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MSSM + $(g-2)_\mu$ + LHC

Sho IWAMOTO（岩本　祥）

21 Aug. 2018
Beyond Standard Model: Where do we go from here? @ GGI

Based on

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

and a few ongoing projects.

(cf. https://github.com/misho104/notes/blob/master/MSSM/journal_20180313.pdf)

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

2. LHC

Sho Iwamoto

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Date:

LHC: ~150 fb^{-1} (2018)
+ 150 fb^{-1} (2021-23)
} < 2σ g-2

SUSY (MSSM): Solution to
- Naturalness if
  - $H \lesssim 200$ GeV
  - $\tilde{t} \lesssim 600$ GeV
  - $\tilde{g} \lesssim 900$ GeV
  } for 20% tuning [1110.6926]
  mostly excluded (except for degenerated region)
- DM
- Gauge coupling unification
- muon g-2 anomaly

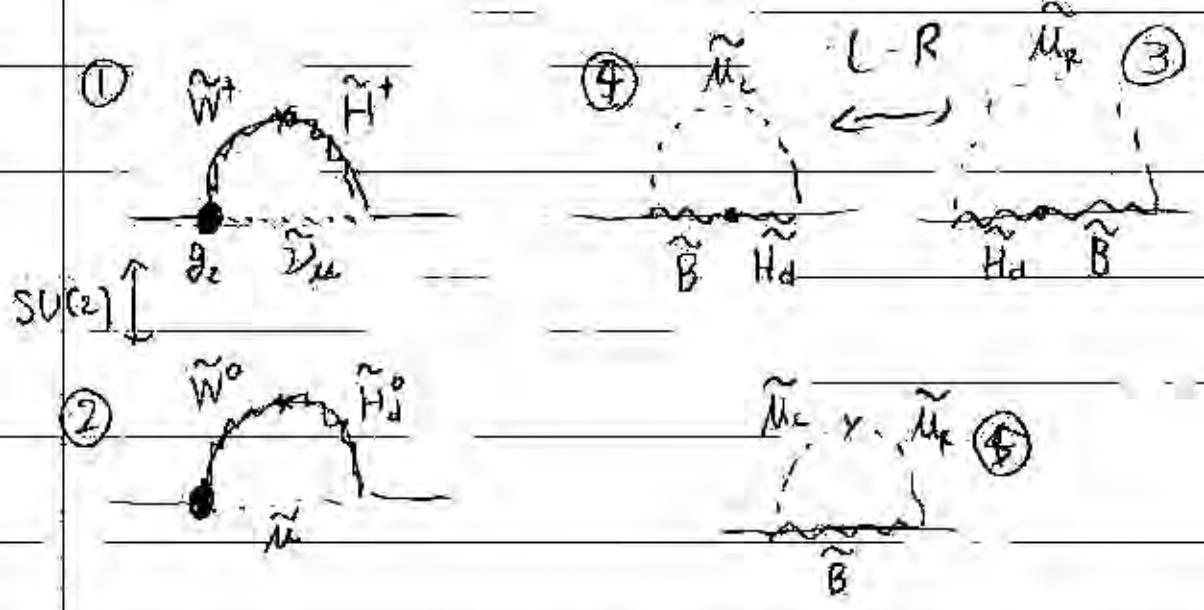
$a_\mu^{SM} = \frac{g_\mu^{SM}-2}{2} = (116\,591\,82.04 \pm 3.56) \times 10^{-10}$ [1802.02995]

BNL 2004:	209.1	±6.3	→ 3.7σ
Fermilab (ongoing):	??	± ~6	data collected (release 2019?)
	??	±1.6	(2020) → 7σ??

$(g-2)_\mu$ from SUSY

$\parallel$

$\mathrm{Re}\left[\mu_L \; \text{(///)} \sim \gamma \; \mu_R\right]$



three SUSY particles ⓐ $\lesssim$ 1 TeV

$① \propto g_2^2 \times \dfrac{m_\mu^2 M_2 \mu \tan\beta}{m_{Loop}^4} \propto \mathrm{sign}(\mu)$ $\quad m_{Loop} = \{m_{\tilde{\mu}_L}, m_{\tilde{H}}, m_{\tilde{W}}\}$, $m_{\tilde{H}} \sim \mu$, $m_{\tilde{W}} \sim M_2$

$② = -\frac{1}{2} \times ①$ $\quad \therefore ① + ② > 0$ for $\mu > 0$

$\Rightarrow \mu > 0, \ \tan\beta = O(10)$

$\tilde{W}, \tilde{H}, \tilde{\mu}_L \lesssim 500 = 1$ TeV GeV

Wino Scenario

Eha Iwamoto

No.
Date

③ $\propto -g_Y^2 \times \frac{M_W^2 M_1 \mu \tan\beta}{m_{LOOP}^4}$ $\Rightarrow \mu < 0$, $\tan\beta = O(10)$,

BHR $\tilde{B}, \tilde{H}, \tilde{M}_R \lesssim 400$ GeV

④ $\propto +g_Y^2 \times$ 〃 "negative μ" because U(1) scenario

⑤ $\propto +g_Y^2 \times \frac{M_1 \mu \tan\beta}{m_{LOOP}^4}$ but μ & $m_{LOOP} = \{M_L, M_E, M_1\}$

$\Rightarrow \propto \mu \tan\beta$ $\mu = +O(1\text{TeV})$

$\tilde{B}, \tilde{M}_L, \tilde{M}_R \lesssim 1$ TeV

pure-bino ($\mu\tan\beta$-enhancement)

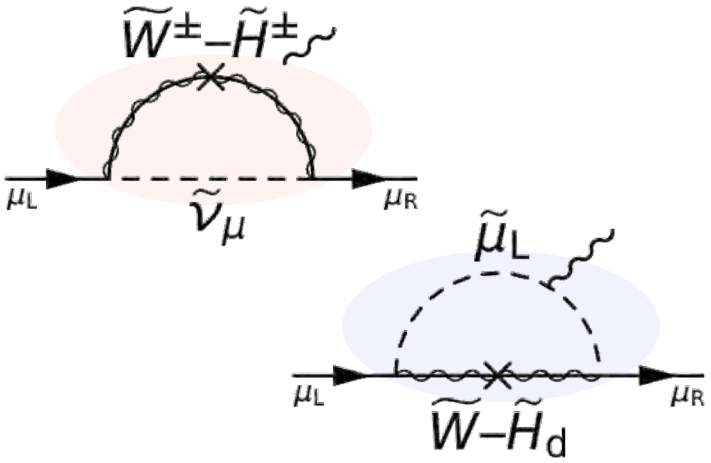
LHC!		500GeV	1TeV
$pp \to$	$\tilde{W}^+ \tilde{W}^0$	33fb	1.0
	$\tilde{W}^+ \tilde{W}^-$	22	0.62
	$\tilde{H}^+ \tilde{H}^0$	11	0.3
	$\tilde{H}^+ \tilde{H}^-$	6.2	0.18
	$\tilde{l}_L \tilde{l}_L^*$	0.47	
	$\tilde{l}_E \tilde{l}_E^*$	0.18	

pure-bino → $pp \to \tilde{l}_{LE} \tilde{l}_{LE} \to 2l + \not{E}_T$

BHR "negative μ" → $pp \to \tilde{H}^+ \tilde{H}^0 \to 3\tau + \not{E}_T$, $3l + \not{E}_T$

Wino → $\tilde{W}^+ \tilde{W}^- \to 3l + \not{E}_T$

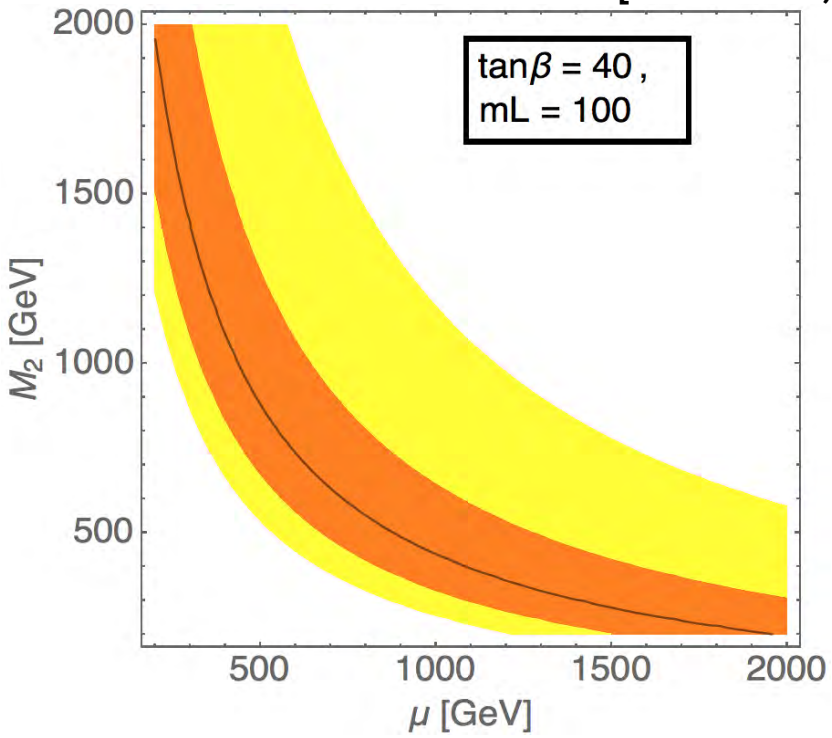
SUSY contribution to muon $g-2$: (1) "Chargino" contributions

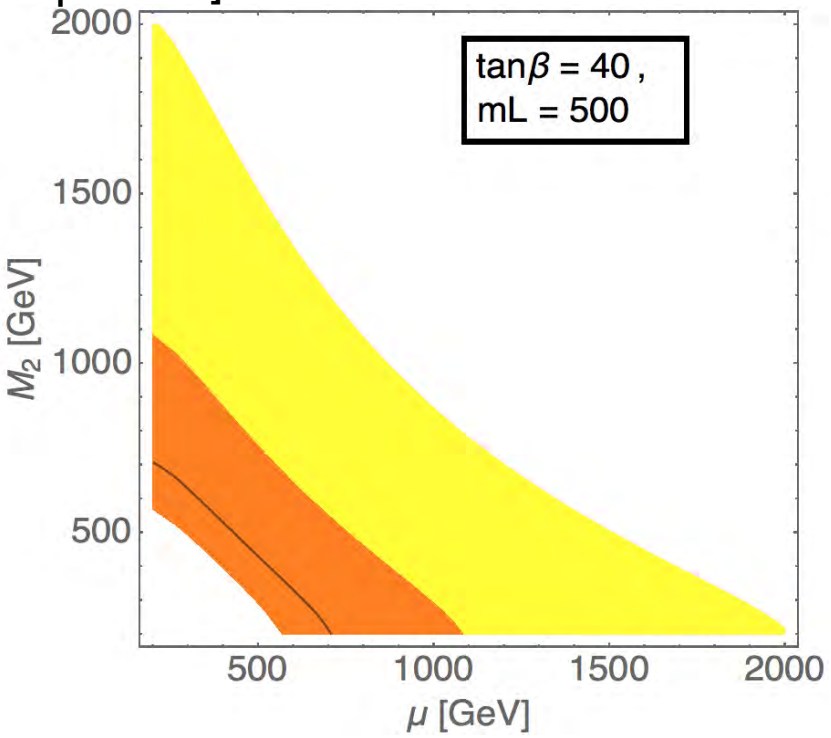


[C] $$\frac{g_2^2 m_\mu^2}{8\pi^2}\frac{M_2\mu\tan\beta}{m^4_{\widetilde{\nu}_\mu}}\cdot F_a\left(\frac{M_2}{m_{\widetilde{\nu}_\mu}},\frac{\mu}{m_{\widetilde{\nu}_\mu}}\right)$$

