SUSY scenarios for muon *g*−2 anomaly: LHC Run 2 and future

Sho Iwamoto （岩本　祥）

ELTE Eötvös Loránd University
http://pppheno.elte.hu/

(2023 Feb.– Natl. Sun Yat-sen U., Taiwan)

8 Jul. 2022
ICHEP2022 @ Bologna

Based on works with

Manimala Chakraborti, Motoi Endo, Koichi Hamaguchi, Jong Soo Kim, Teppei Kitahara, Rafał Masełek, Kazuki Sakurai, Keisuke Yanagi, Tsutomu T. Yanagida, and Norimi Yokozaki, 1704.05287, 2001.11025, 2104.03217, 2104.03223, 2202.12928, and works in progress.

ver. 20220707233000

SUSY scenarios for muon $g-2$ anomaly: LHC Run 2 and future

- hint for better understanding of **SM**?
  ... "lattice QCD vs data-driven calculation"
- hint for **new physics** beyond the SM?
  ... SUSY? → this talk

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■ Motivations for SUSY

- leads to superstring theory, ... beyond this talk
- ~~solves naturalness problem,~~ ... disfavored by LHC (non-discovery of top-squark)
- helps gauge-coupling unification,
- contains dark matter (DM) candidates,
- solves the muon $g-2$ anomaly.

} → current status / prospects?

[Minimal Supersymmetric Standard Model]

❖ This talk focuses on MSSM with *R*-parity.

Extended MSSM scenarios (gravitino, *R*-parity violation)
→ Chakraborti, SI, Kim, Masełek, Sakurai [2202.12928]

The LSP becomes stable: Good dark matter candidate!

[Lightest SUSY Particle]

DM

- 4 candidates:

  Bino $\widetilde{B}$, Wino $\widetilde{W}^0$, Higgsinos $\widetilde{H}^0_u$, $\widetilde{H}^0_d$

  (mixed to form neutralinos $\widetilde{\chi}^0_{1,2,3,4}$)

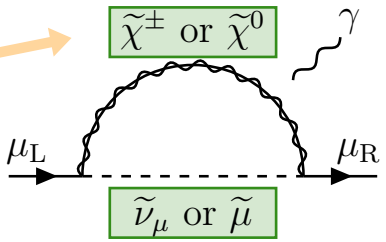
- DM density Ωh^2 is (in "simplest" setup) fixed by annihilation cross section:

  $\widetilde{W}$-LSP → $m_{\rm LSP}$ ~ **2.7 TeV**,
  $\widetilde{H}$-LSP → $m_{\rm LSP}$ ~ **1.1 TeV**,
  $\widetilde{B}$-LSP → extra mechanism to reduce DM,

  to have $(\Omega h^2)_{\rm LSP} = (\Omega h^2)^{\rm obs}_{\rm DM}$.

Muon *g*−2

- Extra contribution



SUSY particles
$\widetilde{\chi}^0$: neutralino
$\widetilde{\chi}^{\pm}$: chargino
$\widetilde{\mu}$: smuon
$\widetilde{\nu}_\mu$: mu-sneutrino

$$a_\mu^{\rm MSSM} \approx \frac{m_\mu^2 \cdot (\text{coupling})^2}{(\text{SUSY-particle mass})^2} \stackrel{!}{=} 2\times10^{-9}$$

→ relevant SUSY-particles should ≲ **1 TeV.**

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

thermally-produced, freeze-out DM with the standard thermal history of Universe.

The LSP becomes stable: Good dark matter candidate!

[Lightest SUSY Particle]

It is not straightforward to achieve both.

