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

(and models beyond the Standard Model)

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ELTE particle physics seminar @ ONLINE

Based on Endo, Hamaguchi, Iwamoto, Yanagi [1704.05287]

Endo, Hamaguchi, Iwamoto, Kitahara [2001.11025] [**2104**.03217],

Iwamoto, Yanagida, Yokozaki [**2104**.03223].

Executive Summary

- A mismatch* in the muon ***g*−2**
- can be **solved by SUSY**.
  - Large parameter space is not-yet constrained by experiments; waiting for future experiments (HL-LHC, XENONnT, ...).

- SUSY has a DM candidate: $\widetilde{\chi}_1^0$. However,
- if we try to explain the 4σ anomaly by SUSY, and if we assume $\widetilde{\chi}_1^0$ is
  - wino-like, then $\widetilde{\chi}_1^0$ will not* explain 100% of DM.
  - Higgsino-like, then $\widetilde{\chi}_1^0$ will not* explain 100% of DM.

    → additional DM or to give up *g*−2.
  - **bino-like**, then $\widetilde{\chi}_1^0$ can* explain 100% of **DM**.

    = SUSY solves DM and *g*−2! ... How about future experiments?

(*) Caveats are there; these are simplified statements.

1. Introduction

- Muon g−2 "anomaly"
- New physics for $(g-2)_\mu$

2. SUSY

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- How SUSY explains $(g-2)_\mu$: Four possibilities
- Scenario 1: "WHL for g-2" Endo, Hamaguchi, Iwamoto, Kitahara [2001.11025] Endo, Hamaguchi, Iwamoto, Kitahara [2104.03217]

3. SUSY and Dark Matter

- Neutralino dark matter with freeze-out
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- Scenario 3&4: "BHL and BHR for g-2" Endo, Hamaguchi, Iwamoto, Yanagi [1704.05287]

Extra) SUSY-breaking scenarios for g−2

Iwamoto, Yanagida, Yokozaki [2104.03223]

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Extra) SUSY-breaking scenarios for *g*−2

Iwamoto, Yanagida, Yokozaki [2104.03223]

Theory Predictions

"White paper" [2006.04822]

$$a_\mu^{\rm SM} = 11659181.0(4.3)\times 10^{-10}$$

BMWc [2002.12347v3]

$$a_\mu^{\text{HVP-LO}} = 707.5(5.5)\times 10^{-10}\ \text{[lattice]}$$

Mainz [2104.02632] (preliminary)

$$a_\mu^{\text{HLbL-LO}uds} = 10.7(1.5)\times 10^{-10}\ \text{[lattice]}$$

Measurements

Brookhaven Nat. Lab. [hep-ex/0602035]

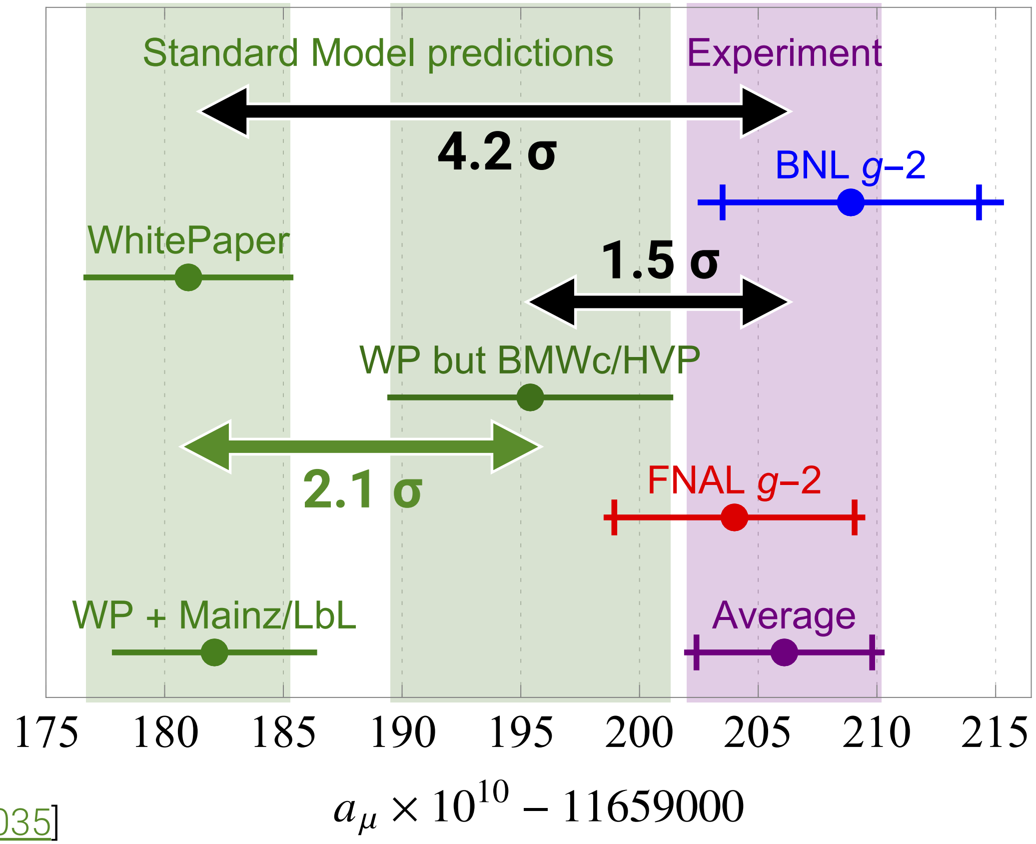
$$a_\mu^{\rm obs} = 11659208.9(5.4)_{\rm stat}(3.3)_{\rm sys}\times 10^{-10}$$

Fermilab [2104.03247]

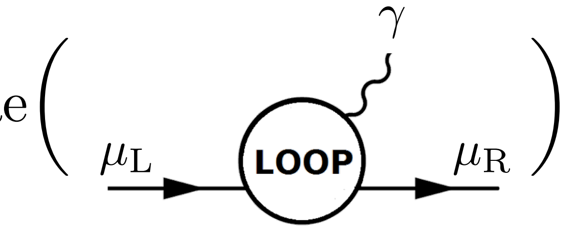
$$a_\mu^{\rm obs} = 11659204.0(5.1)_{\rm stat}(1.9)_{\rm sys}\times 10^{-10}$$

"Average"

$$a_\mu^{\rm obs} = 11659206.1(3.7)_{\rm stat}(1.8)_{\rm sys}\times 10^{-10}$$



Theory Predictions = calculate $a_\mu \equiv \dfrac{g_\mu - 2}{2} \equiv \mathrm{Re}\Big($



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2.1 σ tension

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to update

White paper values

QED:	11 658 471.9	(0.0)	
EW:	15.4	(0.1)	
HVP-LO:	693.1	(4.0)	[data-driven]
HVP-NLO:	−9.8	(0.1)	
HVP-NNLO:	1.2	(0.0)	
HLbL-LO*uds*:	8.9	(1.9)	[data-driven]
HLbL-LO*uds*:	7.9	(3.5)	[lattice]
HLbL-LO*c*:	0.3	(0.1)	
HLbL-NLO:	0.2	(0.1)	
	11 659 181.0	(4.3)	

in agreement

Measurements

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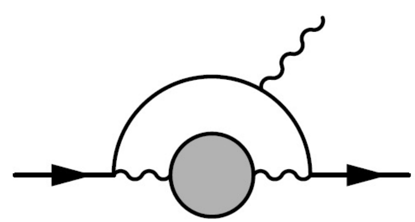
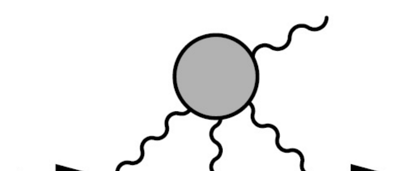


Hadronic Vacuum Polarization (LO)



Hadronic Light-by-Light (LO)

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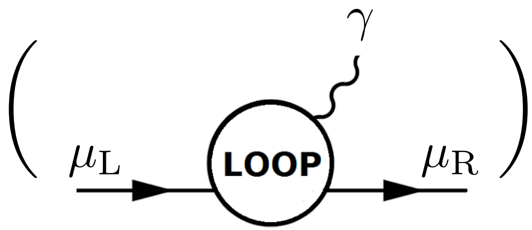

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WP but BMWc

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2.1 σ tension

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in agreement

in agreement (1.5 σ)

4.2 σ anomaly

... hint of physics beyond the SM? (SUSY?)

Measurements

"Average"

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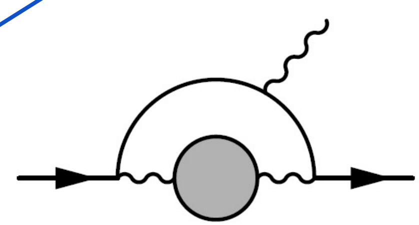

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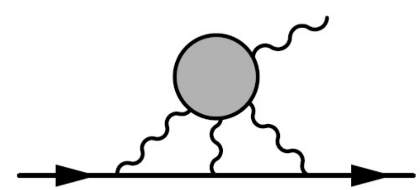
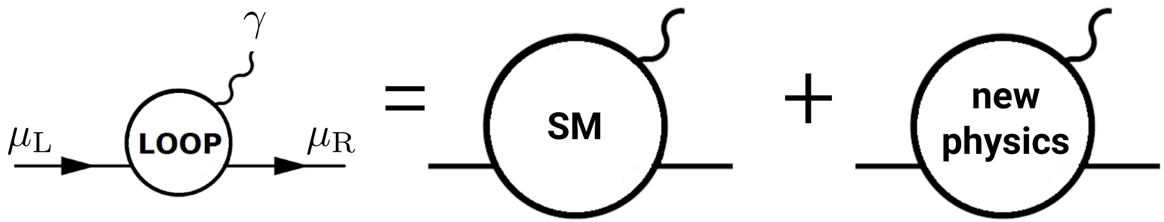


Hadronic Light-by-Light (LO)

- theory: WP $a_\mu^{\rm SM} = 11659181.0(4.3) \times 10^{-10}$
- experiment: average $a_\mu^{\rm obs} = 11659206.1(3.7)_{\rm stat}(1.8)_{\rm sys} \times 10^{-10}$

$$\Delta a_\mu \ (\text{WP}-\text{AVG}) = 25.1(5.9) \times 10^{-10} \ [4.2\,\sigma]$$

$a_\mu =$



???

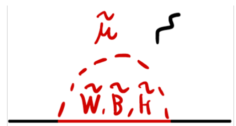
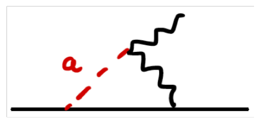
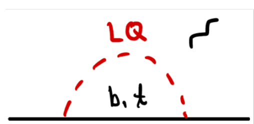
- $a_\mu^{\rm NP} > 0$ **(positive!)**
- $a_\mu^{\rm NP} \sim 10^{-9}$ → 0th order estimation:

$$a_\mu^{\rm NP} \sim \frac{m_\mu^2}{16\pi^2} \frac{(\text{new coupling})^2}{(\text{new mass})^2}$$

$$\Rightarrow \frac{\text{new mass}}{\text{new coupling}} \sim 150\,\text{GeV}$$

New physics interpretations

[Refs: Athron et al., 2104.03691; Buen-Abad et al., 2104.03267; Krnjaic et al., 1902.07715; Dermisek et al., 2103.05645]

NP type	diagrams	mass range	probe
Supersymmetry		200–500 GeV	$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to (h\tilde{\chi}_1^0)\,(W^\pm \tilde{\chi}_1^0)$ $pp \to \gamma\gamma \to \widetilde{\ell\ell^*}$
Scalar extensions		20–100 GeV, 150–250 GeV	$Z \to \tau^+\tau^-$ $h \to AA$
Axion-like particle		40 MeV – 6 GeV	$e^+e^- \to \gamma a, a \to \gamma\gamma$
Leptoquark		1.5–2 TeV	$pp \to \mathrm{LQ}\overline{\mathrm{LQ}}$
U(1) μ–τ		10–200 MeV	$e^+e^- \to \mu^+\mu^- Z'$ $K^- \to \mu^-\bar{\nu} Z'$
Vector-like lepton		< 7 TeV	$h, Z \to \mu^+\mu^-$

Precision measurement で探る新物理
北原鉄平 (名古屋大学 高等研究院/KMI): 高エネルギー将来計画委員会:第9回勉強会, 2021.4.22, オンライン

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slide courtesy of Teppei Kitahara

An example : $L\mu$−$L\tau$ gauge boson

Amaral, Cerdeno, Cheek, Foldenauer [2104.03297]

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

	$U(1)_Y$	"$L_\mu - L_\tau$"		
Q_L	1/6	0		
U_R	2/3	0		
D_R	−1/3	0		
L_L	−1/2	0	ε	−ε
E_R	−1	0	ε	−ε
B	✓			
Z'		✓		
H	1/2	0		

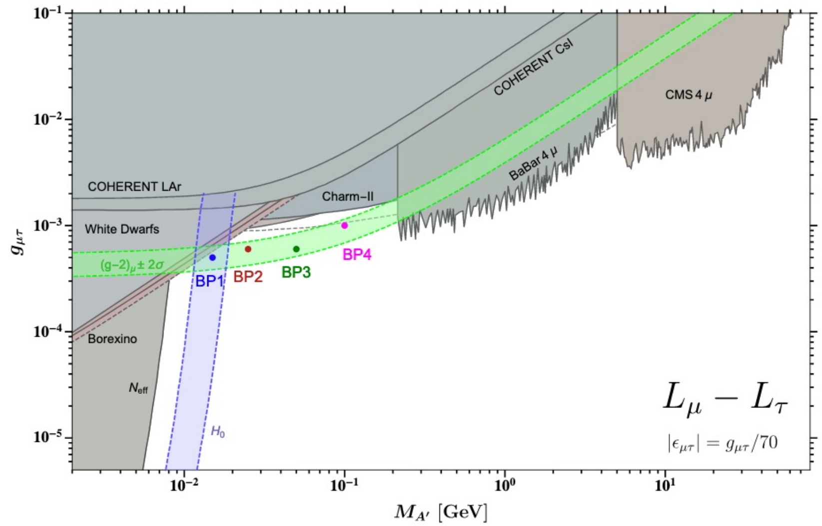

FIG. 1. Current constraints on the parameter space of the gauge boson of a minimal $U(1)_{L_\mu - L_\tau}$ gauge group from $N_{\rm eff}$ [35], Borexino [52], white dwarf cooling [59], COHERENT CsI [51] and LAr [52], neutrino tridents (Charm-II) [60, 61] and BaBar [62] and CMS [63] 4μ searches in grey. We show the neutrino trident constraint from CCFR as a grey dashed line, since some backgrounds have not been properly taken into account [47]. The corresponding plot for a simplified $U(1)_{L_\mu}$ with the same kinetic mixing looks exactly the same with the exception of the BaBar and CMS 4μ limits, which are slightly shifted towards smaller couplings by a factor $\sqrt{{\rm BR}^{\mu-\tau}_{A'\to\mu\mu}/{\rm BR}^{\mu}_{A'\to\mu\mu}} \approx 0.87$ (0.71) below (above) the ditau threshold due to the increased branching ratio of the L_μ boson to muons. The green band shows the region favoured at 2σ by the recent confirmation of the $(g-2)_\mu$ excess by the E989 experiment [1]. The blue band shows the region favoured by H_0 [35]. For illustrative purposes we also show the four benchmark points BP1 - BP4 used for analysis in this work.

