Self-Introduction

**or "SUSY status at the LHC,
focusing on $(g-2)_\mu$ anomaly & DM"**

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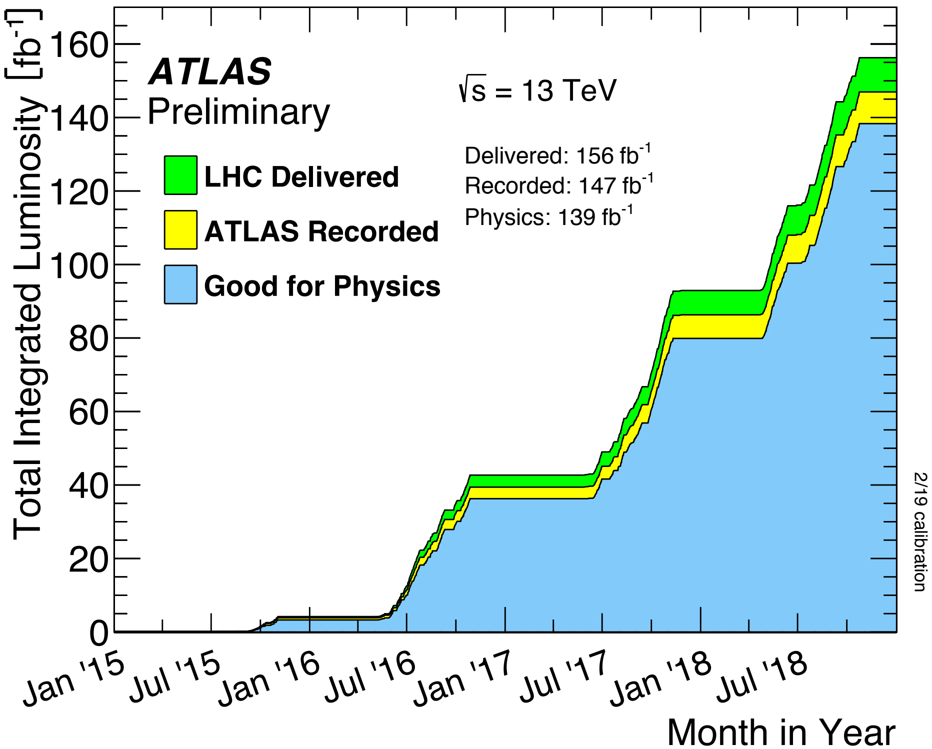
→ Eötvös Loránd Tudományegyetem (ELTE)

29 May 2019
Seminar @ ELTE

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

and a few ongoing projects.

ATLAS & CMS have acquired data corresponding to ~140/fb.



2016-focus: colored new particles

at 13 TeV LHC,

	2016 Dec.	Now
$\sigma(pp \to \text{squarks}) \sim 0.1\,\text{pb}$	3000 ev.	10000 ev.
$\sigma(pp \to \text{winos}) \sim 1\,\text{fb}$	30	100
$\sigma(pp \to \text{sleptons}) \sim 0.1\,\text{fb}$	3	10

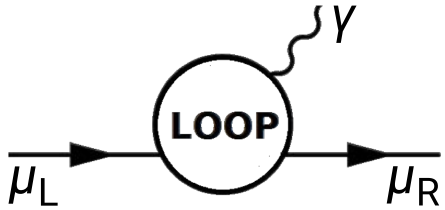
(if their mass is ~1 TeV)

2018-focus: non-colored NP
(and elusive colored NP)

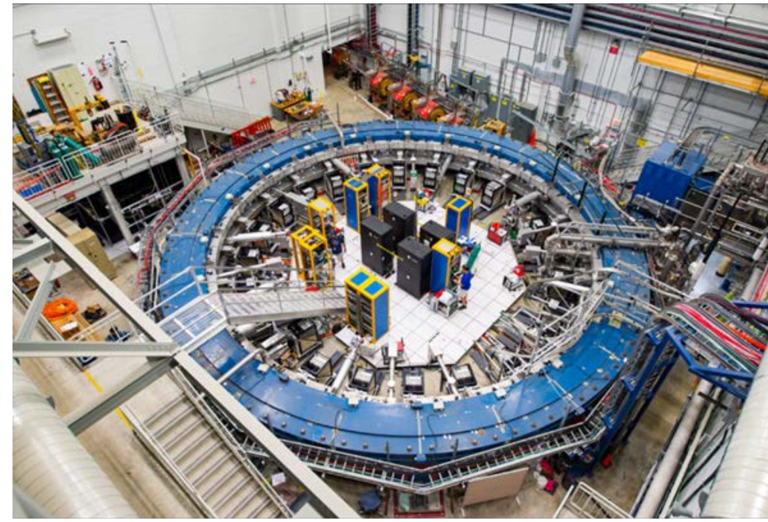
plot from https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

New measurement of muon $g-2$ @ Fermilab is coming out soon.

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



[muon anomalous magnetic moment]



2017 data taking: 2017–2020

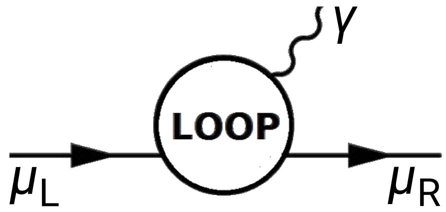
2018

2019 : **First result will be published.**

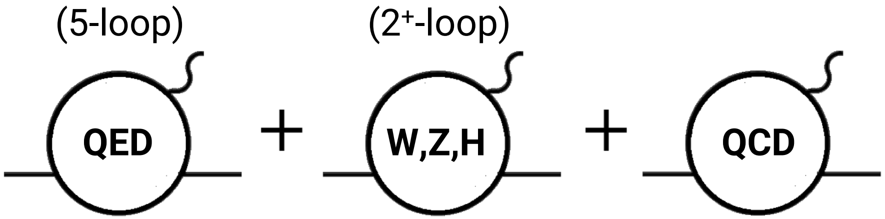
2020

2021 : **Final result will be published?**

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



$$a_\mu^{\mathrm{SM}} \simeq \text{QED} + \text{W,Z,H} + \text{QCD}$$



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

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]

New measurement will judge the fate of muon $g-2$ anomaly.

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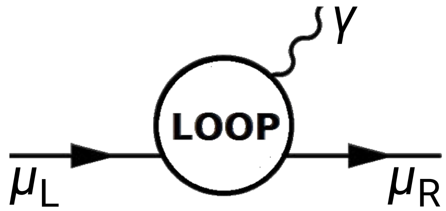
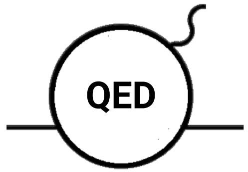


(5-loop) (2⁺-loop) (dispersion rel.) (low-energy EFT)

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



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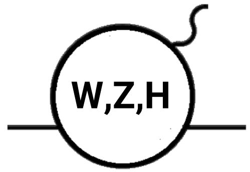

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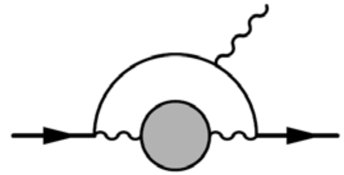
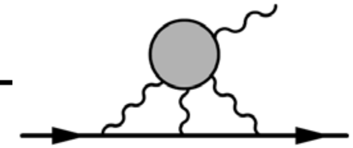


had. vac. polarization

$+$



had. light-by-light

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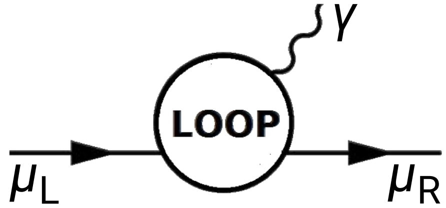
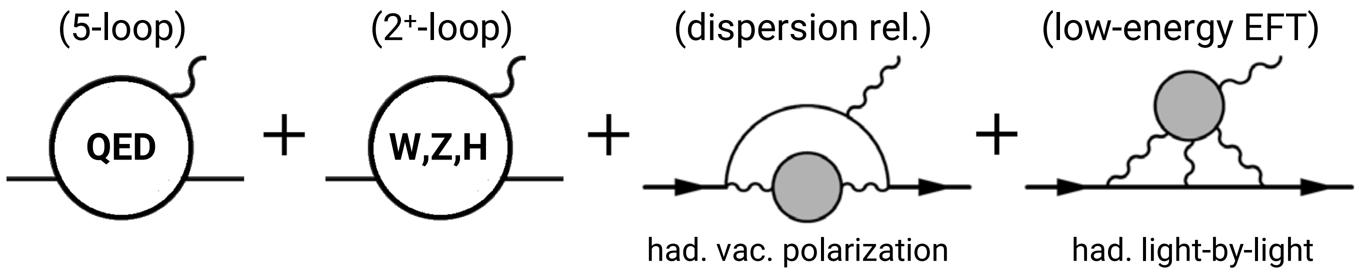


$$a_\mu^{\rm SM} \simeq$$



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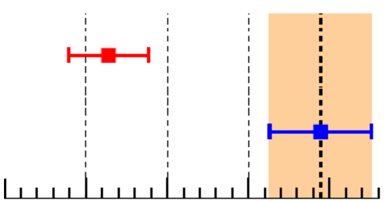
\end{aligned}$$

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

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



~4σ discrepancy

???.? ± 6	Fermilab, 2019?	**confirmation of anomaly????**
???.? ± 1.6	Fermilab, 2021?	**>5σ discrepancy !?**

New measurement will judge the fate of muon $g-2$ anomaly.

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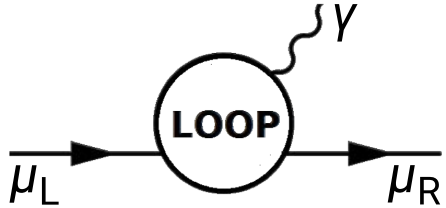

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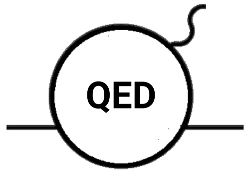
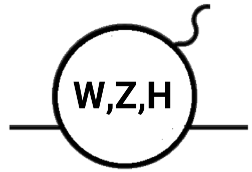
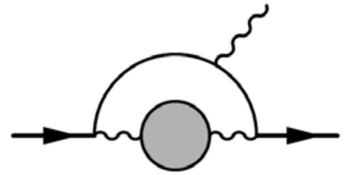
(5-loop)



+ (2⁺-loop)

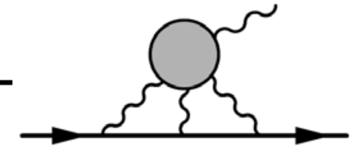


+ (dispersion rel.)



had. vac. polarization

+ (low-energy EFT)



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\end{aligned}$$

if anomaly is confirmed,

$$a_\mu(\text{new physics}) \approx +10^{-10}$$

... what does this imply?

$$\text{a)}\quad 10^{-10} \simeq \frac{\alpha_{\rm em}}{4\pi}\left(\frac{m_\mu}{M_{\rm NP} = 200\,{\rm GeV}}\right)^2$$

O(100)GeV, electro/weak-charged new particle?

✓ the target of 2018-LHC. (as we saw)

✓ provided in TeV-scale SUSY. (as we will discuss)

main topic:
"SUSY status at the LHC, focusing on $(g-2)_\mu$ anomaly & DM"

$$\text{b)}\quad 10^{-10} \simeq \frac{\alpha_{\rm tiny}}{4\pi}\left(\frac{m_\mu}{M_{\rm NP} \sim 100\,{\rm MeV}}\right)^2$$

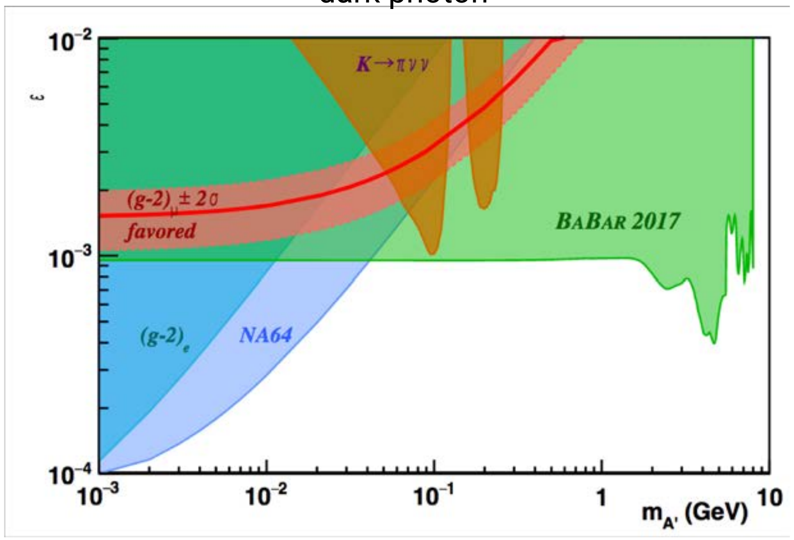
- **"dark photon"** : extra-U(1) gauge boson acquiring tiny mass and tiny interactions through kinetic mixing **... excluded**
- **$L_\mu - L_\tau$ gauge boson** : ≃ dark photon but no electron couplings

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

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

Two main streams to explain the muon $g-2$ anomaly.

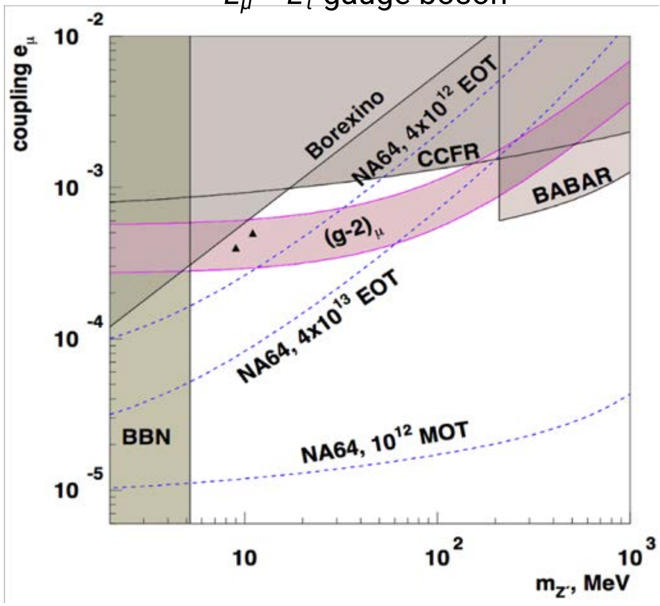
dark photon



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

BaBar [1702.03327]

$L_\mu - L_\tau$ gauge boson



Gninenko, Krasnikov [1801.10448]

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1. Introduction
   - $(g-2)_\mu$ anomaly

2. SUSY with ~TeV non-colored superparticles:
   - it solves the $\boldsymbol{(g-2)_\mu}$ anomaly,
   - it provides **dark matter** candidates, and
   - it was the main focus of **recent LHC** runs.

3. Four typical scenarios, LHC status, and prospects:
   - "**Chargino**": multi-lepton signatures
   - "**Pure-bino**": di-lepton signatures
   - "**BHR**" & "**BHL**": multi-tau + direct detections.

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- 岩本 祥 / Iwamoto Sho
  - Japan/Tokyo → Israel/Technion → Italy/Padova (→ ELTE)

1. Collider phenomenology (+ detectors, statistics)
   - SUSY searches [this talk]
   - Meta-stable particle searches
2. Cosmology & astro-particle physics
   - Leptogenesis
3. Exotic dark matter scenarios
   - "hidden-color"ed dark matter

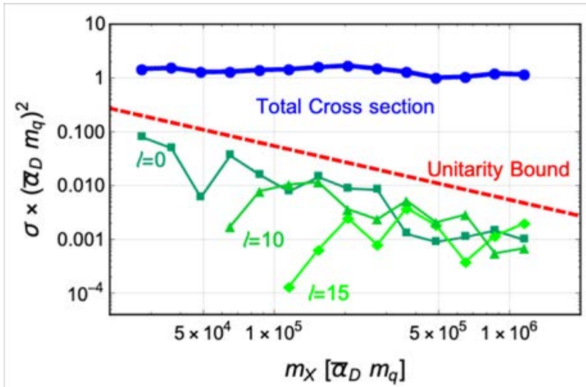
hidden-colored dark matter

M. Geller, Iwamoto, G. Lee, Y. Shadmi, O. Telem [1802.07720]

- Standard Model + extra SU(*N*)
  - SU(*N*): confining ... "hidden color"
- "hidden-quark" are stable.
  → "baryons" are DM candidates.

  cf.) top-quark decay: via weak-interaction

- What we did:
  - calculate their bound-state wavefunctions,
  - calculate the DM annihilation rate σv ,
  - and estimate DM relic density Ωh^2



in a toy model.