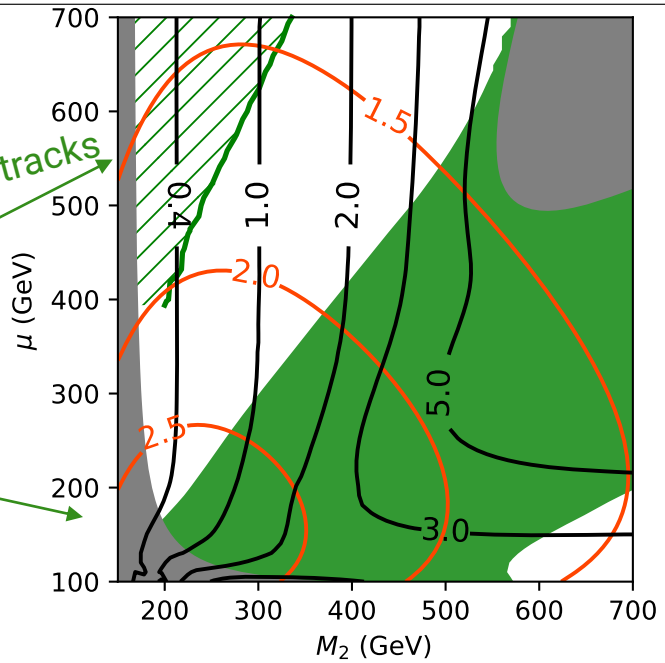
Iwamoto, Yanagida, Yokozaki [2104.03223]

If $g-2$ anomaly = MSSM contribution,
LSP mass $\lesssim O(100)$ GeV. Then...

$\widetilde{W}$-LSP → explains only ~1% of DM
+ constr. from wino searches @ LHC.
$\widetilde{H}$-LSP → explains only ~1% of DM
+ constr. form direct detections.

$\widetilde{W}^{\pm}$ as disapp. tracks

XENON 1T



Example: "SUGRA" framework of SUSY-breaking
(Wino / Higgsino / Wino-Higgsino mixed DM)

$(m_0, M_1, M_3) = (0, 3800, 2500)\,\mathrm{GeV}, \quad (\tan\beta, m_A) = (40, 2000\,\mathrm{GeV}),$
$(A_u, A_d, A_e) = (-1000, 0, 0)\,\mathrm{GeV}.$

Price: Avoid constraints && (extra DM || non-simple cosmology)

— : $\Omega_{\mathrm{LSP}}/\Omega_{\mathrm{DM}}$ [%]
— : $a_\mu^{\mathrm{MSSM}} \times 10^9$
Green: exclusions

$\widetilde{B}$-LSP → needs extra mechanism to reduce bino-DM.

- ~~Bino-Higgsino mixing~~ ← disfavored by DM direct detections.
- Coannihilation

latter half of this talk

+ constraints from LHC searches.

Price: Avoid LHC && (DM reduction mechanism || non-simple cosmology)

* Wino disappearing track searches: ATLAS [2201.02472], CMS [2004.05153]
[$2\ell + \not{p}_{\mathrm{T}}$ from $pp \to \tilde{\nu}\tilde{\nu}^* \to \widetilde{W}^+\widetilde{W}^-$ may also provide constraints.]

* direct det. by XENON1T [1805.12562]; not included are PandaX-4T [2107.13438] and LZ (2022).

SUSY now: DM and muon $g-2$

1. DM ⇔ $g-2$: tightly connected in MSSM
   - ➢ $\widetilde{W}$-LSP & $g-2$ = partial DM + LHC constraints
   - ➢ $\widetilde{H}$-LSP & $g-2$ = partial DM + direct det. constraints
   - ➢ $\widetilde{B}$-LSP & $g-2$ = too much DM + LHC constraints

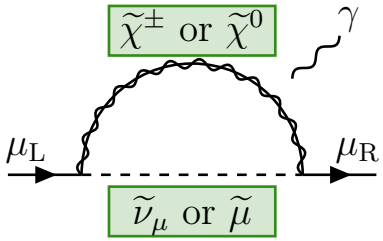
extra DM?
non-simple cosmology?

coannihilation?
non-simple cosmology?

2. MSSM provides 4 scenarios (solutions) to the $g-2$ anomaly.
   1. WHL:
   2. BLR:
   3. BHL, BHR:

3. Conclusion

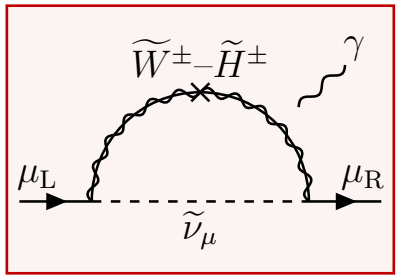
MSSM has four dominant contributions to the muon $g-2$.