U(1) μ−τ

10–200 MeV

$e^+e^- \to \mu^+\mu^- Z'$

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$$\frac{\text{new mass}}{\text{new coupling}} \sim \frac{100\,\text{MeV}}{10^{-3}} \sim 150\,\text{GeV}$$

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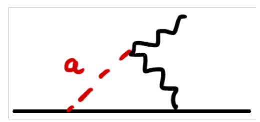
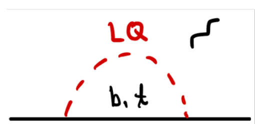
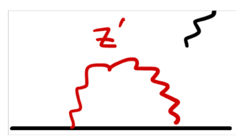
Axion-like particle		40 MeV – 6 GeV	$e^+e^- \to \gamma a, a \to \gamma\gamma$
Leptoquark		1.5–2 TeV	$pp \to \mathrm{LQ}\overline{\mathrm{LQ}}$
U(1) μ−τ		10–200 MeV	$e^+e^- \to \mu^+\mu^- Z'$ $K^- \to \mu^-\bar{\nu}Z'$
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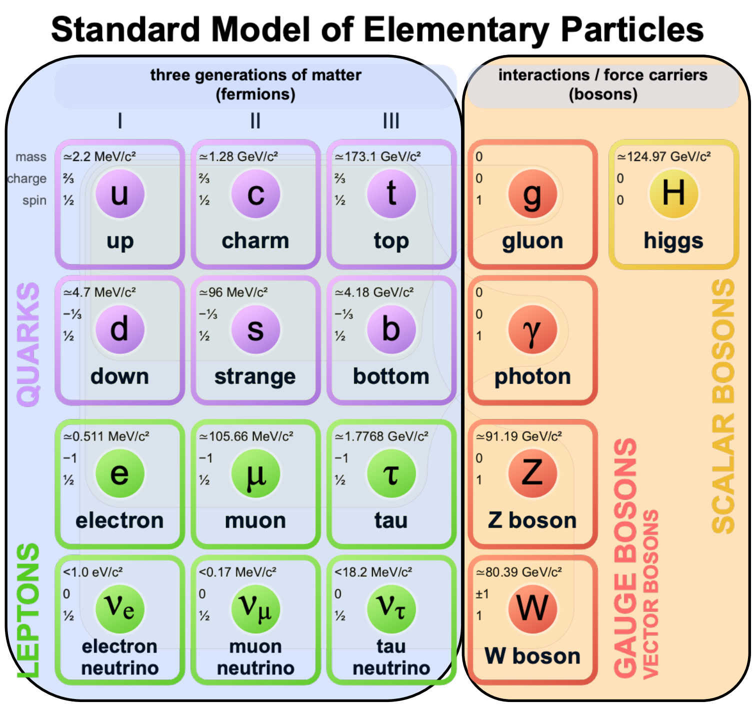
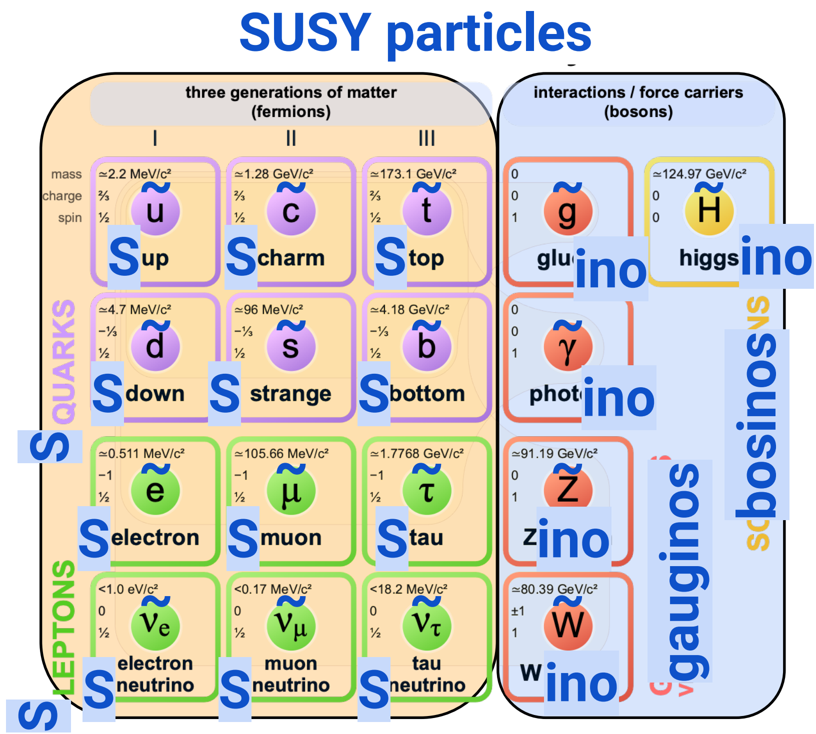
- SUSY = **super**symmetry ... **boson** ⇔ **fermion**
  - extra bosons: **s**quarks & **s**leptons
  - extra fermions: higgs**ino**s & gaug**ino**s



SM fermions SM bosons

⇔



extra bosons (squarks/sleptons) extra fermions (higgsinos, gauginos)

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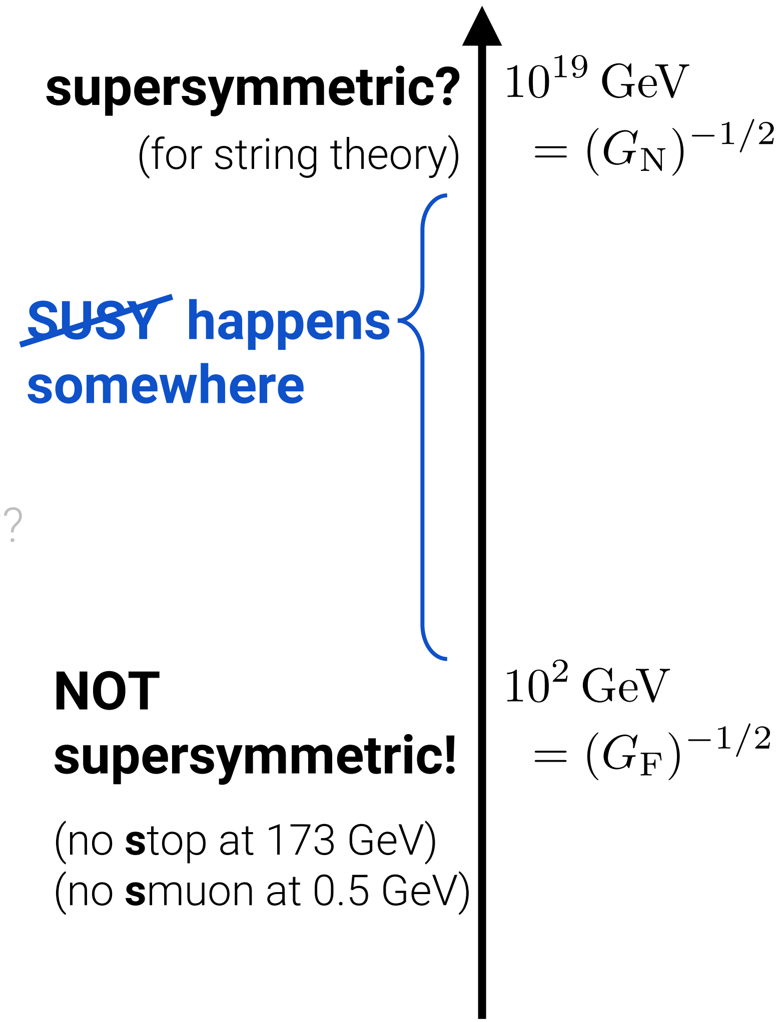
- Why SUSY?
  - "superstring theory" at 10^{19} GeV

- Why TeV-scale SUSY?

  i.e., why $M_{\text{SUSY}} \sim 10^3\,\text{GeV}$ $(m_{\text{sparticles}} \sim 10^3\,\text{GeV})$??
  - naturalness
  - gauge-coupling unification
  - muon $g-2$
  - dark matter



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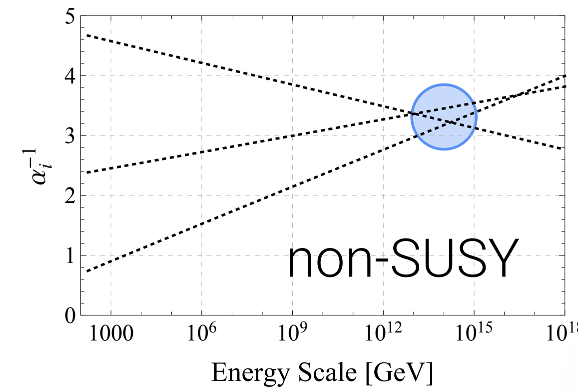
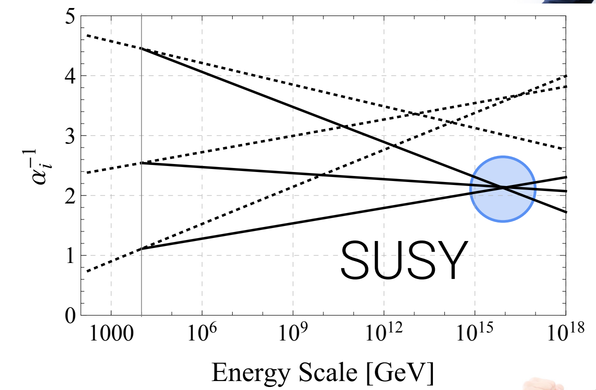
  - muon g−2 → next slides
  - dark matter → postpone to next section





■ **Minimal** Supersymmetric Standard Model [MSSM]

➢ extra bosons: **s**quarks & **s**leptons & extra Higgs bosons (H^0, H^+, H^-, A^0)

- squarks $\widetilde{u}_{1\text{–}6} \simeq (\widetilde{u}_\mathrm{L}, \widetilde{u}_\mathrm{R}, \widetilde{c}_\mathrm{L}, \widetilde{c}_\mathrm{R}, \widetilde{t}_1, \widetilde{t}_2)$

  $\widetilde{d}_{1\text{–}6} \simeq (\widetilde{d}_\mathrm{L}, \widetilde{d}_\mathrm{R}, \widetilde{s}_\mathrm{L}, \widetilde{s}_\mathrm{R}, \widetilde{b}_1, \widetilde{b}_2)$

- sleptons $\widetilde{e}_{1\text{–}6} \simeq (\widetilde{e}_\mathrm{L}, \widetilde{e}_\mathrm{R}, \widetilde{\mu}_\mathrm{L}, \widetilde{\mu}_\mathrm{R}, \widetilde{\tau}_1, \widetilde{\tau}_2)$

  $\widetilde{\nu}_{1\text{–}3} \simeq (\widetilde{\nu}_e, \widetilde{\nu}_\mu, \widetilde{\nu}_\tau)$


"minimal"...

➢ extra fermions: higgs**ino**s & gaug**ino**s

- higgsinos $(\widetilde{H}^0_\mathrm{d}, \widetilde{H}^0_\mathrm{u}, \widetilde{H}^\pm)$
- bino / winos / gluino $\widetilde{B}$ / $(\widetilde{W}^0, \widetilde{W}^\pm)$ / $\widetilde{g}$

We only consider this "MSSM" in the following discussion.

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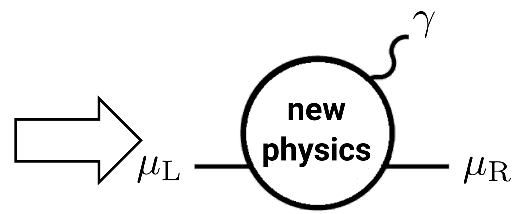

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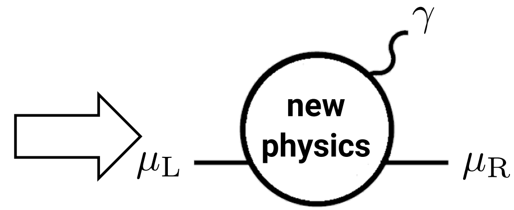
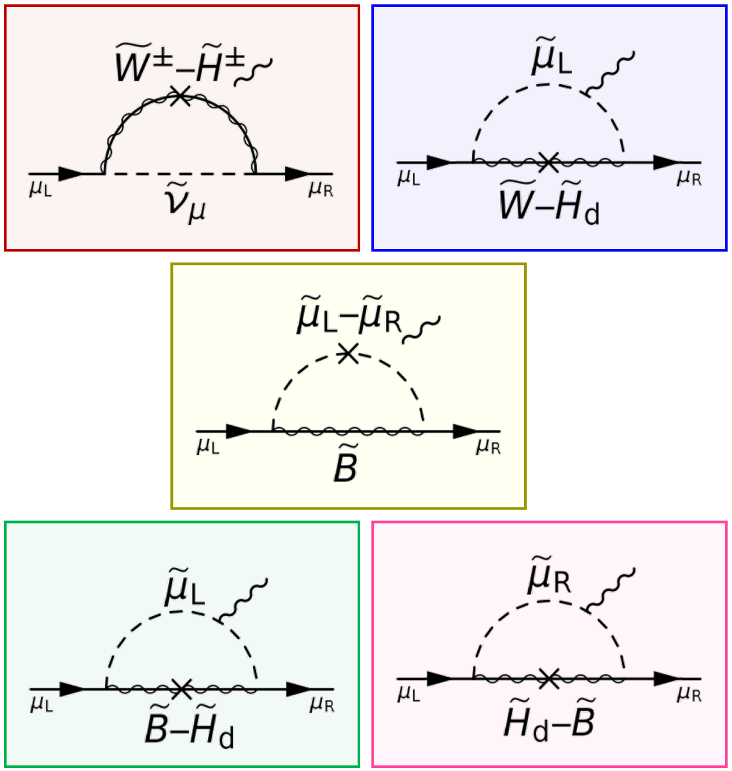
➢ extra fermions: higgs**ino**s & gaug**ino**s

- higgsinos $(\tilde{H}^0_\mathrm{d}, \tilde{H}^0_\mathrm{u}, \tilde{H}^\pm)$
- bino / winos / gluino $\tilde{B}$ / $(\tilde{W}^0, \tilde{W}^\pm)$ / $\tilde{g}$



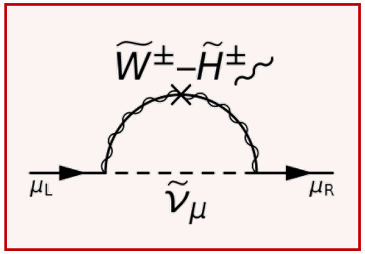
5 diagrams at the 1-loop level

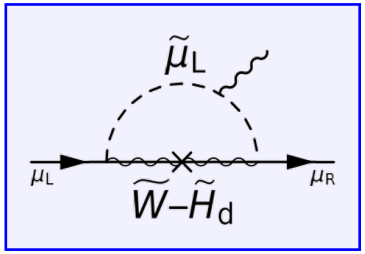


Lopez, Nanopoulos, Wang [ph/9308336]
Chattopadhyay, Nath [ph/9507386]
Moroi [ph/9512396]
(cf. Cho et al. [1104.1769])

1) WHL scenario

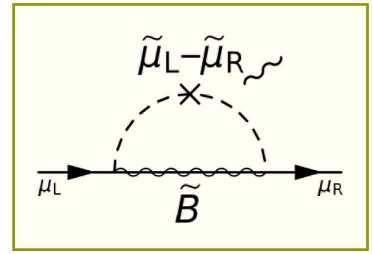
SU(2) symmetric... always in similar size.