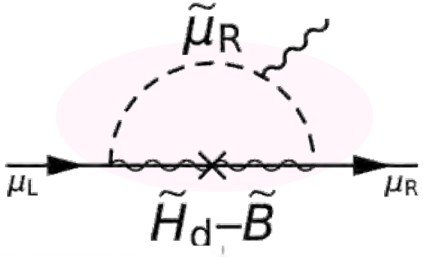
[C'] $$-\frac{g_2^2 m_\mu^2}{16\pi^2}\frac{M_2\mu\tan\beta}{m^4_{\widetilde{\mu}_L}}\cdot F_b\left(\frac{M_2}{m_{\widetilde{\mu}_L}},\frac{\mu}{m_{\widetilde{\mu}_L}}\right)$$

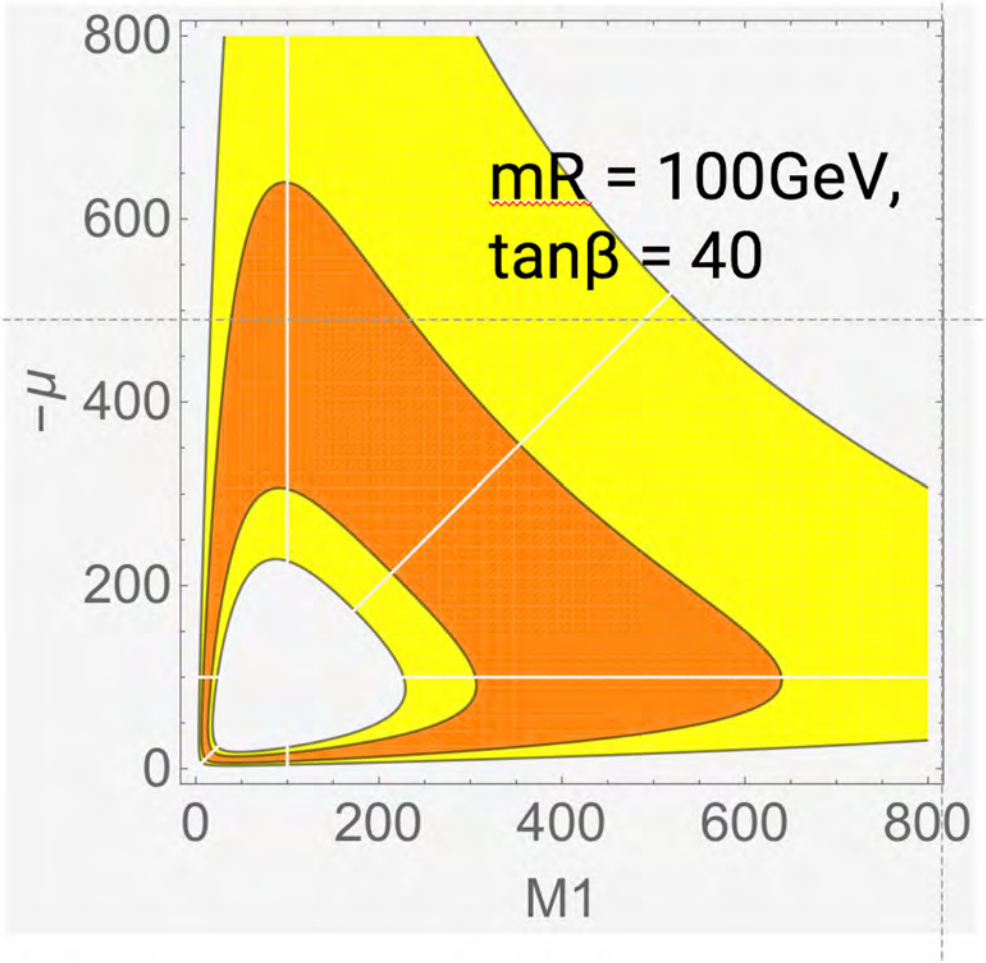
C+C'-contribution [tree-level; slep=sneu]

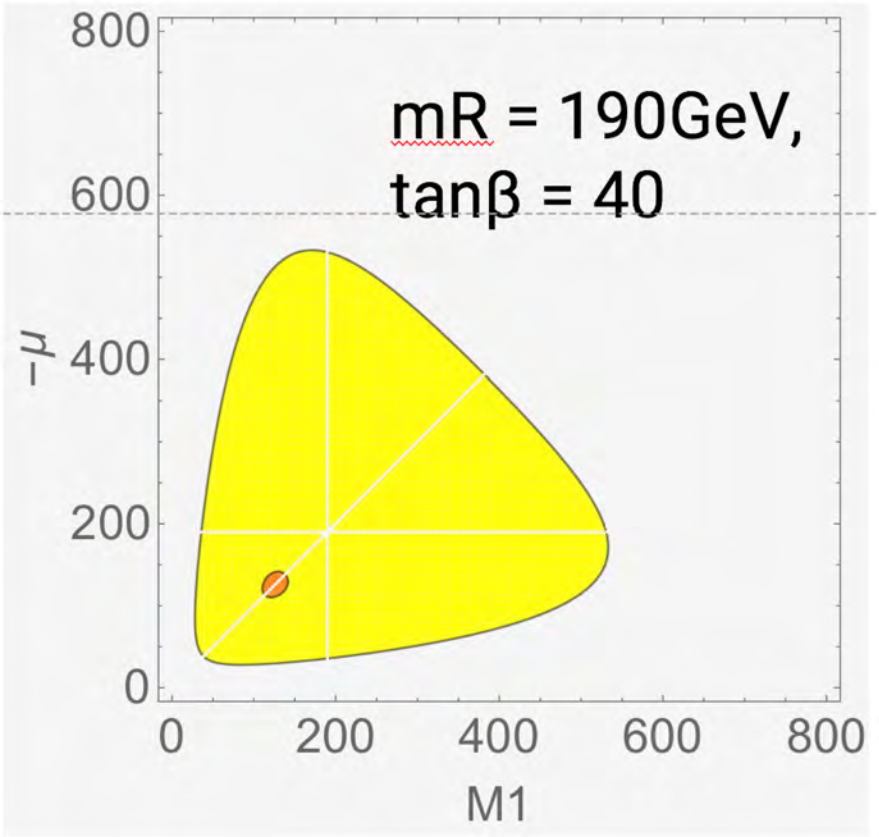




SUSY contribution to muon $g-2$: gauge basis

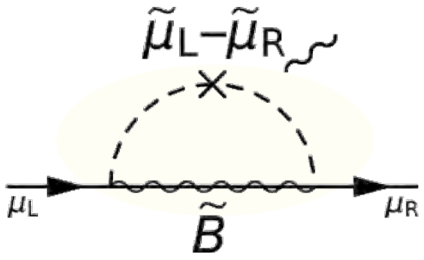


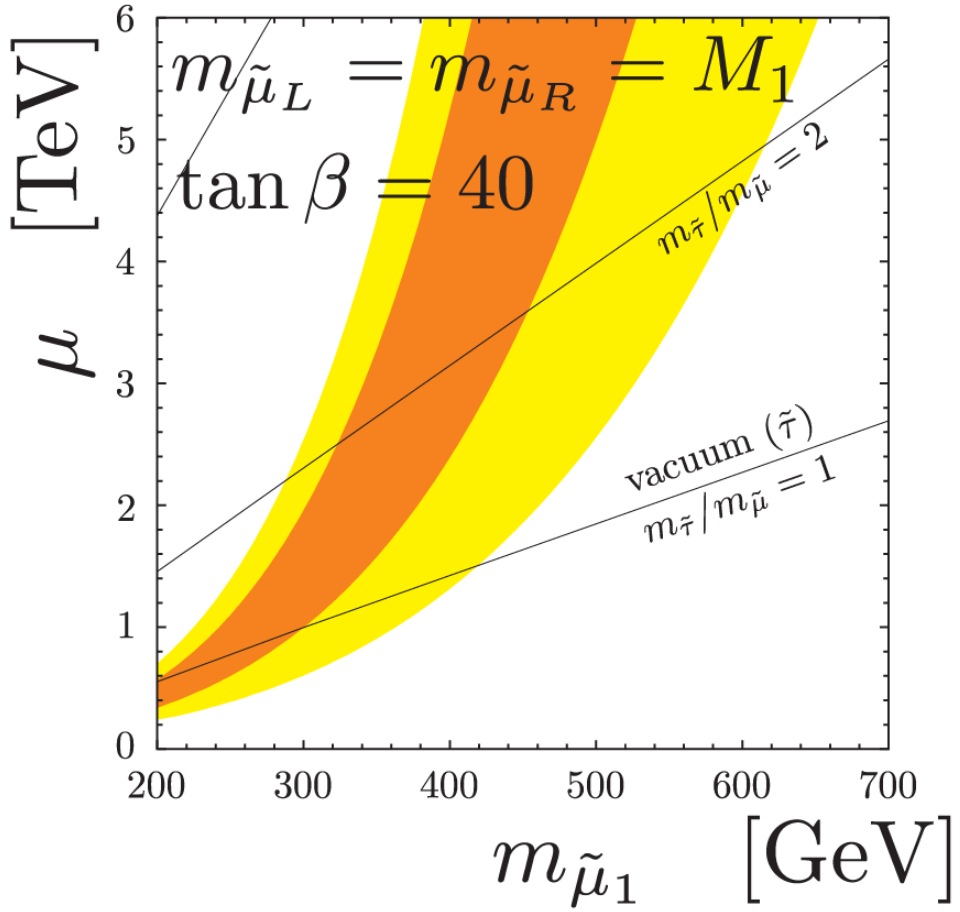




SUSY contribution to muon $g-2$: (3) pure-Bino contribution

Endo, Hamaguchi, Kitahara, Yoshinaga [1309.3065]

