{3-4x+x^2+2\log x}{(1-x)^3},\qquad N_2(x)=\frac{1-x^2+2x\log x}{(1-x)^3}.$$

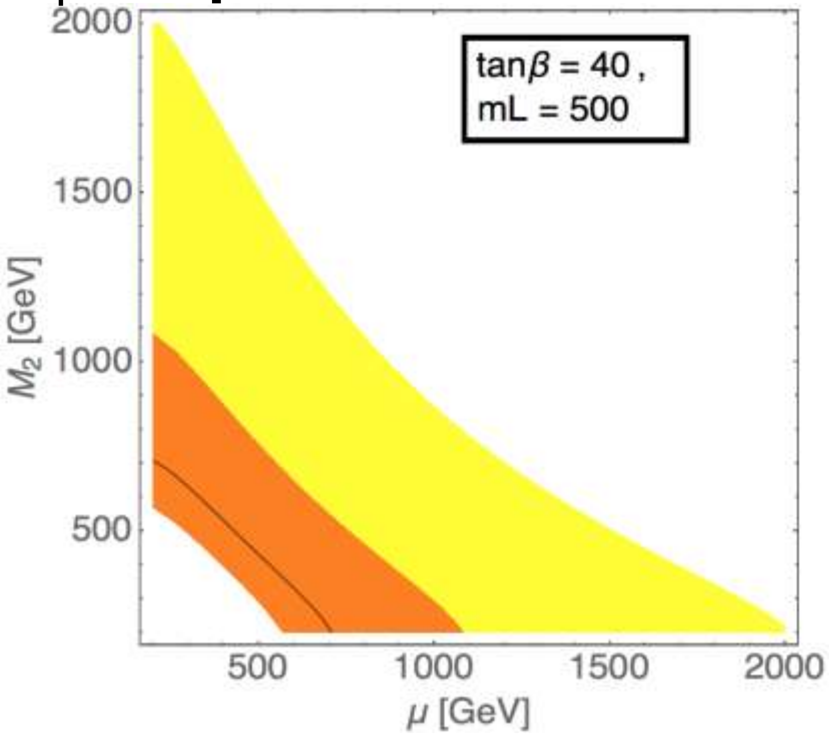


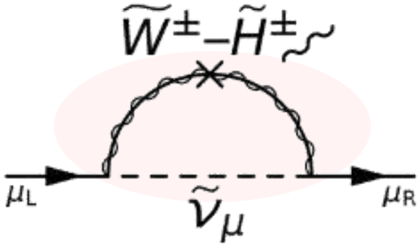
[C]
$$\frac{g_2^2 m_\mu^2}{8\pi^2}\frac{M_2\mu\tan\beta}{m_{\widetilde{\nu}_\mu}^4}\cdot F_a\left(\frac{M_2}{m_{\widetilde{\nu}_\mu}},\frac{\mu}{m_{\widetilde{\nu}_\mu}}\right)$$

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

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

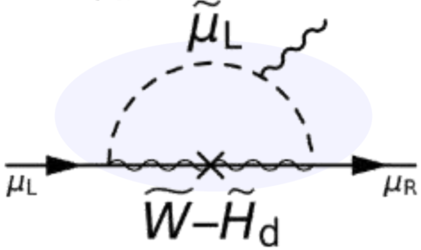






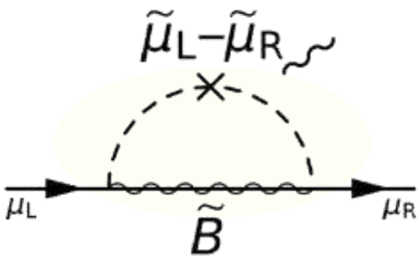
[C]

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



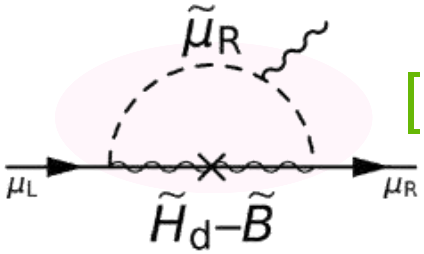
[C']

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



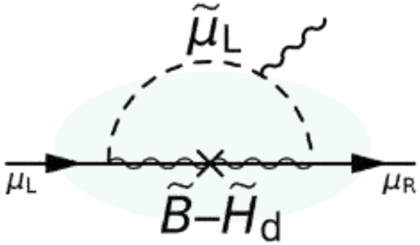
[B]

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



[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]

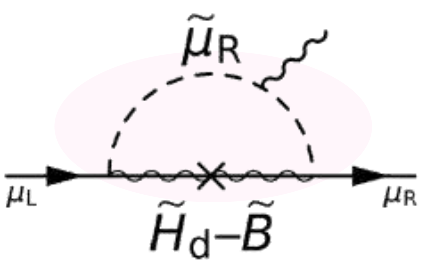
$$\frac{g_Y^2 m_\mu^2}{16\pi^2}\frac{M_1\mu\tan\beta}{m_{\tilde{\mu}_L}^4}\cdot F_b\left(\frac{M_1}{m_{\tilde{\mu}_L}},\frac{\mu}{m_{\tilde{\mu}_L}}\right)$$

F_a, F_b are loop functions and positive.

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

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

- "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)
- $\propto g_Y^2$



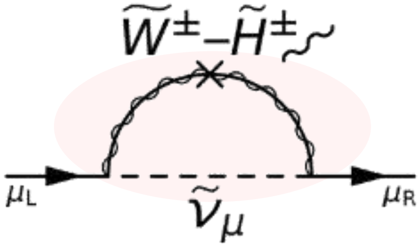
[BHR] $$-\frac{g_Y^2 m_\mu^2}{8\pi^2}\frac{M_1 \mu \tan\beta}{m_{\tilde{\mu}_R}^4}\cdot F_b\left(\frac{M_1}{m_{\tilde{\mu}_R}}, \frac{\mu}{m_{\tilde{\mu}_R}}\right)$$

F_a, F_b are loop functions and positive.

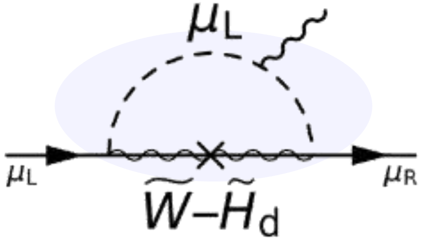
$$F_a(x,y) = \frac{1}{2}\frac{C_1(x^2)-C_1(y^2)}{x^2-y^2}, \qquad F_b(x,y) = -\frac{1}{2}\frac{N_2(x^2)-N_2(y^2)}{x^2-y^2};$$

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

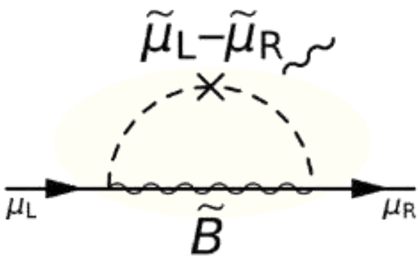
SUSY contribution to muon $g-2$: (3) pure-Bino contribution



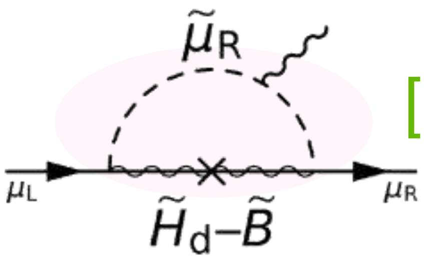
[C] $$\frac{g_2^2 m_\mu^2}{8\pi^2}\frac{M_2 \mu \tan\beta}{m_{\tilde{\nu}_\mu}^4}\cdot F_a\left(\frac{M_2}{m_{\tilde{\nu}_\mu}},\frac{\mu}{m_{\tilde{\nu}_\mu}}\right)$$



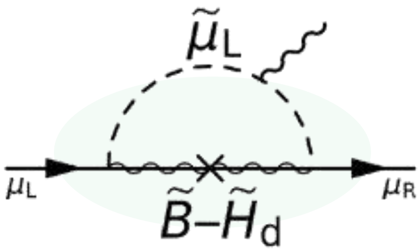
[C'] $$-\frac{g_2^2 m_\mu^2}{16\pi^2}\frac{M_2 \mu \tan\beta}{m_{\tilde{\mu}_\mathrm{L}}^4}\cdot F_b\left(\frac{M_2}{m_{\tilde{\mu}_\mathrm{L}}},\frac{\mu}{m_{\tilde{\mu}_\mathrm{L}}}\right)$$



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



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



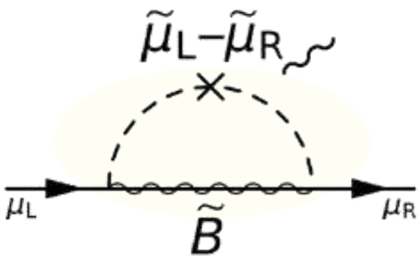
[BHL] $$\frac{g_Y^2 m_\mu^2}{16\pi^2}\frac{M_1 \mu \tan\beta}{m_{\tilde{\mu}_\mathrm{L}}^4}\cdot F_b\left(\frac{M_1}{m_{\tilde{\mu}_\mathrm{L}}},\frac{\mu}{m_{\tilde{\mu}_\mathrm{L}}}\right)$$

F_a, F_b are loop functions and positive.

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

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

- "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.



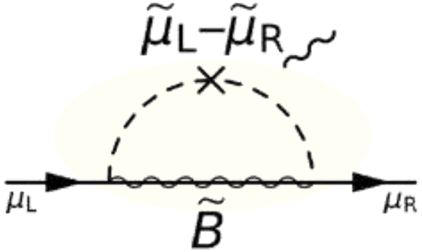
[B] $$\frac{g_Y^2 m_\mu^2}{8\pi^2}\frac{\mu\tan\beta}{M_1^3} \cdot F_b\left(\frac{m_{\tilde{\mu}_L}}{M_1}, \frac{m_{\tilde{\mu}_R}}{M_1}\right)$$

F_a, F_b are loop functions and positive.

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

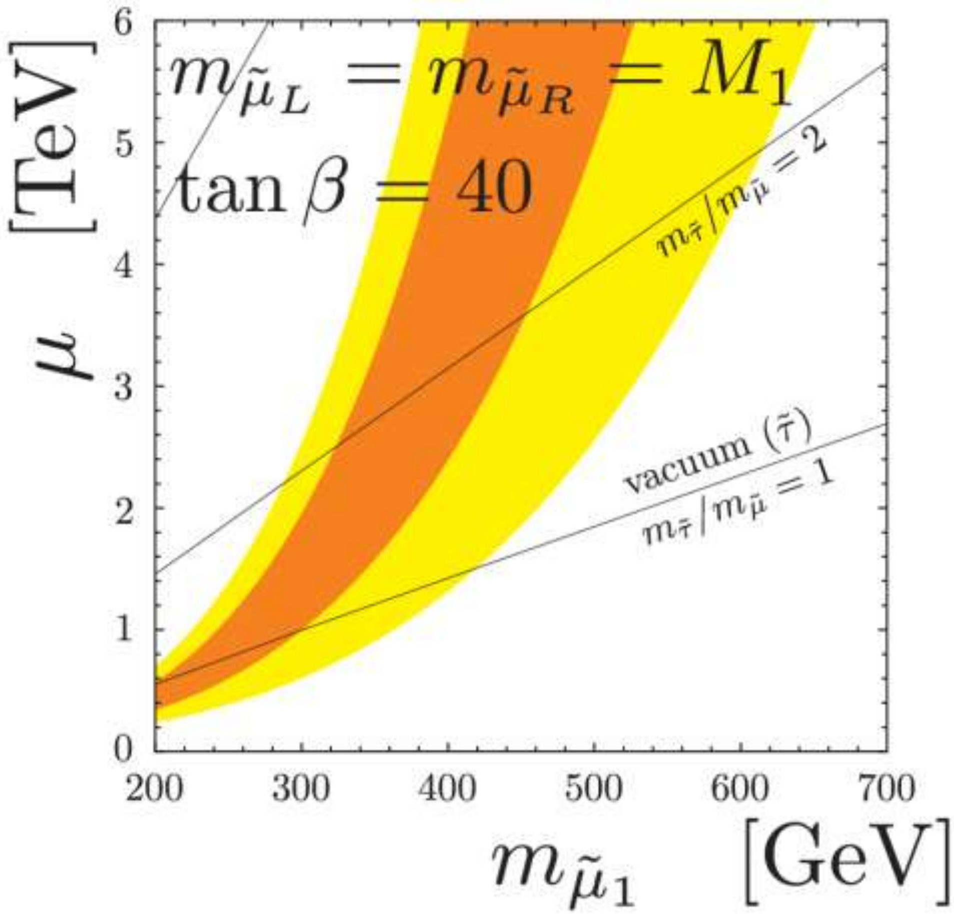
$$C_1(x) = \frac{3-4x+x^2+2\log x}{(1-x)^3}, \qquad N_2(x) = \frac{1-x^2+2x\log x}{(1-x)^3}.$$