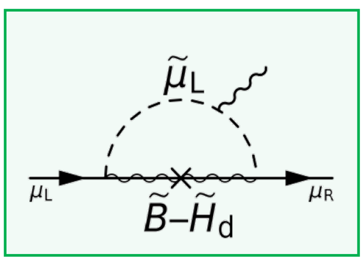
$$a_\mu^{\rm WHL} = \frac{\alpha_2}{4\pi}\frac{m_\mu^2}{M_2\mu}\tan\beta\cdot f_C\left(\frac{M_2^2}{m_{\tilde{\nu}_\mu}^2}, \frac{\mu^2}{m_{\tilde{\nu}_\mu}^2}\right) - \frac{\alpha_2}{8\pi}\frac{m_\mu^2}{M_2\mu}\tan\beta\cdot f_N\left(\frac{M_2^2}{m_{\tilde{\mu}_L}^2}, \frac{\mu^2}{m_{\tilde{\mu}_L}^2}\right)$$

2) BLR scenario



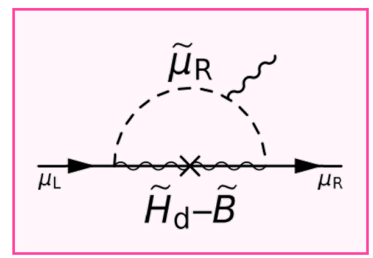
$$a_\mu^{\rm BLR} = \frac{\alpha_Y}{4\pi}\frac{m_\mu^2 M_1\mu}{m_{\tilde{\mu}_L}^2 m_{\tilde{\mu}_R}^2}\tan\beta\cdot f_N\left(\frac{m_{\tilde{\mu}_L}^2}{M_1^2}, \frac{m_{\tilde{\mu}_R}^2}{M_1^2}\right)$$

3) BHL scenario



$$a_\mu^{\rm BHL} = \frac{\alpha_Y}{8\pi}\frac{m_\mu^2}{M_1\mu}\tan\beta\cdot f_N\left(\frac{M_1^2}{m_{\tilde{\mu}_L}^2}, \frac{\mu^2}{m_{\tilde{\mu}_L}^2}\right)$$

4) BHR scenario



$$a_\mu^{\rm BHR} = -\frac{\alpha_Y}{4\pi}\frac{m_\mu^2}{M_1\mu}\tan\beta\cdot f_N\left(\frac{M_1^2}{m_{\tilde{\mu}_R}^2}, \frac{\mu^2}{m_{\tilde{\mu}_R}^2}\right)$$

$$f_C(x,y) = xy\left[\frac{5-3(x+y)+xy}{(x-1)^2(y-1)^2} - \frac{2\ln x}{(x-y)(x-1)^3} + \frac{2\ln y}{(x-y)(y-1)^3}\right]$$

$$f_N(x,y) = xy\left[\frac{-3+x+y+xy}{(x-1)^2(y-1)^2} + \frac{2x\ln x}{(x-y)(x-1)^3} - \frac{2y\ln y}{(x-y)(y-1)^3}\right].$$

1. Introduction

- muon g−2 "anomaly"
- New physics for $(g-2)_\mu$

2. SUSY

- Why SUSY?
- How MSSM explains $(g-2)_\mu$: **Four** possibilities
- Scenario 1: "WHL for g-2" — Endo, Hamaguchi, Iwamoto, Kitahara [2001.11025]; Endo, Hamaguchi, Iwamoto, Kitahara [2104.03217]

3. MSSM and Dark Matter

- Neutralino dark matter with freeze-out
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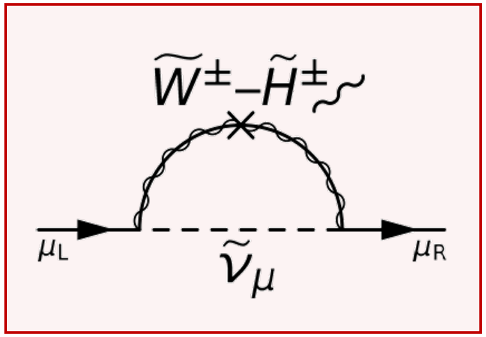
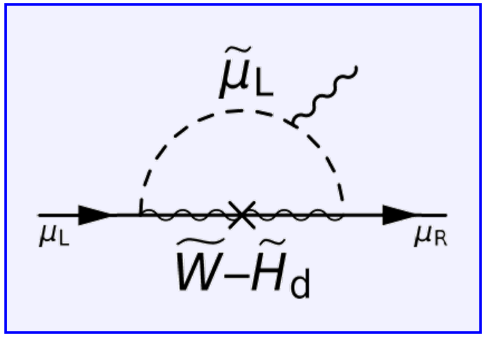
- Scenario 3&4: "BHL and BHR for g-2" — Endo, Hamaguchi, Iwamoto, Yanagi [1704.05287]

Extra) SUSY-breaking scenarios for *g*−2

Iwamoto, Yanagida, Yokozaki [2104.03223]

1) **W**ino–**H**iggsino–**L**eft-smuon scenario





$$a_\mu^{\rm WHL} = \frac{\alpha_2}{4\pi}\frac{m_\mu^2}{M_2\mu}\tan\beta\cdot f_C\left(\frac{M_2^2}{m_{\tilde\nu_\mu}^2},\frac{\mu^2}{m_{\tilde\nu_\mu}^2}\right) - \frac{\alpha_2}{8\pi}\frac{m_\mu^2}{M_2\mu}\tan\beta\cdot f_N\left(\frac{M_2^2}{m_{\tilde\mu_{\rm L}}^2},\frac{\mu^2}{m_{\tilde\mu_{\rm L}}^2}\right)$$

- tend to be larger (for similar sparticle mass) because $\alpha_2 > \alpha_Y$.
- $a_\mu^{\rm NP} > 0$ if "mu-parameter" is positive.
- **W**ino, **H**iggsino, and **L**eft-smuons should be $\lesssim$ 1 TeV.

→ **LHC search?**

$$a_\mu^{\rm BLR} = \frac{\alpha_Y}{4\pi}\frac{m_\mu^2 M_1\mu}{m_{\tilde\mu_{\rm L}}^2 m_{\tilde\mu_{\rm R}}^2}\tan\beta\cdot f_N\left(\frac{m_{\tilde\mu_{\rm L}}^2}{M_1^2},\frac{m_{\tilde\mu_{\rm R}}^2}{M_1^2}\right)$$

$$a_\mu^{\rm BHL} = \frac{\alpha_Y}{8\pi}\frac{m_\mu^2}{M_1\mu}\tan\beta\cdot f_N\left(\frac{M_1^2}{m_{\tilde\mu_{\rm L}}^2},\frac{\mu^2}{m_{\tilde\mu_{\rm L}}^2}\right)$$

$$a_\mu^{\rm BHR} = -\frac{\alpha_Y}{4\pi}\frac{m_\mu^2}{M_1\mu}\tan\beta\cdot f_N\left(\frac{M_1^2}{m_{\tilde\mu_{\rm R}}^2},\frac{\mu^2}{m_{\tilde\mu_{\rm R}}^2}\right)$$

 Endo, Hamaguchi, Iwamoto, Kitahara [2104.03217]

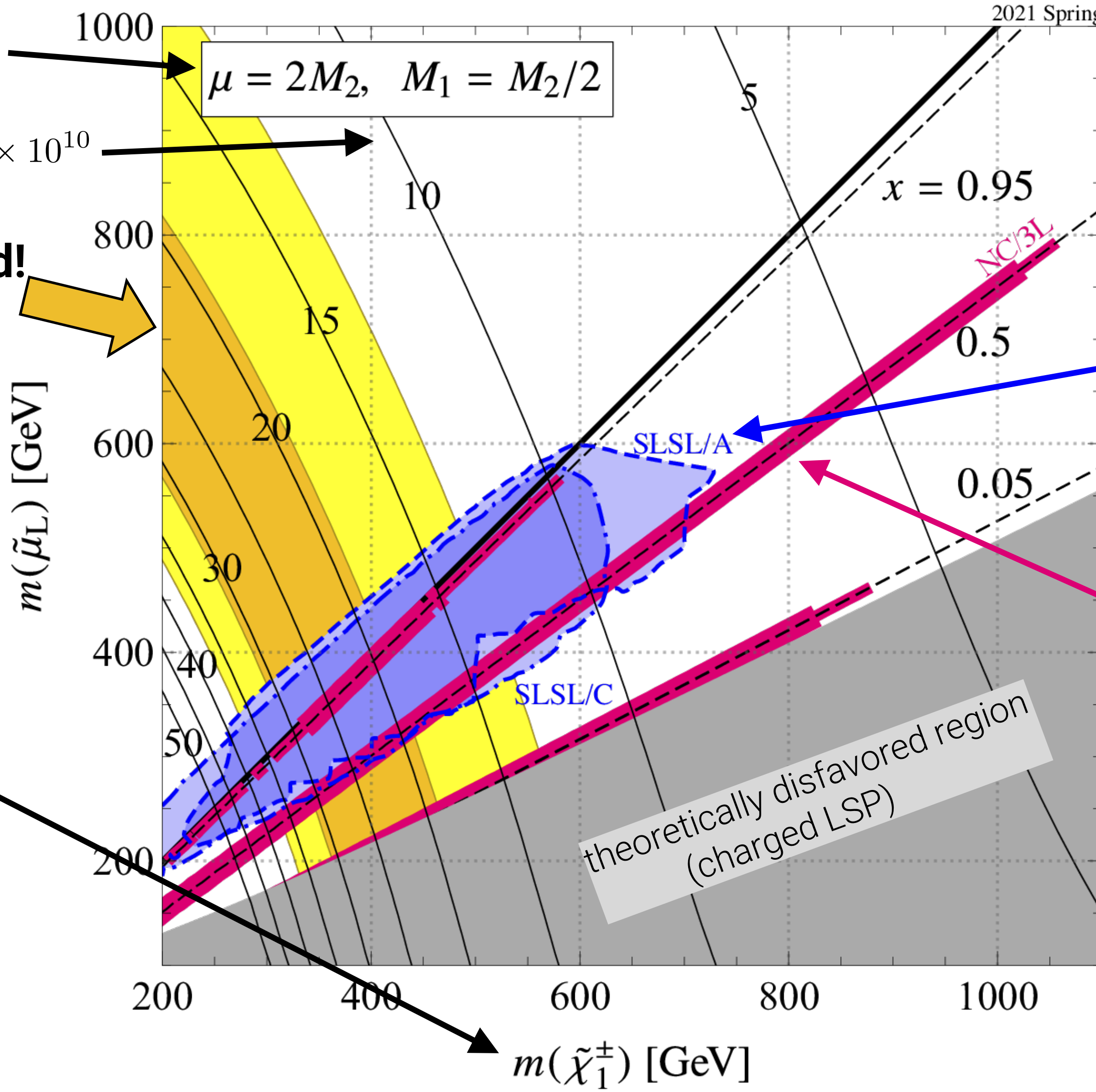
fixed parameters

contours: $a_\mu^{\text{MSSM}} \times 10^{10}$

anomaly solved!
[1σ / 2σ levels]

Slep**L** mass

Something like
Wino mass

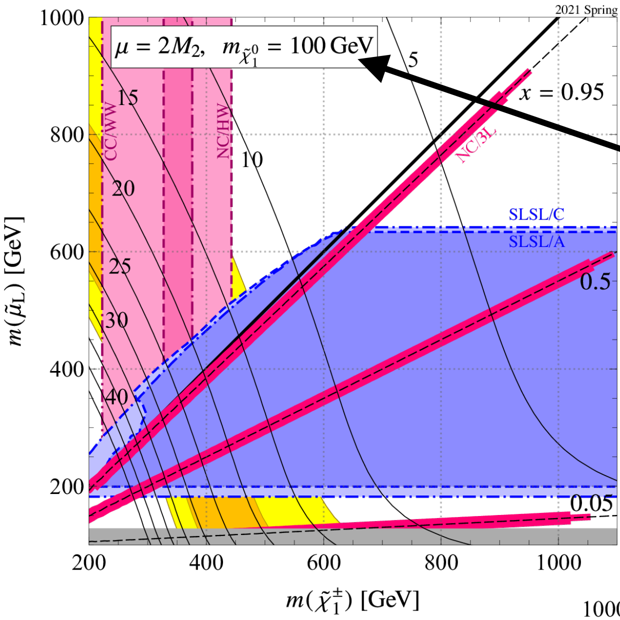


Excluded by LHC
(slepton searches
by **A**TLAS/**C**MS)