"neutrino-option" leptogenesis

V. Brdar, A. Helmboldt, S. Iwamoto, K. Schmitz [1905.12634]

- SM + right-handed neutrinos
  - neutrino mass
  - leptogenesis
  - "neutrino-option"

$$V_{\rm higgs} = \lambda|\phi|^4$$ "conformal"

↓ radiative corrections from 10^7 GeV N_R

$$V_{\rm higgs} = \lambda'|\phi|^4 - \mu^2|\phi|^2$$

- What we proved:
  - "neutrino-option" is compatible with leptogenesis + neutrino mass.

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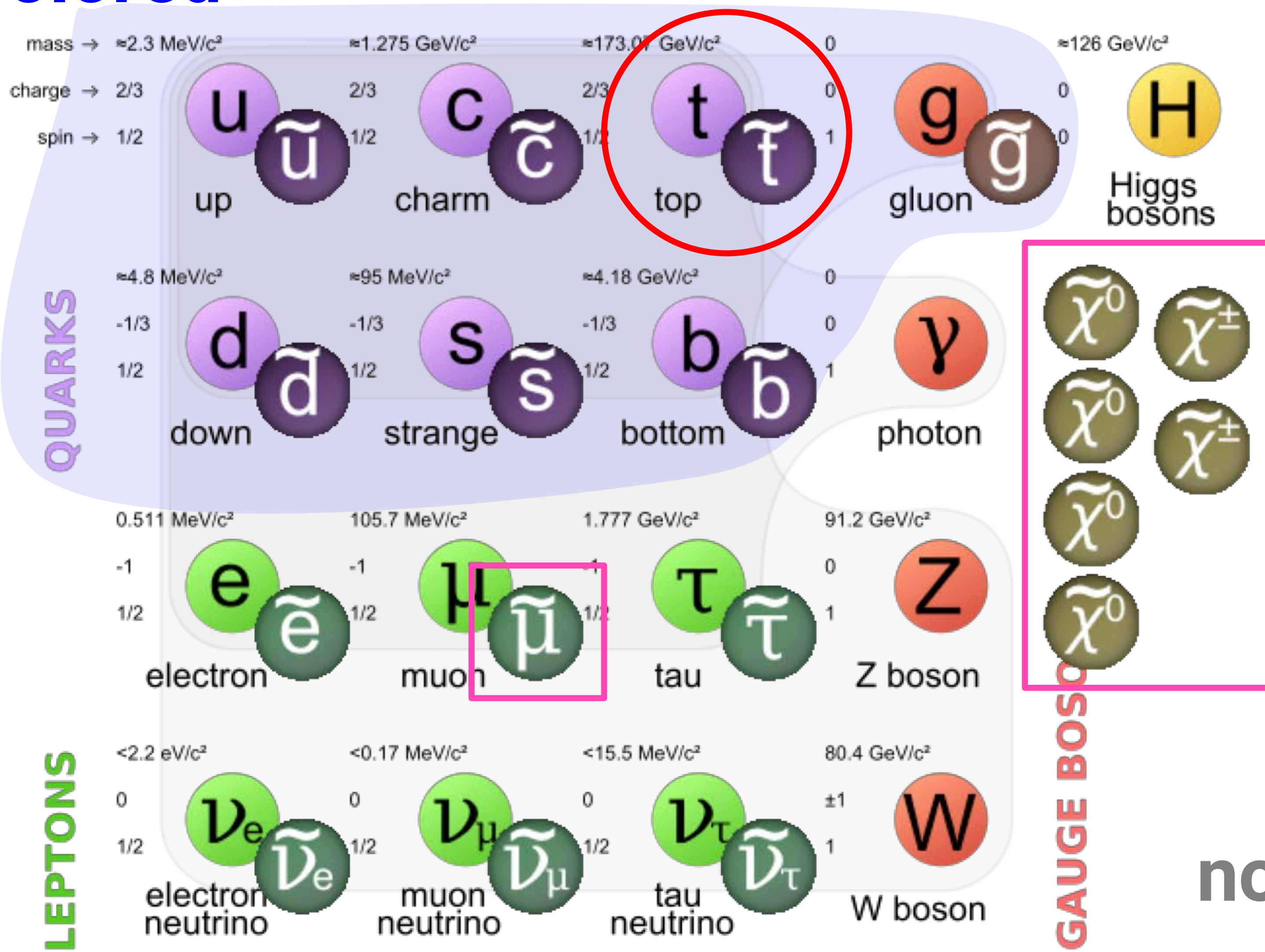
colored

important for "hierarchy problem"

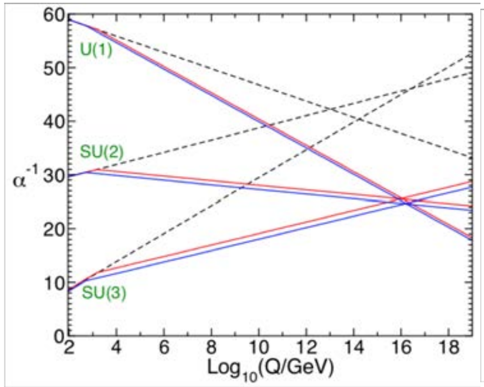


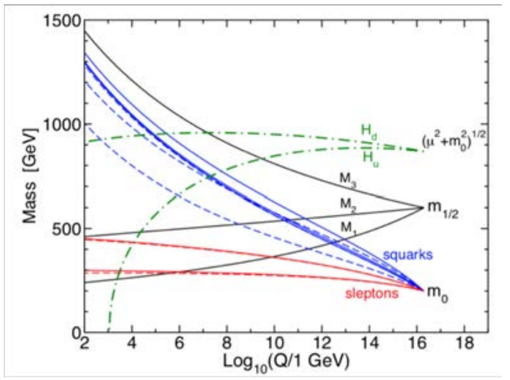
non-colored

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

* $g-2$ = anomalous magnetic moment

- **TeV-scale MSSM**
  - Gauge-coupling unification
  - Negative mass in V_{higgs}
  - **$(g-2)_\mu$ anomaly → next slides**
  - Hierarchy problem
  - Dark matter problem ("WIMP miracle")





[figs. from hep-ph/9709356]

in simplest scenarios, (= DM as a thermal relic, freezing out by pair-annihilation)

$$\langle\sigma v\rangle_{\text{DM DM}\to\text{any}} \text{ should be } \sim 3\times10^{-26}\text{cm}^3/\text{s} = \frac{\alpha_{\text{em}}^2}{(150\,\text{GeV})^2}$$ → DM @ ~0.1 TeV?

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

→ DM candidate if ~(0.1 (or 0.1–2)) TeV.

depending on models, as we will discuss later.

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

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

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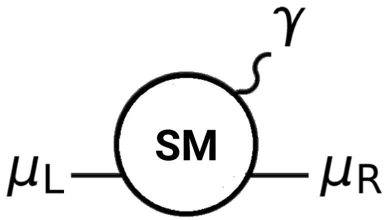
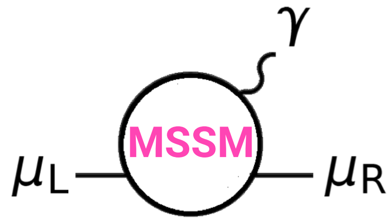
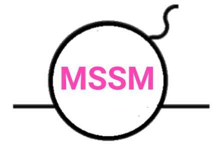


+

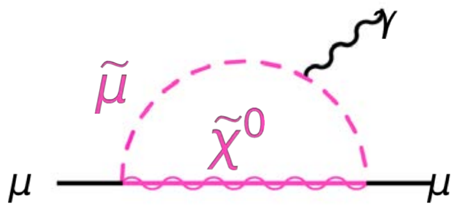


?

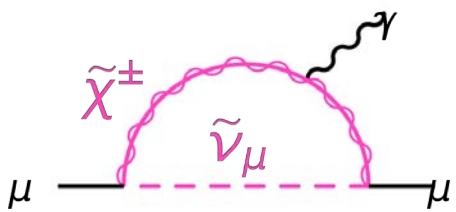
$a_\mu^{\rm SUSY} = {\rm Re}$



$\cdots \Delta a_\mu \simeq 10^{-10} \approx \frac{\alpha_{\rm em}}{4\pi} \frac{m_\mu^2}{(200\,{\rm GeV})^2}$



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



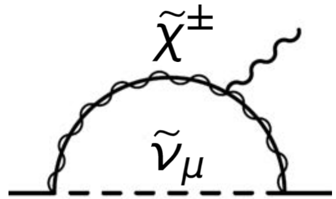
$$a_\mu^{\rm SUSY}(\tilde\chi^\pm, \tilde\nu_\mu) \approx \frac{g_2^2}{(4\pi)^2} \frac{m_\mu^2}{m_{\rm soft}^2}\, {\rm sgn}(\mu) \tan\beta.$$

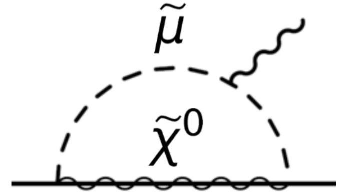
$$a_\mu^{\rm SUSY} \propto \frac{\tan\beta}{M_{\rm loop}^2}$$

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

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

$+$ 

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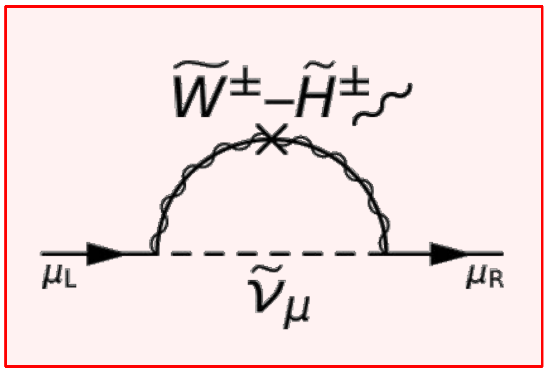
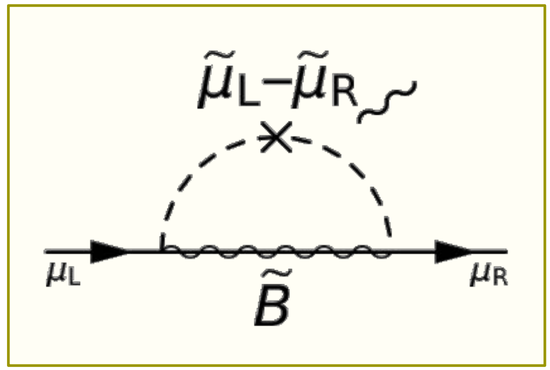
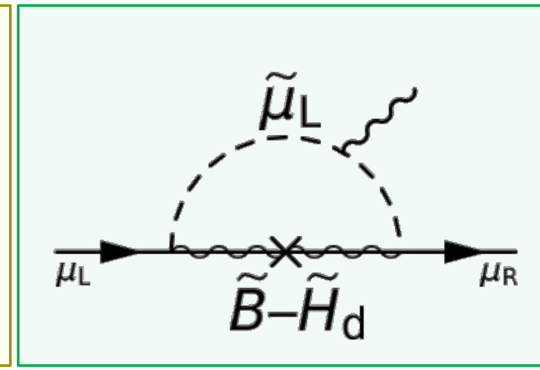
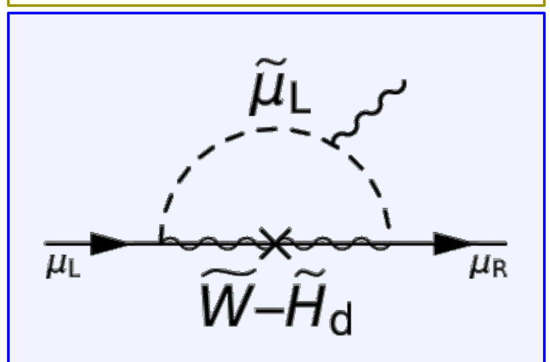
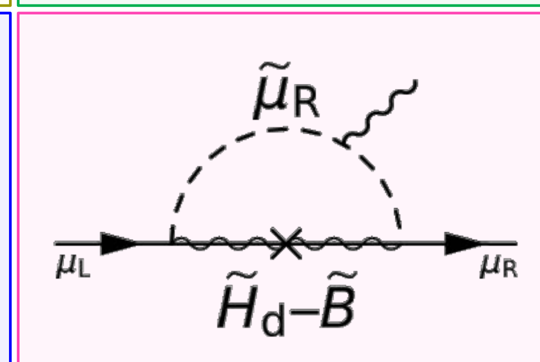
gauge eigenstates



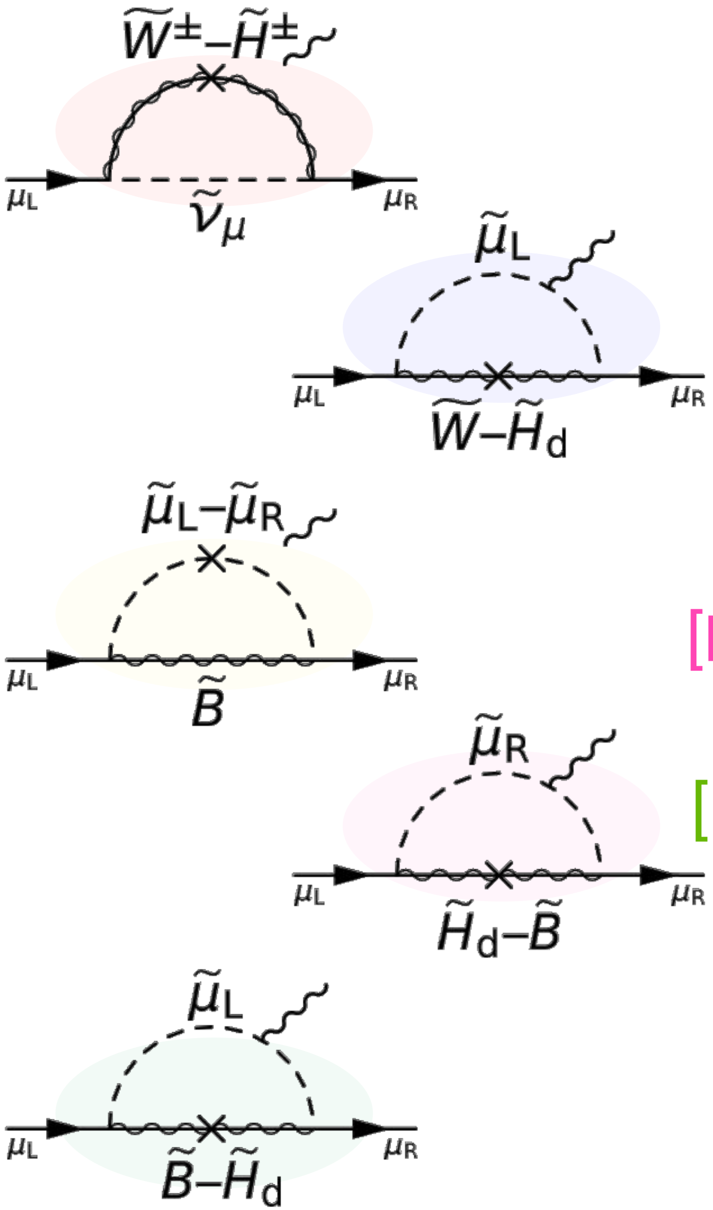








("mass insertion" technique)



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

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   - **of myself**

2. SUSY with ~TeV non-colored superparticles:
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   - "**Pure-bino**": di-lepton signatures
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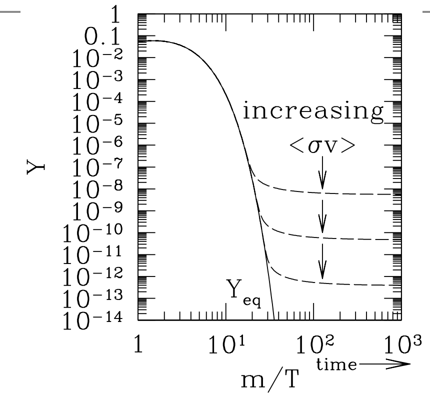

We assume Simplest $\tilde{\chi}^0$-DM scenario.