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:

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

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

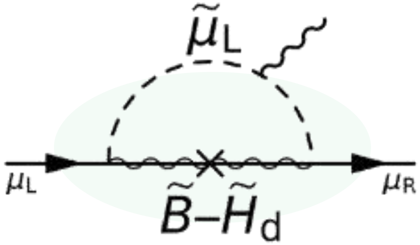
$= 1 \;\Rightarrow m_{\tilde{\mu}} \lesssim 300(420)$ GeV

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

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

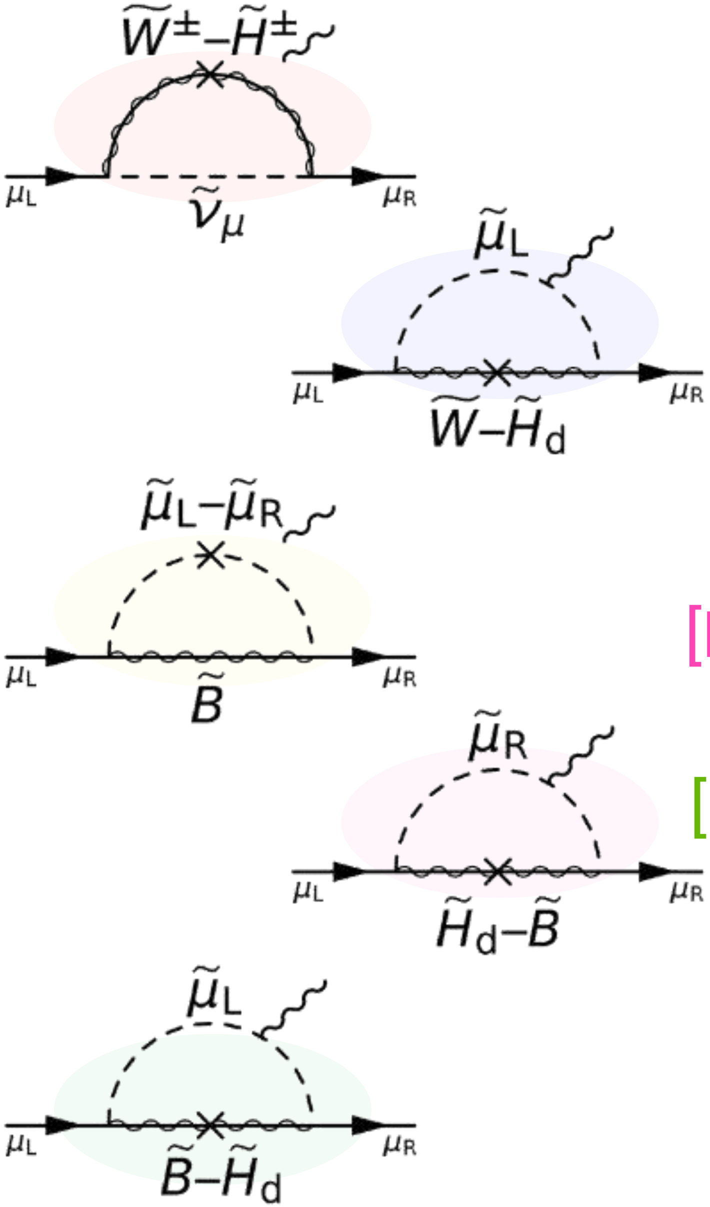
- "BHL contribution" (Bino, Higgsino, $\tilde{\mu}_{\mathrm{L}}$ must be $O(100)$GeV)
- nothing special.

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



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

tend to be large/dominant

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

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

μ-enhancement

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

negative

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

nothing special

F_a, F_b are loop functions and positive.

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

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

1. Introduction

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

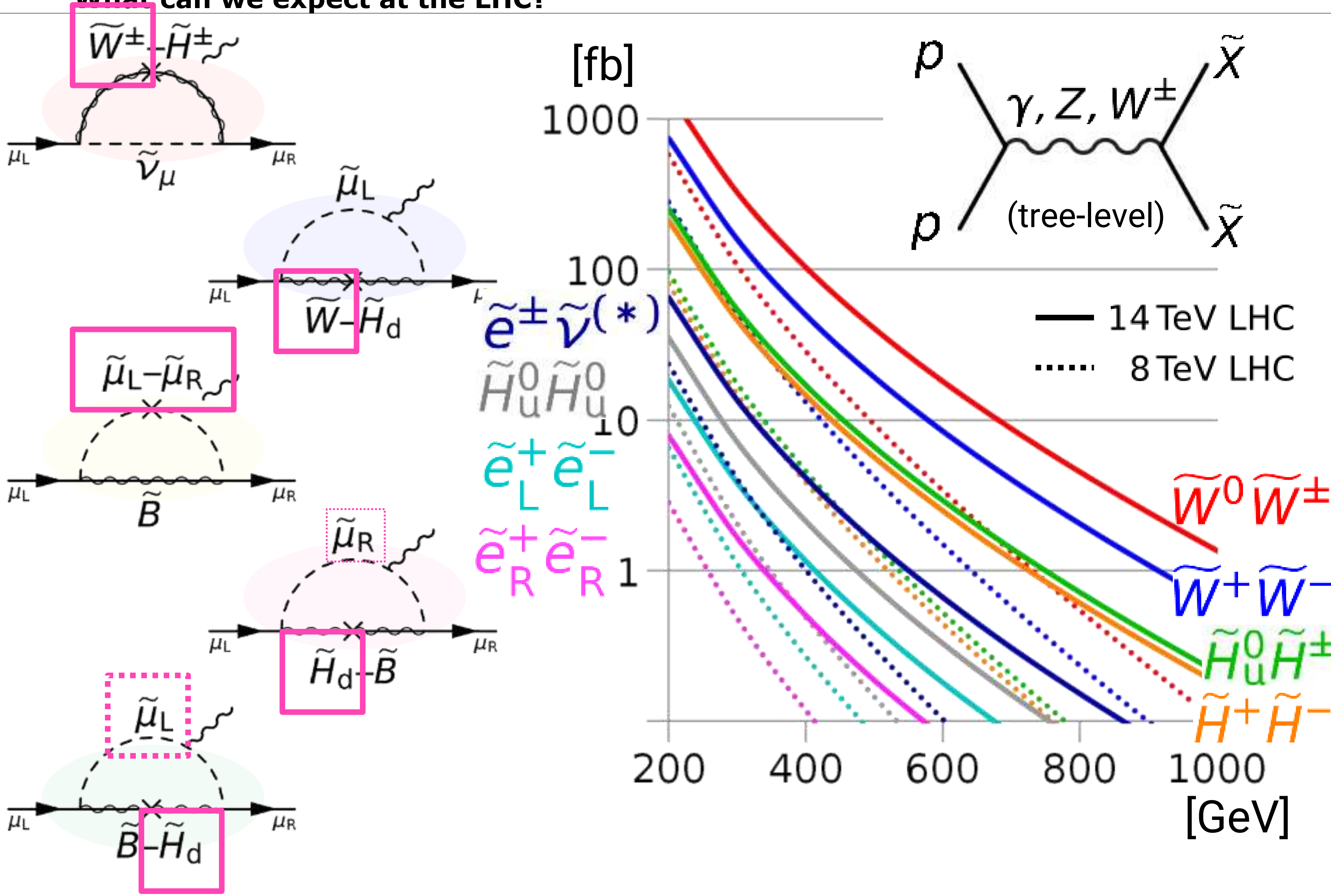
2. Four scenarios of MSSM as the solution of $(g-2)_\mu$ anomaly

- 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.

What can we expect at the LHC?



1. Introduction

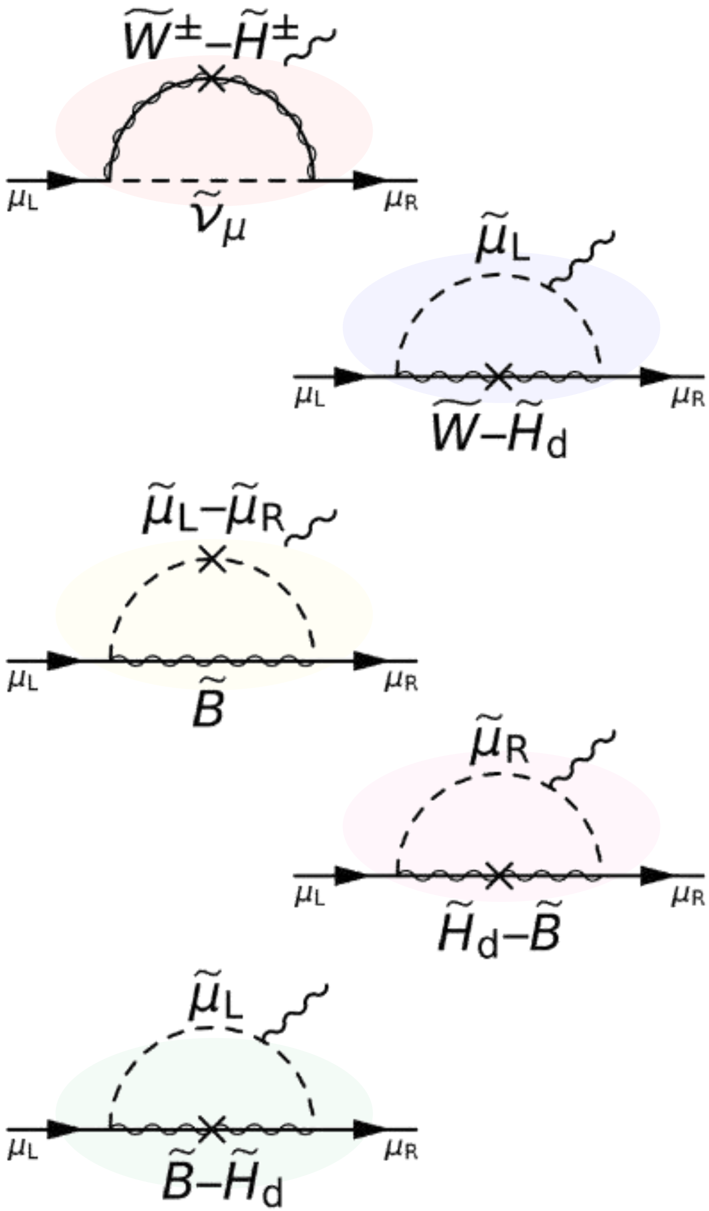
- Why did we expect new physics @ LHC?
- $(g-2)_\mu$ anomaly

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.