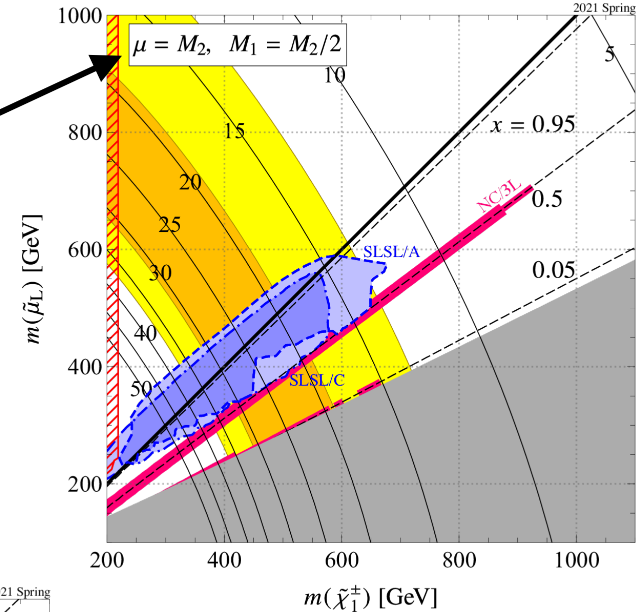
Excluded by LHC
(CMS Wino search)

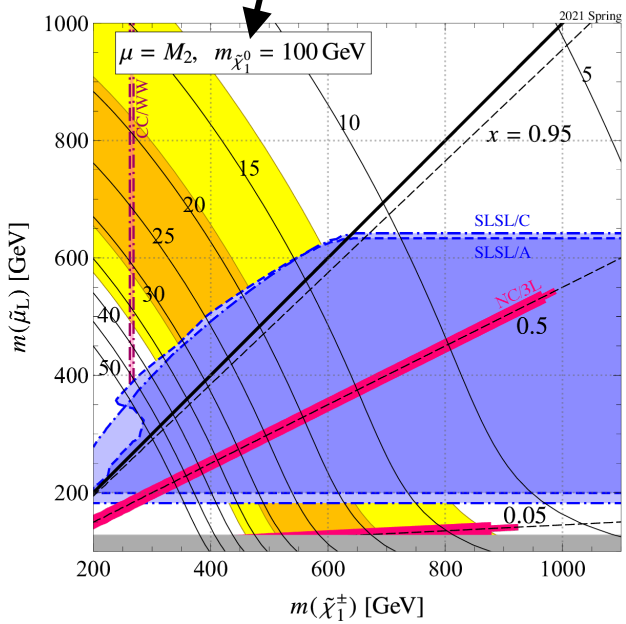
[three lines to be joined]

Conclusion 1: MSSM can (still) explain the anomaly!



different
parameters





Conclusion 1: MSSM can (still) explain the anomaly!

- MSSM has 6 important parameters for $g-2$:

  $\tan\beta := \langle H_\mathrm{u}\rangle/\langle H_\mathrm{d}\rangle$ → fixed to 40.

  $M_1 \approx \widetilde{B}$-mass, $\mu \approx \widetilde{H}$-mass } varied among 4 figs.

  $M_2 \approx \widetilde{W}$-mass, $m_\mathrm{L}^2 \approx \widetilde{l}_\mathrm{L}$-mass } axes.

  $m_\mathrm{R}^2 \approx \widetilde{l}_\mathrm{R}$-mass → assumed heavy (1 TeV).

$$a_\mu^\mathrm{WHL} = \frac{\alpha_2}{4\pi}\frac{m_\mu^2}{M_2\mu}\tan\beta\cdot f_C\left(\frac{M_2^2}{m_{\widetilde{\nu}_\mu}^2}, \frac{\mu^2}{m_{\widetilde{\nu}_\mu}^2}\right) - \frac{\alpha_2}{8\pi}\frac{m_\mu^2}{M_2\mu}\tan\beta\cdot f_N\left(\frac{M_2^2}{m_{\widetilde{\mu}_\mathrm{L}}^2}, \frac{\mu^2}{m_{\widetilde{\mu}_\mathrm{L}}^2}\right)$$

  - Lepton universality maintained. $(\widetilde{e}\approx\widetilde{\mu}\approx\widetilde{\tau})$
  - Other particle masses are also set "heavy". [squarks, gluino, extra Higgses]

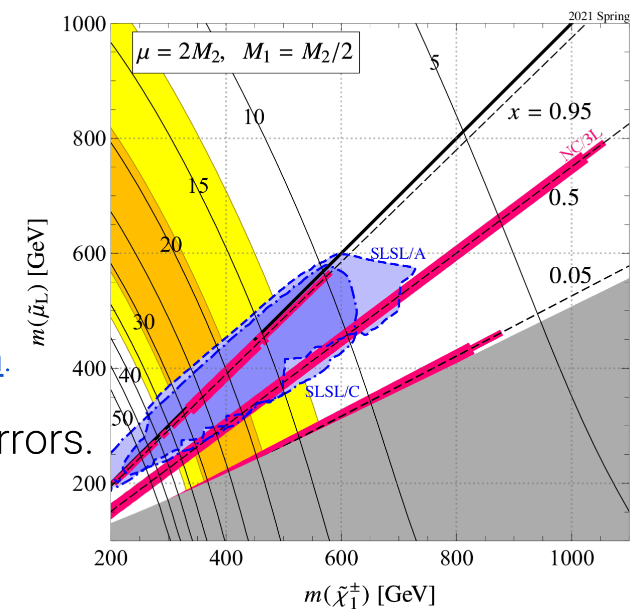
- LHC bounds are recasted analytically.

  [their result] ⊗ [cross section reduction] ⊗ [Branching factor]

  They use "simplified models."

  Realistic models will have different production rate & complicated decay pattern.

  - No Monte Carlo simulation = free from extra systematic errors.
  - NC/3L is analyzed only at 3 strips.



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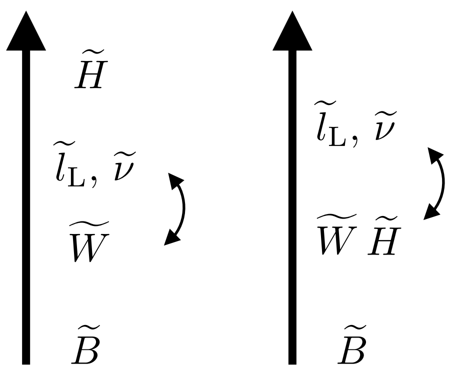
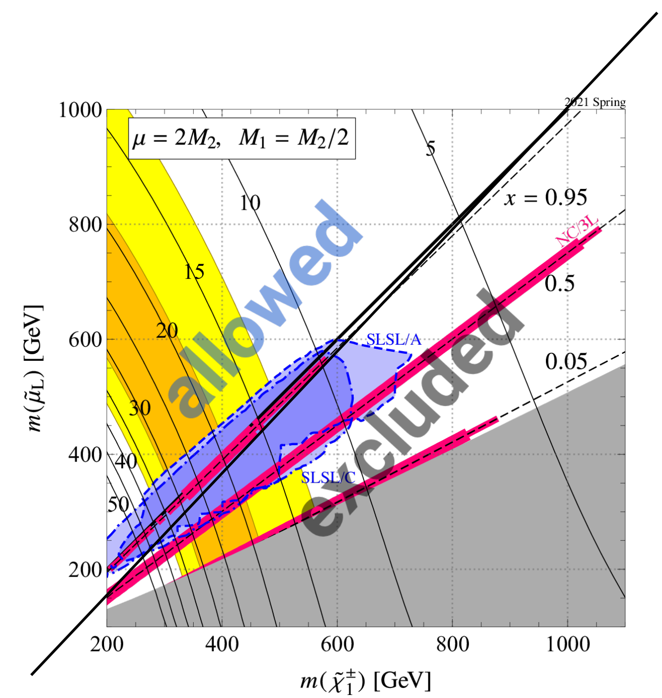
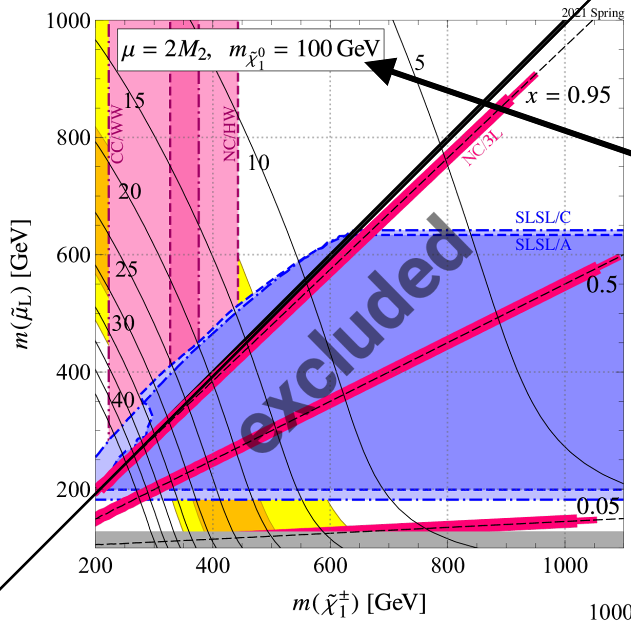
- Only some "typical" spectra are considered:

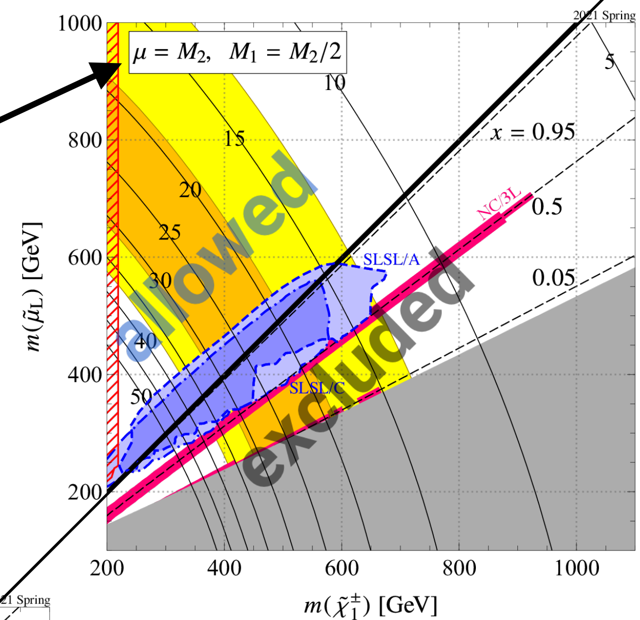


- $\tilde{l}_\mathrm{L} > \widetilde{W} \overset{\approx}{\Longrightarrow}$ **widely allowed.**
- $\tilde{l}_\mathrm{L} < \widetilde{W} \overset{\approx}{\Longrightarrow}$ **excluded.**

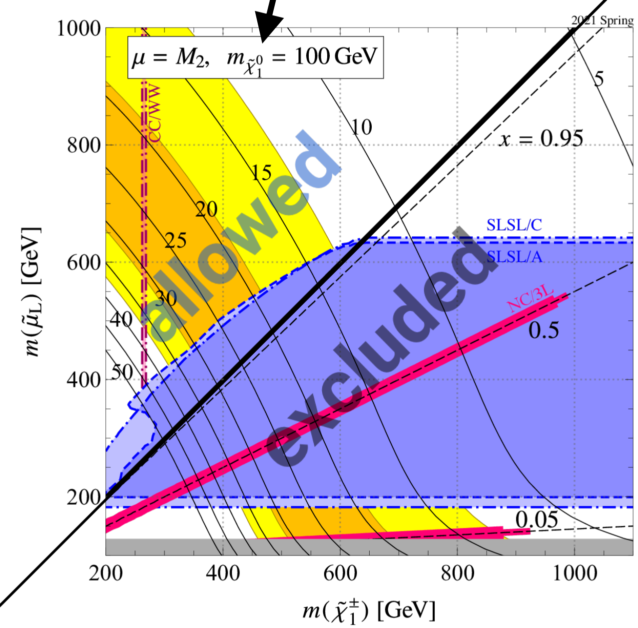


 Endo, Hamaguchi, Iwamoto, Kitahara [2104.03217]





different parameters



Conclusion 1: MSSM can explain the anomaly, but LHC also did well.

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Extra) SUSY-breaking scenarios for *g*−2

Iwamoto, Yanagida, Yokozaki [2104.03223]

■ **Minimal** Supersymmetric Standard Model [MSSM]

- extra bosons: **s**quarks & **s**leptons & extra Higgs bosons (H^0, H^+, H^-, A^0)
  - squarks $\widetilde{u}_{1\text{–}6} \simeq (\widetilde{u}_{\rm L}, \widetilde{u}_{\rm R}, \widetilde{c}_{\rm L}, \widetilde{c}_{\rm R}, \widetilde{t}_1, \widetilde{t}_2)$
    $\widetilde{d}_{1\text{–}6} \simeq (\widetilde{d}_{\rm L}, \widetilde{d}_{\rm R}, \widetilde{s}_{\rm L}, \widetilde{s}_{\rm R}, \widetilde{b}_1, \widetilde{b}_2)$
  - sleptons $\widetilde{e}_{1\text{–}6} \simeq (\widetilde{e}_{\rm L}, \widetilde{e}_{\rm R}, \widetilde{\mu}_{\rm L}, \widetilde{\mu}_{\rm R}, \widetilde{\tau}_1, \widetilde{\tau}_2)$
    $\widetilde{\nu}_{1\text{–}3} \simeq (\widetilde{\nu}_e, \widetilde{\nu}_\mu, \widetilde{\nu}_\tau)$
- extra fermions: higgs**ino**s & gaug**ino**s
  - higgsinos $(\widetilde{H}^0_{\rm d}, \widetilde{H}^0_{\rm u}, \widetilde{H}^\pm)$
  - bino / winos / gluino $\widetilde{B}$ / $(\widetilde{W}^0, \widetilde{W}^\pm)$ / $\widetilde{g}$

■ MSSM needs *R*-parity [or similar symmetries]

- to forbid proton decay.
- biproduct: the **L**ightest **S**USY **P**article becomes stable.

→ DM!!