$\tilde{\chi}^0 = \tilde{B} \oplus \tilde{W}^0 \oplus \tilde{H}_d \oplus \tilde{H}_u$

- DM is $\tilde{\chi}^0$, and was in thermal equilibrium in early Universe. → freeze-out.
- No other component of DM.

$\langle\sigma v\rangle_{\text{DM DM}\to\text{any}} \sim 3\times10^{-26}\,\text{cm}^3/\text{s}$

- **If $\tilde{\chi}^0$ is almost...**
  - pure-$\tilde{B}$: almost no interactions → over-abundant. (annihilation too small)
  - pure-$\tilde{H}$: ✓ $m_{\text{DM}}\sim$ 1TeV for correct abundance.
  - pure-$\tilde{W}$: ✓ $m_{\text{DM}}\sim$ 2.5TeV for correct abundance.

- **Simplest possibilities:**
  - Bino-like (100−500GeV) + *some mechanism* to reduce the relic density
    - **Bino-slepton co-annihilation**
    - H- or Z-resonance ("funnel")
    - 4th-generation leptons Abdullah, Feng [1510.06089], Abdullah, Feng, SI, Lillard [1608.00283]
  - $\tilde{H}$-DM (~1TeV), or $\tilde{B}$−$\tilde{H}$ mixed DM (100−1TeV) ("well-tempered") ...almost excluded by XENON1T
    Badziak, Olechowski, Szczerbiak [1701.05869]
  - Bino−Wino mixed DM. (100−2.5TeV) ... theoretically not nice

Figure from Gelmini and Gondolo, 1009.3690

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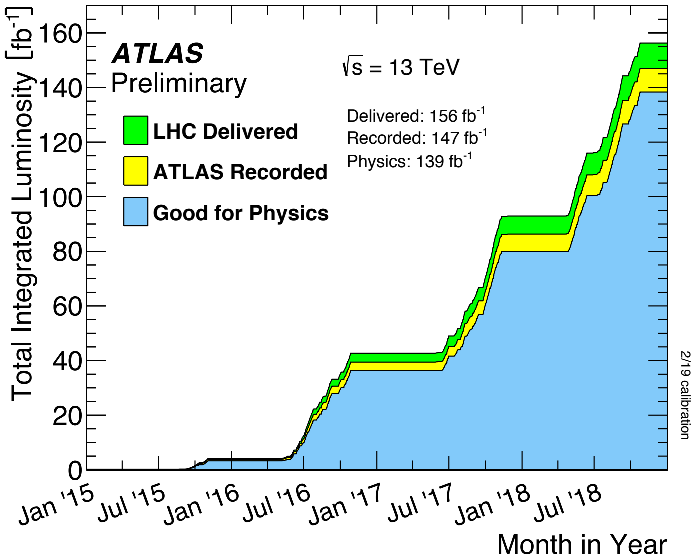

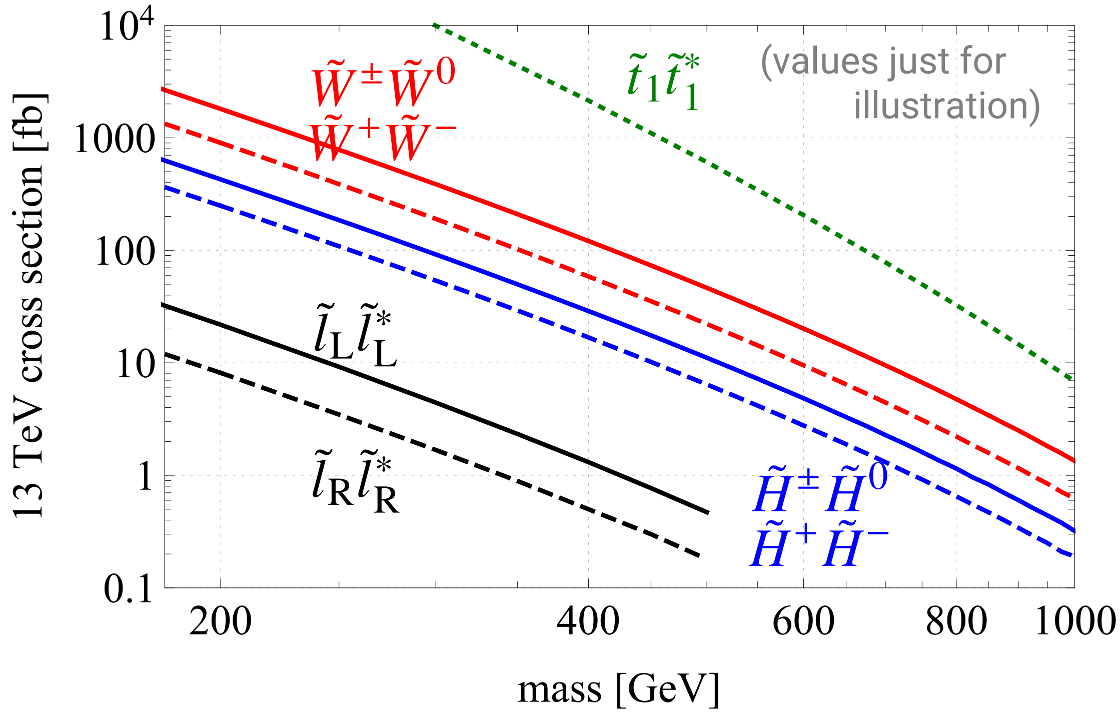

LHC Run 2 coverage:

  up to 1 TeV **(heavily depends on decay pattern)**

sleptons (e.g. ) up to 500 GeV

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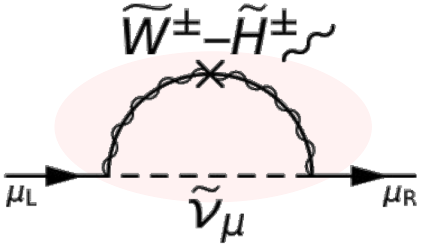

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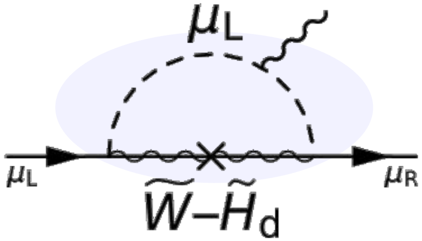

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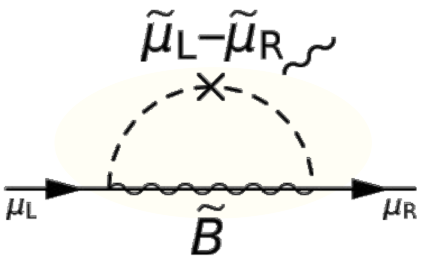

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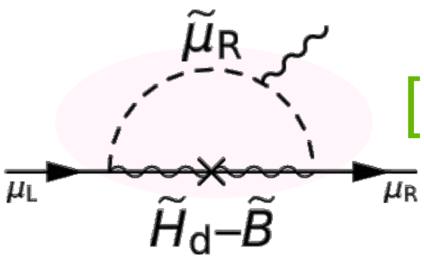

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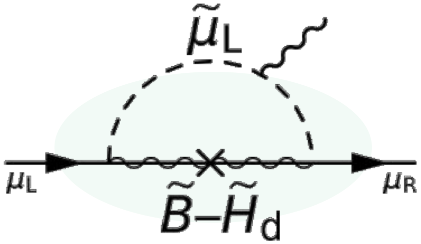

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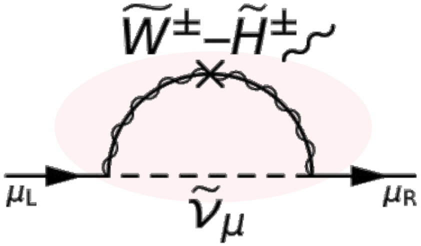

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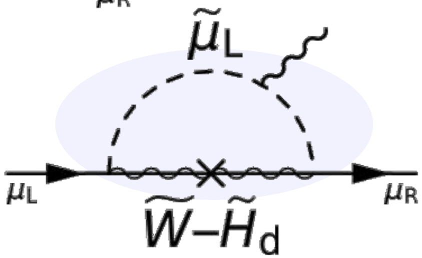
"chargino"



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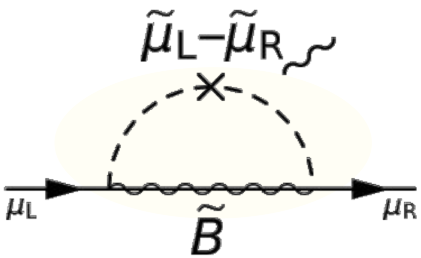

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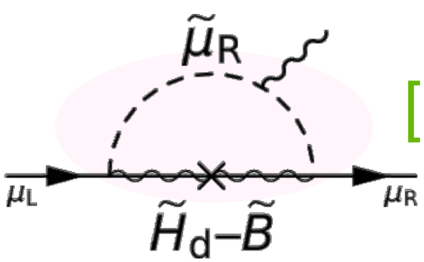
"pure-bino"



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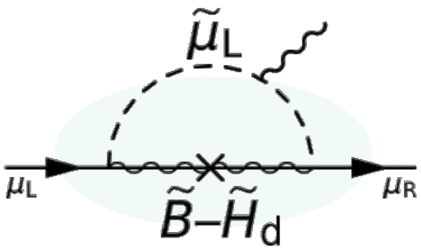
"BHR"



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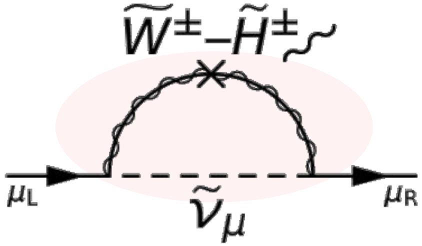
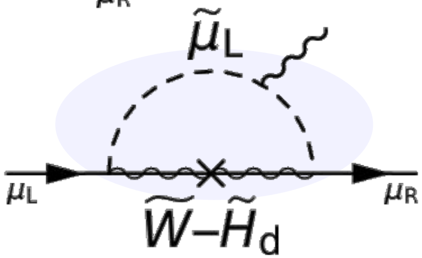
(1) "Chargino" scenario

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- "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 $\tilde\mu_L$ must be $O(100)$GeV.

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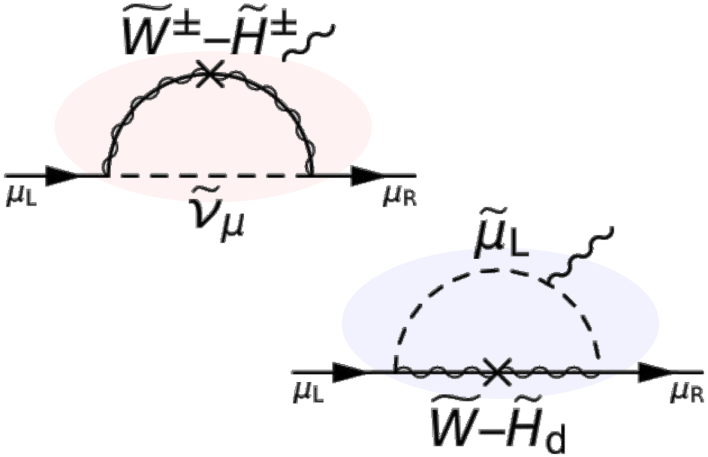

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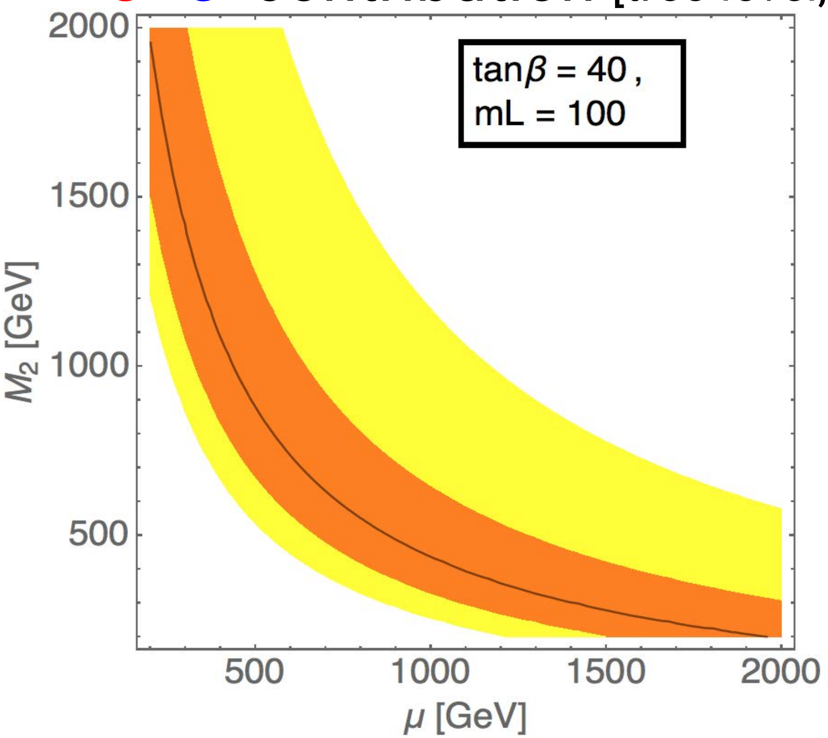
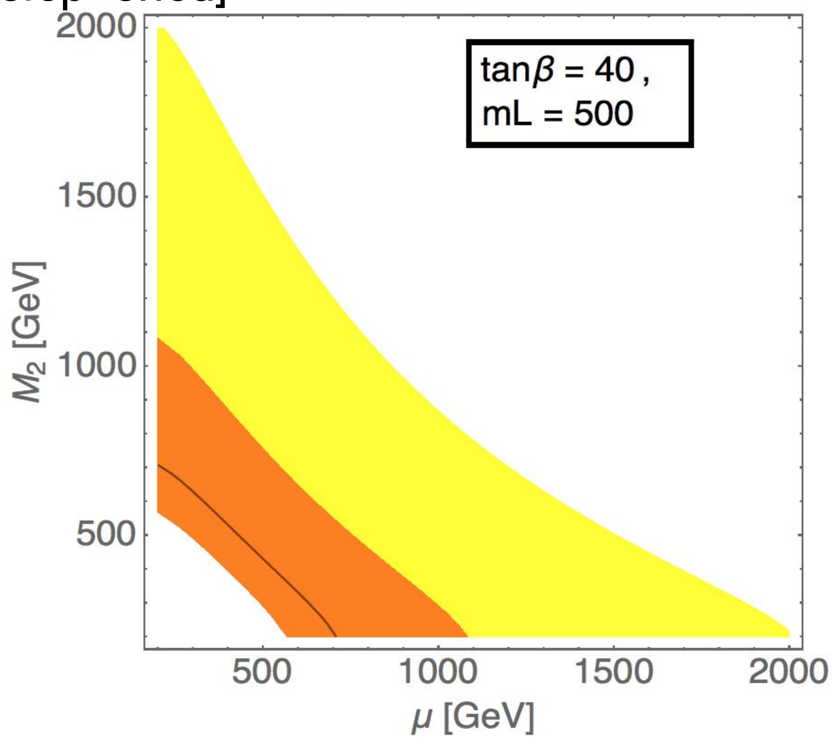
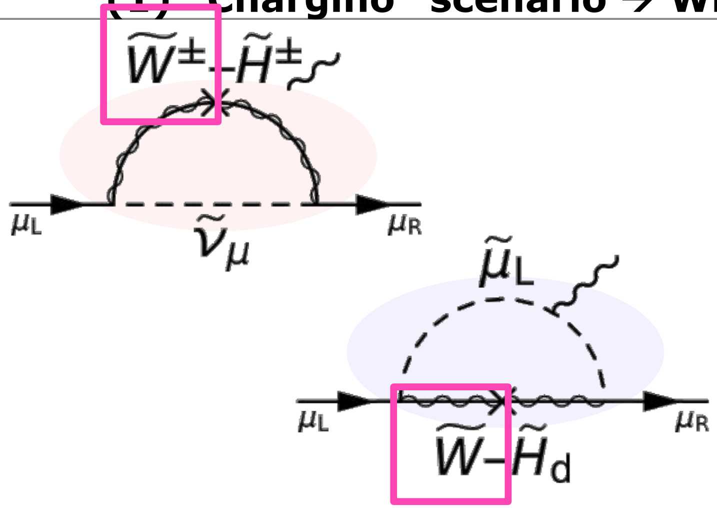
C+C'-contribution [tree-level; slep=sneu]





(1) "Chargino" scenario → Wino pair-production gives 3-lepton signature.