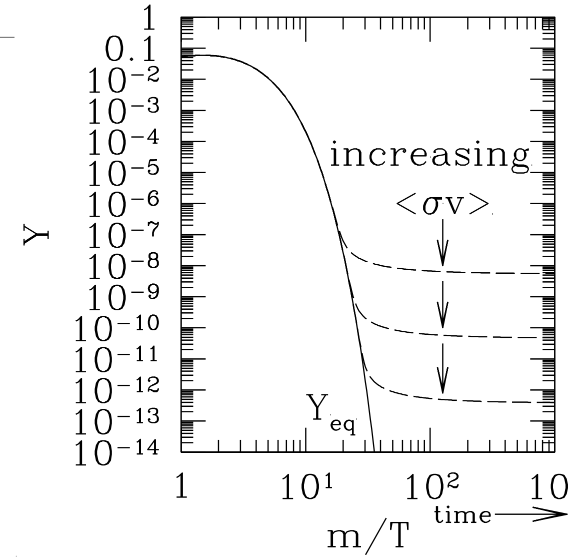
- $(g-2)_\mu$ always requires $\widetilde{\chi}^0$
  → good DM candidate!

- 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.

    $\cdots \langle \sigma v \rangle_{\mathrm{DM\,DM} \to \mathrm{any}} \sim 3 \times 10^{-26}\,\mathrm{cm^3/s}$
  - 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

> - **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]

n –

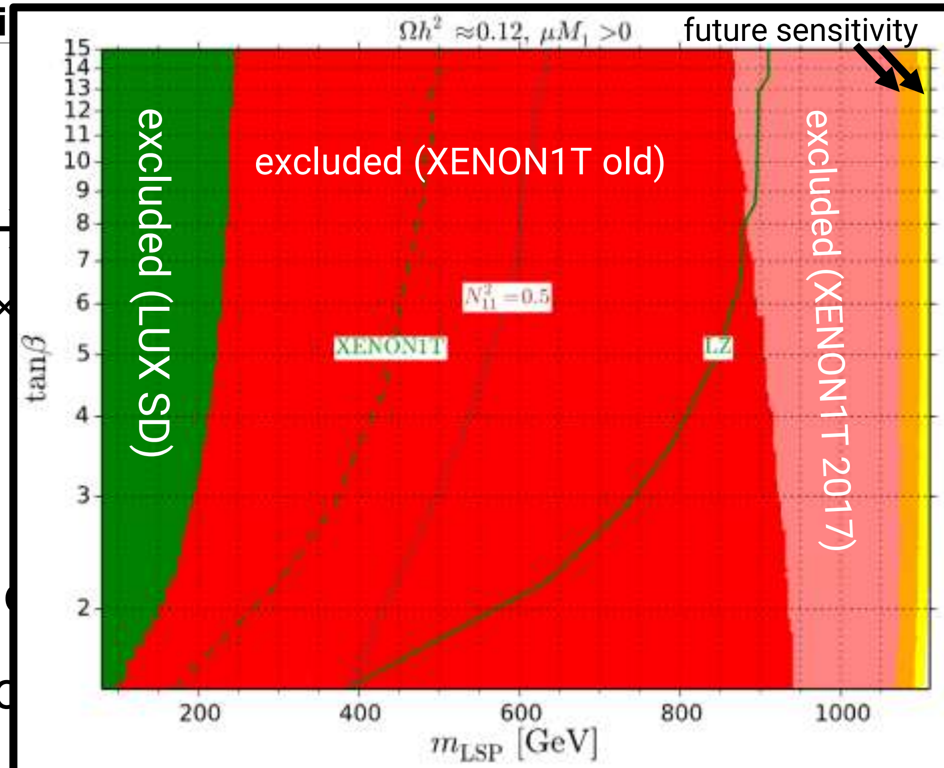
3 ×

cti

/ fo

- 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.

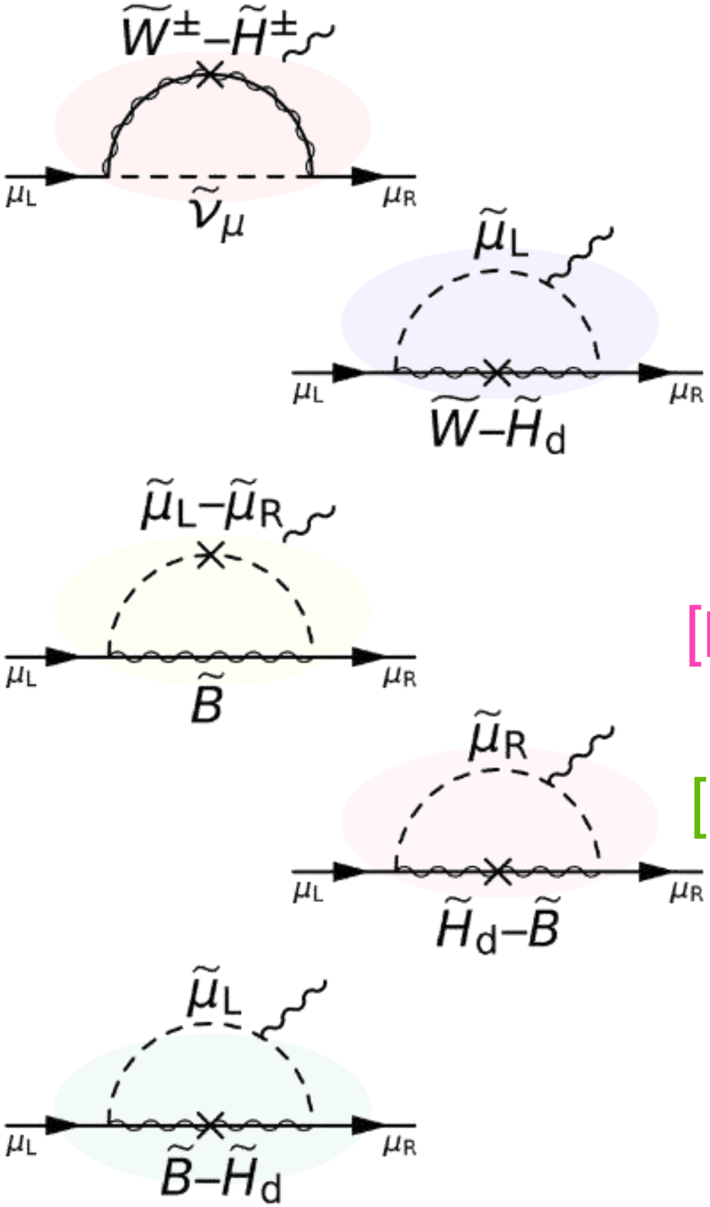


almost excluded by XENON1T

Badziak, Olechowski, Szczerbiak [1701.05869]

theoretically not nice

Figure from Gelmini and Gondolo, 1009.3690



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

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

μ-enhancement

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

negative

[BHL] $\frac{g_Y^2 m_\mu^2}{16\pi^2}$ … $m_{\tilde{\mu}_L}$ … $\frac{\mu}{m_{\tilde{\mu}_L}}$

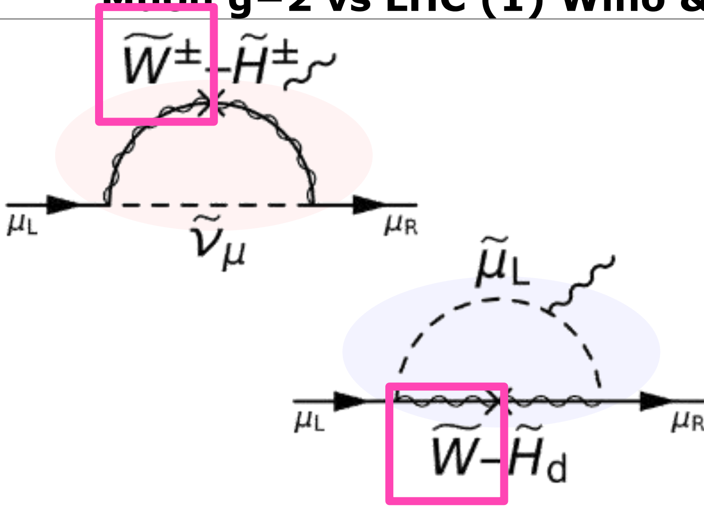
nothing special

F_a, F_b are loop functions and positive.

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

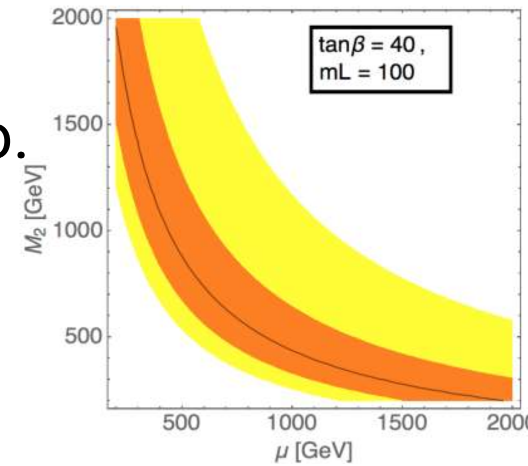
$$C_1(x)=\frac{3-4x+x^2+2\log x}{(1-x)^3},\qquad N_2(x)=\frac{1-x^2+2x\log x}{(1-x)^3}.$$

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



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

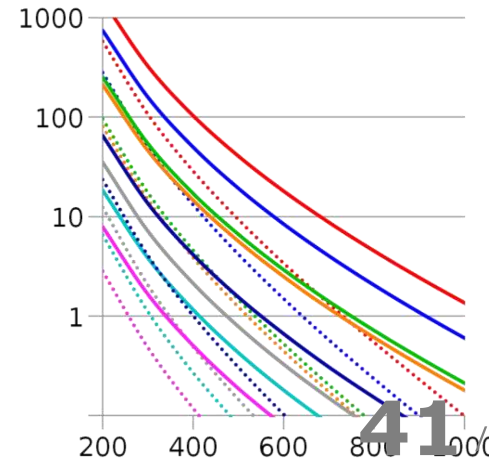
$$-\frac{g_2^2 m_\mu^2}{16\pi^2}\frac{M_2\mu\tan\beta}{m_{\tilde{\mu}_L}^4}\cdot F_b\left(\frac{M_2}{m_{\tilde{\mu}_L}},\frac{\mu}{m_{\tilde{\mu}_L}}\right)$$



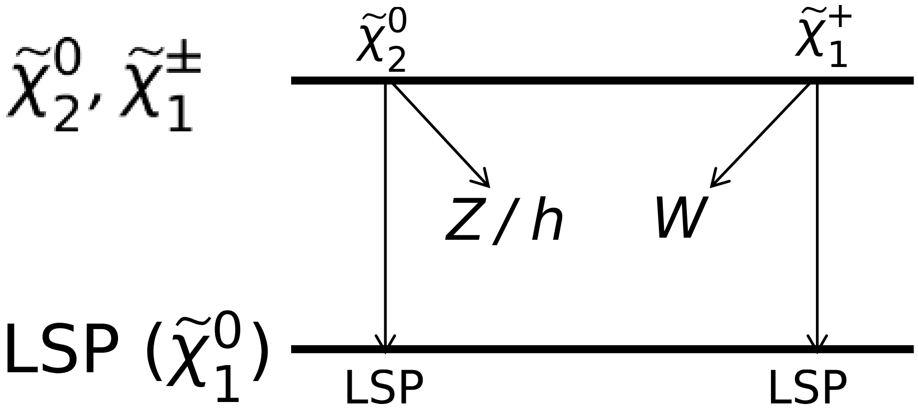
- Wino&Higgsino < TeV → chargino scenario.
  - $\propto g_2^2$ → relevant particles $\lesssim 1\,\mathrm{TeV}$
  - DM: not considered here
    - $(g-2)_\mu \Leftarrow (\widetilde{W},\widetilde{H},\widetilde{\mu}_L)$; DM $\Leftarrow (\widetilde{l}_L,\widetilde{B})$ ... "orthogonal"
    - co-annihilation 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

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

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



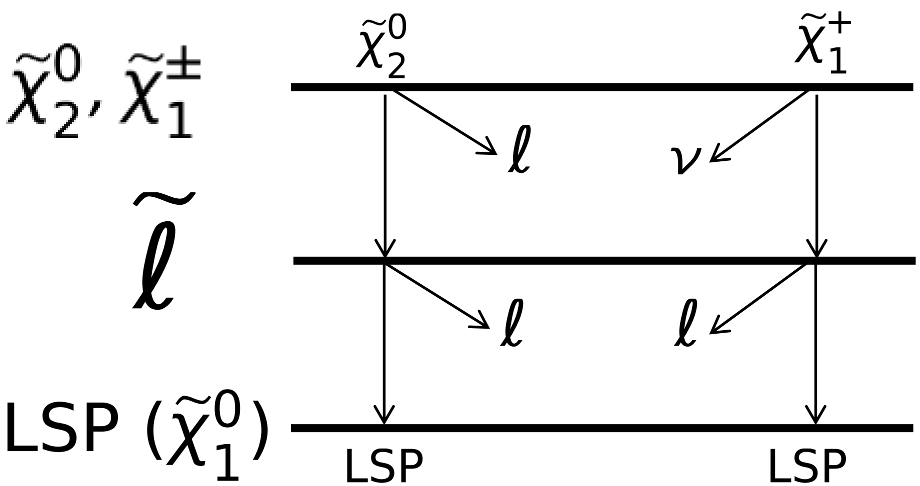
$pp \to \tilde{\chi}^0 \tilde{\chi}^+ \ \ (\widetilde{W}^0 \widetilde{W}^+$ or $\widetilde{H}^0 \widetilde{H}^+)$; then?