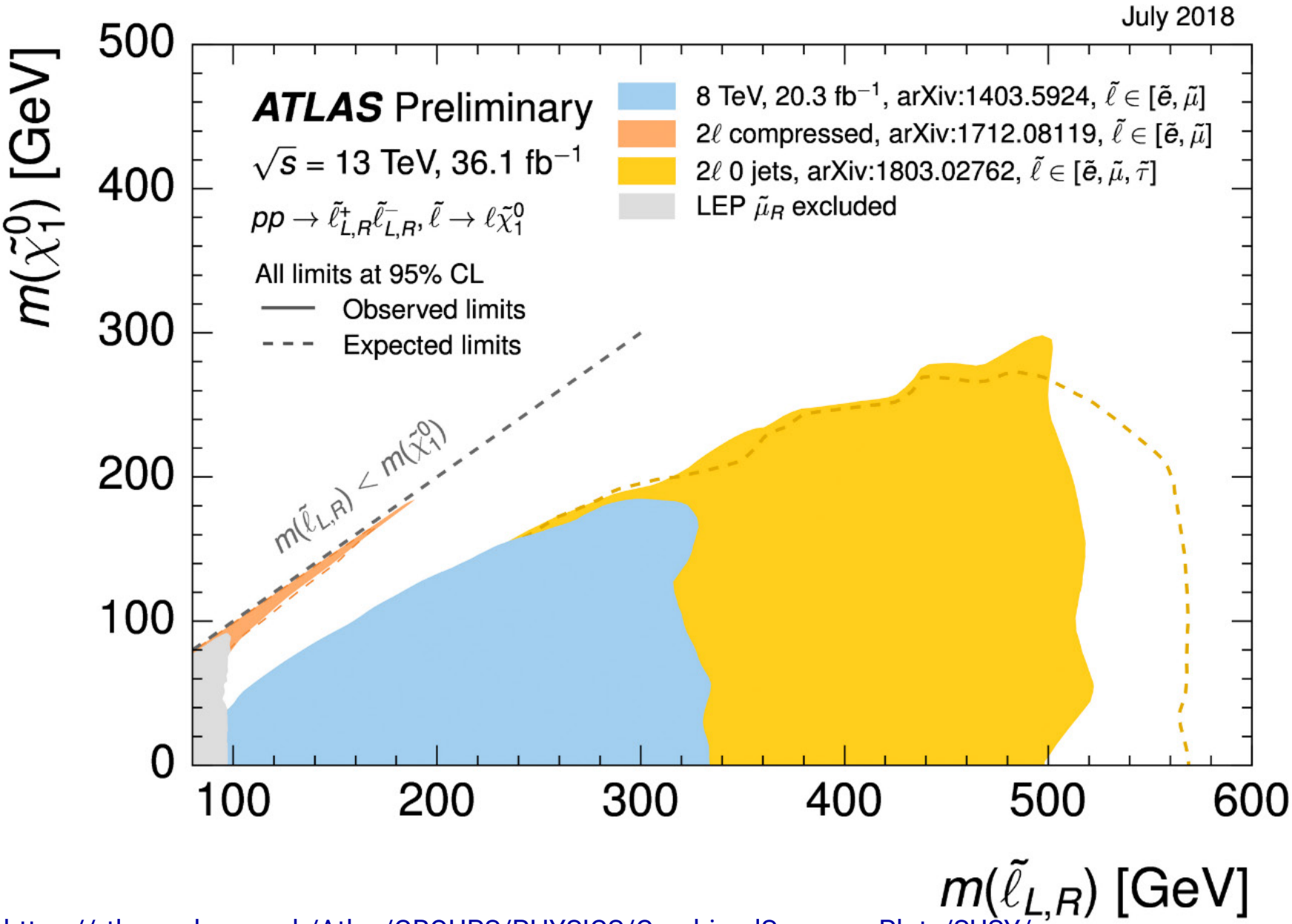




1. $(g-2)_\mu$

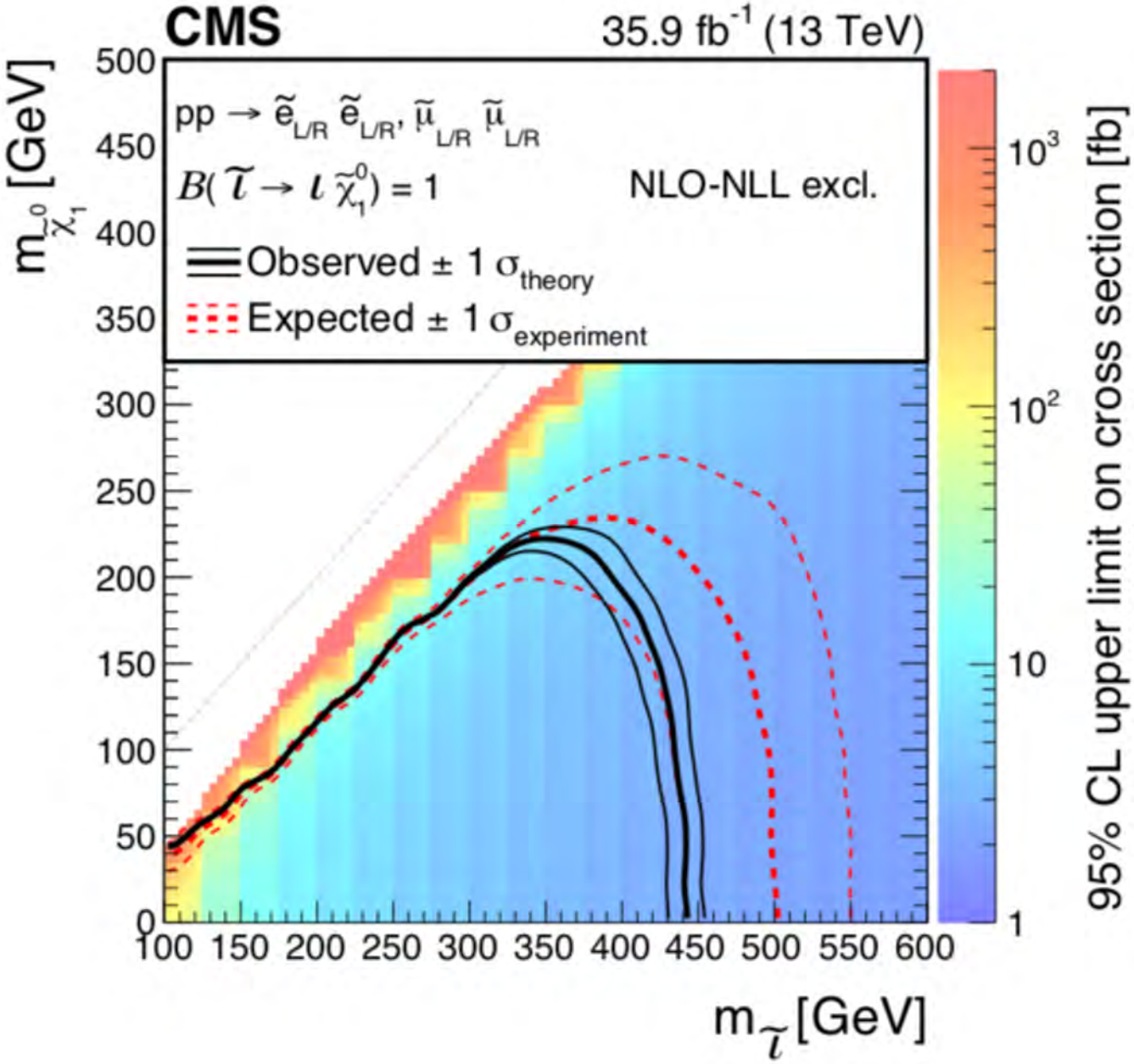
2. LHC

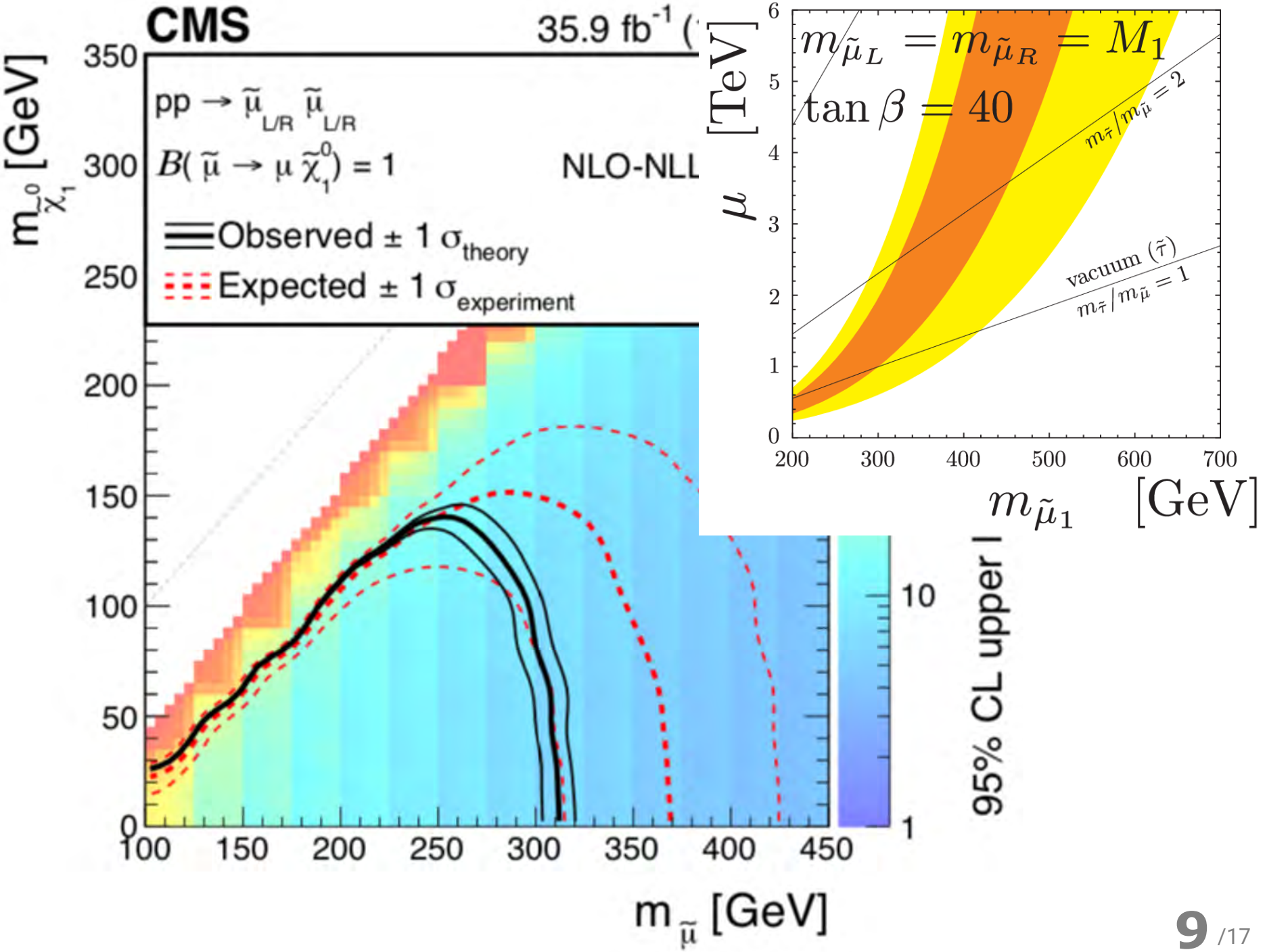
[1803.02762]