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

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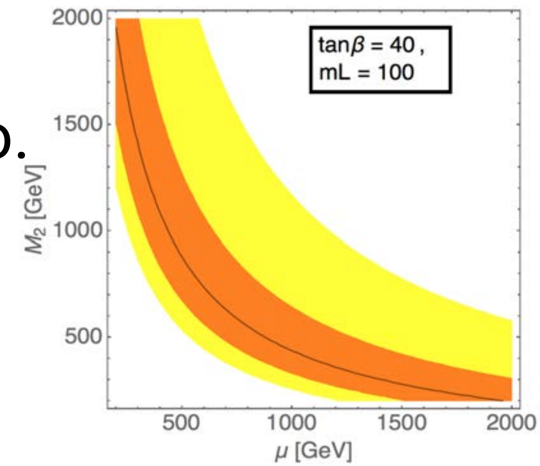
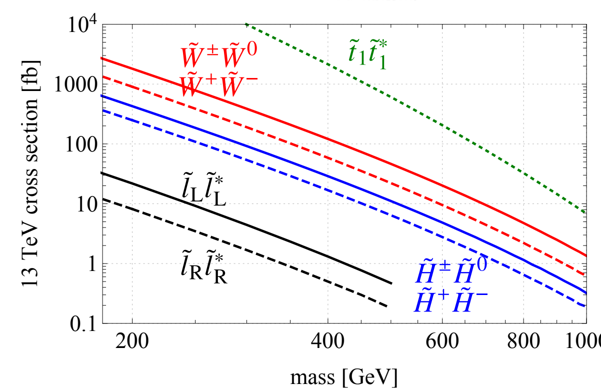


- Wino&Higgsino < TeV → chargino scenario.
  - $\propto g_2^2$ → relevant particles $\lesssim$ 1 TeV
  - DM: not considered here
    - $(g-2)_\mu \Leftarrow (\widetilde{W}, \widetilde{H}, \widetilde{\mu}_L)$; DM $\Leftarrow (\widetilde{l}_L, \widetilde{B})$ ... "orthogonal"
    - co-annihilation or resonance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

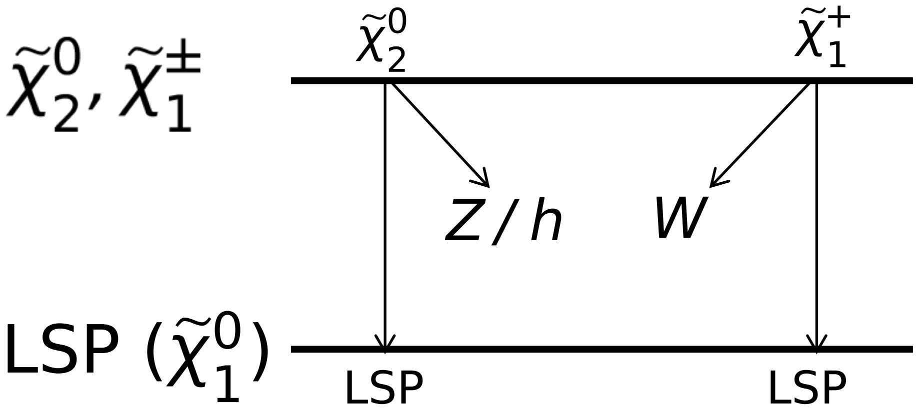
$$\sigma(pp \to \widetilde{W}\widetilde{W})_{14\,\text{TeV}} \sim 50\,\text{fb} \quad @\ m_{\widetilde{W}} = 500\,\text{GeV}$$

1.5 fb 1 TeV



(1) "Chargino" scenario → Wino pair-production gives 3-lepton signature.

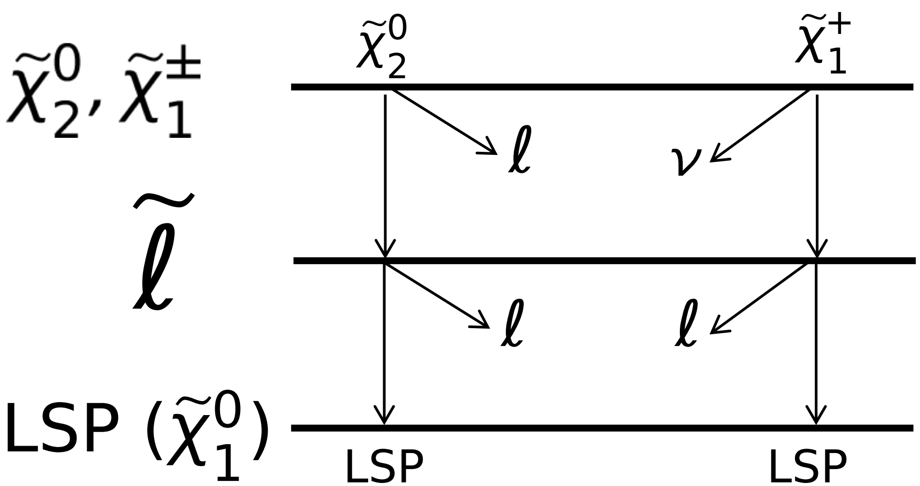
$pp \to \tilde{\chi}^0 \tilde{\chi}^+ \quad (\widetilde{W}^0 \widetilde{W}^+ \text{ or } \widetilde{H}^0 \widetilde{H}^+)$; then?



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

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

but Z-like leptons



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

Z-unlike

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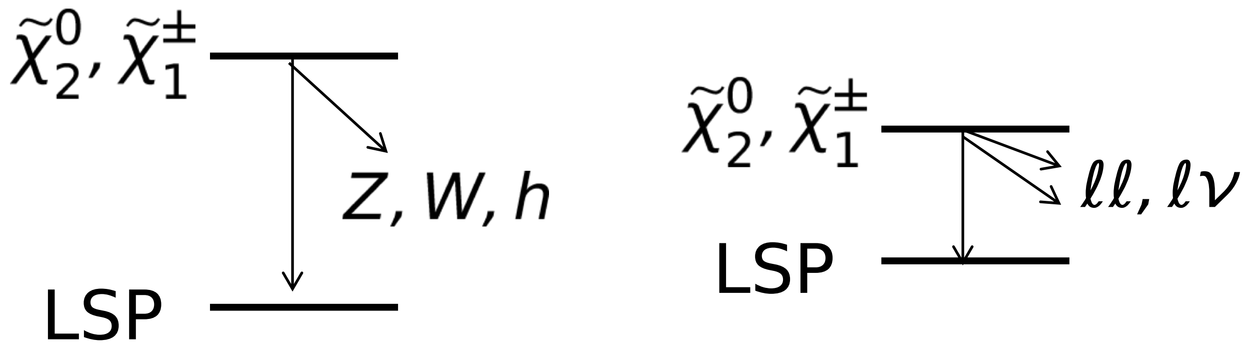
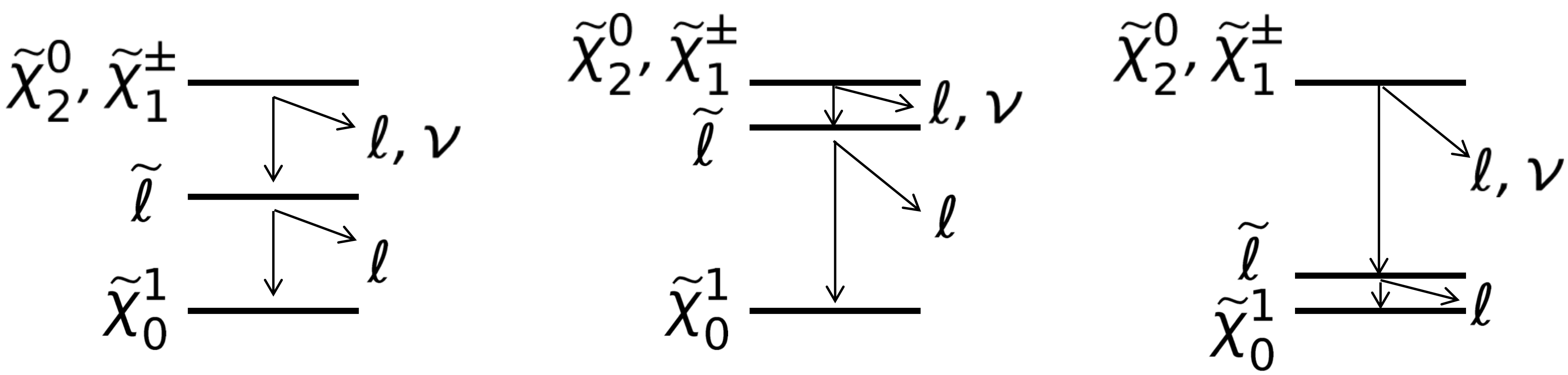
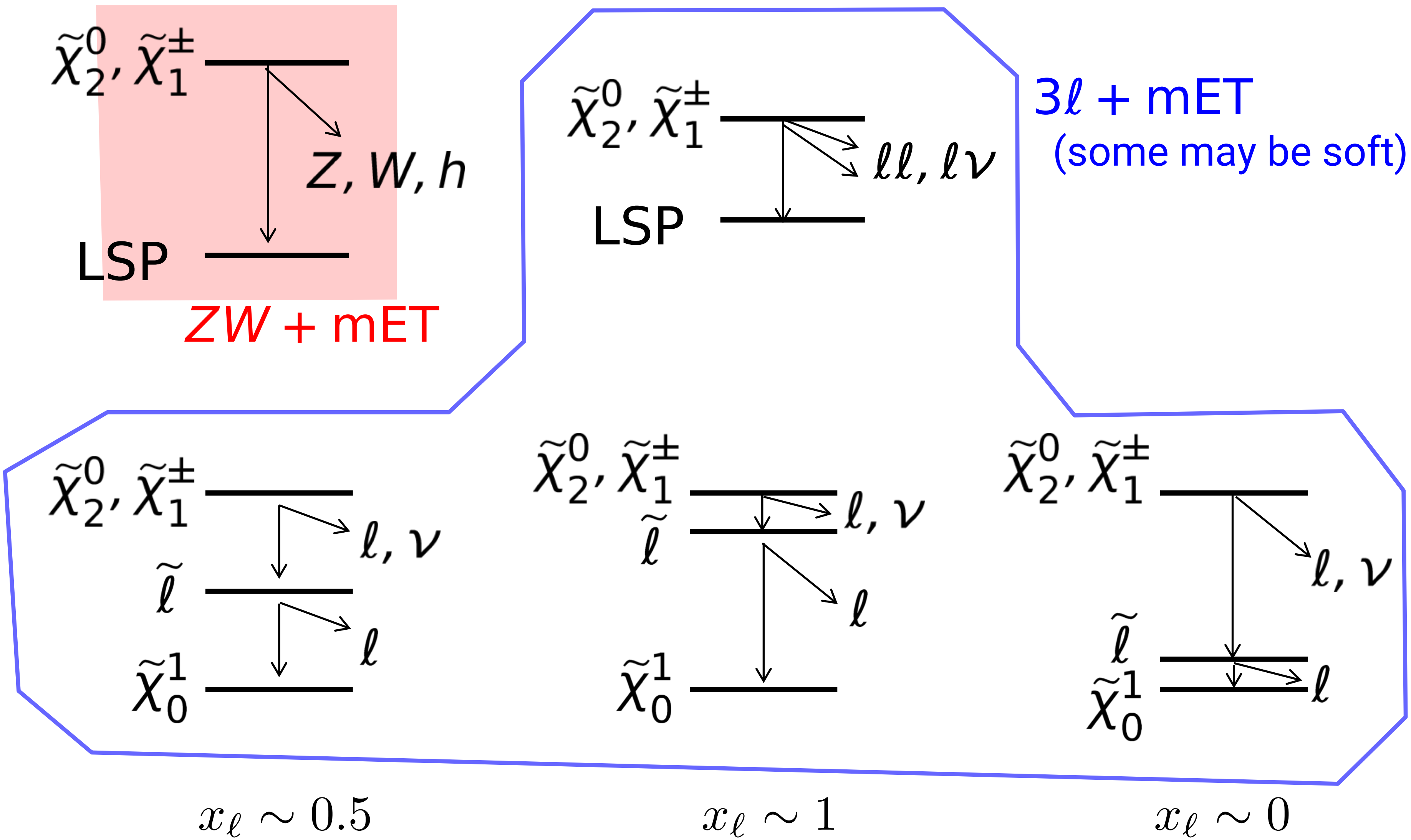
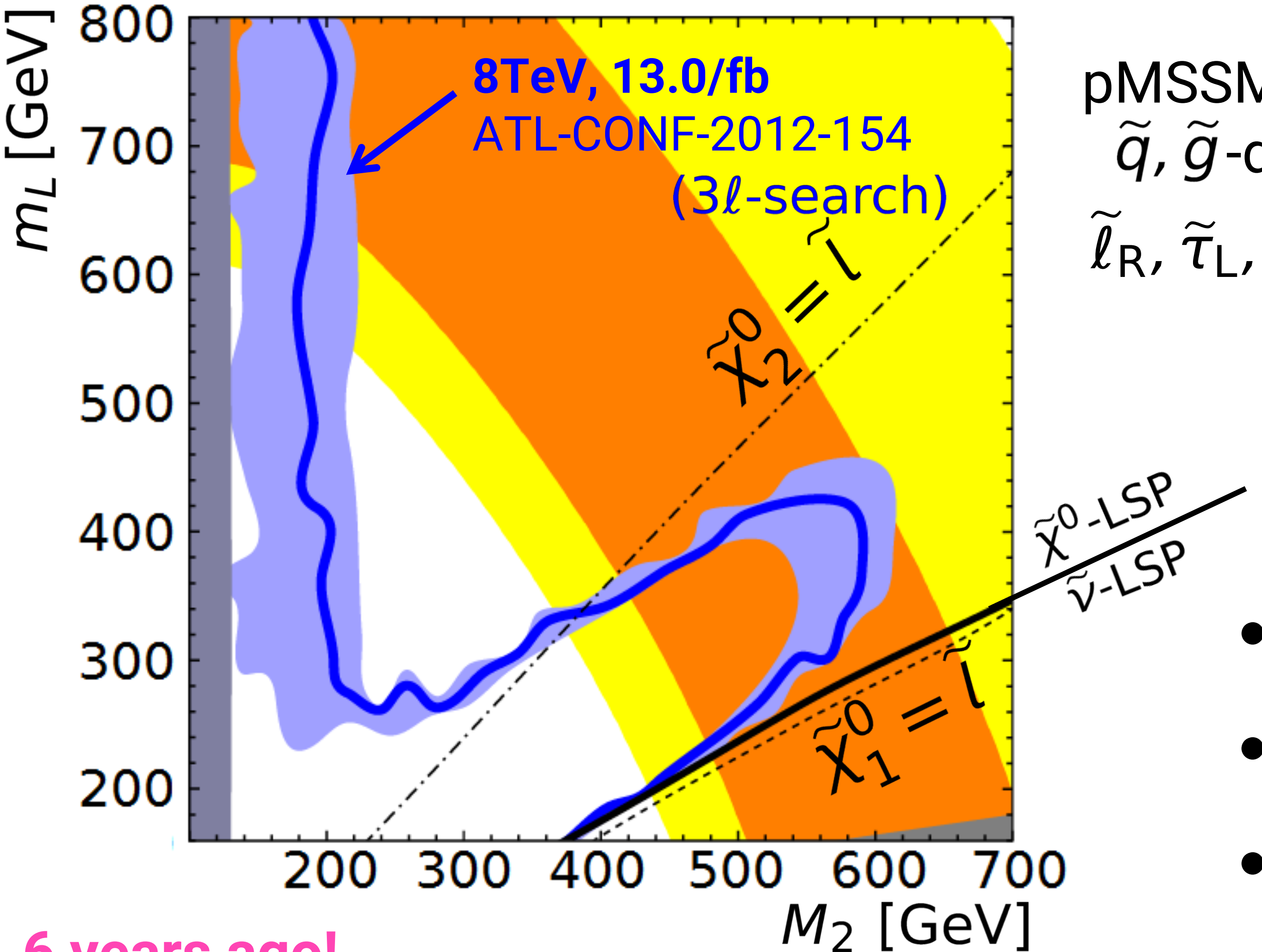