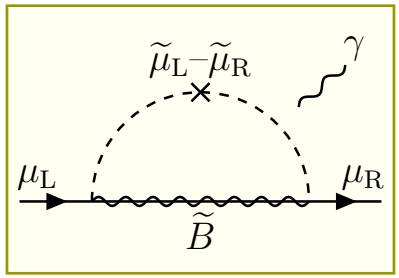
SUSY particles
- $\widetilde{\chi}^0$: neutralino
- $\widetilde{\chi}^{\pm}$: chargino
- $\widetilde{\mu}$: smuon
- $\widetilde{\nu}_\mu$: mu-sneutrino

mass insertion approx.

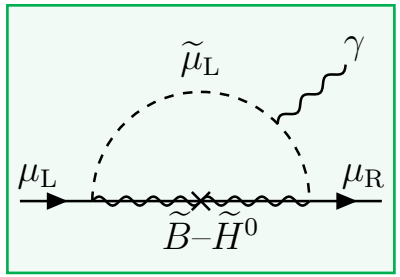
WHL



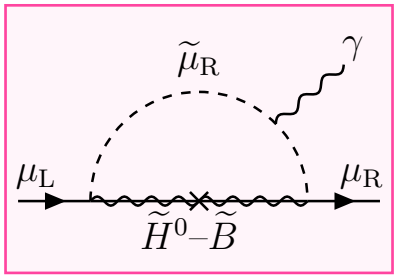
BLR



BHL



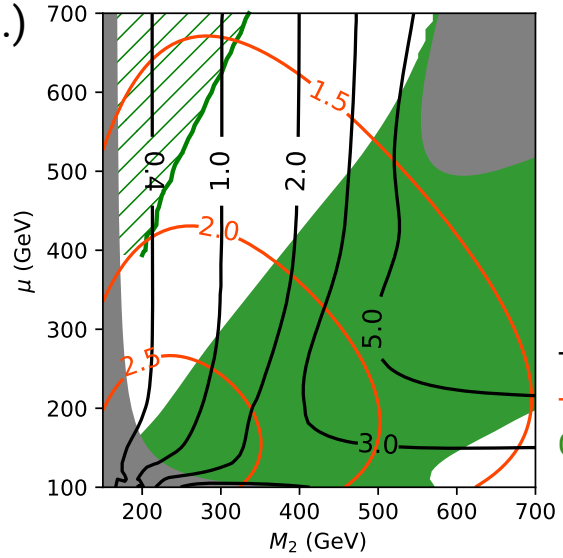
BHR



(cf. Cho et al. [1104.1769])

Three light particles = sufficient for $g-2$.

e.g.)



– : $\Omega_{\rm LSP}/\Omega_{\rm DM}$ [%]
– : $a_\mu^{\rm MSSM} \times 10^9$
Green: exclusions

Left-handed slepton

$= \widetilde{W}, \widetilde{H}, \tilde{\nu} \sim \mathcal{O}(100)\,\mathrm{GeV}$: "**WHL** scenario"