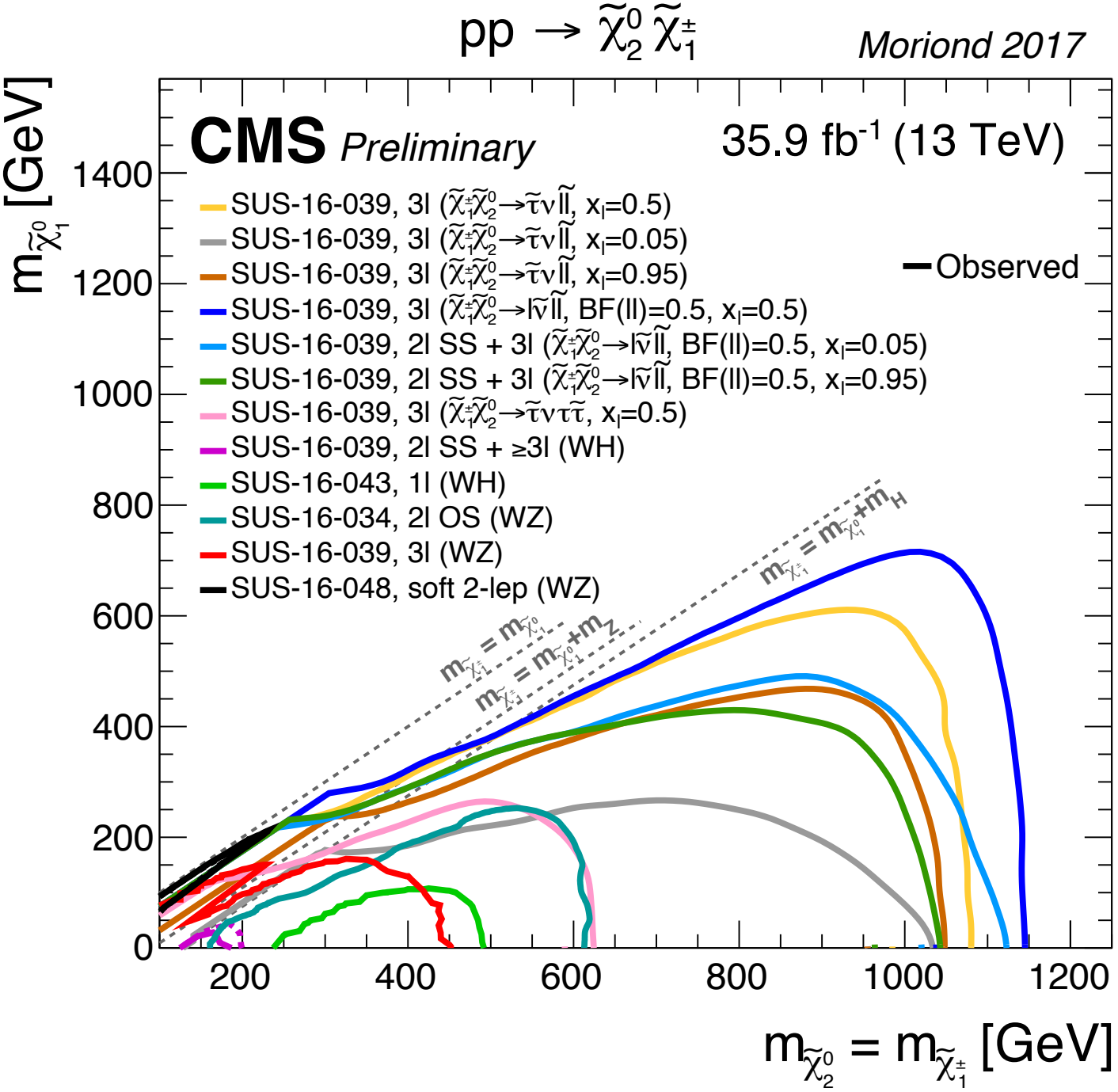


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/

[1806.05264]


CMS
35.9 fb-1 (13 TeV)
pp → ẽL/R ẽL/R, μ̃L/R μ̃L/R
B(l̃ → l χ̃01) = 1
NLO-NLL excl.
Observed ± 1 σtheory
Expected ± 1 σexperiment
mχ̃01 [GeV]
ml̃ [GeV]
95% CL upper limit on cross section [fb]
0
50
100
150
200
250
300
350
400
450
500
100
150
200
250
300
350
400
450
500
550
600
1
10
10²
10³


CMS
35.9 fb-1 (
pp → μ̃L/R μ̃L/R
B(μ̃ → μ χ̃01) = 1
NLO-NLL
Observed ± 1 σtheory
Expected ± 1 σexperiment
mχ̃01 [GeV]
mμ̃ [GeV]
95% CL upper l
mμ̃L = mμ̃R = M1
tan β = 40
μ [TeV]
mμ̃1 [GeV]
mτ̃/mμ̃ = 2
vacuum (τ̃)
mτ̃/mμ̃ = 1



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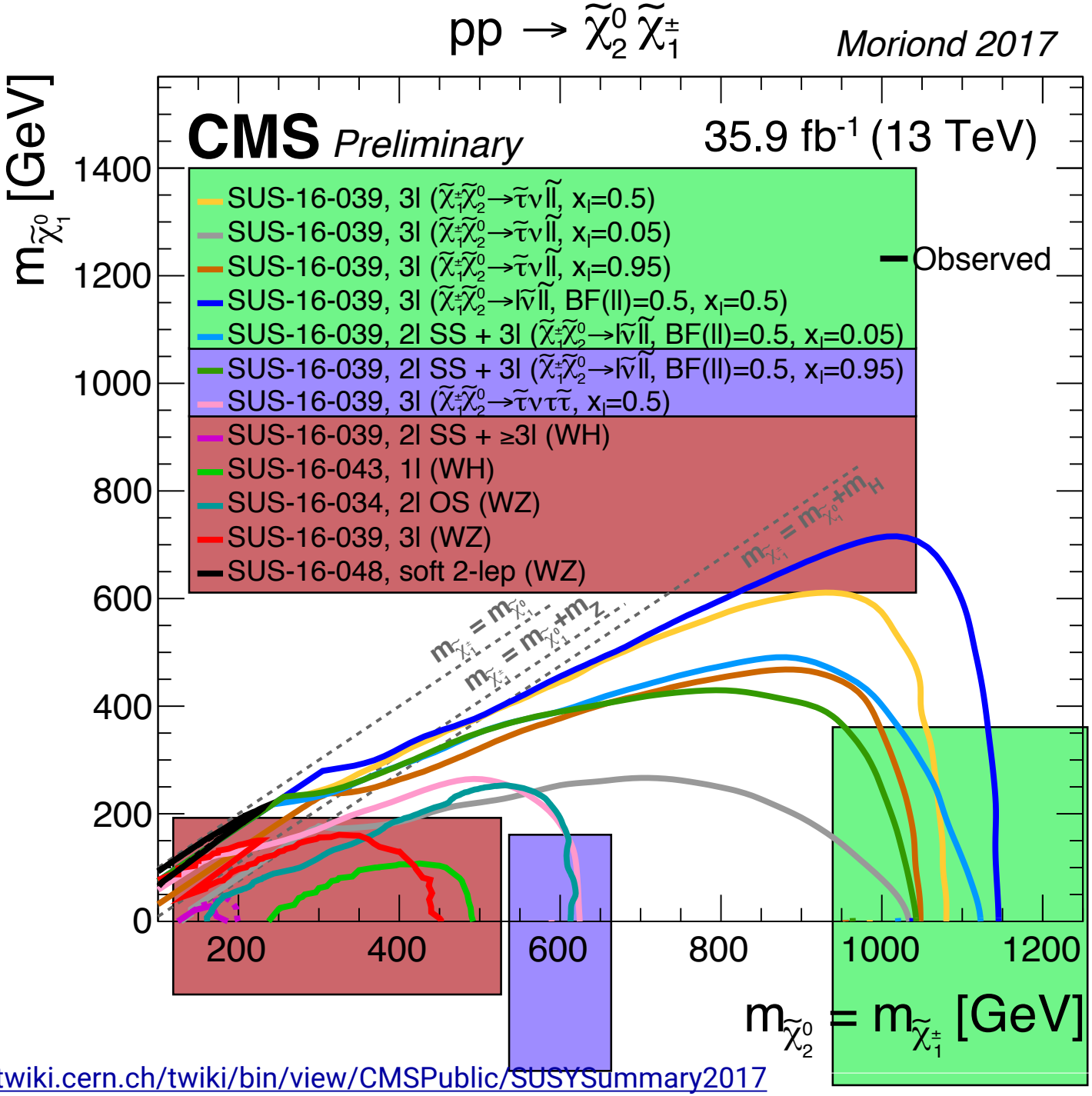

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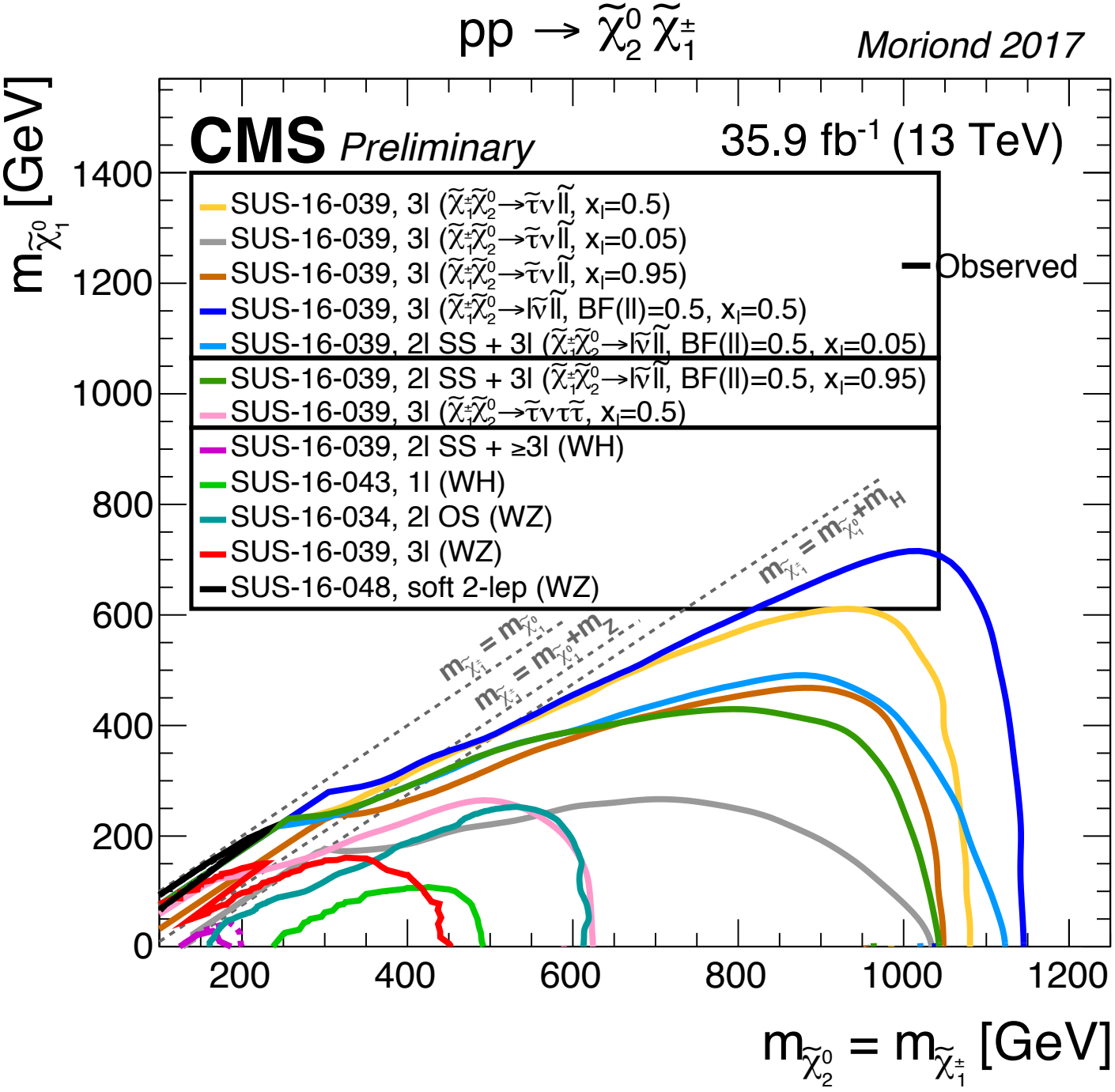
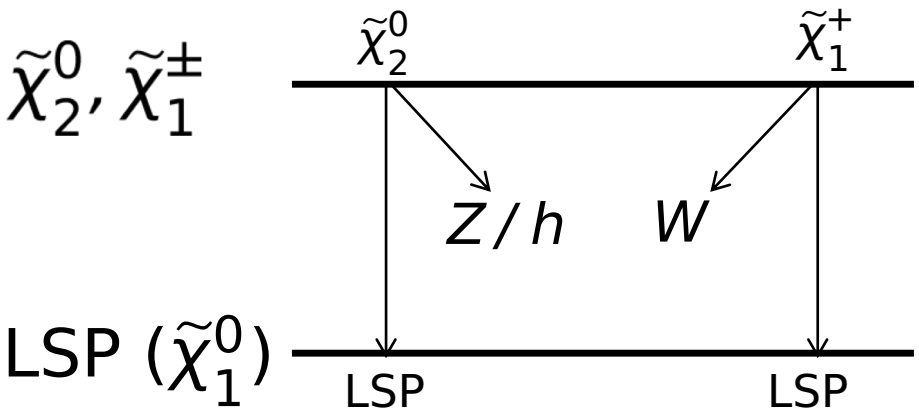