$x_\ell \sim 0.5$ $x_\ell \sim 1$ $x_\ell \sim 0$

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

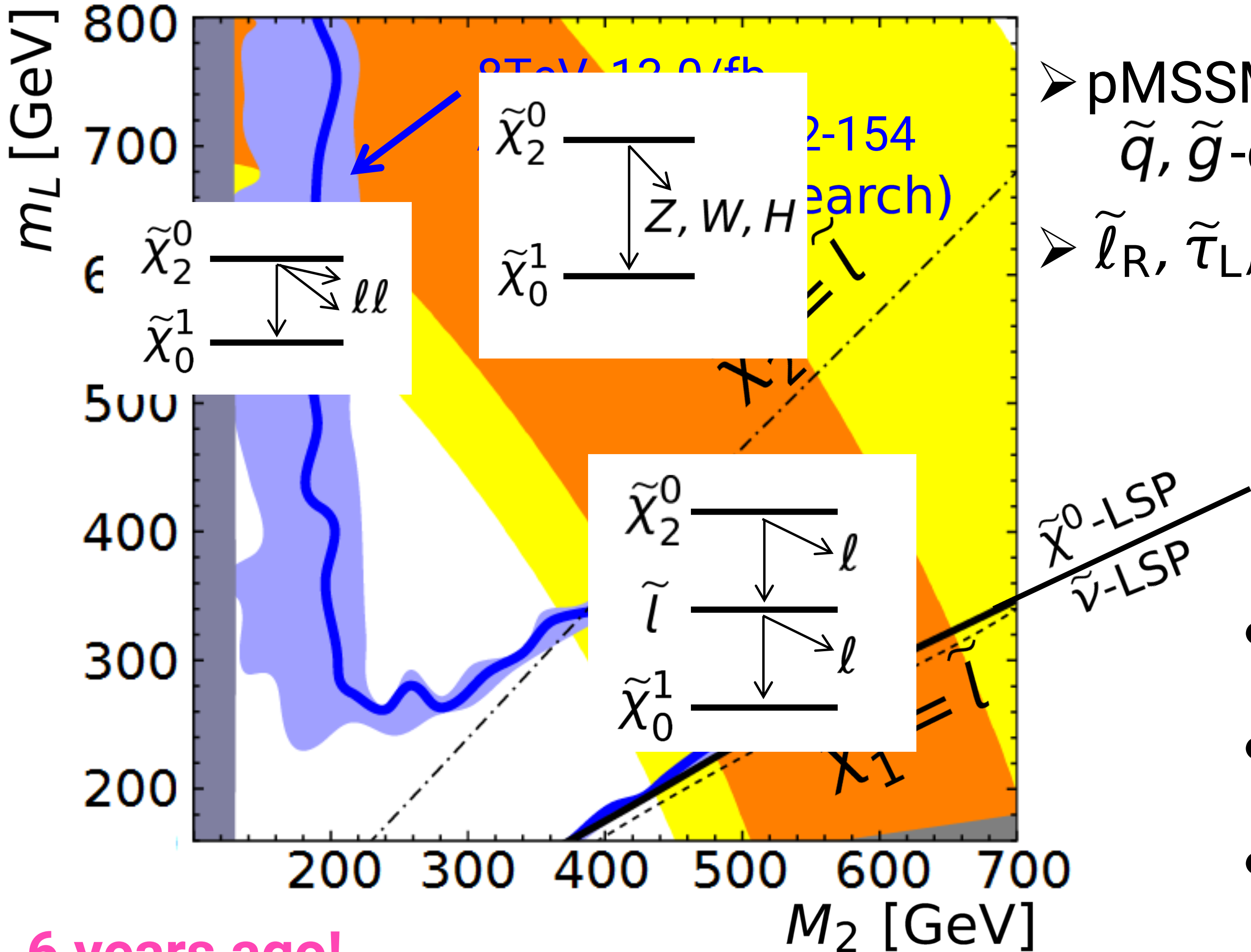




pMSSM w.
$\tilde{q}, \tilde{g}$-decoupled.
$\tilde{\ell}_R, \tilde{\tau}_L, \tilde{\tau}_R$ also decoupled.

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

6 years ago!



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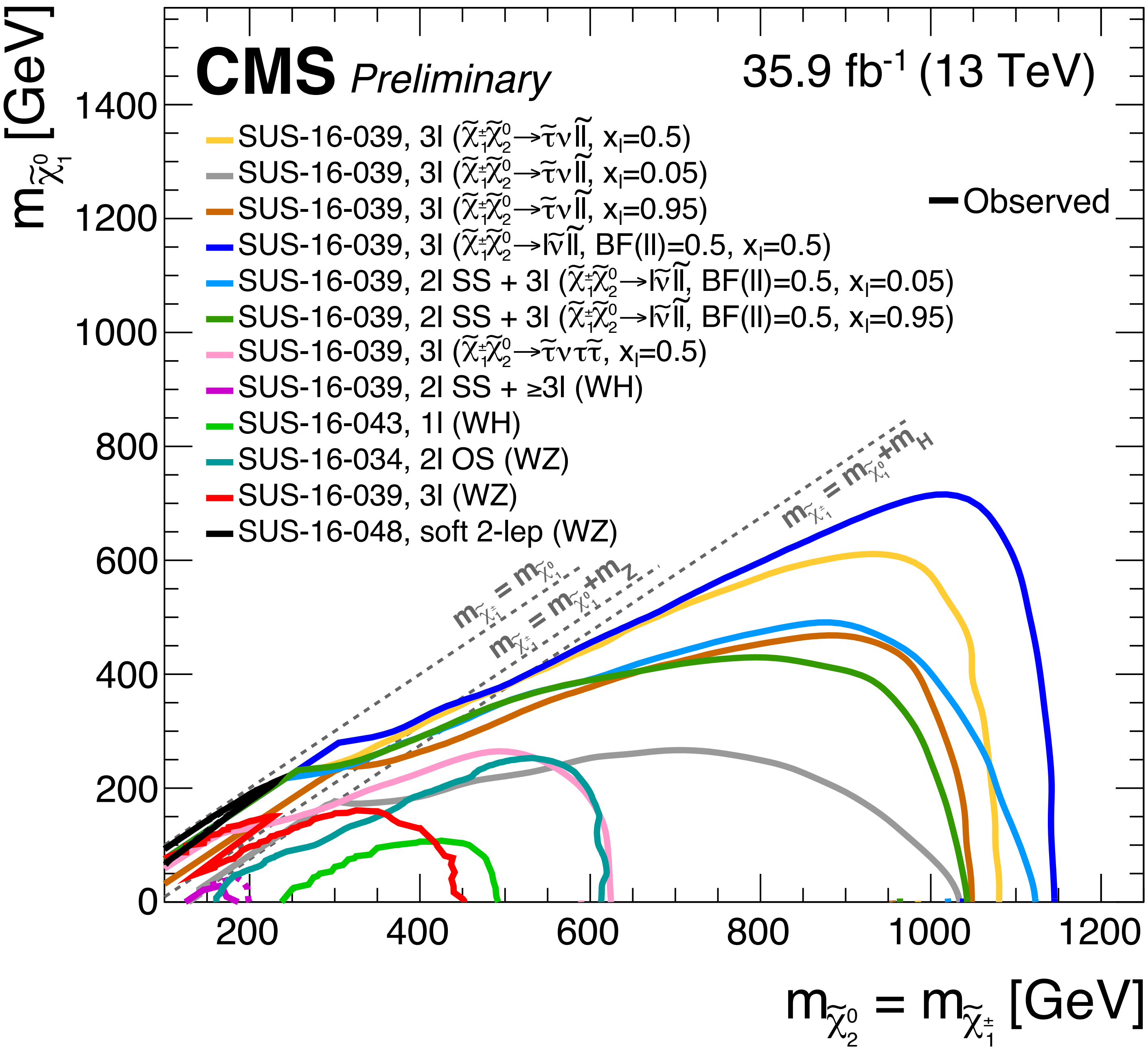
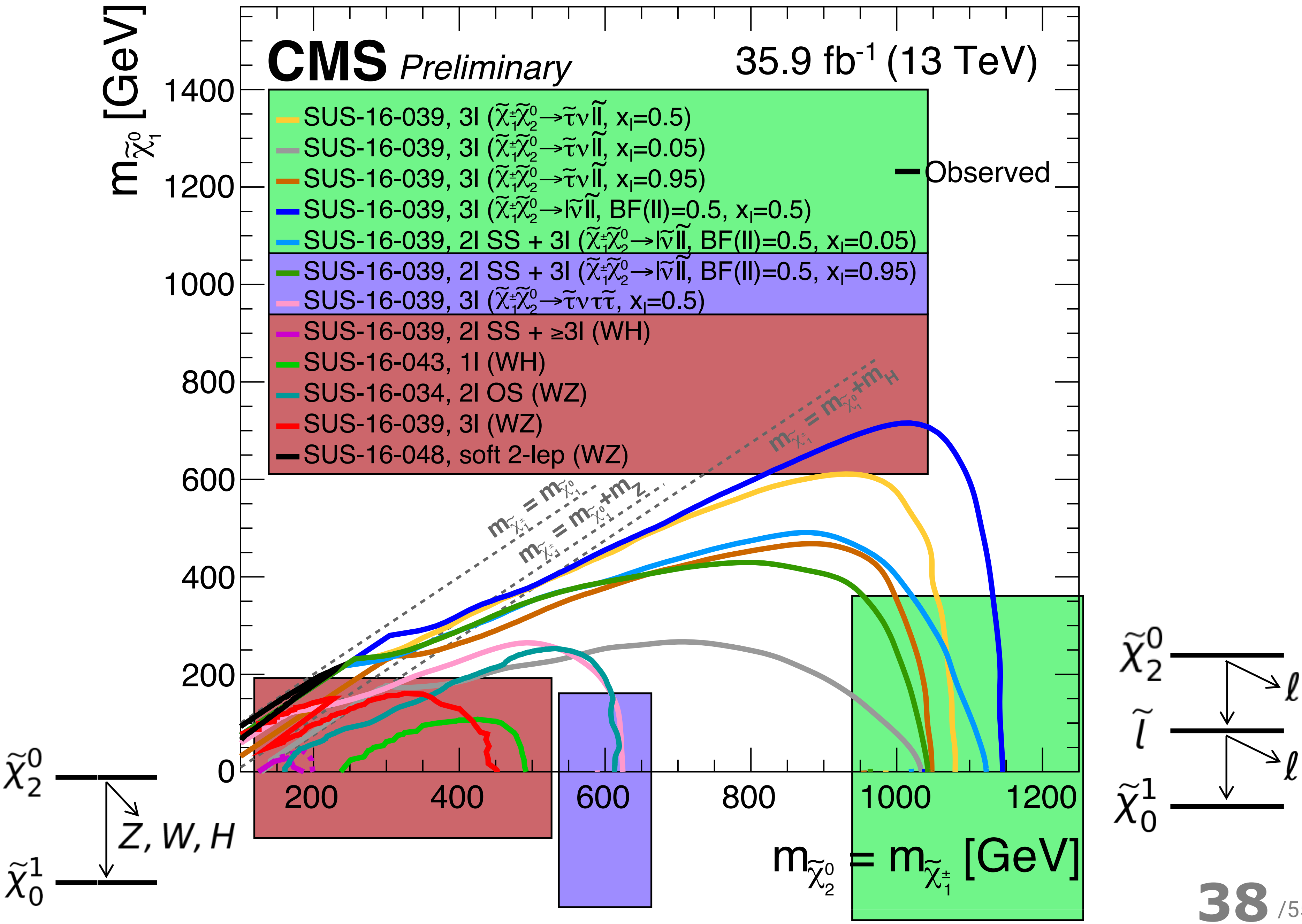
$pp \rightarrow \tilde{\chi}^0_2 \tilde{\chi}^\pm_1$