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

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

but Z-like leptons

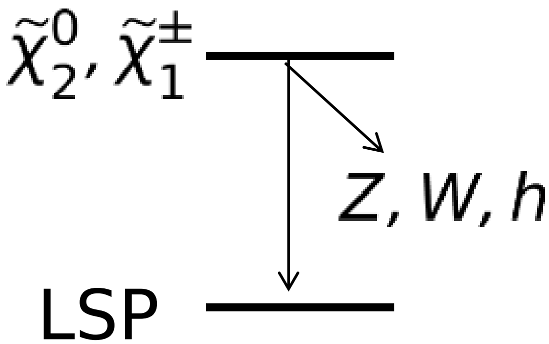


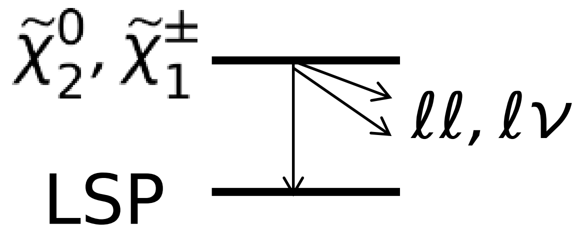
$\tilde{\chi}^0_2 \tilde{\chi}^+_1 \to 3\ell + \text{mET}$

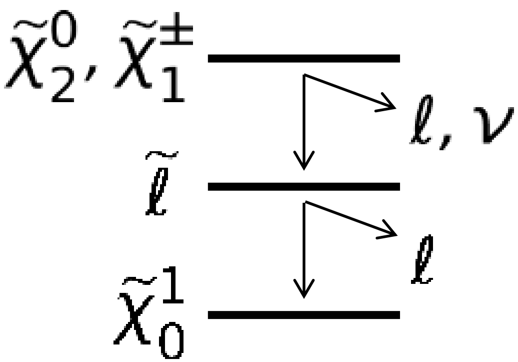
Z-unlike

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

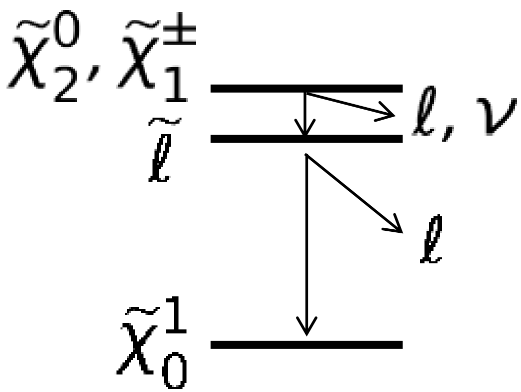
$pp \to \tilde{\chi}^0 \tilde{\chi}^+$ $(\widetilde{W}^0 \widetilde{W}^+$ or $\widetilde{H}^0 \widetilde{H}^+)$; then?