https://twiki.cern.ch/twiki/bin/view/CMSPublic/SUSYSummary2017

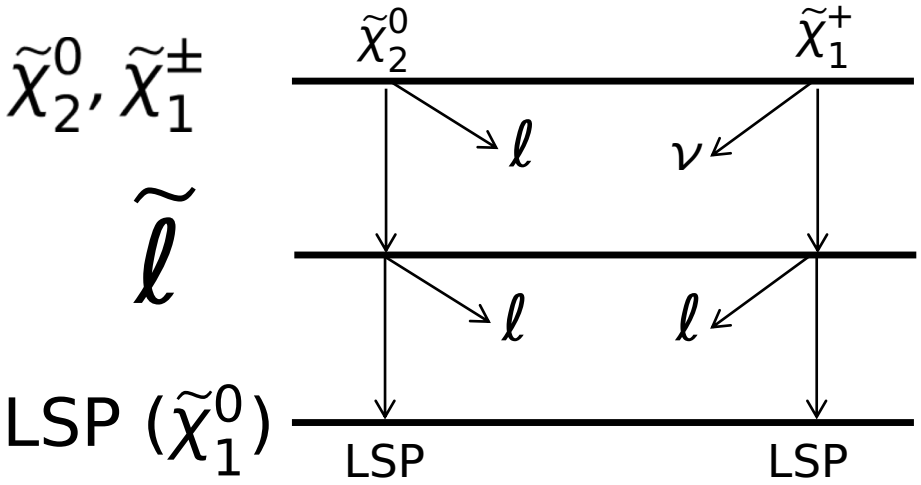
$pp \to \tilde{\chi}^0 \tilde{\chi}^+$ ($\widetilde{W}^0 \widetilde{W}^+$ or $\tilde{H}^0 \tilde{H}^+$); then?



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

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

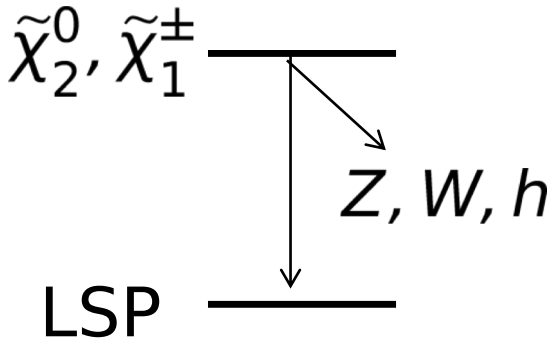
but *Z*-like leptons

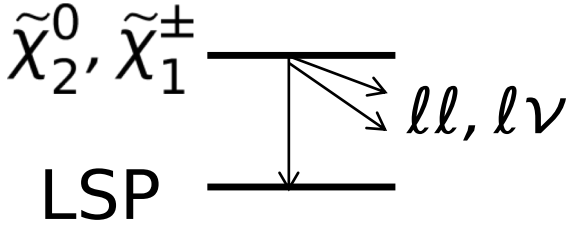


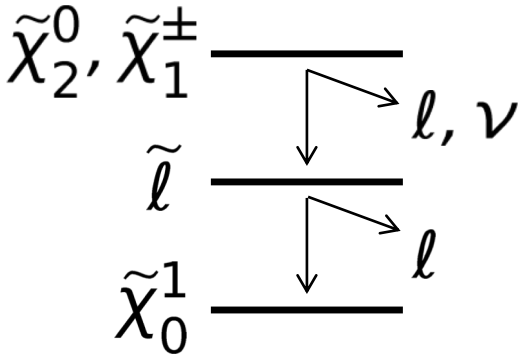
$\tilde{\chi}_2^0 \tilde{\chi}_1^+ \to 3\ell + \text{mET}$

Z-unlike

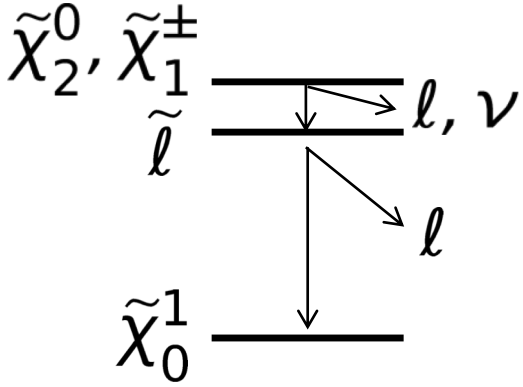
$pp \to \tilde{\chi}^0 \tilde{\chi}^+$ ($\widetilde{W}^0 \widetilde{W}^+$ or $\tilde{H}^0 \tilde{H}^+$); then?