...if it is non-colored & non-charged.

gauge eigenstates → mass eigenstates

$$(\widetilde{B}, \widetilde{W}^0, \widetilde{H}^0_{\rm u}, \widetilde{H}^0_{\rm d}) \xrightarrow{\rm mix} (\widetilde{\chi}^0_1, \widetilde{\chi}^0_2, \widetilde{\chi}^0_3, \widetilde{\chi}^0_4)$$

DM!? "neutralinos"

$$(\widetilde{W}^\pm, \widetilde{H}^\pm) \xrightarrow{\rm mix} (\widetilde{\chi}^\pm_1, \widetilde{\chi}^\pm_2)$$

"charginos"

- extra fermions: higgs**ino**s & gaug**ino**s
  - higgsinos $(\widetilde{H}^0_{\rm d}, \widetilde{H}^0_{\rm u}, \widetilde{H}^\pm)$
  - bino / winos / gluino $\widetilde{B}$ / $(\widetilde{W}^0, \widetilde{W}^\pm)$ / $\widetilde{g}$

■ MSSM needs *R*-parity [or similar symmetries]

- to forbid proton decay.
- biproduct: the **L**ightest **S**USY **P**article becomes stable.

→ DM!!

...if it is **non-colored & non-charged**.

MSSM has a good DM candidate.

gauge eigenstates → mass eigenstates

$$(\widetilde{B}, \widetilde{W}^0, \widetilde{H}^0_{\mathrm{u}}, \widetilde{H}^0_{\mathrm{d}}) \xrightarrow{\text{mix}} (\widetilde{\chi}^0_1, \widetilde{\chi}^0_2, \widetilde{\chi}^0_3, \widetilde{\chi}^0_4)$$

DM!? "neutralinos"

$$(\widetilde{W}^\pm, \widetilde{H}^\pm) \xrightarrow{\text{mix}} (\widetilde{\chi}^\pm_1, \widetilde{\chi}^\pm_2)$$

"charginos"

- Neutralino DM
  = bino-like, wino-like, higgsino-like (or mixed).

- If DM density is determined by freeze-out mechanism
  under "standard" thermal history of Universe:
  - bino-like DM → $m_{\mathrm{LSP}} < 100$ GeV
  - higgsino-like DM → $m_{\mathrm{LSP}} \sim 1$ TeV
  - wino-liike DM → $m_{\mathrm{LSP}} \sim 3$ TeV

Cf. Hisano, Matsumoto, et al. [ph/0610249]
Farina, Pappadopulo, Strumia [1303.7244]

Then, *g*−2?

- g−2 motivates SUSY mass of 100−1000 GeV.
  - **bino**-like DM with ~100 GeV = **overabundance.**
    - non-standard thermal history?
    - with helpers for annihilation?

too heavy = too small annihilation

→ co-annihilation: Binetruy, Girardi, Salati (1984), Griest, Seckel (1991)
vectorlike leptons: Abdullah, Feng [1510.06089], Abdullah, Feng, Iwamoto, Lillard [1608.00283]

  - **wino-** or **higgsino**-like DM with ~100 GeV = **underabundance.**
    - non-standard thermal history?
    - extra particles for DM?

too light = too much annihilation

  - **bino-higgsino** mixture = strong constraints from DM direct detections.

"well-tempered scenario" ... not talking today

by freeze-out mechanism
under "standard" thermal history of Universe:

- bino-like DM → m_{LSP} < 100 GeV
- higgsino-like DM → m_{LSP} ~ 1 TeV
- wino-liike DM → m_{LSP} ~ 3 TeV

Cf. Hisano, Matsumoto, et al. [ph/0610249]
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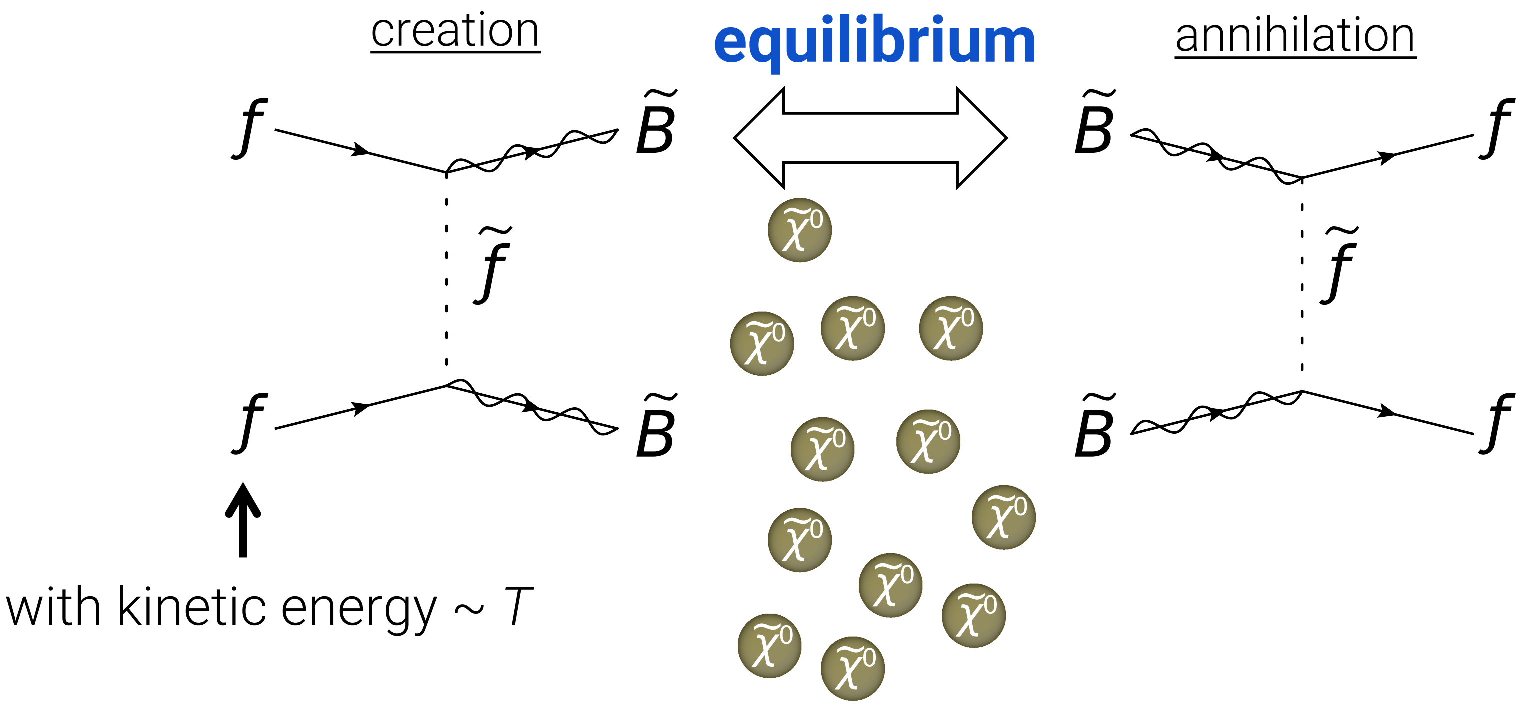
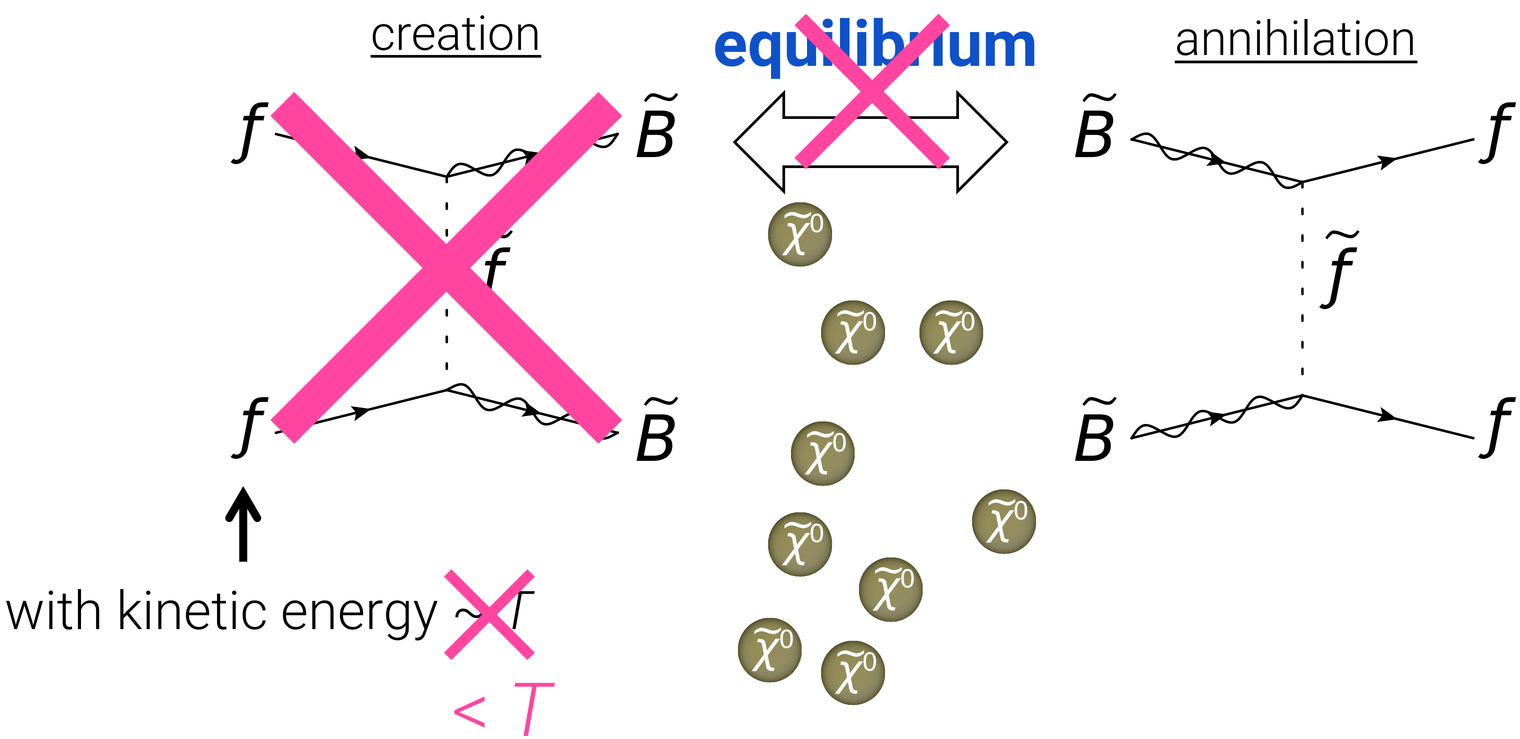
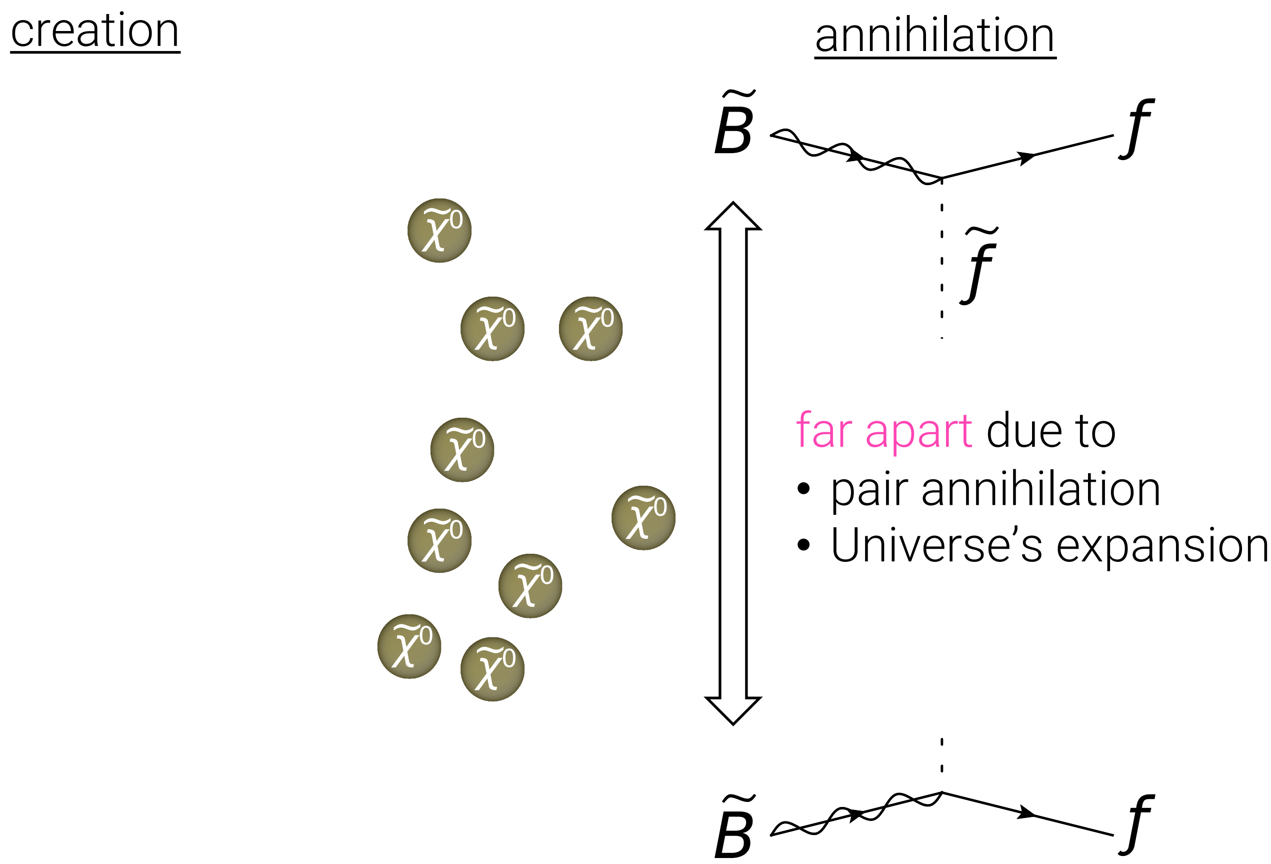
- Early Universe with $T > m_{\widetilde{B}}$