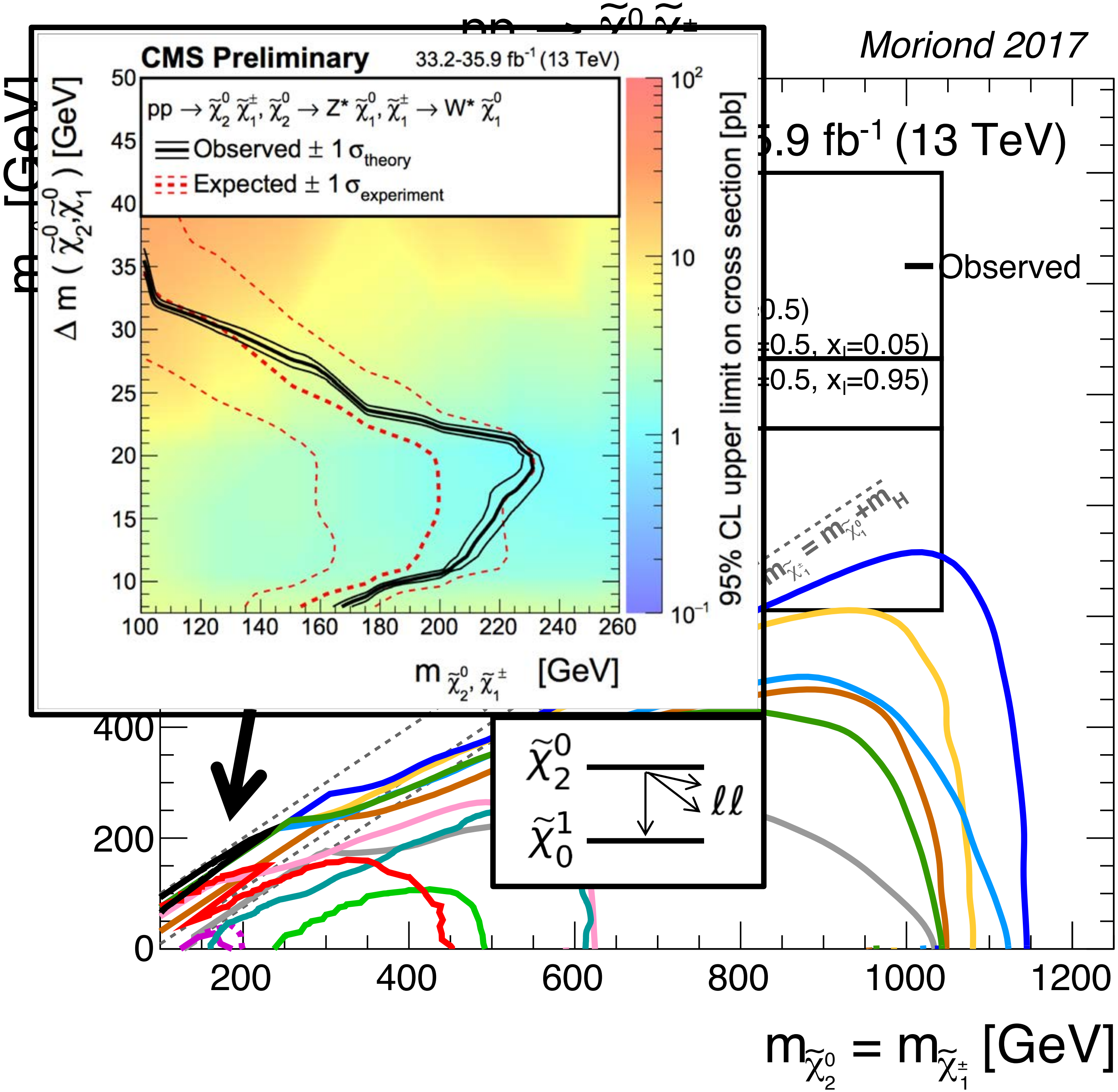
Moriond 2017



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

Moriond 2017

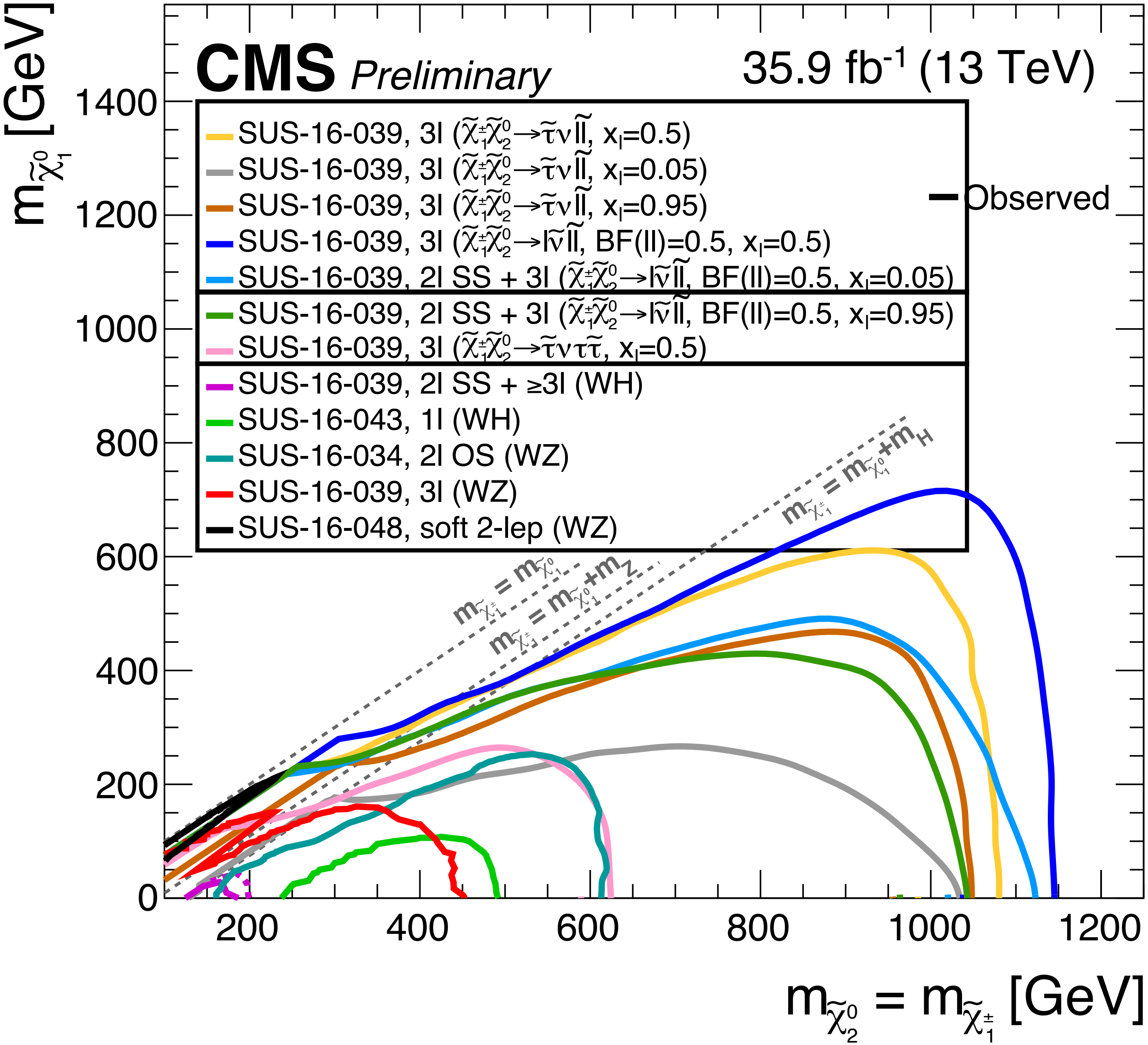




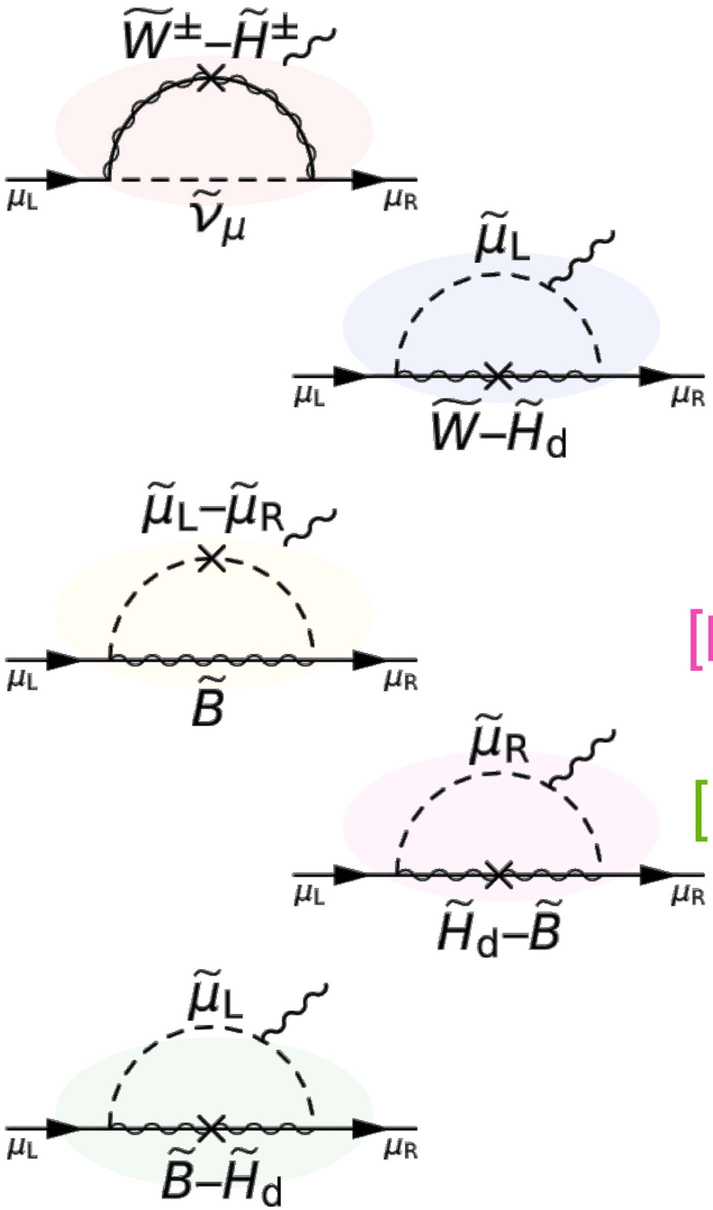
Moriond 2017
CMS Preliminary
33.2-35.9 fb^{-1} (13 TeV)
$pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm, \tilde{\chi}_2^0 \to Z^* \tilde{\chi}_1^0, \tilde{\chi}_1^\pm \to W^* \tilde{\chi}_1^0$
Observed ± 1 σ_{theory}
Expected ± 1 $\sigma_{experiment}$
$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ [GeV]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

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

Moriond 2017



(2) "Pure-bino" scenario: it has "μ-term enhancement."



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

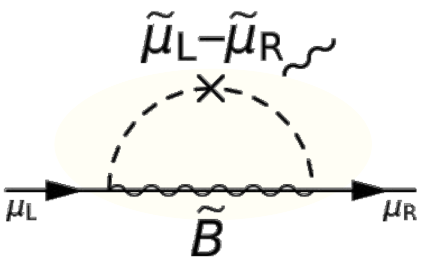
[BHL] $$\frac{g_Y^2 m_\mu^2}{16\pi^2}\frac{M_1\mu\tan\beta}{m_{\tilde{\mu}_\mathrm{L}}^4}\cdot F_b\left(\frac{M_1}{m_{\tilde{\mu}_\mathrm{L}}},\frac{\mu}{m_{\tilde{\mu}_\mathrm{L}}}\right)$$

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

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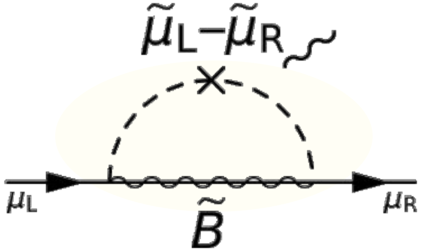
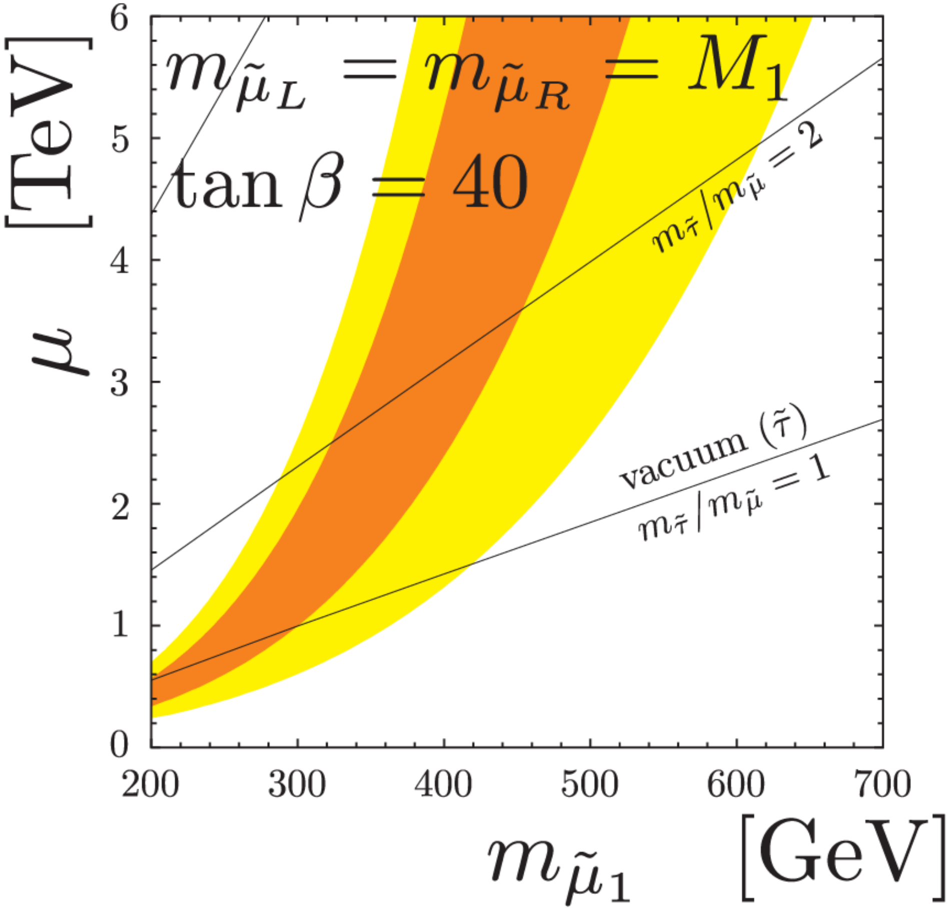
(2) "Pure-bino" scenario: it has "μ-term enhancement."

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:

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

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

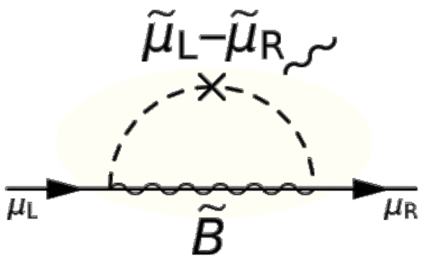
$=1 \Rightarrow m_{\tilde\mu}\lesssim 300(420)$ GeV

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

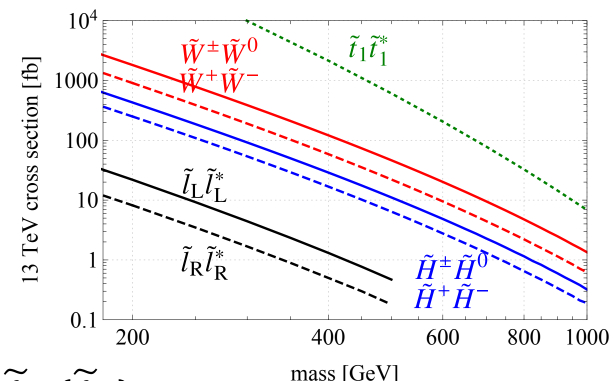
$=\infty \Rightarrow \lesssim 1.4(1.9)$ TeV

(2) "Pure-bino" scenario → Slepton production only is available; less constrained.

- Higgsino > TeV → pure-Bino scenario.
  - μ-enhancement v.s. vacuum stability
  - DM: not considered here ("orthogonal")
    - co-annihilation or resonance may work.

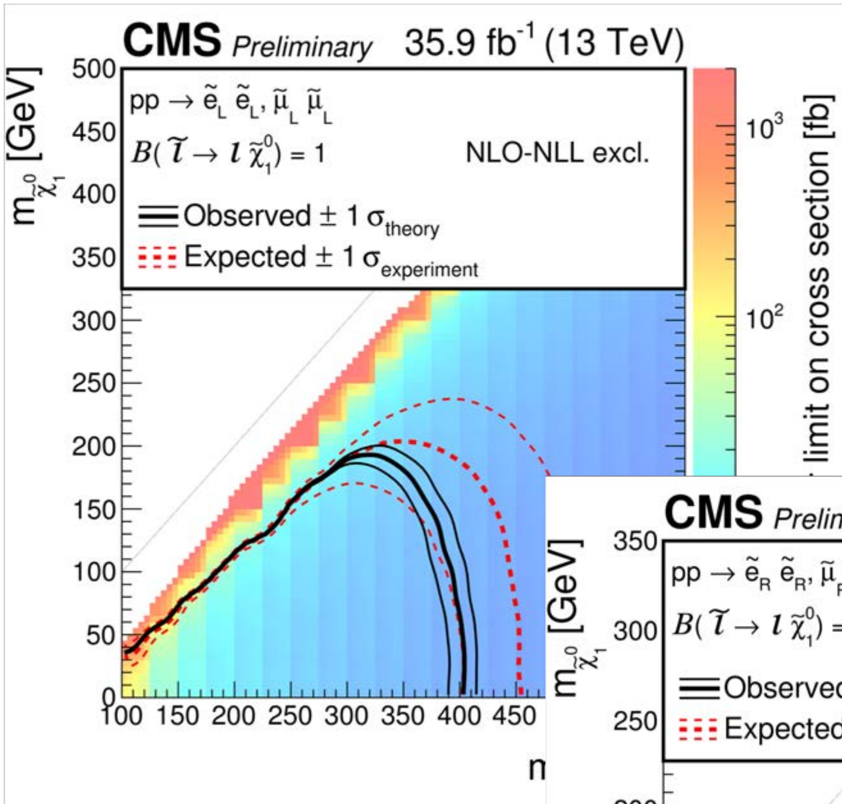


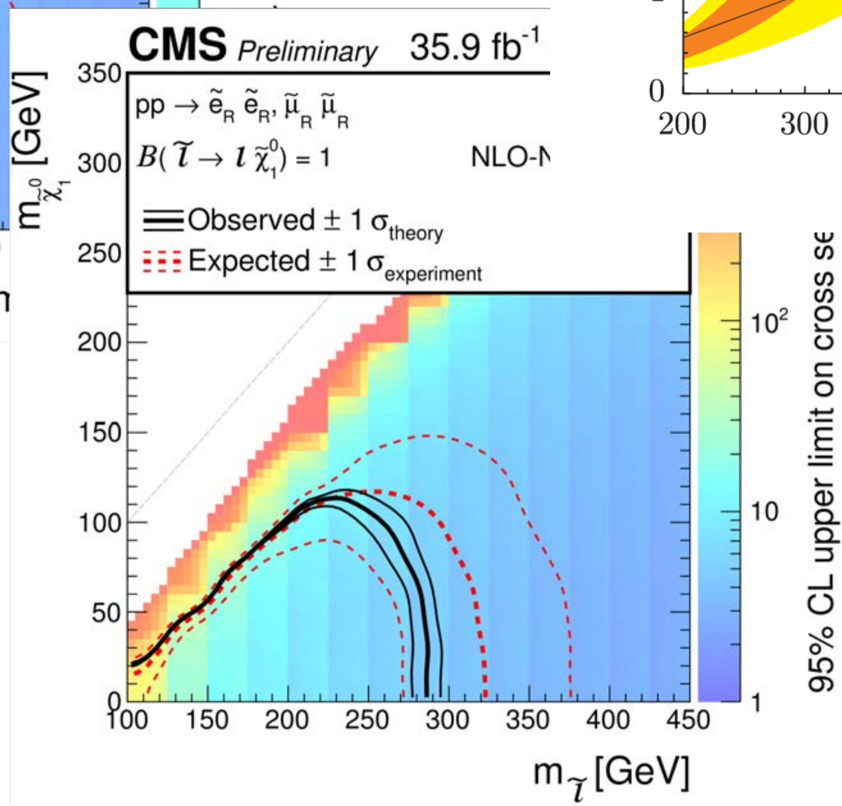
[B] $$\frac{g_Y^2 m_\mu^2}{8\pi^2}\,\frac{\mu\tan\beta}{M_1^3}\cdot F_b\left(\frac{m_{\tilde\mu_L}}{M_1},\frac{m_{\tilde\mu_R}}{M_1}\right)$$

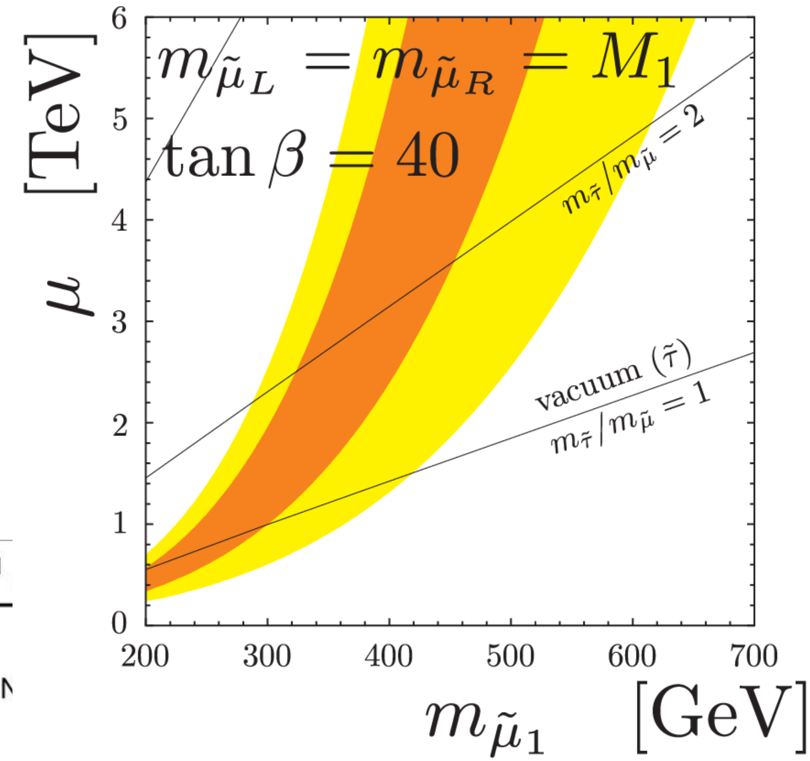


- LHC: only slepton pair-production
  - small cross section: 0.47 (0.18) fb for 500 GeV $\tilde\ell_L$ ($\tilde\ell_R$)
  - "di-lepton + missing" signature ... not easy.