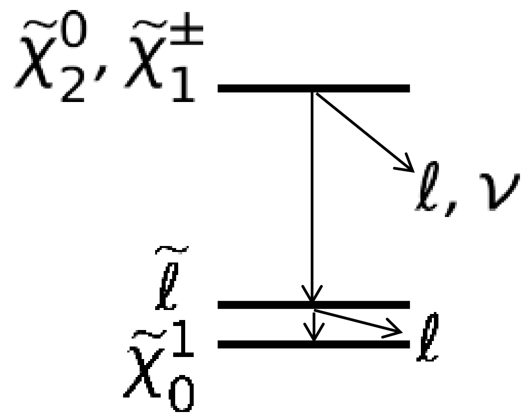




$x_\ell \sim 0.5$

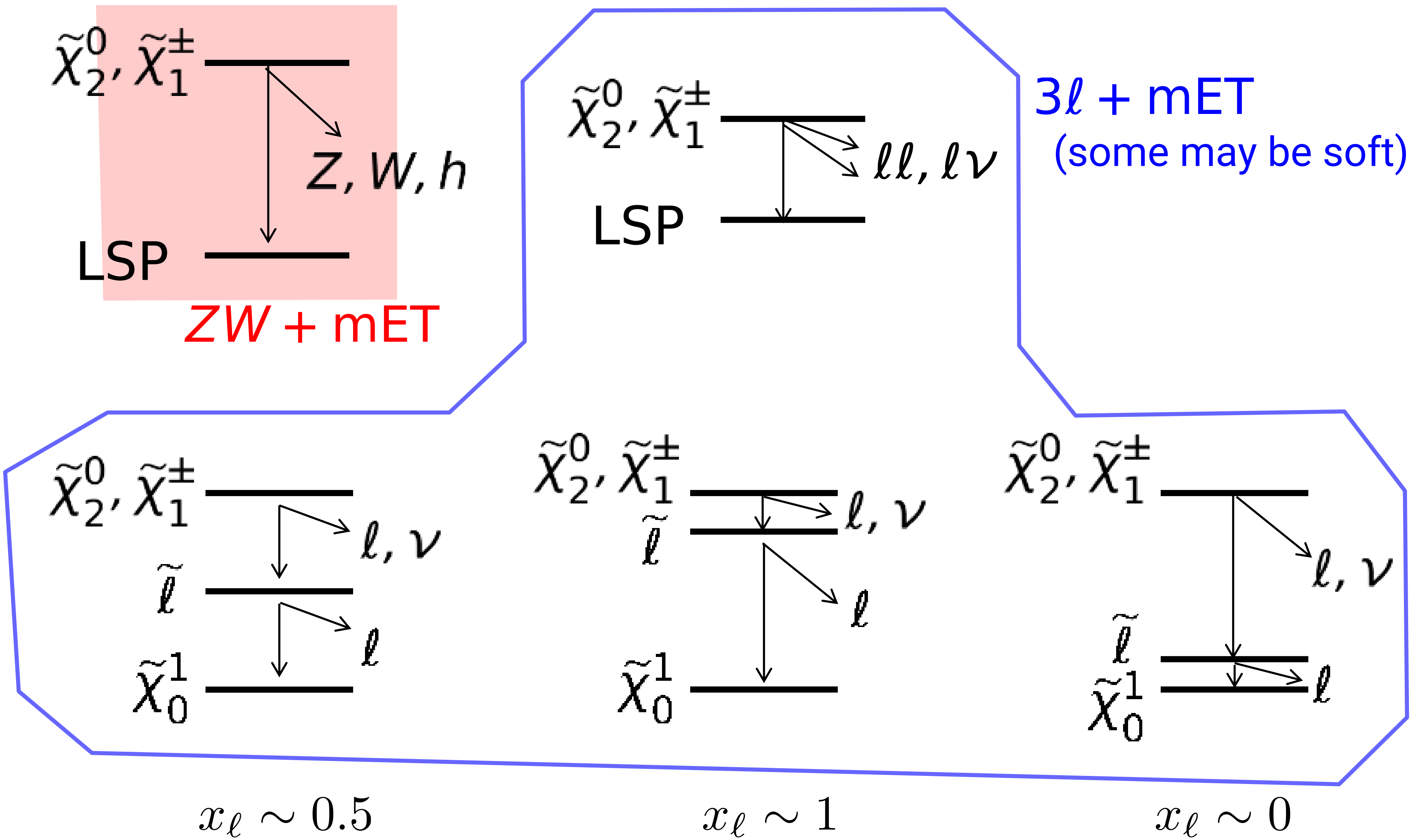


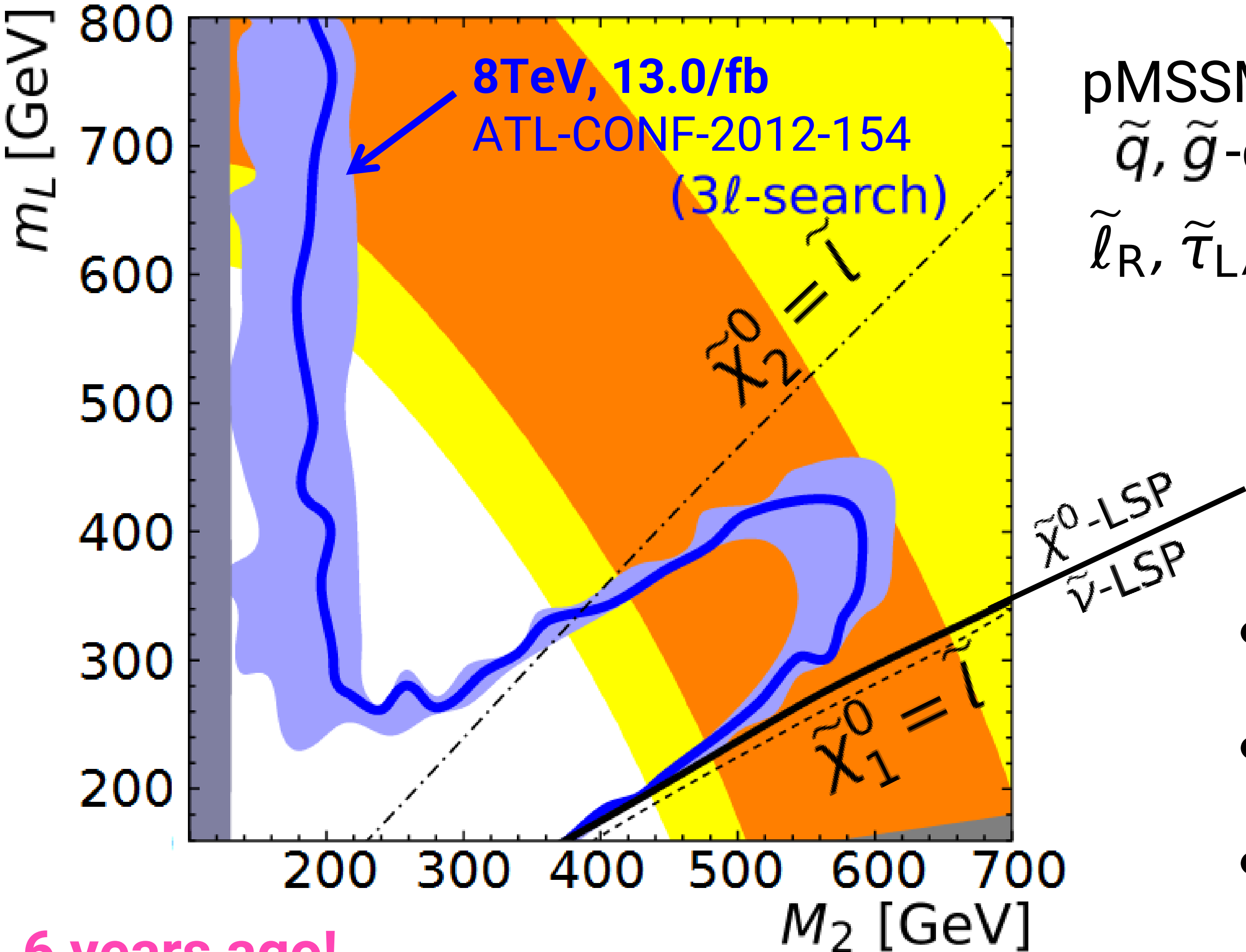
$x_\ell \sim 1$



$x_\ell \sim 0$

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

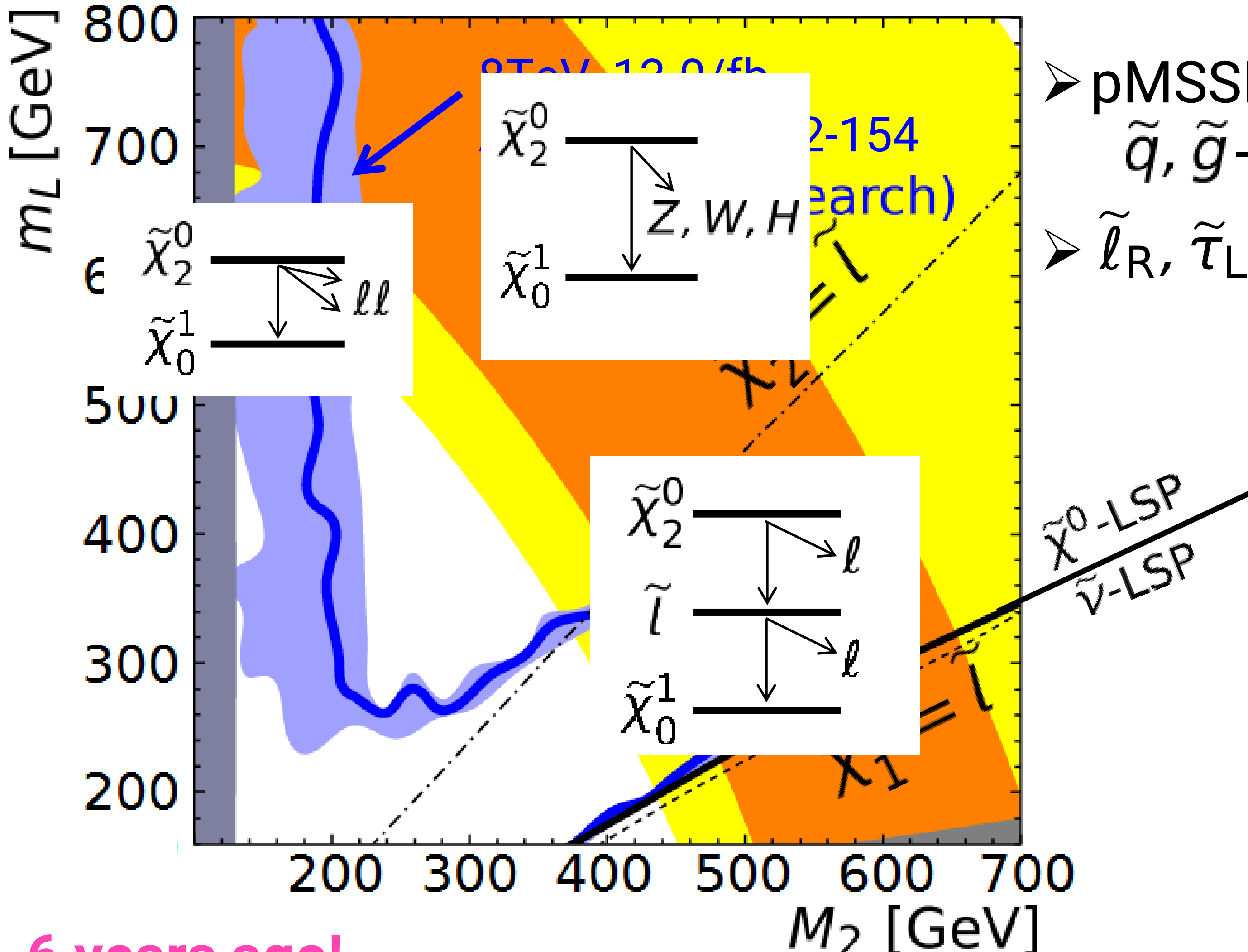




6 years ago!

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

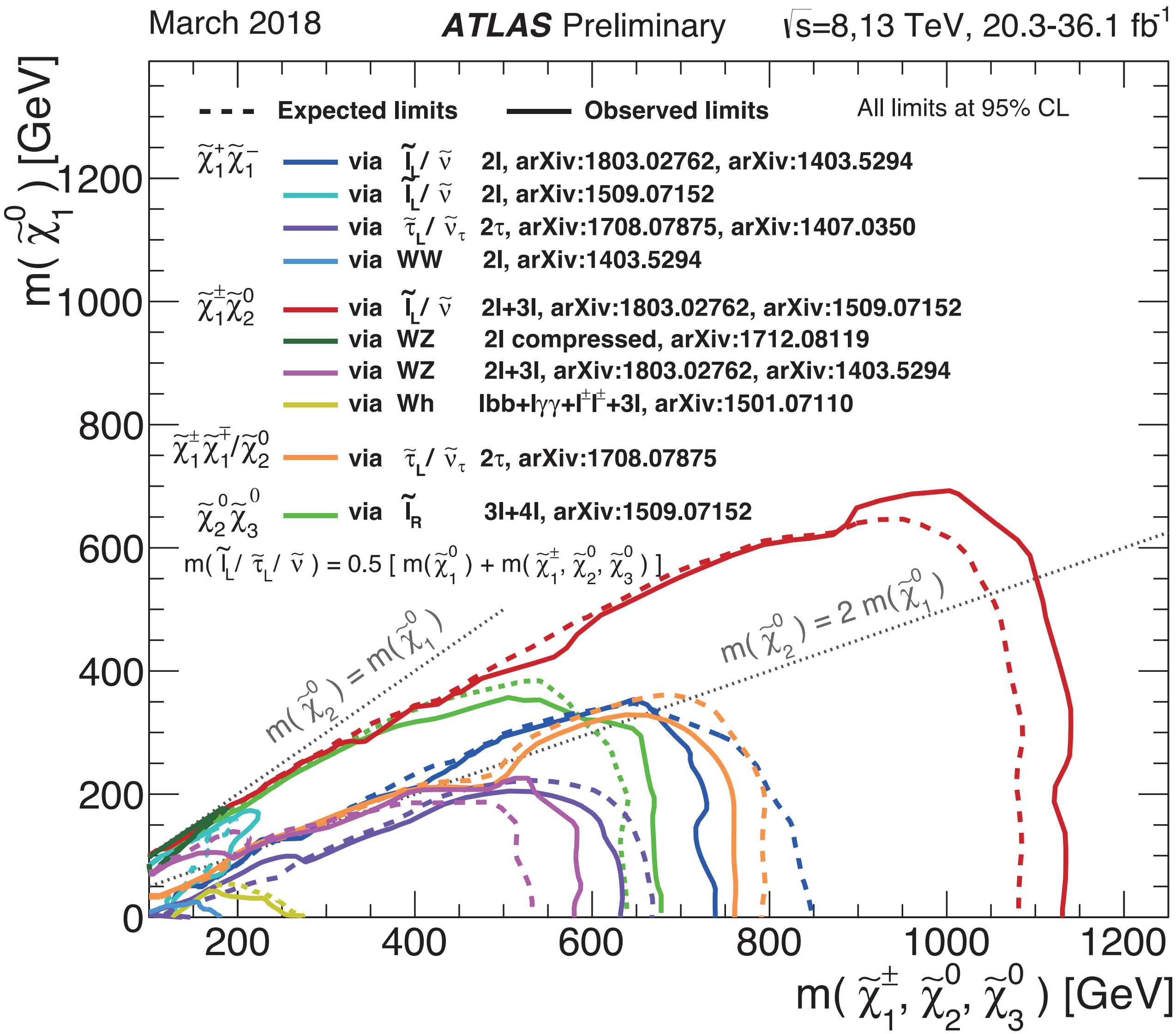
- $\tan\beta = 40$
- $M_1 = M_2/2$
- $\mu = M_2$

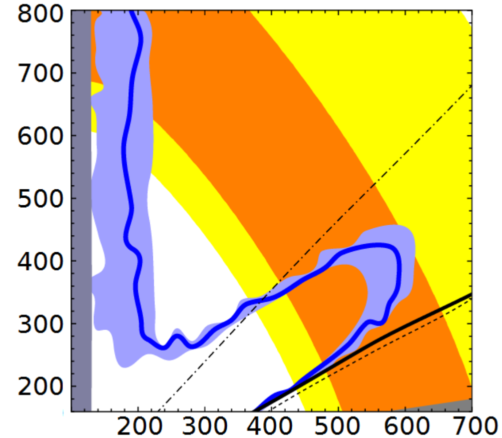


- pMSSM w. $\tilde{q}, \tilde{g}$-decoupled.
- $\tilde{\ell}_R, \tilde{\tau}_L, \tilde{\tau}_R$ also decoupled.

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

6 years ago!





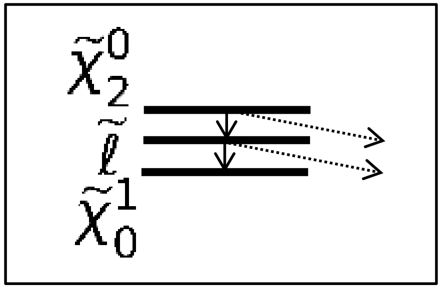
Warning

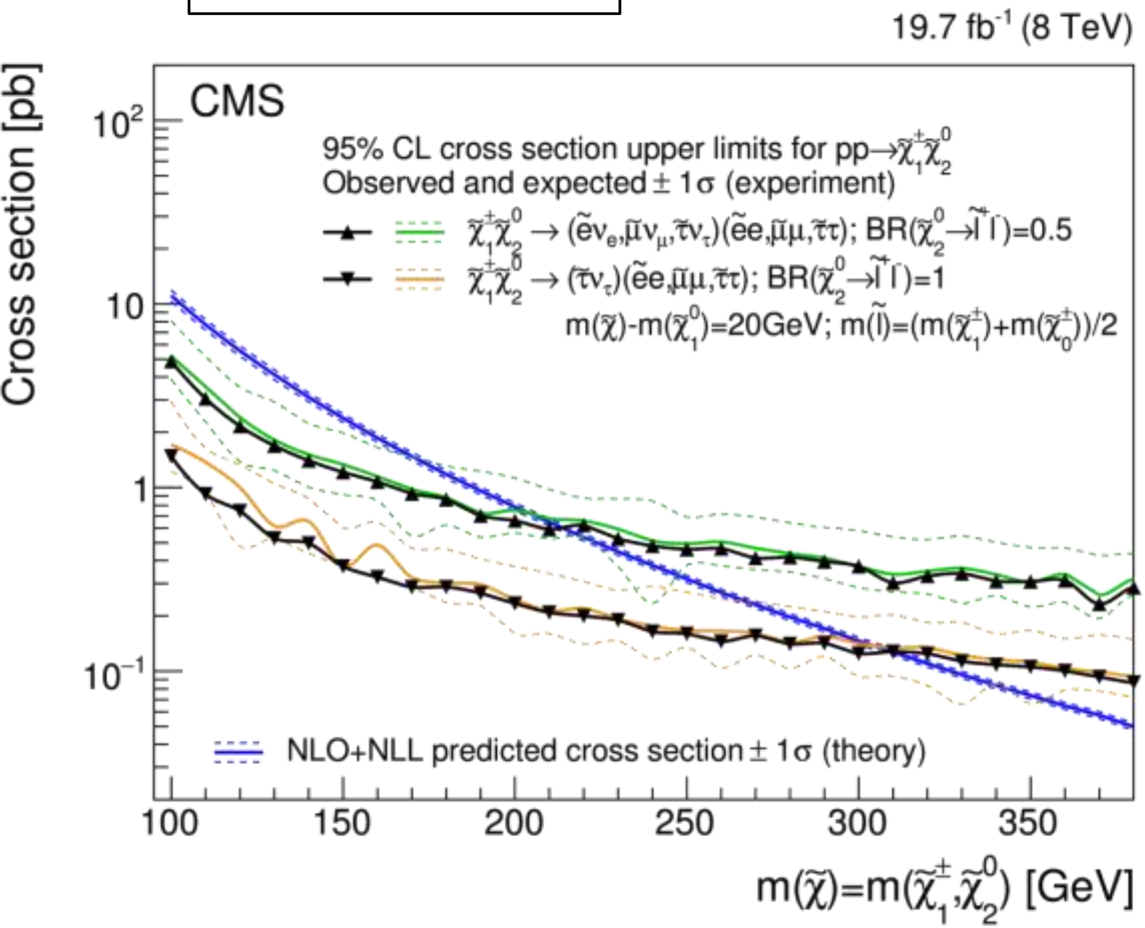
Assumptions for model simplification!