- Early Universe with $T \lesssim m_{\widetilde{B}}$



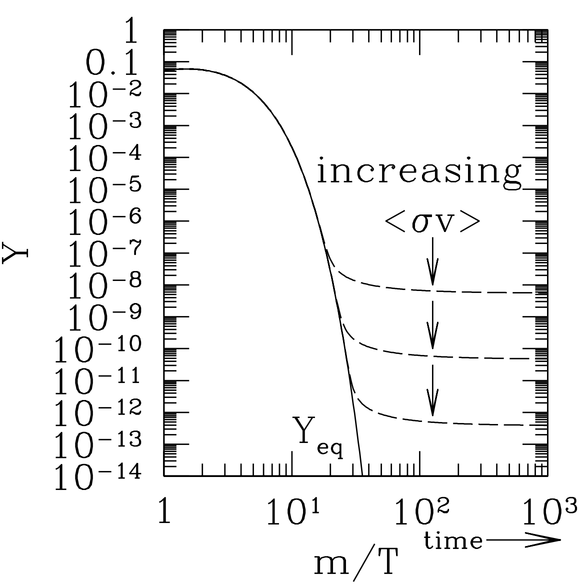
- Early Universe with $T \lesssim m_{\widetilde{B}}/20$

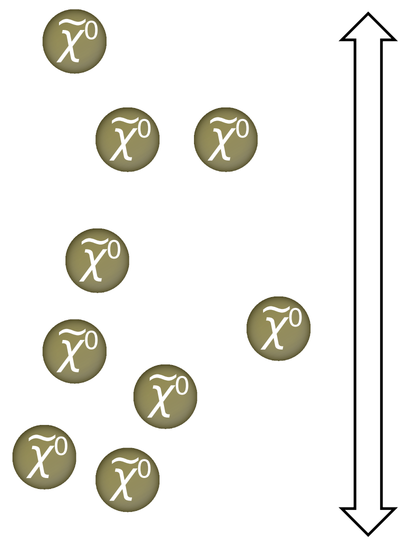


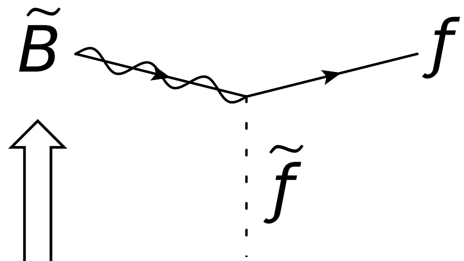
■ Early Universe with $T \lesssim m_{\widetilde{B}}/20$

creation

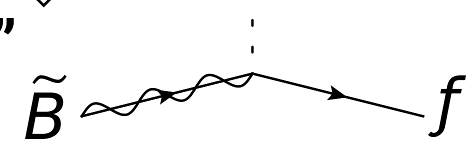
annihilation







far apart due to
- pair annihilation
- Universe's expansion



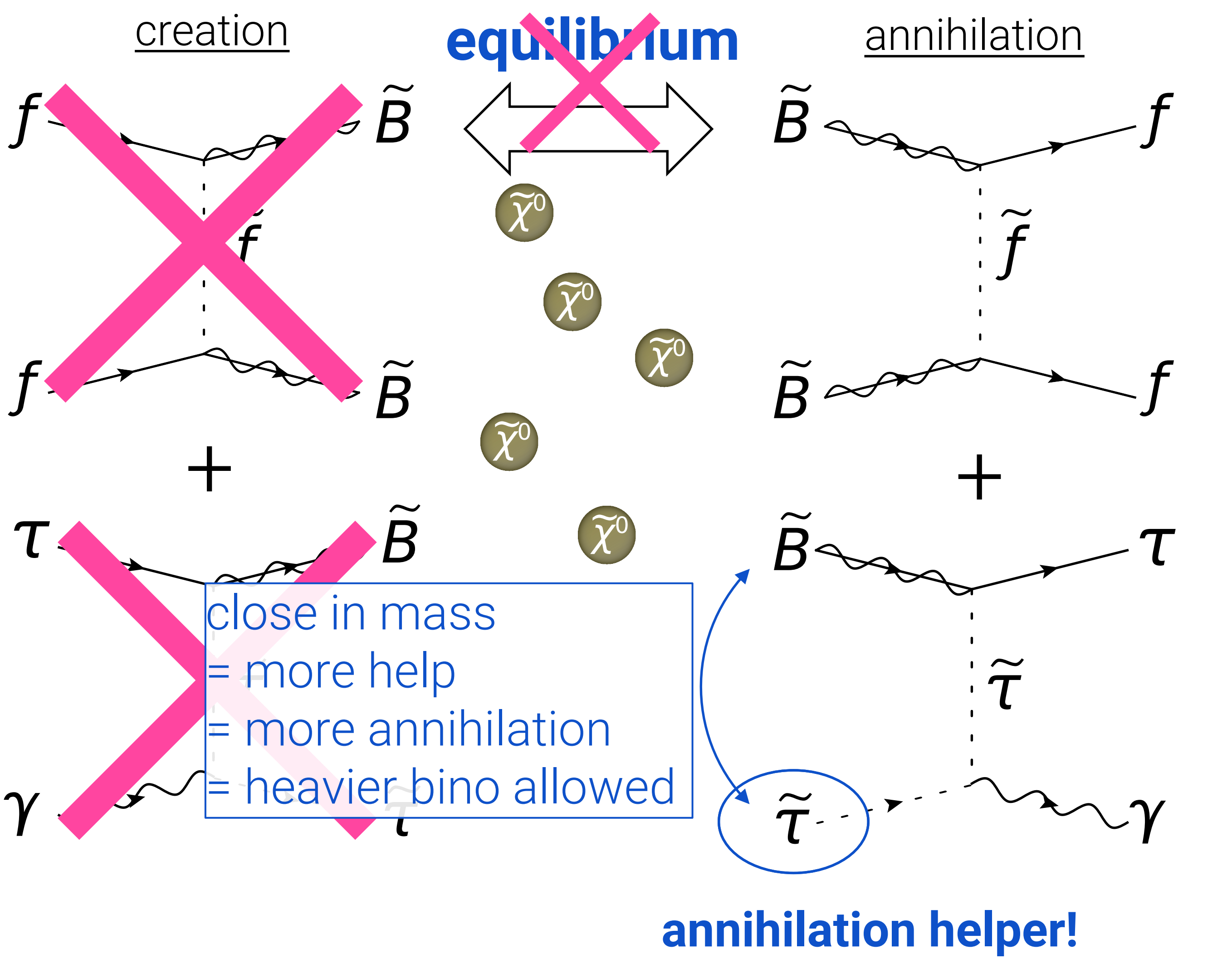
"thermal relic"

... too much for ~100GeV bino-like DM.

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

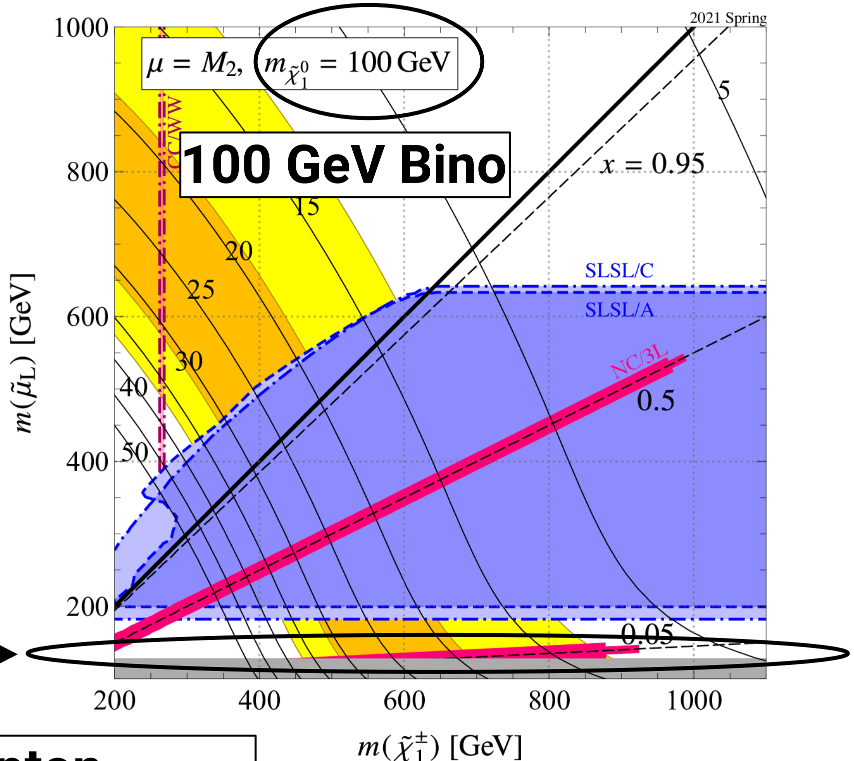
Gelmini and Gondolo, 1009.3690

- Early Universe with $T \lesssim m_{\tilde{B}}$ **with stau-coannihilation**

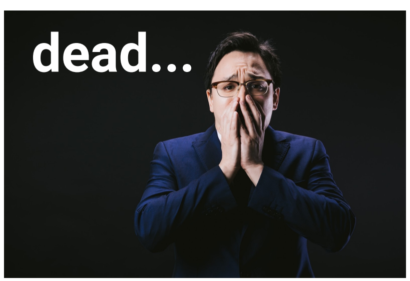


cf. Edsjö, Schelke, Ullio, Gondolo, hep-ph/0301106

Freeze-out of Bino DM = overabundance in standard thermal history.

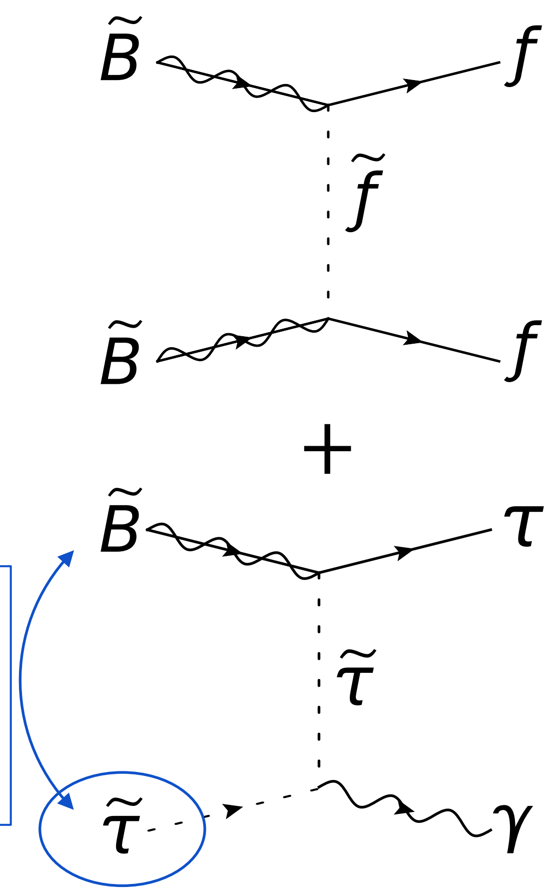


slepton
close in mass



close in mass
= more help
= more annihilation
= heavier bino allowed

annihilation



annihilation helper!

cf. Edsjö, Schelke, Ullio, Gondolo, hep-ph/0301106

- DM & $g-2$
  - **bino**-like DM
    - + non-standard thermal history?
    - **+ coannihilation?**
      - "Minimal" and simplest.
      - Fine-tuning between slepton/bino mass.
      - WHL seems disfavored by LHC. **→ Let's see the other three!**
  - **Wino-** or **higgsino**-like DM
    - + non-standard thermal history?
    - + extra particles for DM?
  - **bino-higgsino** mixture ("well-tempered" scenario)
    - but need to avoid direct detections.

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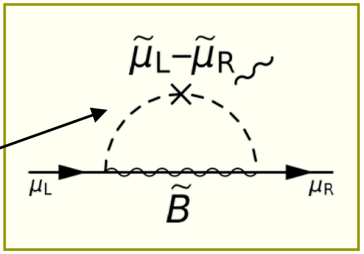
Extra) SUSY-breaking scenarios for g−2

Iwamoto, Yanagida, Yokozaki [2104.03223]

2) BLR scenario



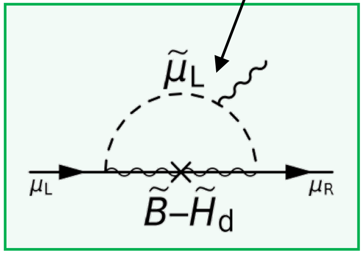
$$a_\mu^{\rm BLR} = \frac{\alpha_Y}{4\pi}\frac{m_\mu^2 M_1 \mu}{m_{\tilde\mu_L}^2 m_{\tilde\mu_R}^2}\tan\beta \cdot f_N\left(\frac{m_{\tilde\mu_L}^2}{M_1^2}, \frac{m_{\tilde\mu_R}^2}{M_1^2}\right)$$

Bino & sleptons are required to light.

→ (naturally)

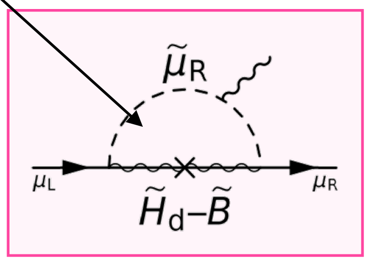
bino-DM with coannihilation.