(2) "Pure-bino" scenario → Slepton production only is available; less constrained.

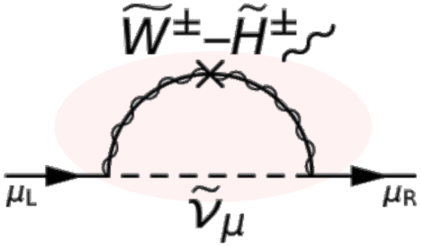




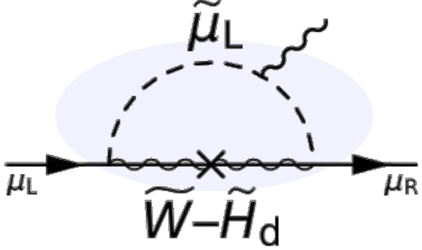


top-right figure from Endo, Hamaguchi, Kitahara, Yoshinaga [1309.3065]

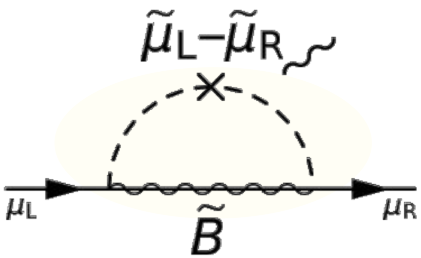
(3) "BHR" scenario: negative μ-term; "BHL" scenario: nothing special.



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



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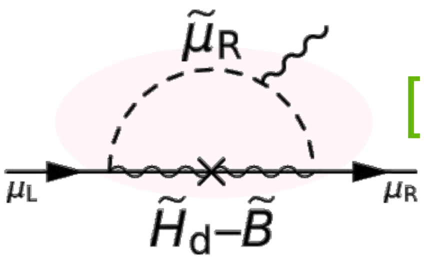

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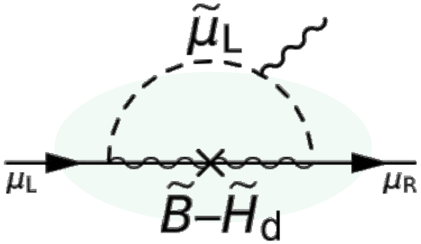

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(3) "BHR" scenario: negative μ-term; "BHL" scenario: nothing special.

- "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)
- "BHL contribution" (Bino, Higgsino, $\tilde{\mu}_L$ must be O(100)GeV)
  - nothing special.
- $\propto g_Y^2$

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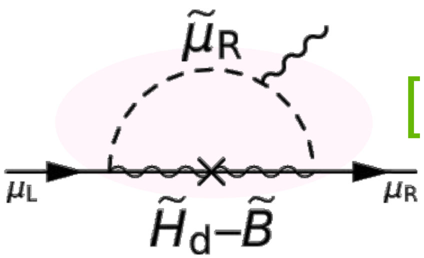
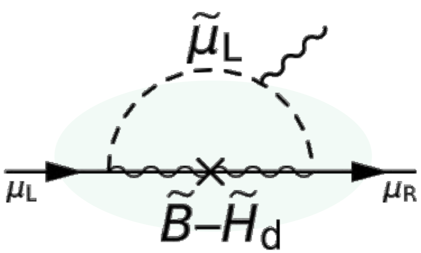
$$\frac{g_Y^2 m_\mu^2}{16\pi^2}\frac{M_1\mu\tan\beta}{m_{\tilde{\mu}_L}^4}\cdot F_b\left(\frac{M_1}{m_{\tilde{\mu}_L}},\frac{\mu}{m_{\tilde{\mu}_L}}\right)$$





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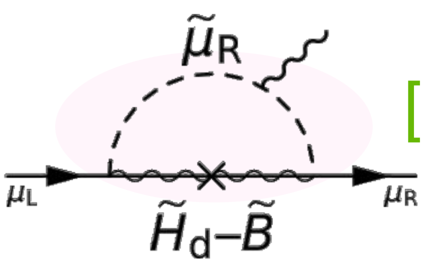
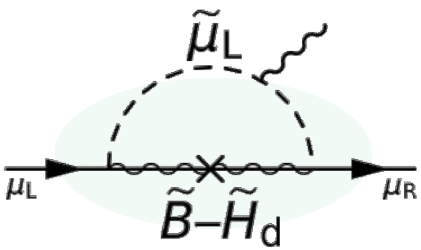
(3) "BHR"/"BHR": Higgsino production provides multi-tau signature.

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





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

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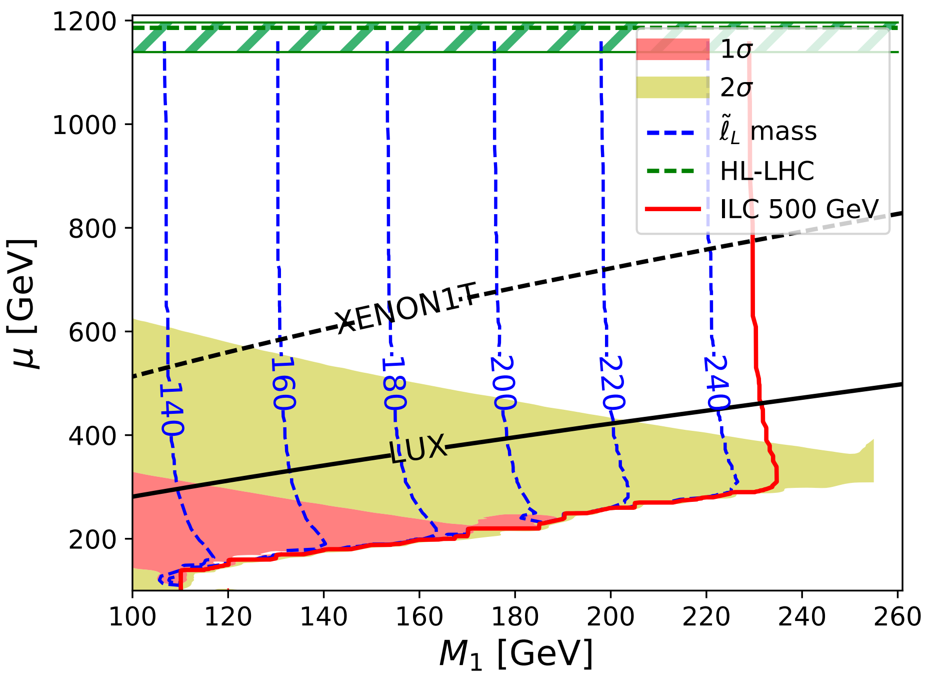
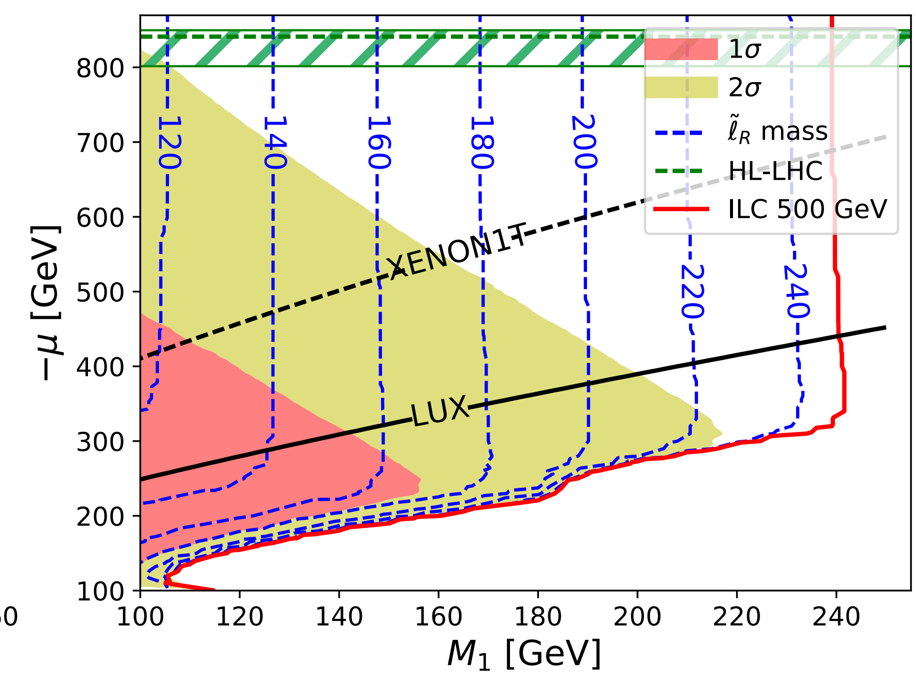
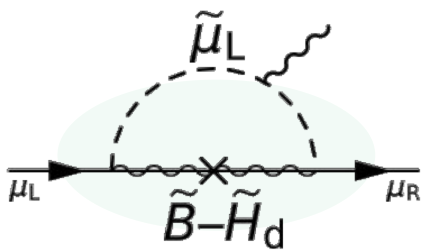
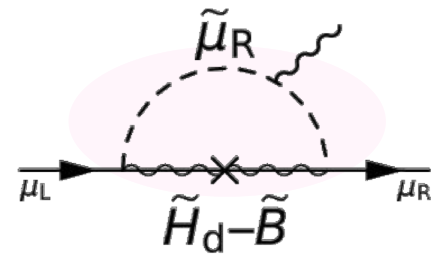


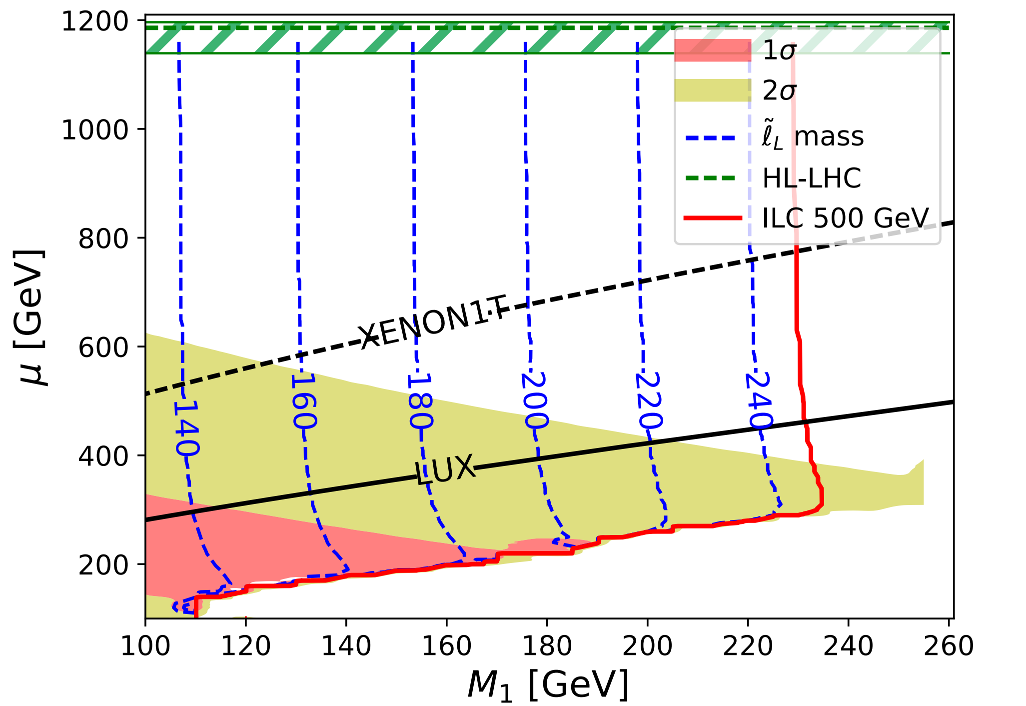






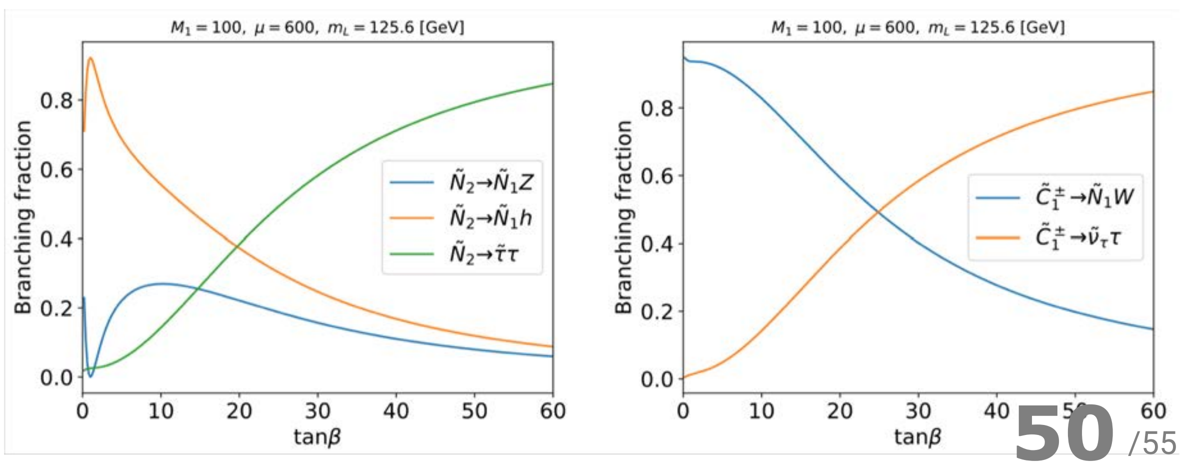
- Bino−slepton (stau) co-annihilation → $m_{\tilde{\nu}_\tau}$ (or $m_{\tilde{\tau}_R}$) $\simeq m_{\tilde{B}}$.
- We assumed:
  - slepton universality,
  - DM density is realized at each point in the plots.