Crosssection is for $pp \to \widetilde{W}^0\widetilde{W}^+$!!

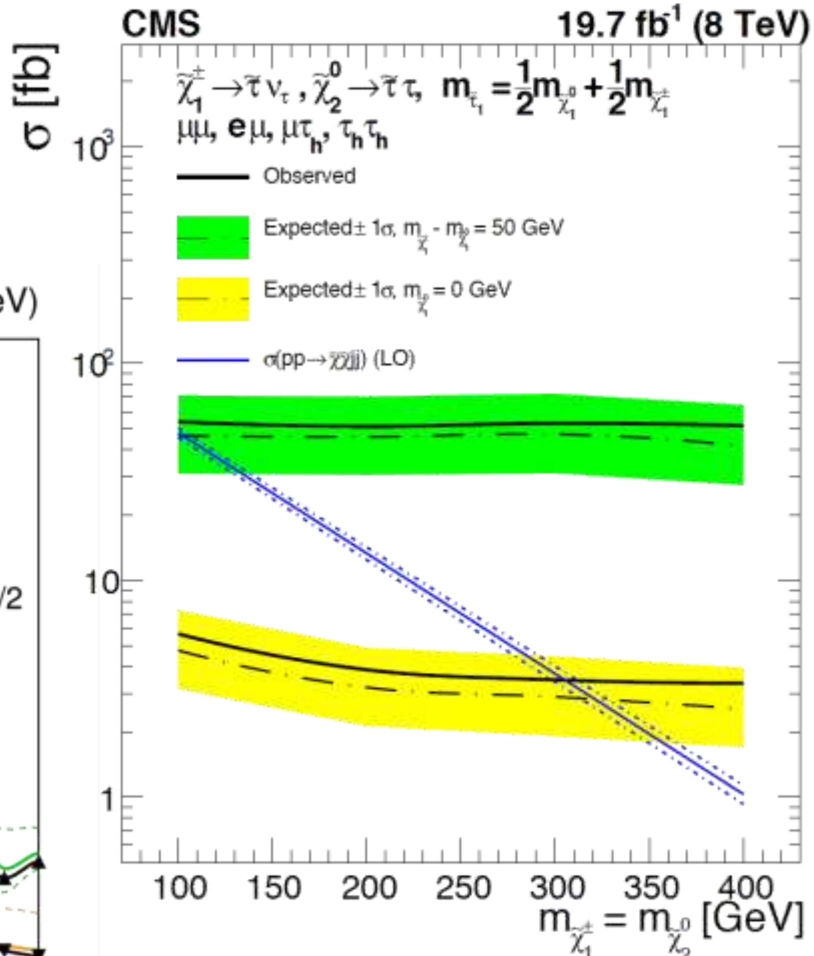
Read the papers!

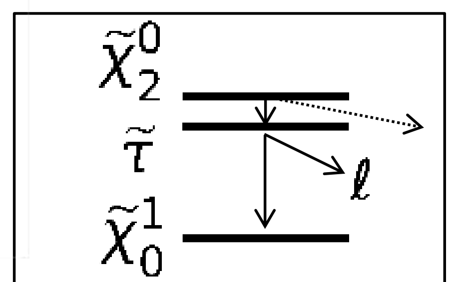
- ISR + 2-lepton [1512.08002]





- VBF + 2-lepton [1508.07628]





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

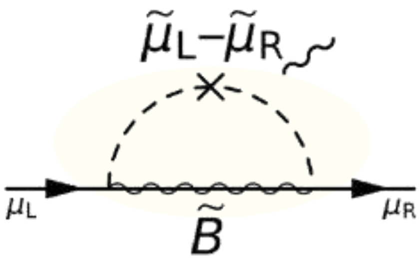
- Overview
- Collider physics
- Dark Matter

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.

Higgsino > TeV → pure-Bino scenario.

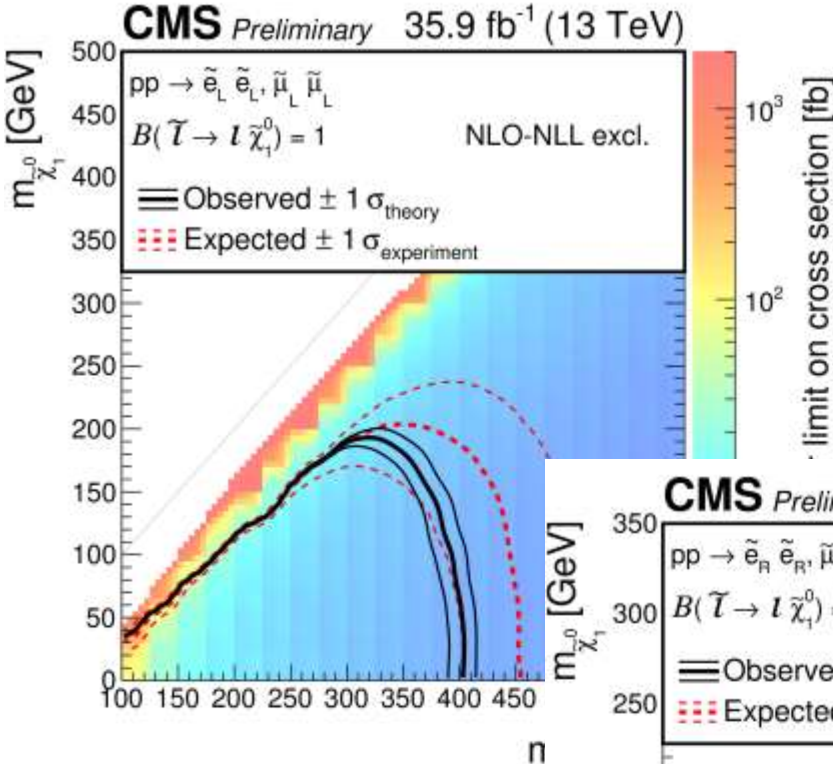
- μ-enhancement v.s. vacuum stability
- DM: not considered here ("orthogonal")
  - co-annihilation or resonance may work.

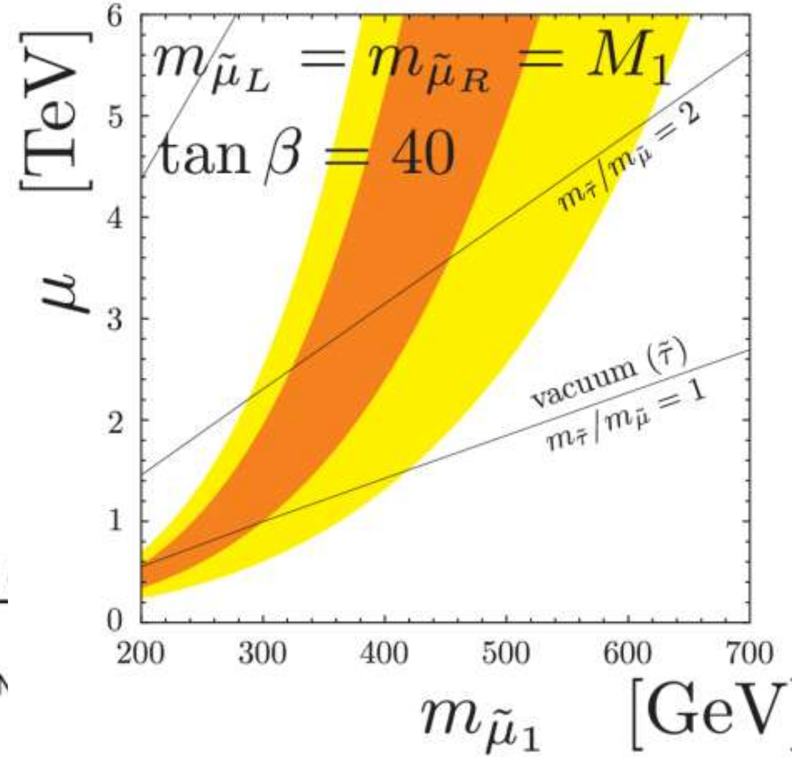


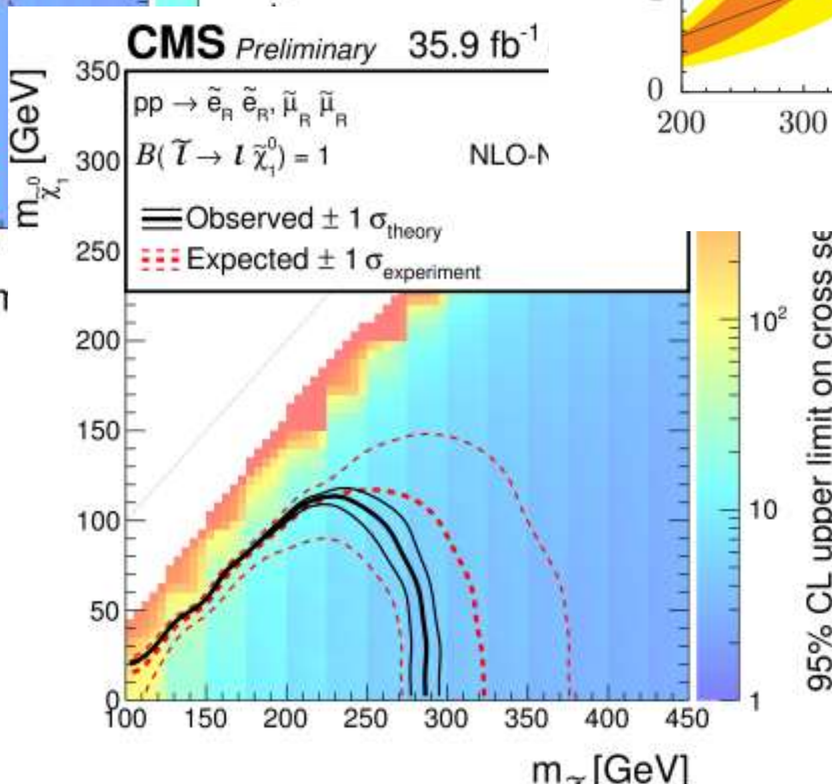
[B] $\frac{g_Y^2 m_\mu^2}{8\pi^2}$ **μ-enhancement** $, \frac{m_{\tilde\mu_R}}{M_1} \Big)$

- 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]

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.