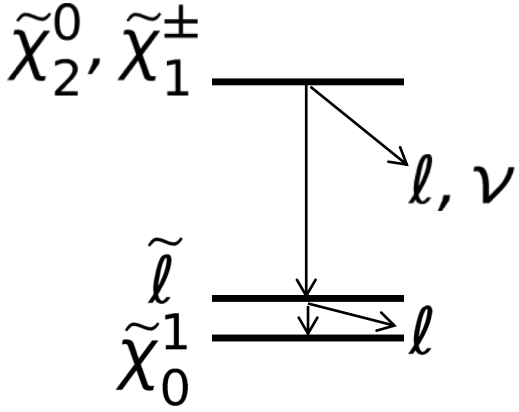




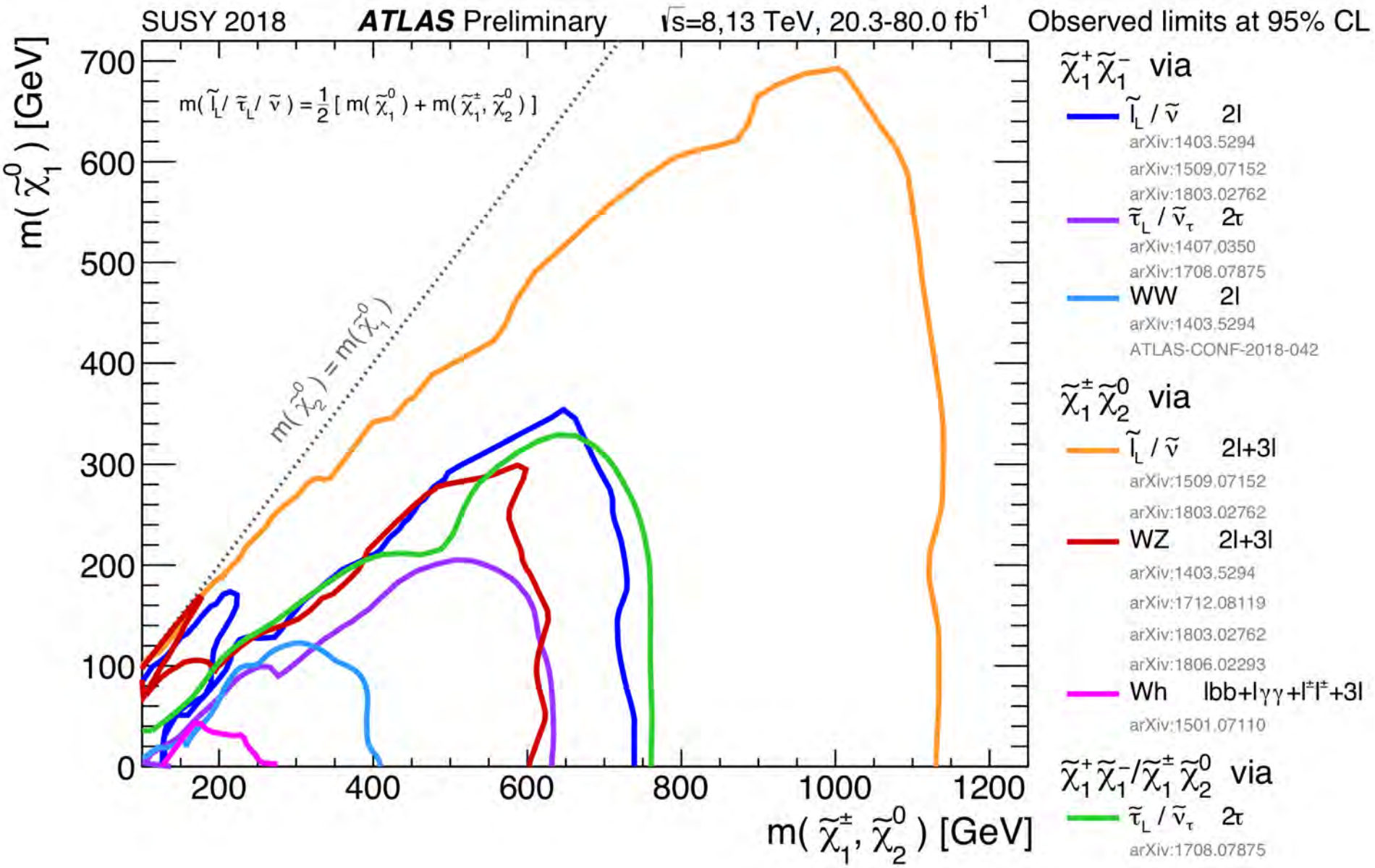
$x_\ell \sim 0.5$



$x_\ell \sim 1$



$x_\ell \sim 0$



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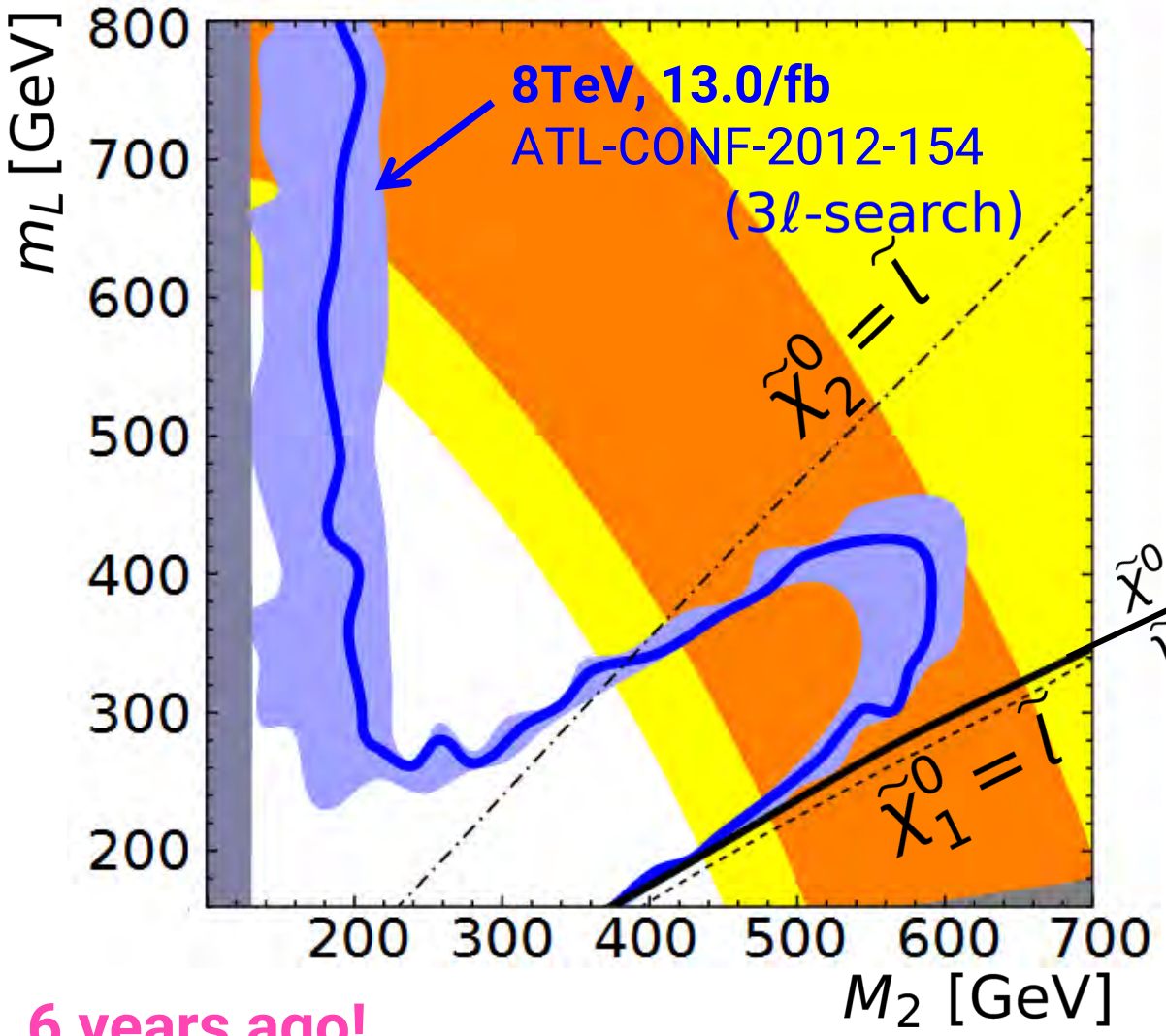
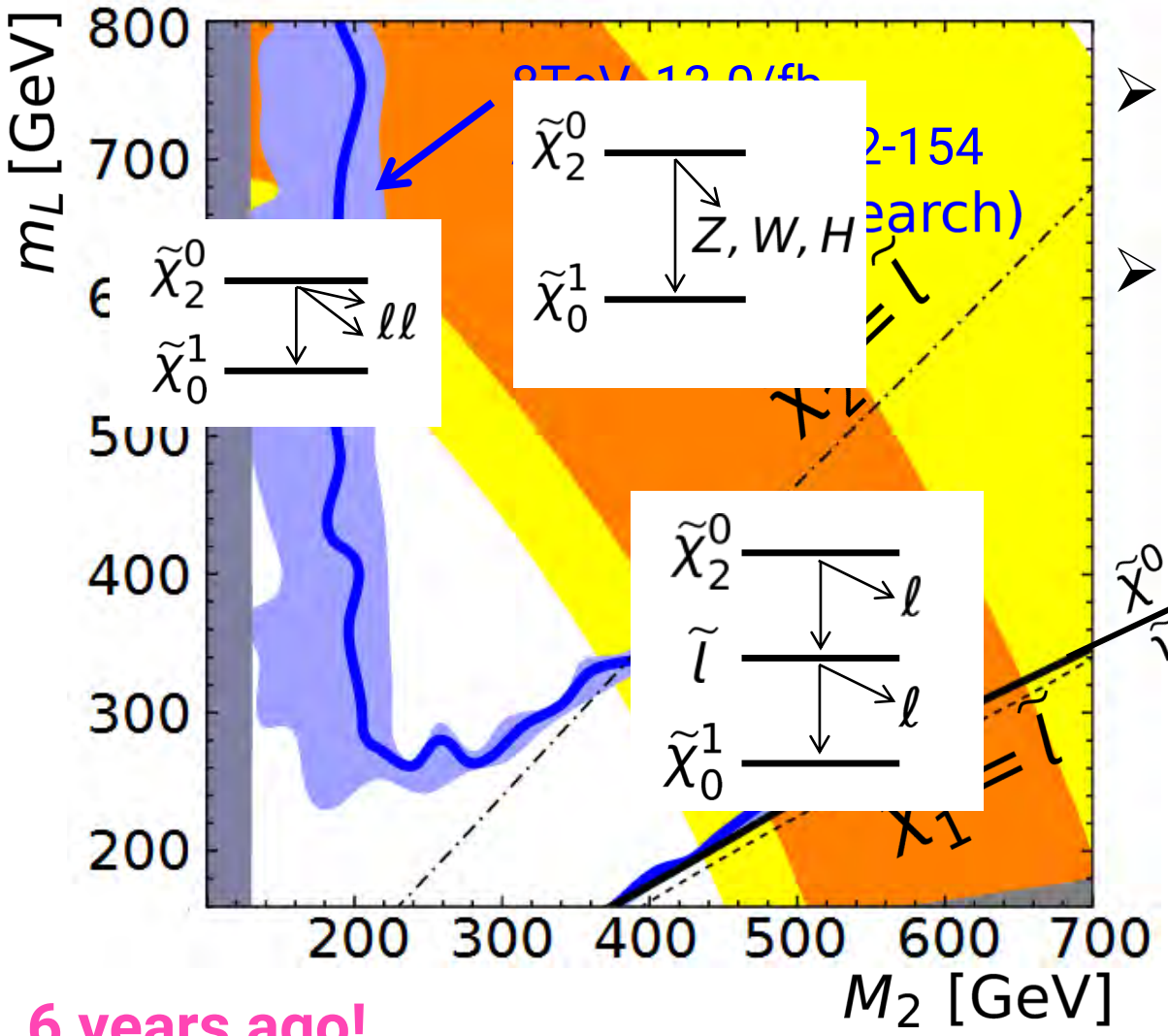


pMSSM w.
$\tilde{q}, \tilde{g}$-decoupled.

$\tilde{\ell}_R, \tilde{\tau}_L, \tilde{\tau}_R$ also decoupled.

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

6 years ago!



6 years ago!

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

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

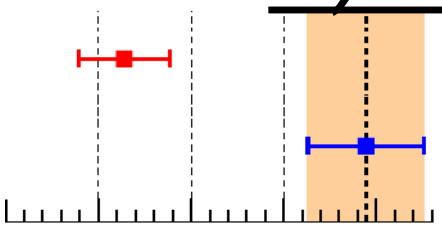
Backup

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

$a_\mu^{\rm SM} \simeq$ (5-loop) QED + (2^+-loop) W,Z,H + (dispersion rel.) had. vac. polarization + (low-energy EFT) had. light-by-light

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

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



$$a_\mu^{\rm SM} = (11\,659\,178.3 \pm 4.3) \times 10^{-10}$$
$$a_\mu^{\rm SM} = (11\,659\,209.2 \pm 6.3) \times 10^{-10} \quad \text{(BNL '04+CODATA '14)}$$

→ ±1.6 @ Fermilab in 1–2 year!

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 $g-2$ anomaly: What is the origin?

- Just a statistical fluctuation.
- Just an issue in the experiment.

we assume it is "actual".

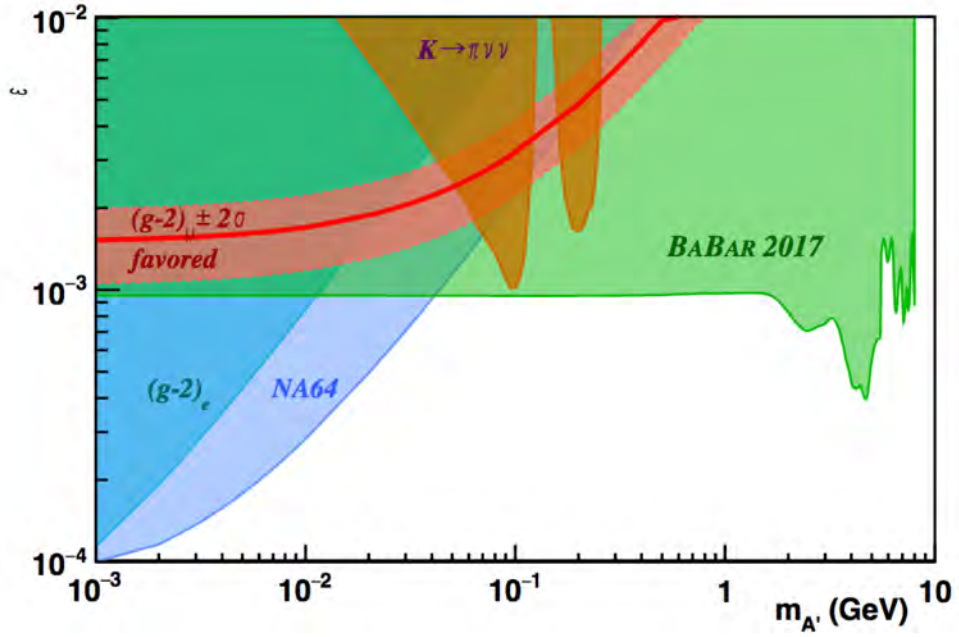
- $O(100)$ GeV particles with $O(0.1)$ couplings
  - KK gravition, MSSM
- keV–MeV particles with tiny couplings.
  - dark photon (extra U(1) gauge boson)

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

$m_{\rm new}$ ~200GeV

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

$m_{\rm new}$ 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 experiment.~~

we assume it is "actual".

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

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

$m_{\rm new}$ ~200GeV

  - MSSM

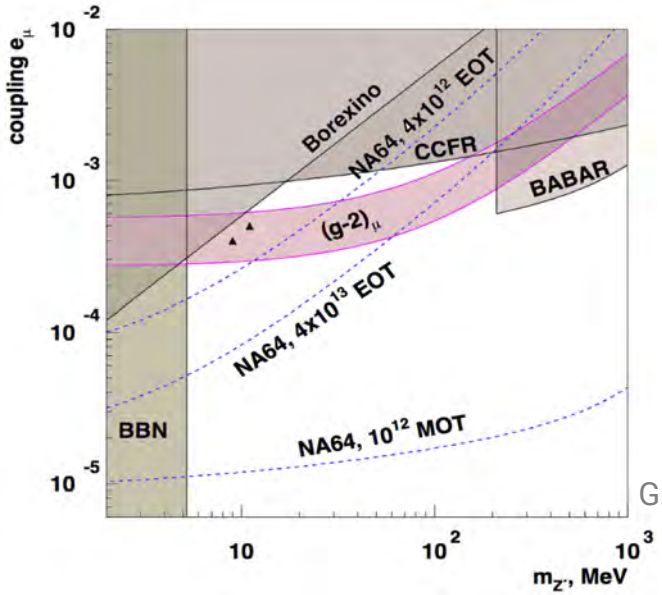
- keV–MeV particles with tiny couplings.