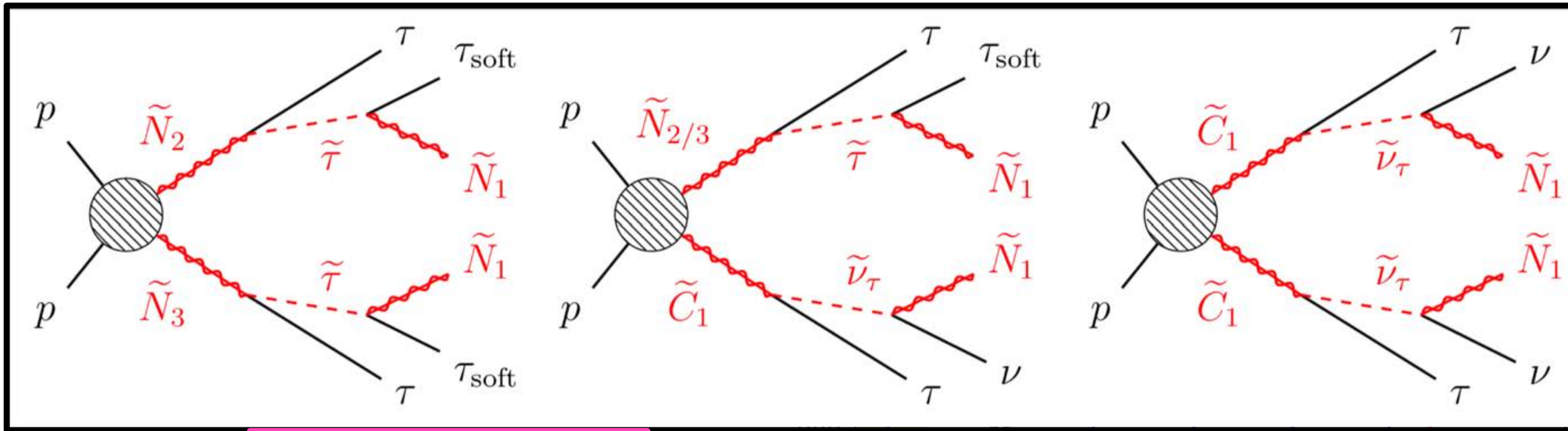
  → $m_{\tilde{B}} \lesssim m_{\tilde{\mu}} < m_{\tilde{H}}$
  $(\sim M_1)$ $(\sim \mu)$



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

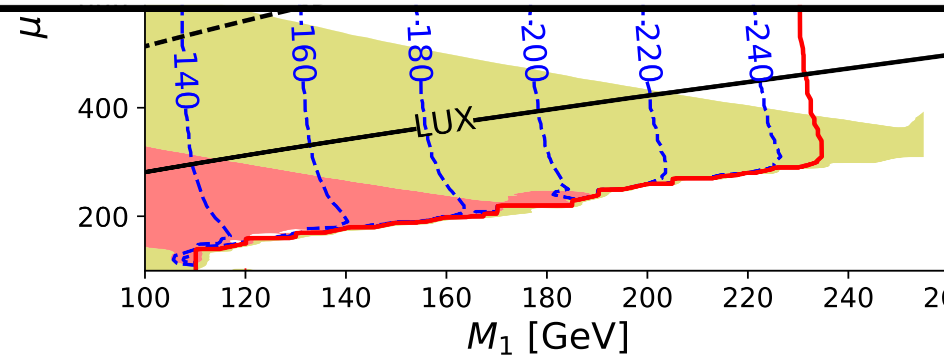
  → multi-tau signature





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

(~M_1) (~μ)



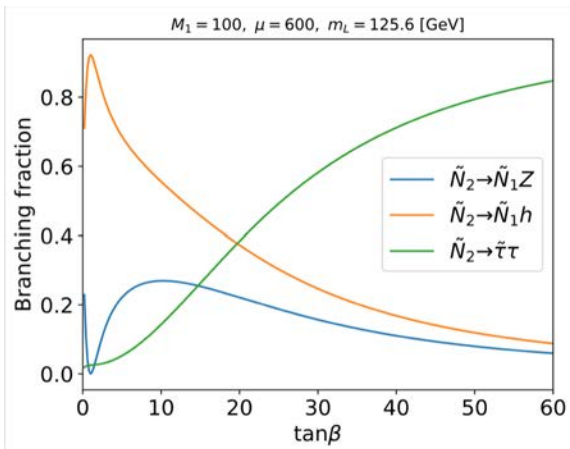
■ HL-LHC?

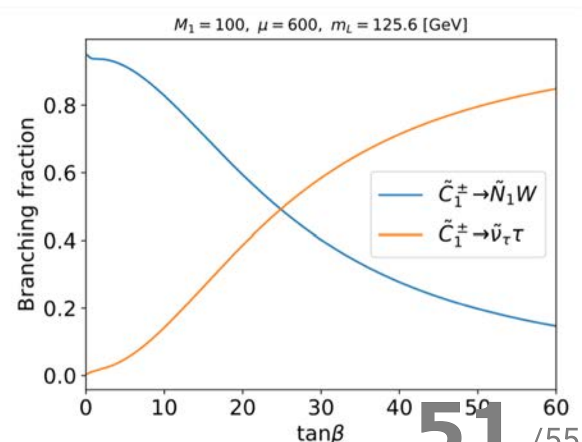
➢ $pp \rightarrow \tilde{H}^+\tilde{H}^0,\ \tilde{H}^+\tilde{H}^-$

➢ $\tilde{H}^0 \rightarrow \tau\tilde{\tau},\ \ \tilde{H}^+ \rightarrow \tau\tilde{\nu}_\tau$
because of tanβ

$\rightarrow$ multi-tau signature

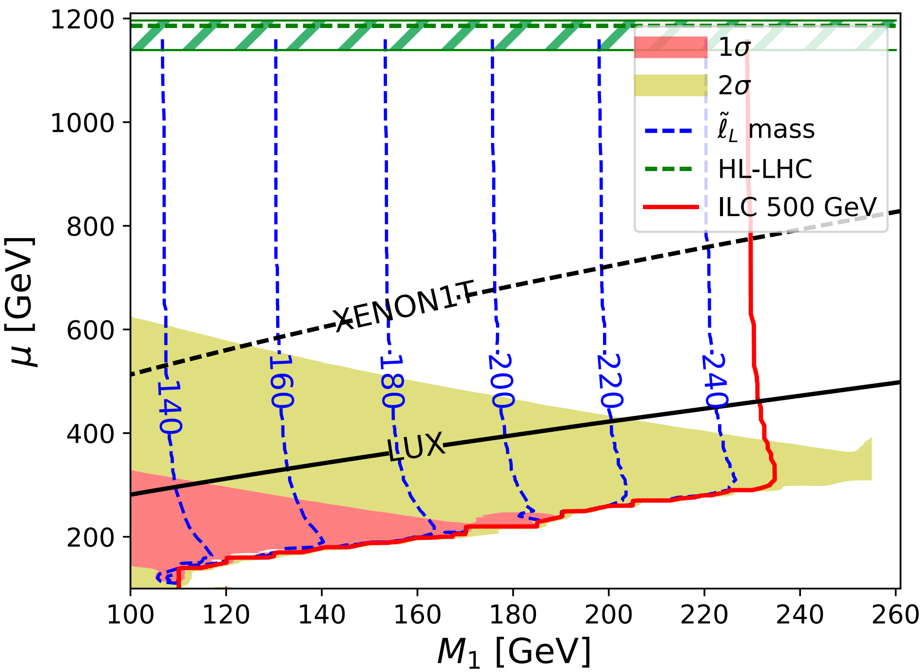
"2τ (+ soft) + missing"

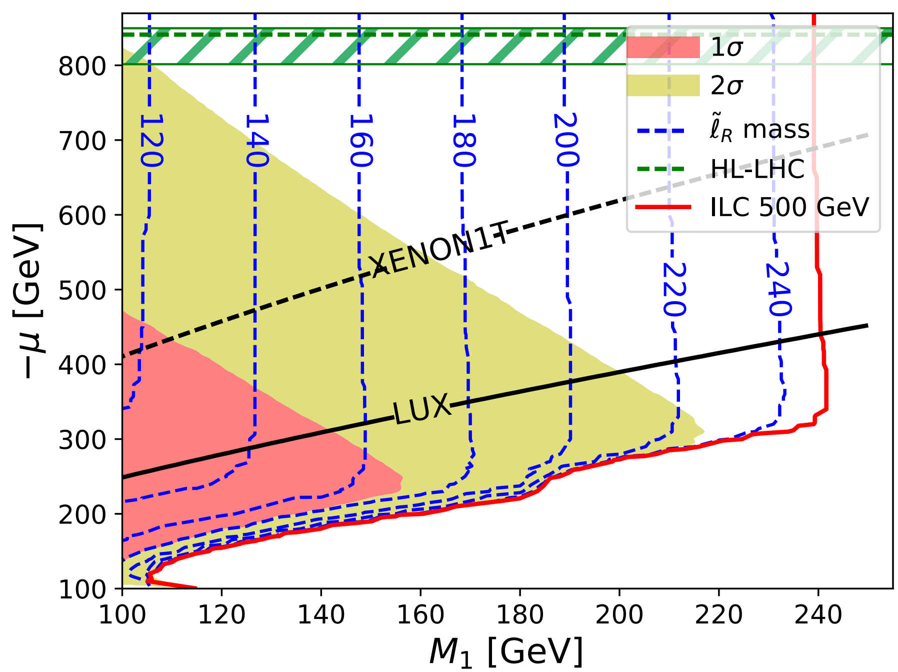


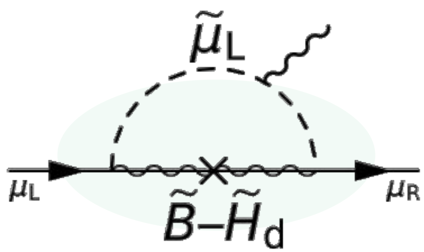


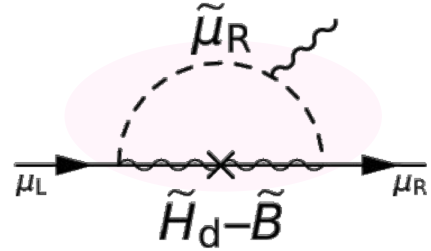
(3) "BHR"/"BHR": Higgsino production provides multi-tau signature.

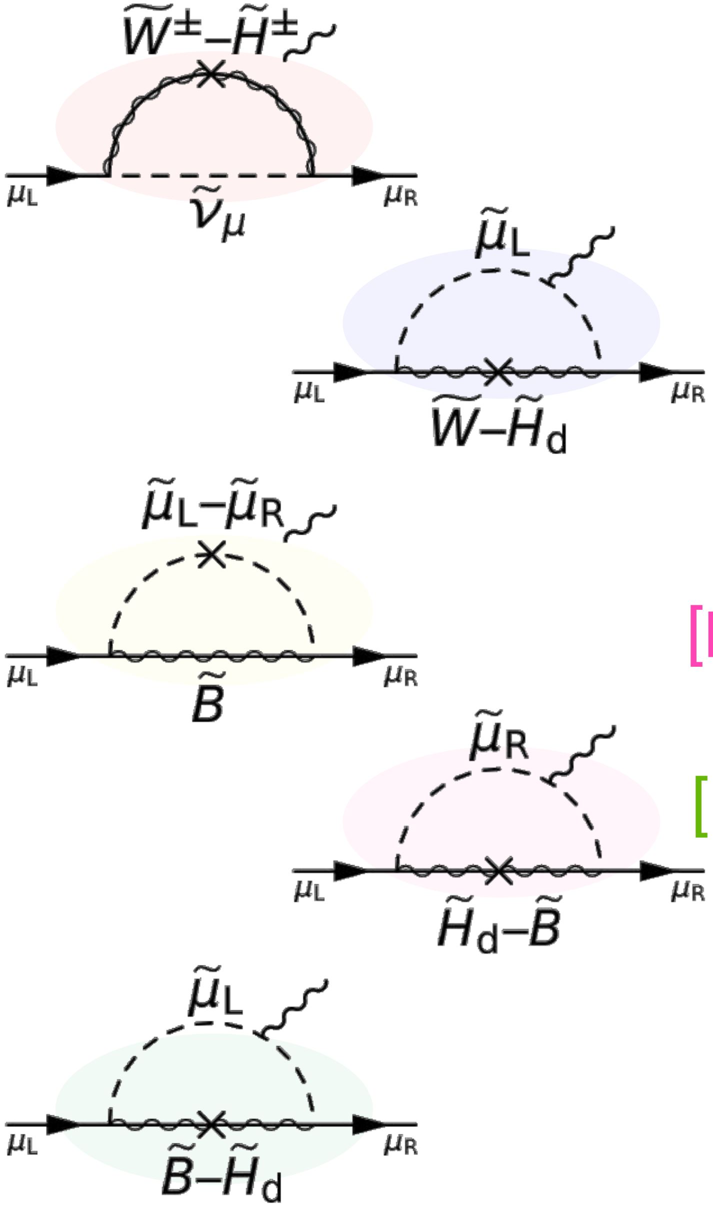
- Wino >> TeV & Higgsino < TeV → BHL or BHR scenario. ($\mu > 0$) ($\mu < 0$)
  - DM: Bino−stau co-annihilation → $m_{\tilde{B}} \simeq (m_{\tilde{\tau}_R} \text{ or } m_{\tilde{\nu}_\tau}) \lesssim m_{\tilde{\mu}} < m_{\tilde{H}}$
  - DM has small Higgsino component → **LUX/XENON1T** constraint.
  -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











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

μ-enhancement

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

negative

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

nothing special

F_a, F_b are loop functions and positive.

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

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

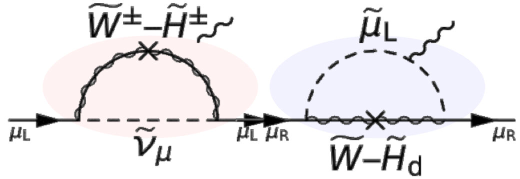
1. Introduction
   - of $(g-2)_\mu$ anomaly

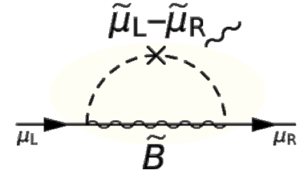
   - of myself: "Iwamoto Sho"
     1. collider phenomenology (SUSY, meta-stable particles, ...)
     2. cosmology & astro-particle physics (leptogenesis, cosmic-rays, ...)
     3. exotic DM models (hidden-colored DM)

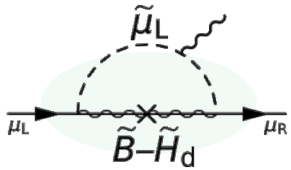
2. SUSY with ~TeV non-colored superparticles:
   - **it solves the $(g-2)_\mu$ anomaly,**
   - **it provides dark matter candidates, and**
   - **it was the main focus of recent LHC runs.**

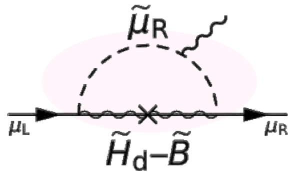
3. Four typical scenarios, LHC status, and prospects.

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:

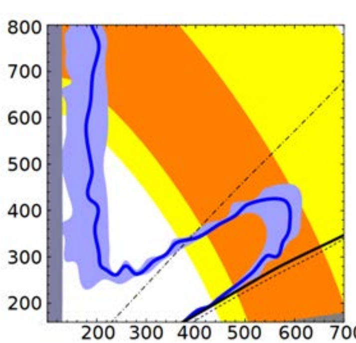
multi-lepton
→ promising

("stay tuned!")

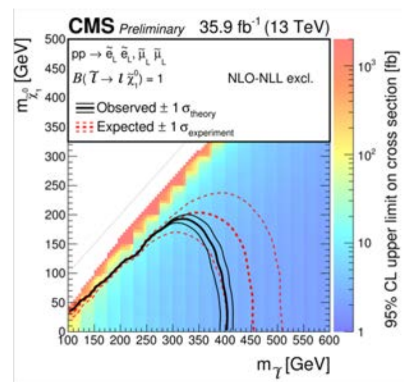
di-lepton
→ **difficult @LHC**

Higgsino → multi-tau

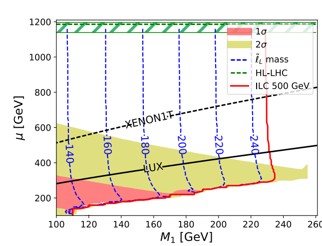
"**covered@HL-LHC if we seriously consider the relic density**"

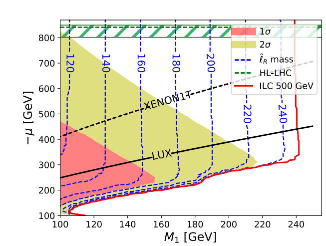


Endo, Hamaguchi, ***SI***, Yoshinaga [1303.4256]



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





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