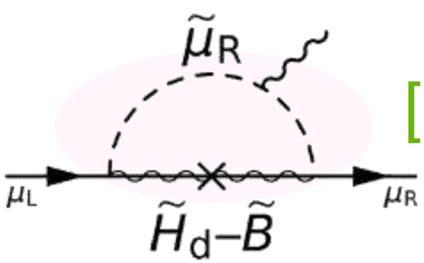
- Wino >> TeV & Higgsino < TeV → BHL or BHR scenario.
  ($\mu > 0$) ($\mu < 0$)
  - $\propto g_Y^2$ → relevant particles $\lesssim 500\,\mathrm{GeV}$
  - LHC: $pp \to \tilde{H}^+\tilde{H}^0,\ \tilde{H}^+\tilde{H}^-$ "not much, but enough"
  - DM: ~~Bino–Higgsino mixing~~ (excl. by XENON1T), bino–slepton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

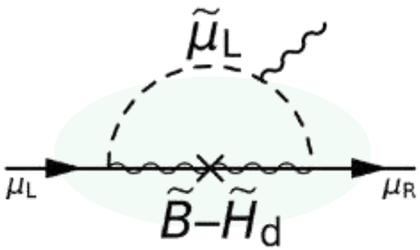
[BHR]

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

[BHL]

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



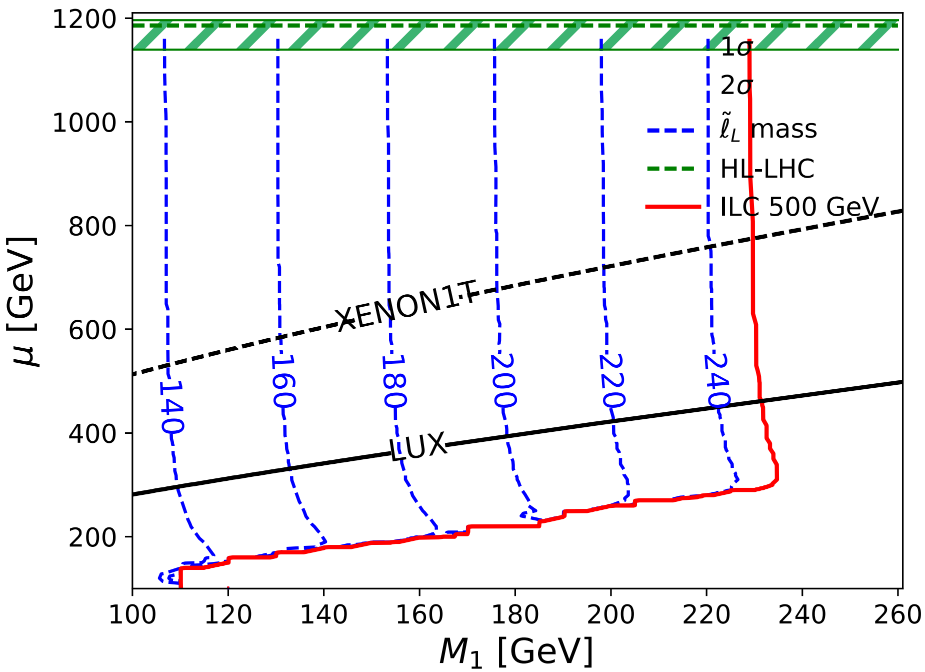


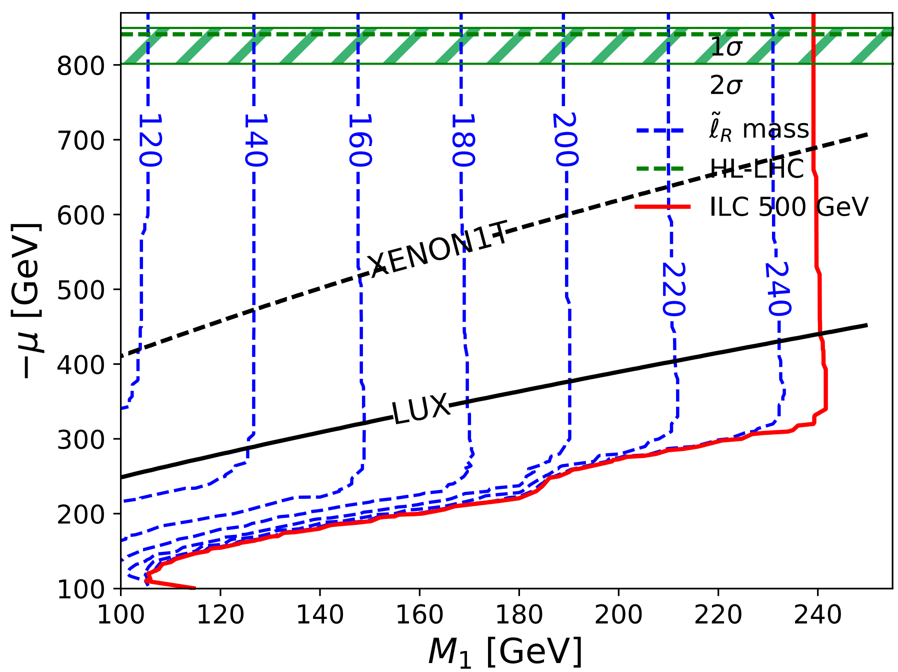
F_a, F_b are loop functions and positive.

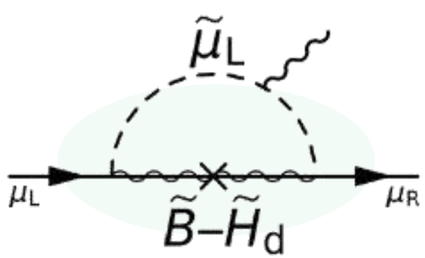
$$F_a(x,y) = \frac{1}{2}\frac{C_1(x^2)-C_1(y^2)}{x^2-y^2}, \qquad F_b(x,y) = -\frac{1}{2}\frac{N_2(x^2)-N_2(y^2)}{x^2-y^2};$$

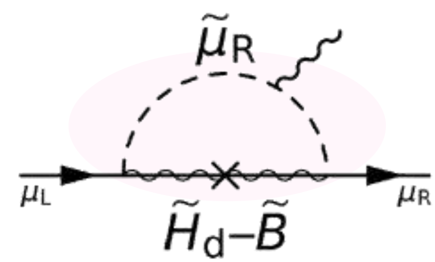
$$C_1(x) = \frac{3-4x+x^2+2\log x}{(1-x)^3}, \qquad N_2(x) = \frac{1-x^2+2x\log x}{(1-x)^3}.$$

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



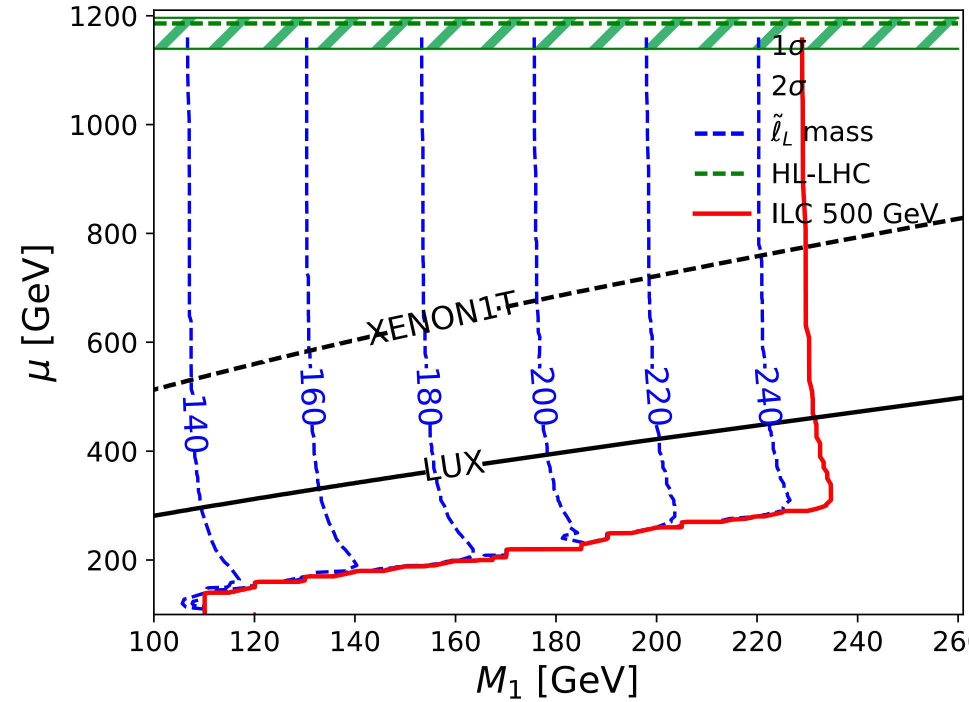






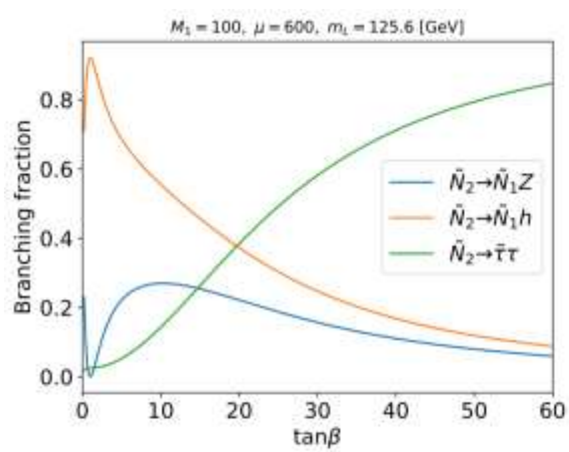
- Bino−slepton (stau) co-annihilation → $m_{\tilde{\nu}_\tau}$ (or $m_{\tilde{\tau}_R}$) $\simeq m_{\tilde{B}}$.
- We assumed:
  - ➢ slepton universality,
  - ➢ DM density is realized at each point in the plots.

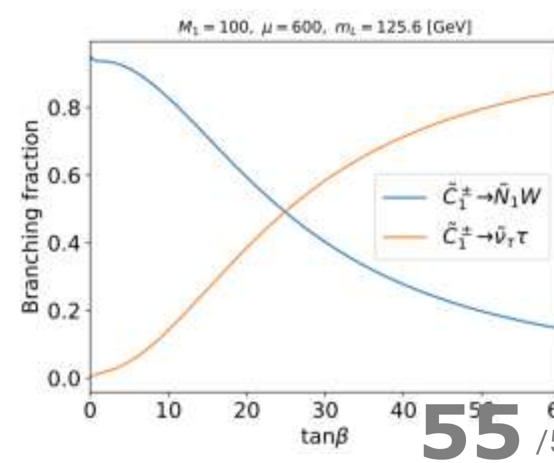
  → $m_{\tilde{B}} \lesssim m_{\tilde{\mu}} < m_{\tilde{H}}$
  $(\sim M_1)$ $(\sim \mu)$

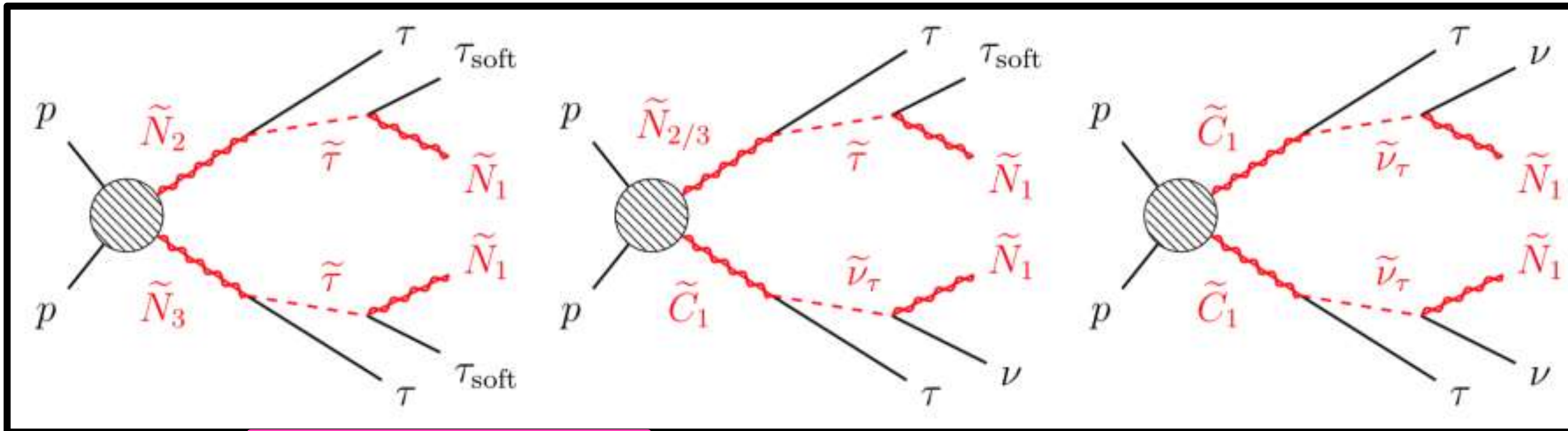


- HL-LHC?
  - ➢ $pp \to \tilde{H}^+\tilde{H}^0,\ \tilde{H}^+\tilde{H}^-$
  - ➢ $\tilde{H}^0 \to \tau\tilde{\tau},\ \ \tilde{H}^+ \to \tau\tilde{\nu}_\tau$ because of tanβ