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

$m_{\rm new}$ keV–MeV

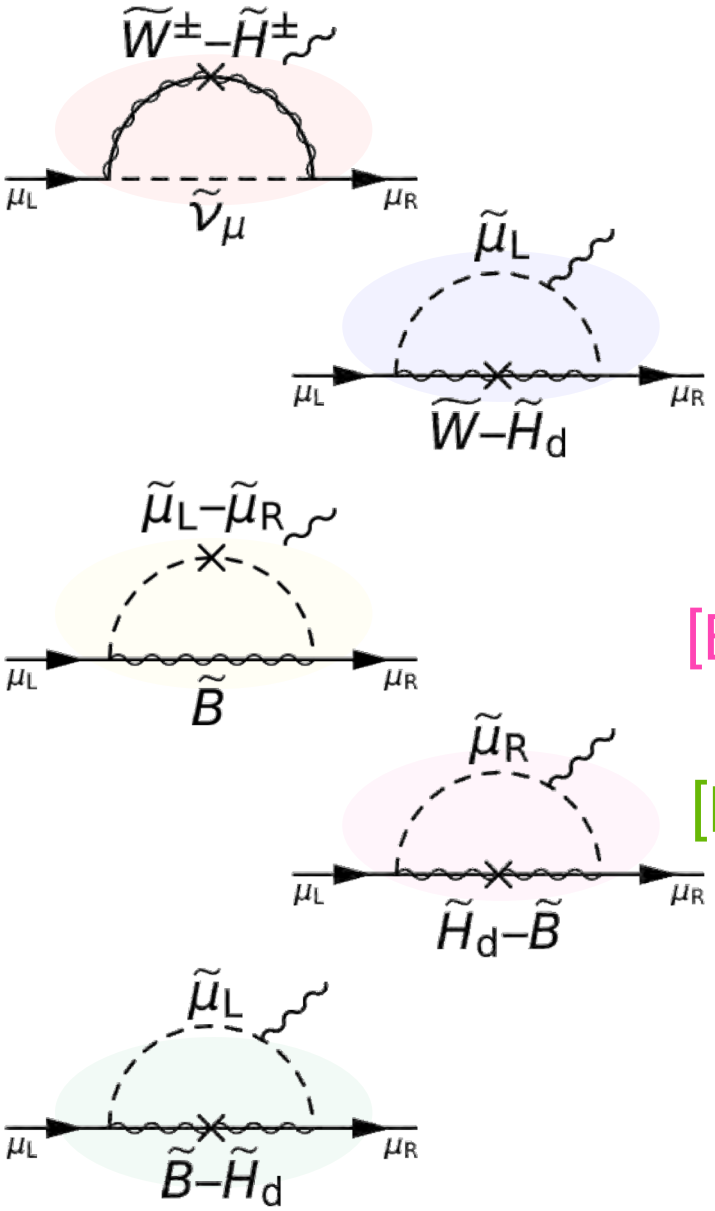
  - ~~dark photon (extra U(1) gauge boson)~~
  - extra $L_\mu - L_\tau$ gauge boson

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



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

Gninenko, Krasnikov [1801.10448]



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

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

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

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

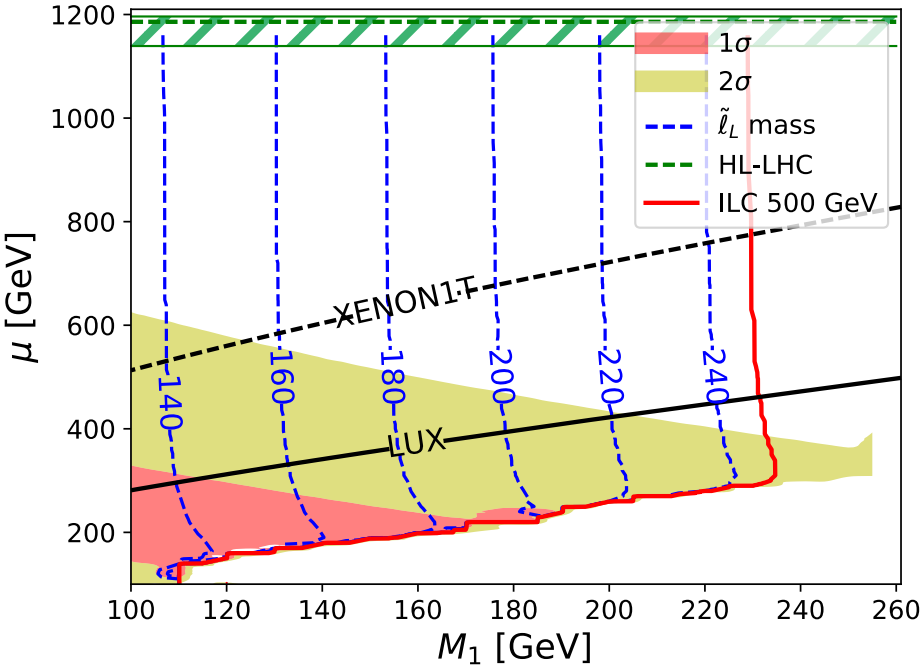
[BHL] $$\frac{g_Y^2 m_\mu^2}{16\pi^2}\frac{M_1\mu\tan\beta}{m^4_{\widetilde{\mu}_L}}\cdot F_b\left(\frac{M_1}{m_{\widetilde{\mu}_L}},\frac{\mu}{m_{\widetilde{\mu}_L}}\right)$$

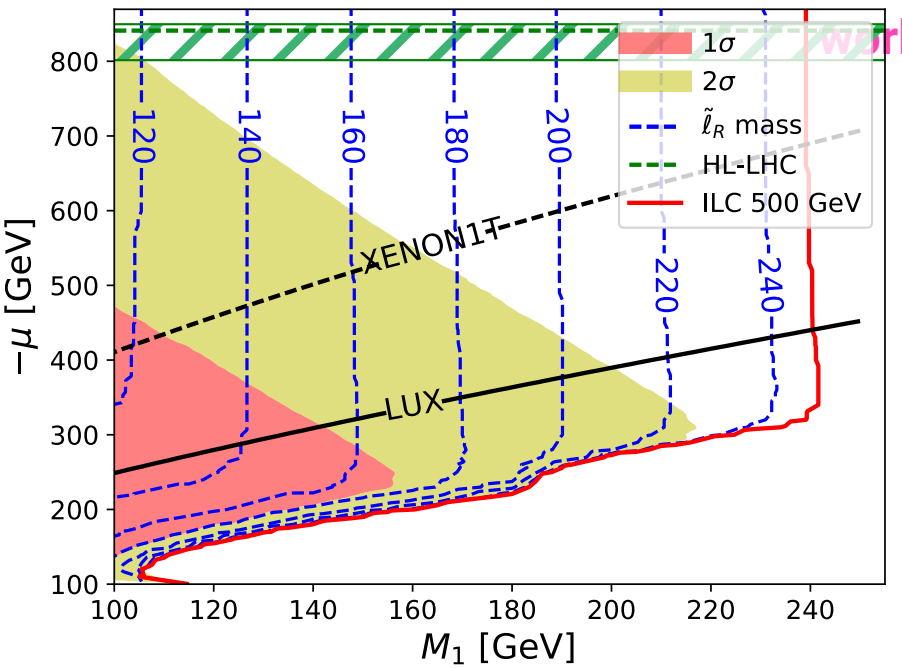
F_a, F_b are loop functions and positive.

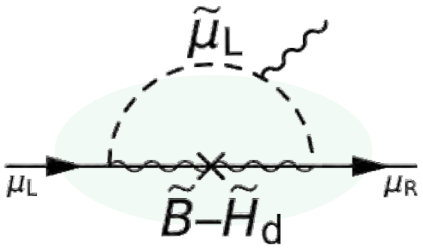
$$F_a(x,y)=\frac{1}{2}\frac{C_1(x^2)-C_1(y^2)}{x^2-y^2},\qquad F_b(x,y)=-\frac{1}{2}\frac{N_2(x^2)-N_2(y^2)}{x^2-y^2};$$

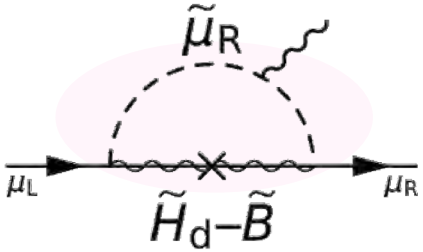
$$C_1(x)=\frac{3-4x+x^2+2\log x}{(1-x)^3},\qquad N_2(x)=\frac{1-x^2+2x\log x}{(1-x)^3}.$$

- 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, resonance. → future works



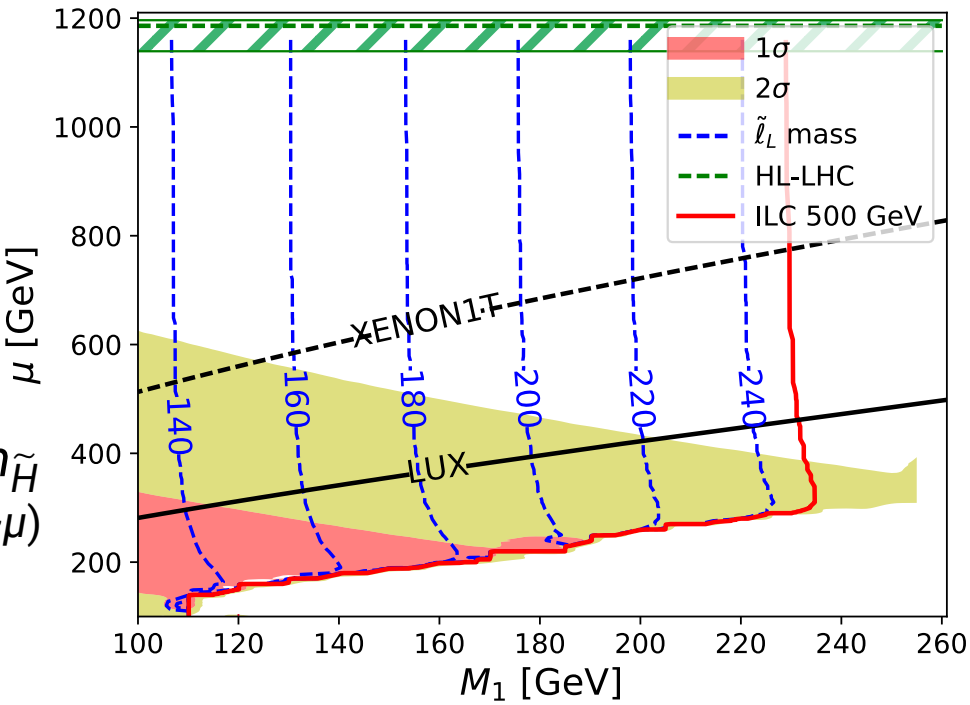






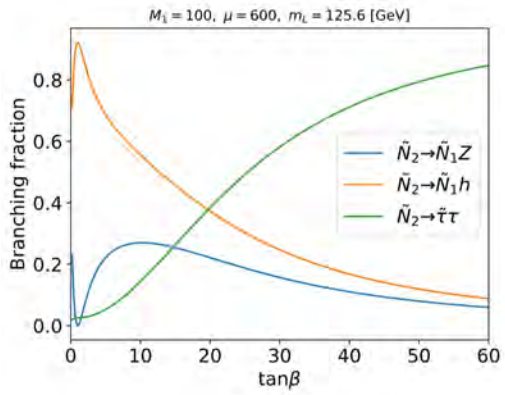
- Bino–slepton (stau) co-annihilation → $m_{\tilde{\nu}_\tau}$ (or $m_{\tilde{\tau}_R}$) $\simeq m_{\tilde{B}}$.
- We assumed:
  - slepton universality,
  - DM density is realized at each point in the plots.