3) BHL scenario



$$a_\mu^{\rm BHL} = \frac{\alpha_Y}{8\pi}\frac{m_\mu^2}{M_1 \mu}\tan\beta \cdot f_N\left(\frac{M_1^2}{m_{\tilde\mu_L}^2}, \frac{\mu^2}{m_{\tilde\mu_L}^2}\right)$$

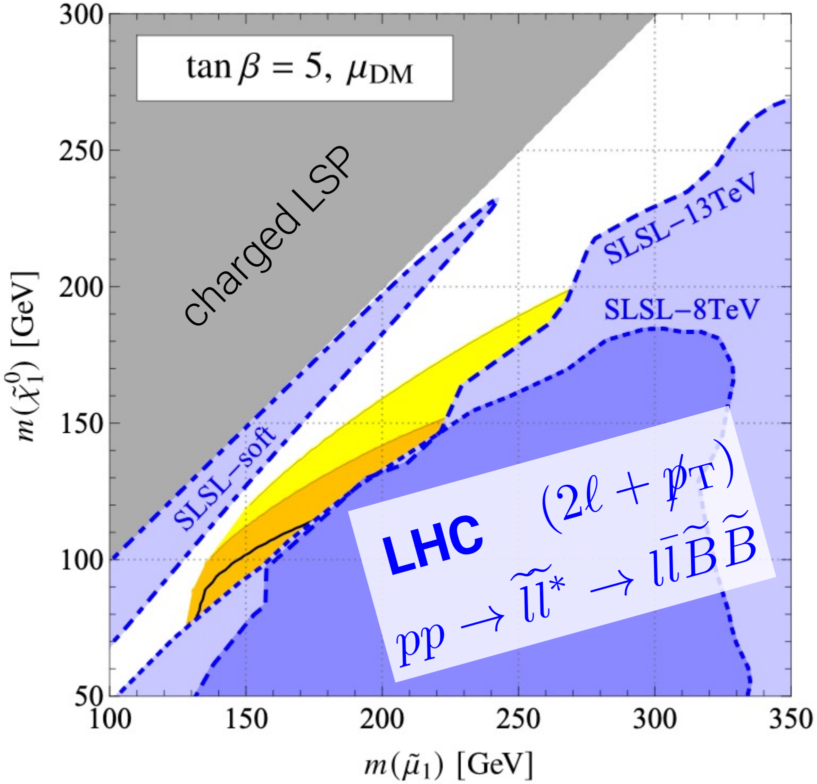
4) BHR scenario

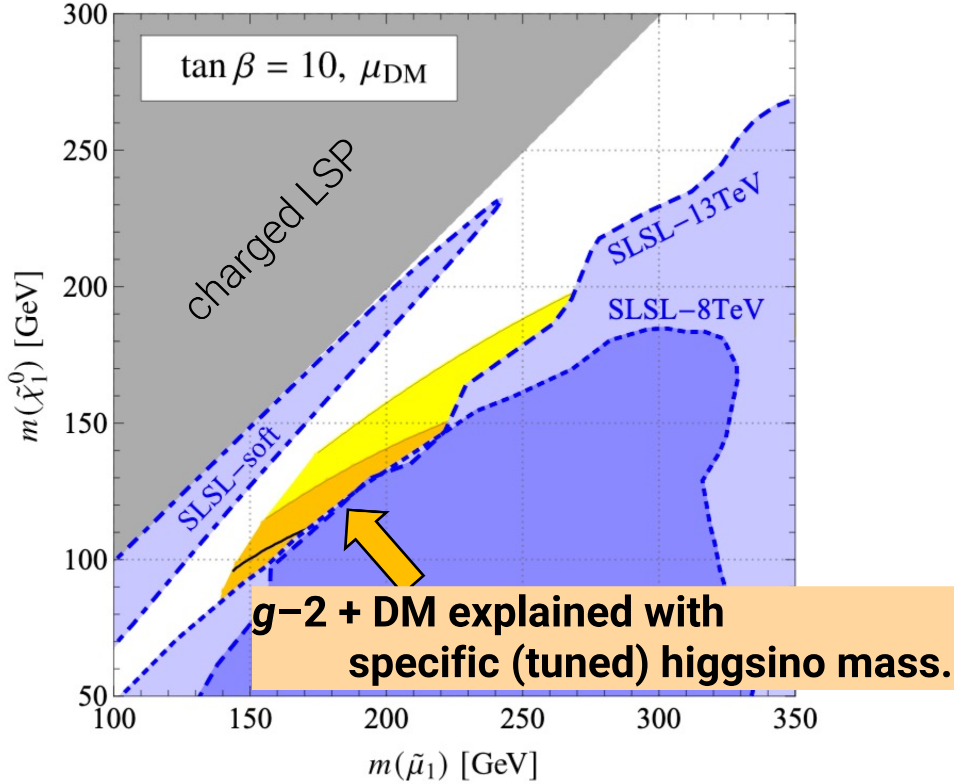


$$a_\mu^{\rm BHR} = -\frac{\alpha_Y}{4\pi}\frac{m_\mu^2}{M_1 \mu}\tan\beta \cdot f_N\left(\frac{M_1^2}{m_{\tilde\mu_R}^2}, \frac{\mu^2}{m_{\tilde\mu_R}^2}\right)$$

$$f_C(x,y) = xy\left[\frac{5-3(x+y)+xy}{(x-1)^2(y-1)^2} - \frac{2\ln x}{(x-y)(x-1)^3} + \frac{2\ln y}{(x-y)(y-1)^3}\right]$$
$$f_N(x,y) = xy\left[\frac{-3+x+y+xy}{(x-1)^2(y-1)^2} + \frac{2x\ln x}{(x-y)(x-1)^3} - \frac{2y\ln y}{(x-y)(y-1)^3}\right].$$

Endo, Hamaguchi, Iwamoto, Kitahara [2104.03217]





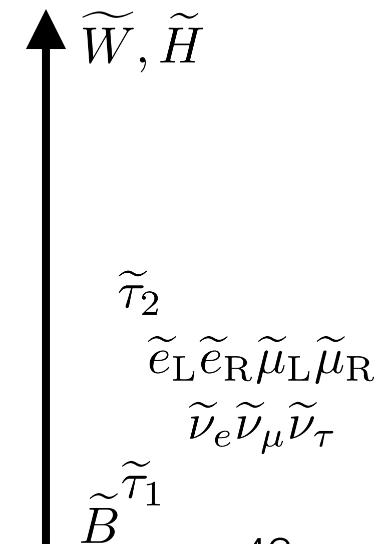
$\tan\beta := \langle H_{\rm u}\rangle/\langle H_{\rm d}\rangle$ → 5, 10.

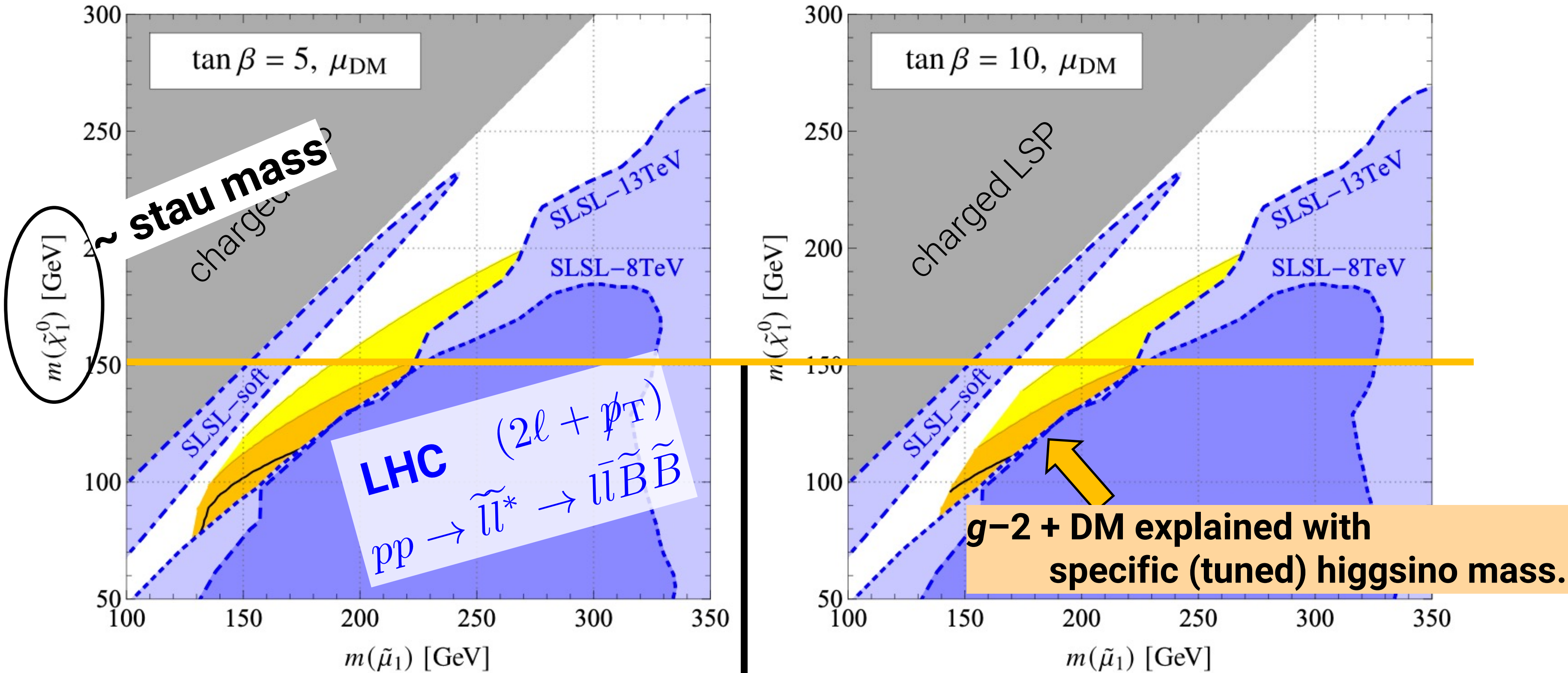
$M_1 \approx \widetilde{B}$-mass → axis.

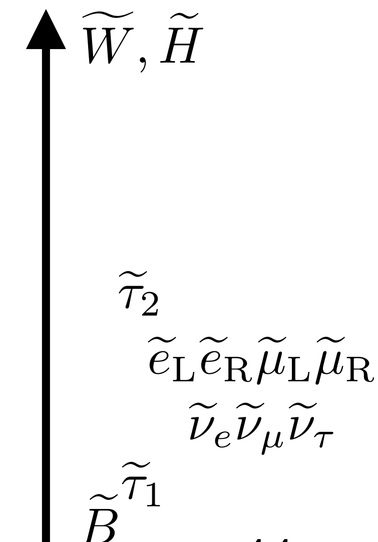
$\mu \approx \widetilde{H}$-mass → tuned to satisfy ***g*−2 + DM + XENON1T + vacuum stability**.

$M_2 \approx \widetilde{W}$-mass → assumed heavy

$m_{\rm L}^2 \approx \widetilde{l}_{\rm L}$-mass, $m_{\rm R}^2 \approx \widetilde{l}_{\rm R}$-mass } $m_{\rm L} = m_{\rm R}$; axis.







- How to search in future?
  - ➢ ILC stau search! (stau < 150−200 GeV).
  - ➢ LHC as photon colliders? → Beresford, Liu [1811.06465]
  - ➢ (any other ideas?)

1. Introduction

- Muon *g*−2 "anomaly"
- New physics for $(g-2)_\mu$

2. SUSY

- Why SUSY?
- How MSSM explains $(g-2)_\mu$: **Four** possibilities
- Scenario 1: "WHL for *g*-2" — Endo, Hamaguchi, Iwamoto, Kitahara [2001.11025]; Endo, Hamaguchi, Iwamoto, Kitahara [2104.03217]

3. MSSM and Dark Matter

- Neutralino dark matter with freeze-out
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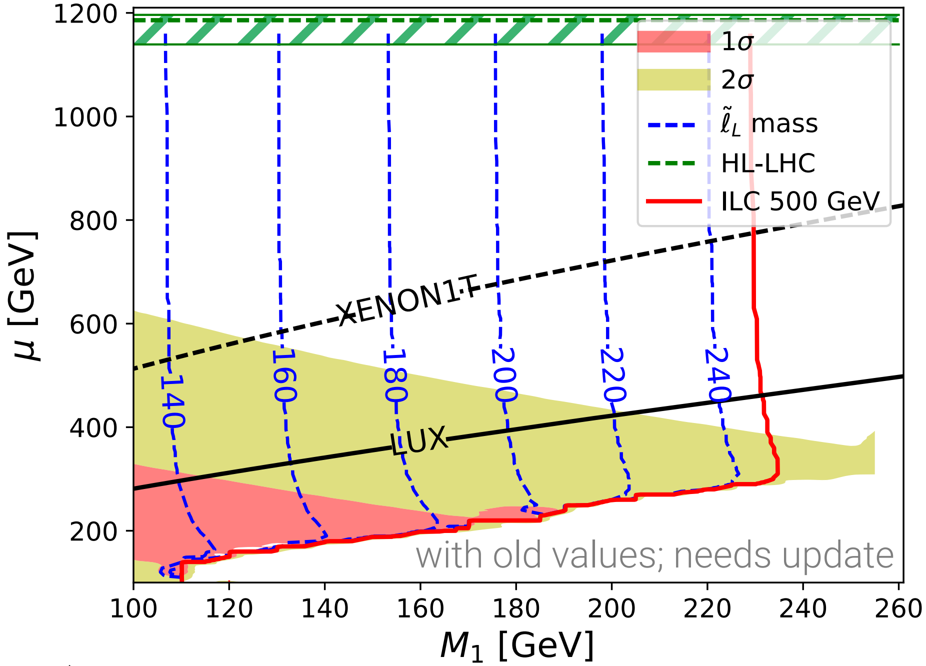
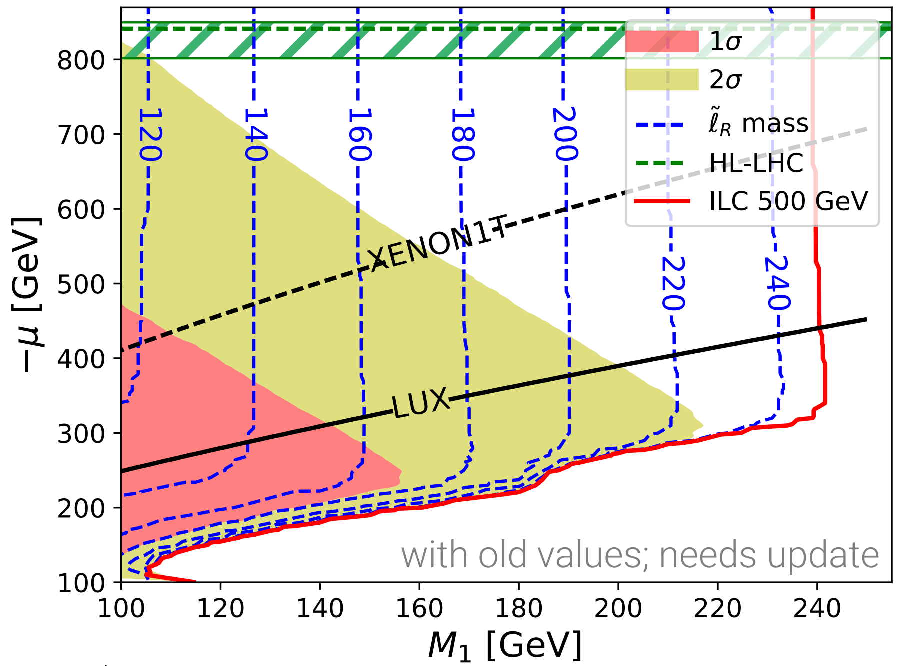
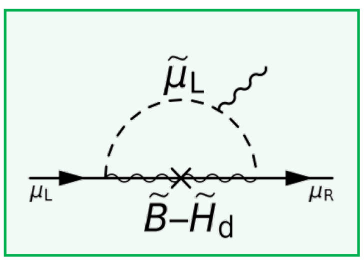