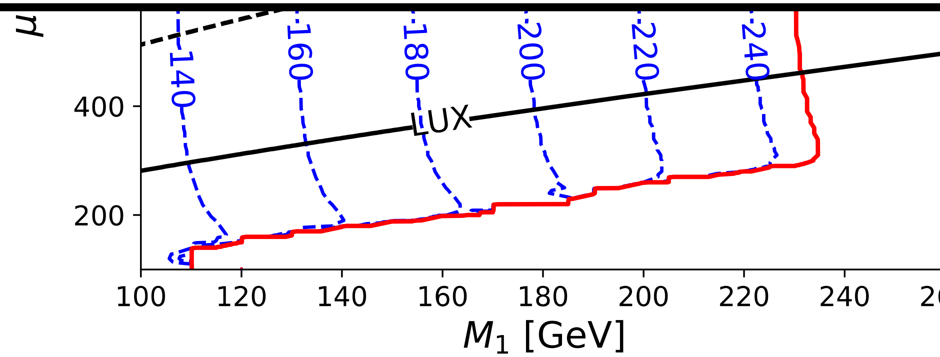
  → multi-tau signature







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

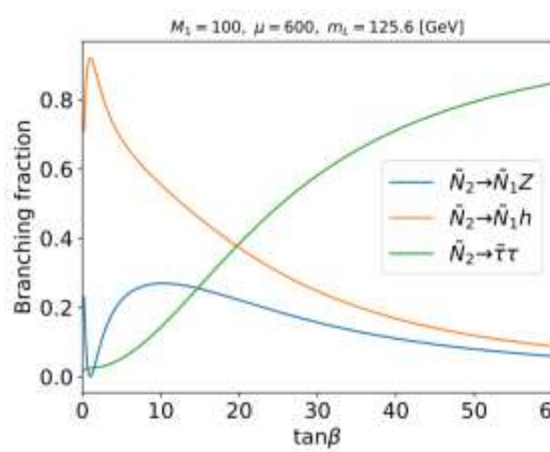


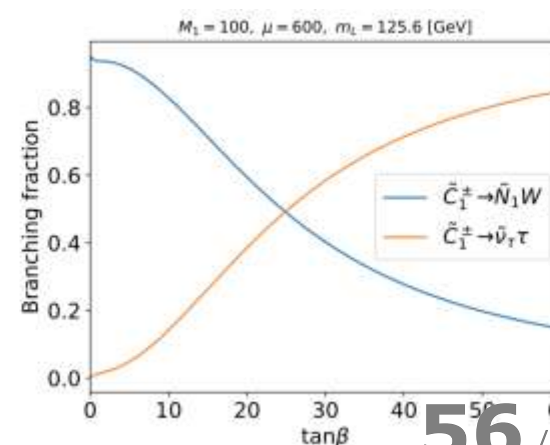
■ HL-LHC?

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

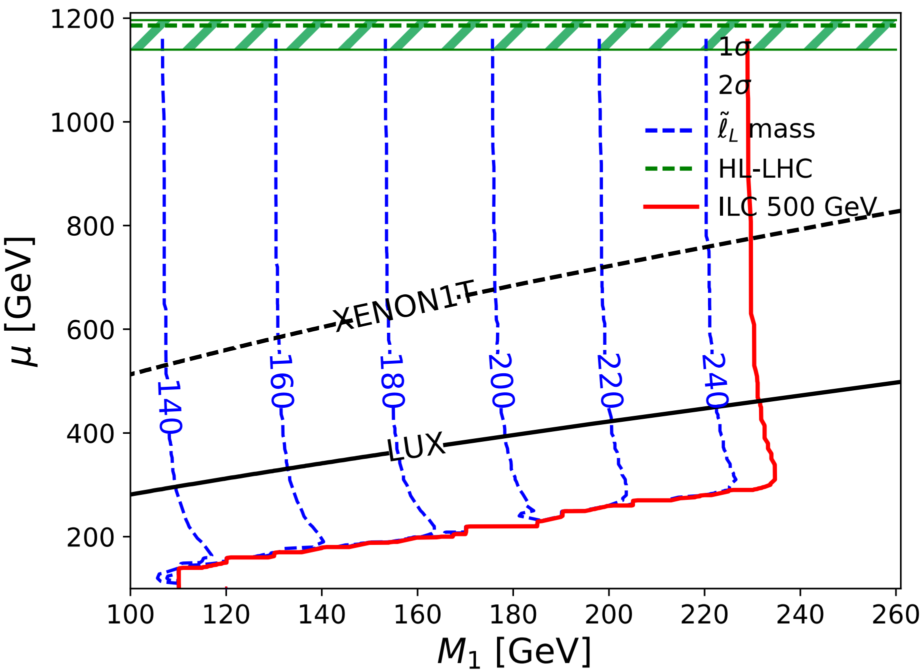
→ multi-tau signature

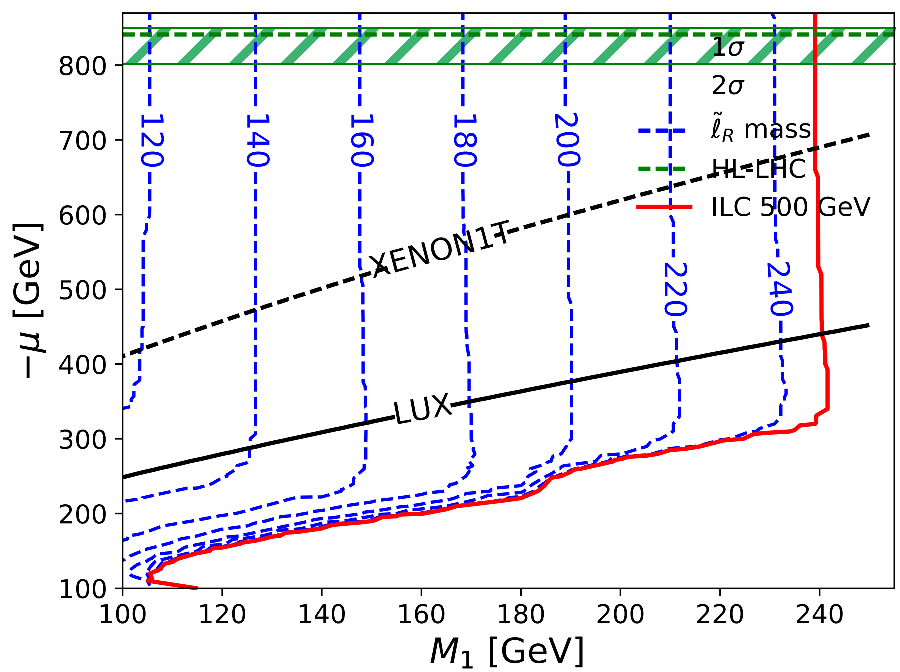
"2τ (+ soft) **+ missing"**

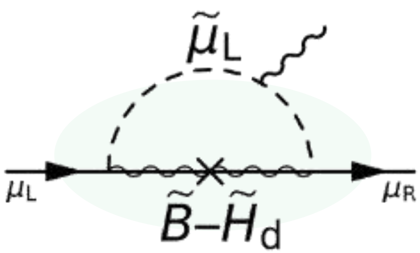


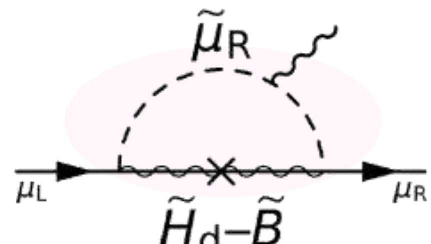


- Wino >> TeV & Higgsino < TeV → BHL $(\mu > 0)$ or BHR $(\mu < 0)$ scenario.
  - DM: Bino−stau co-annihilation → $m_{\tilde{B}} \simeq (m_{\tilde{\tau}_R} \text{ or } m_{\tilde{\nu}_\tau}) \lesssim m_{\tilde{\mu}} < m_{\tilde{H}}$
  - DM has small Higgsino component → **LUX/XENON1T** constraint.
  -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

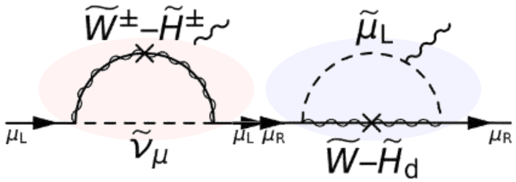


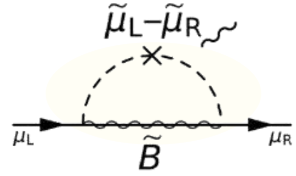


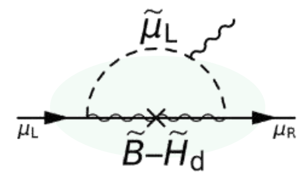


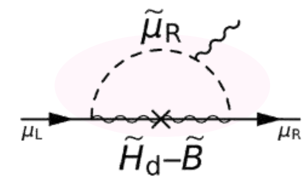


Scenario: "chargino" | "pure-Bino" | BHL / BHR









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

DM:

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

... coannihilation / resonance

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

coannihilation / resonance

we discussed

future work

Collider:

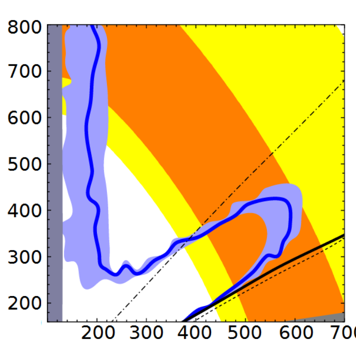
multi-lepton
→ promising

("stay tuned!")

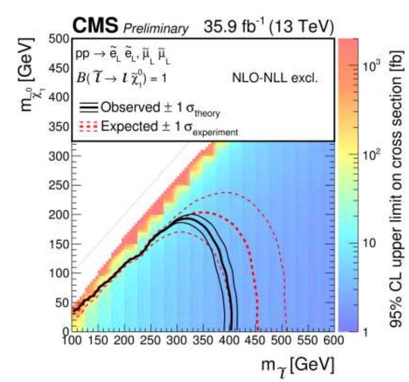
di-lepton
→ **difficult @LHC**

Higgsino → multi-tau

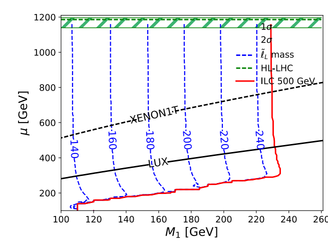
"**covered@HL-LHC**
if we seriously consider
the relic density"

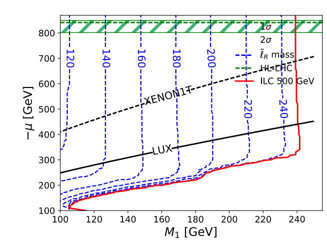


Endo, Hamaguchi, ***SI***, Yoshinaga [1303.4256]



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





Endo, Hamaguchi,
SI, Yanagi [1704.05287]