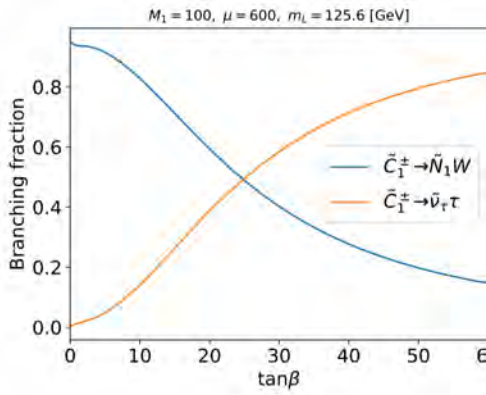
→ $m_{\tilde{B}} \simeq (m_{\tilde{\tau}_R} \text{ or } m_{\tilde{\nu}_\tau}) \lesssim m_{\tilde{\mu}} < m_{\tilde{H}}$
($\sim M_1$) ($\sim \mu$)

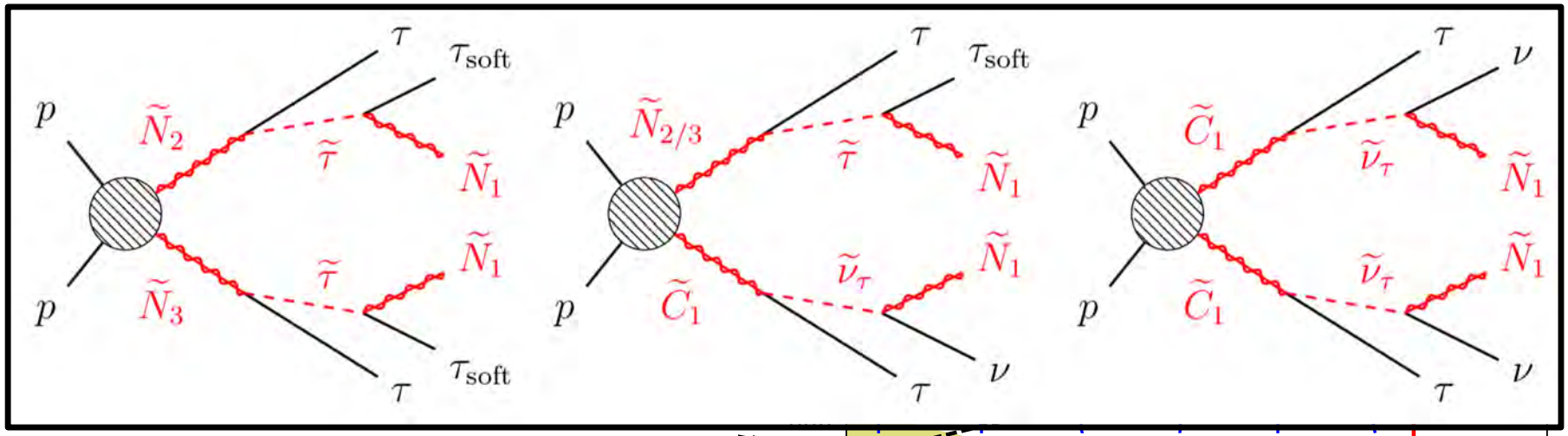


- HL-LHC?
  - $pp \to \tilde{H}^+\tilde{H}^0,\ \tilde{H}^+\tilde{H}^-$
  - $\tilde{H}^0 \to \tau\tilde{\tau},\ \tilde{H}^+ \to \tau\tilde{\nu}_\tau$ due to tanβ + mass spectrum

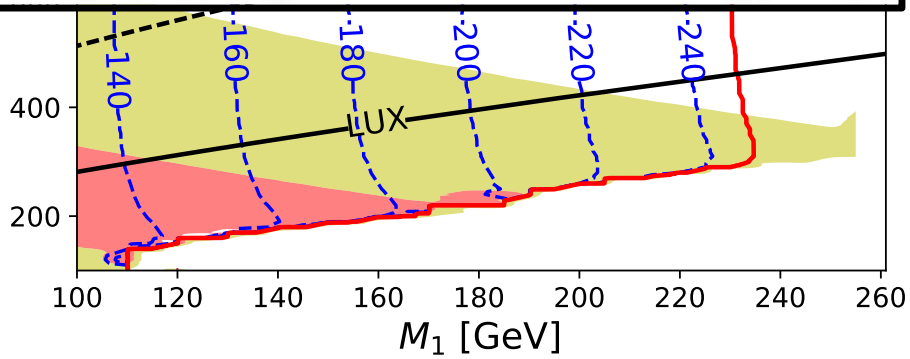
→ multi-tau signature



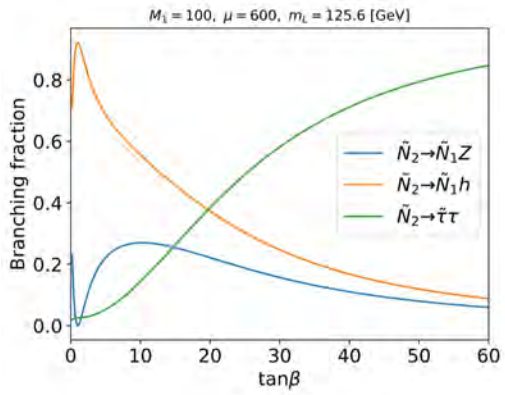


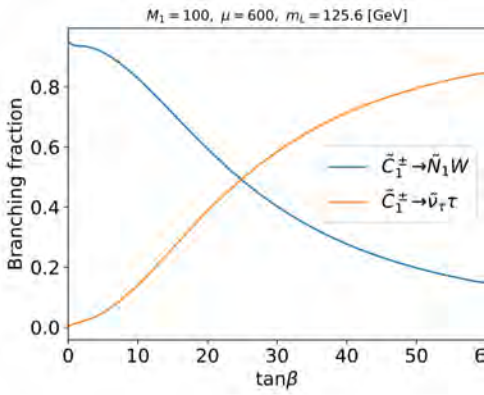


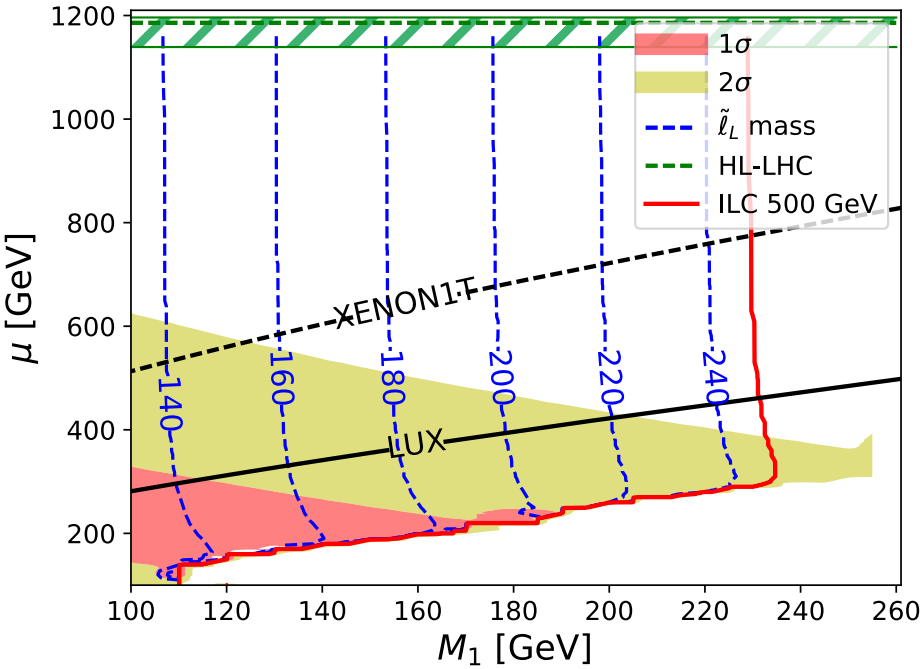
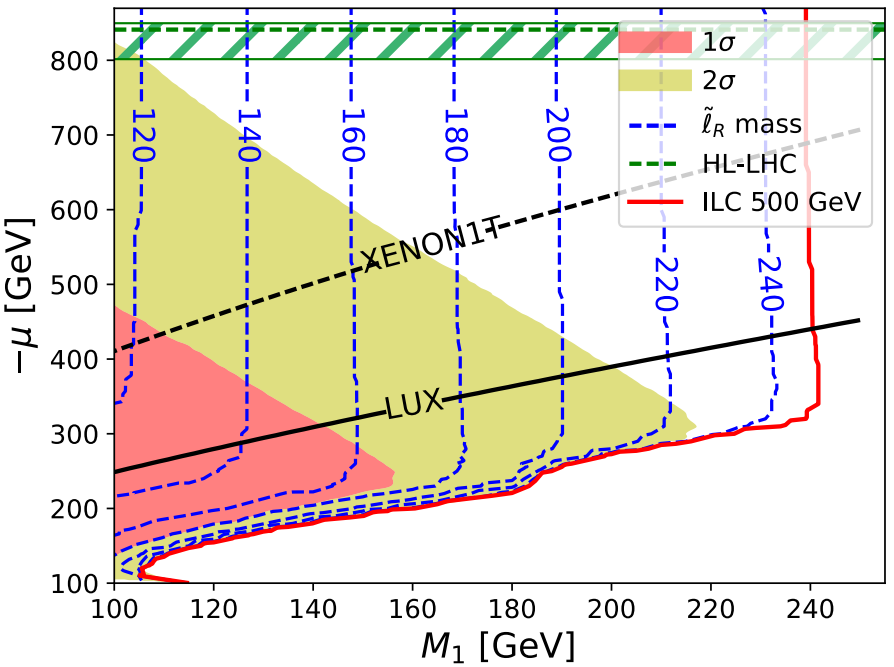
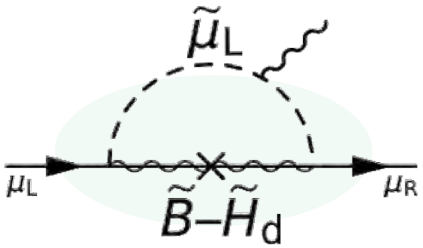
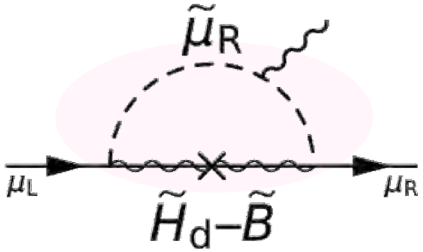
→ $m_{\widetilde{B}} \simeq (m_{\widetilde{\tau}_R} \text{ or } m_{\widetilde{\nu}_\tau}) \lesssim m_{\widetilde{\mu}} < m_{\widetilde{H}}$
($\sim M_1$) ($\sim \mu$)



- HL-LHC?
  - $pp \to \widetilde{H}^+\widetilde{H}^0,\ \widetilde{H}^+\widetilde{H}^-$
  - $\widetilde{H}^0 \to \tau\widetilde{\tau},\ \widetilde{H}^+ \to \tau\widetilde{\nu}_\tau$
    due to tanβ + mass spectrum
  - → multi-tau signature
    "2τ (+ soft) + missing"





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

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