3) BHL scenario



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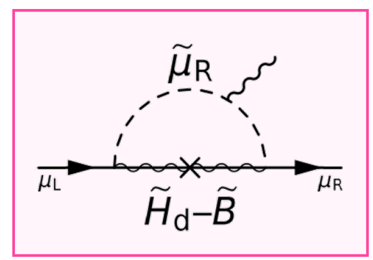

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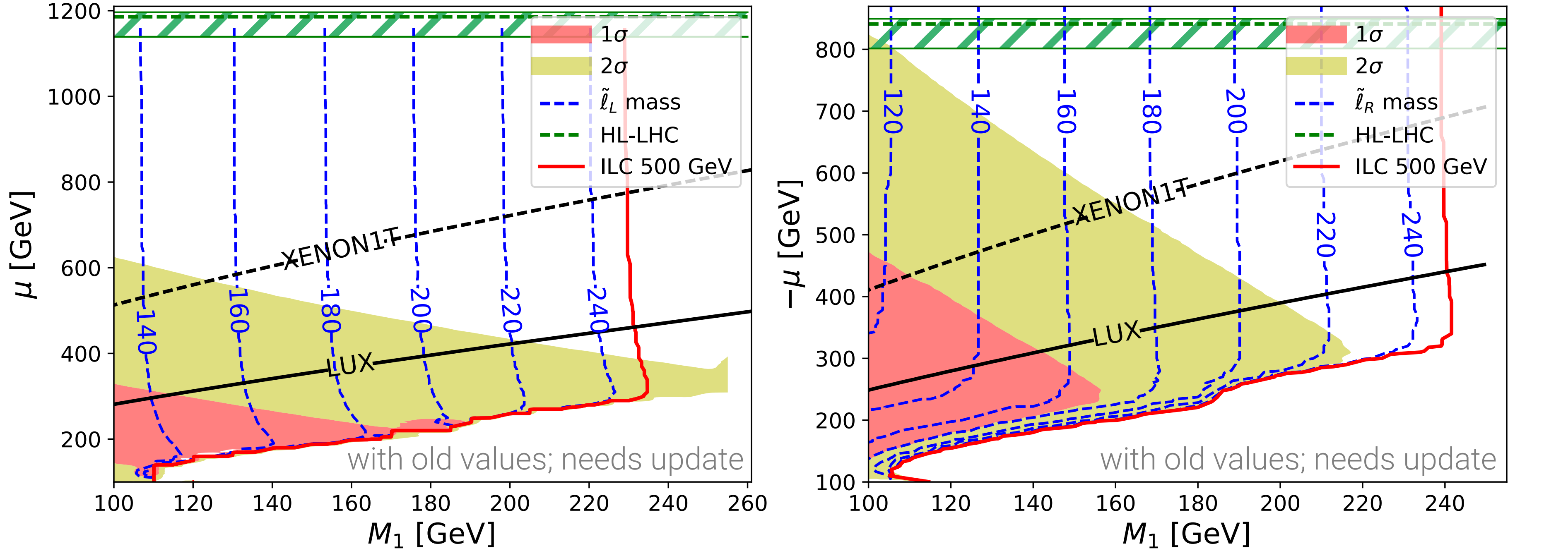
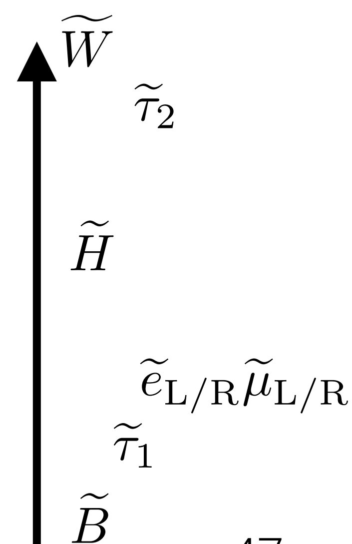
BHL or BHR for $g-2$ + DM

Endo, Hamaguchi, Iwamoto, Yanagi [1704.05287]



- Here,
  - Assumed Slepton universality.
  - Correct DM density by tuning slepton masses.
- How to search in future?
  - $pp \to \widetilde{H}^+\widetilde{H}^0,\ \widetilde{H}^+\widetilde{H}^-$
  - $\widetilde{H}^0 \to \tau\widetilde{\tau},\ \ \widetilde{H}^+ \to \tau\widetilde{\nu}_\tau$ because of large tanβ. → multi-τ search.



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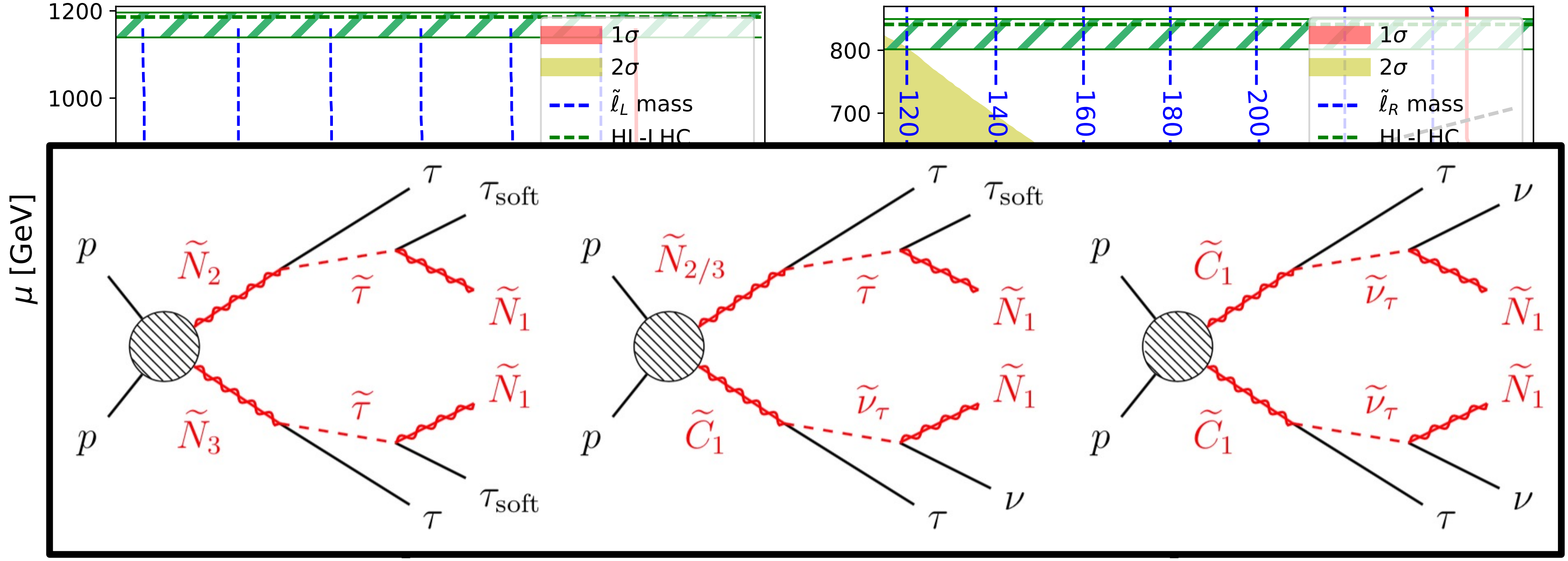

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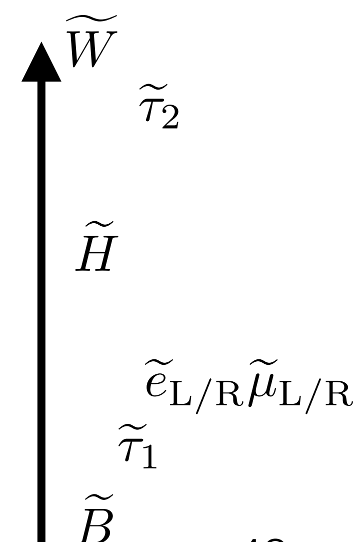
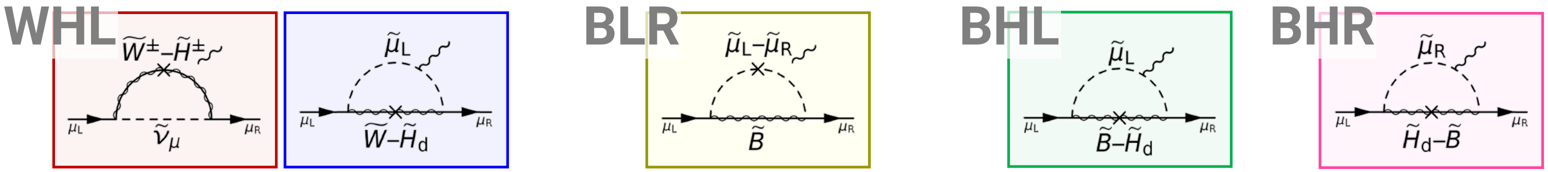
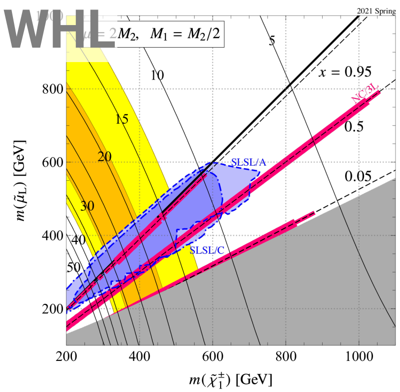
"2 τ (+ soft) + missing"



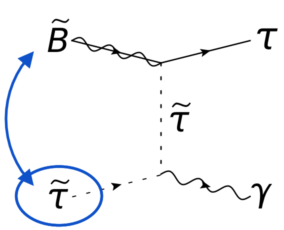
- The 4.2 σ anomaly[*if indeed] can be solved by **MSSM**.



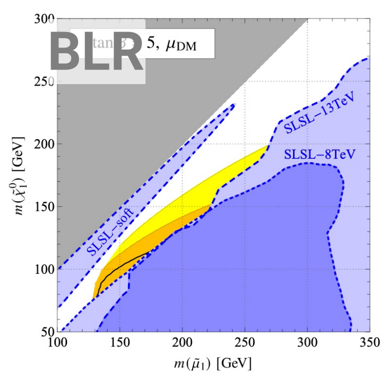
Wide parameter still allowed; LHC did well.

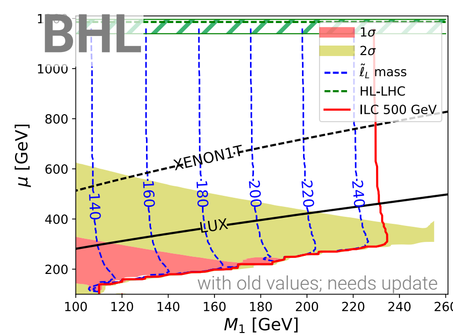


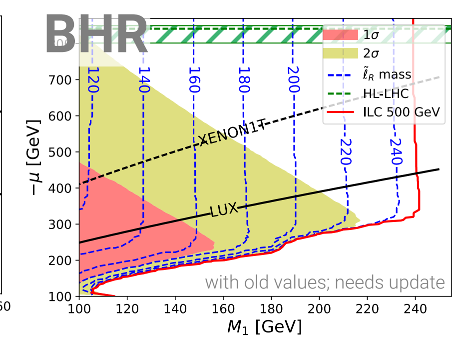
- **Bino DM + coannihilation** can explain full DM + g−2.



annihilation helper! (only if close in mass)

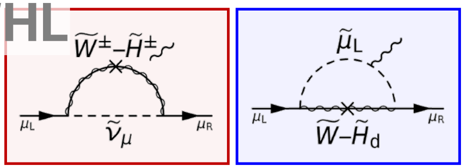




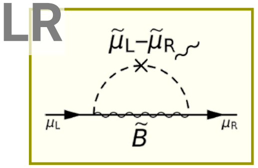


■ The 4.2 σ anomaly*if indeed can be solved by **MSSM**.

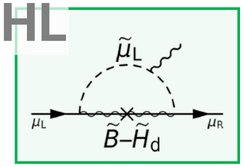
WHL



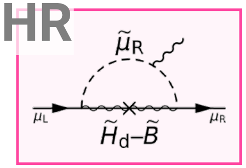
BLR



BHL



BHR



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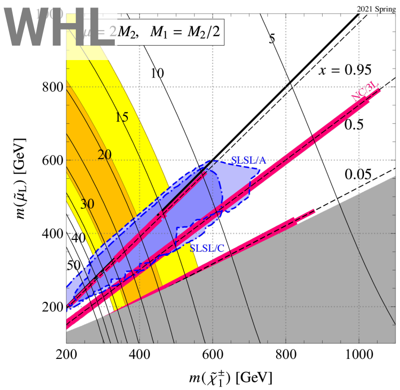
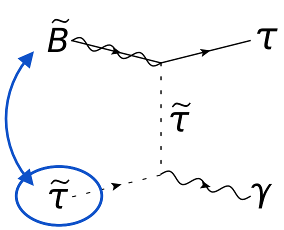


wait for HL-LHC (neutralino-chargino, sleptons)

ILC (other ideas?) all degenerate = difficult

will be covered by
HL-LHC + XENONnT

■ **Bino DM + coannihilation** can explain full DM + g−2.



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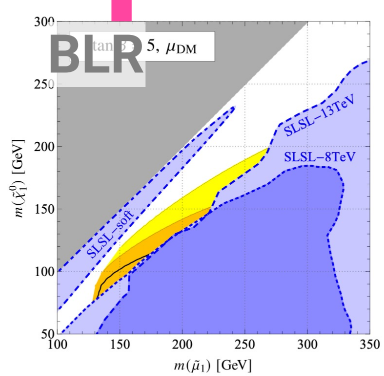
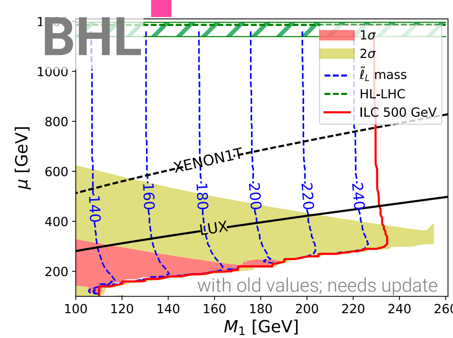
BLR



BHL



BHR