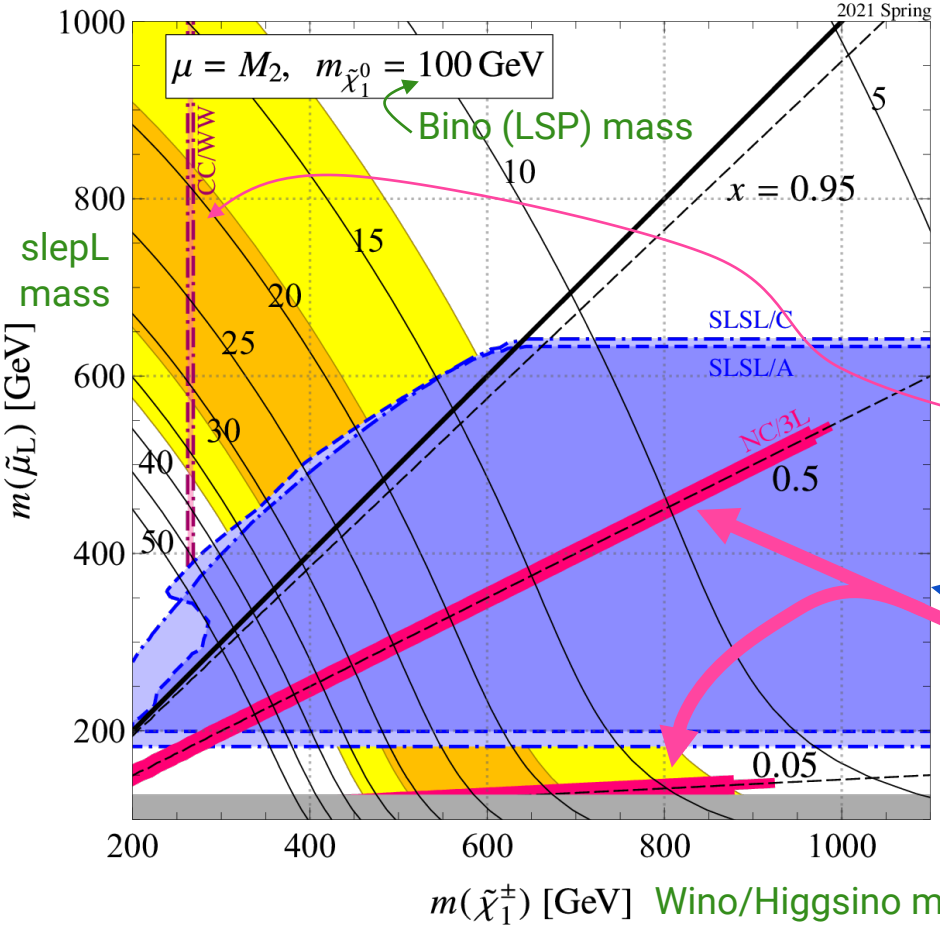
→ **What if Bino is also light?**
(i.e., Bino-LSP with WHL?)

*In terms of gauge multiplets. Flavor universality is often assumed.
Hence $\widetilde{W}^{\pm}, \widetilde{W}^{0}$, $\widetilde{H}^{\pm}, \widetilde{H}^{0}_{1,2}$, $\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L$, and $\tilde{\nu}_e$, $\tilde{\nu}_\mu$, $\tilde{\nu}_\tau$ are light here.

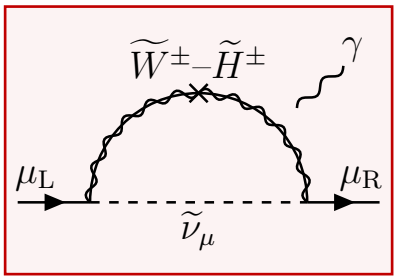
$$a_\mu^{\rm WHL} = \frac{\alpha_2}{4\pi}\frac{m_\mu^2}{M_2\mu}\tan\beta \cdot f_C\left(\frac{M_2^2}{m_{\tilde{\nu}_\mu}^2}, \frac{\mu^2}{m_{\tilde{\nu}_\mu}^2}\right) - \frac{\alpha_2}{8\pi}\frac{m_\mu^2}{M_2\mu}\tan\beta \cdot f_N\left(\frac{M_2^2}{m_{\tilde{\mu}_L}^2}, \frac{\mu^2}{m_{\tilde{\mu}_L}^2}\right)$$

Example of WHL model with by-hand bino-LSP.

Endo, Hamaguchi, SI, Kitahara [2001.11025][2104.03217]



WHL



LHC constraints

- $\tilde{\mu}_\mathrm{L} > \widetilde{W}^\pm, \widetilde{H}^\pm$

  $\widetilde{W}^+\widetilde{W}^- \to W^+W^- \not{p}_\mathrm{T}$ (CC/WW)

  $\widetilde{W}^0\widetilde{W}^+ \to ZW + \not{p}_\mathrm{T},\ HW + \not{p}_\mathrm{T}$ (NC/HW, NC/ZW)

- $\tilde{\mu}_\mathrm{L} < \widetilde{W}^\pm, \widetilde{H}^\pm$

  $\tilde{\mu}_\mathrm{L}\tilde{\mu}_\mathrm{L}^* \to 2\mu + \not{p}_\mathrm{T}$ (SLSL)

  $\widetilde{W}^0\widetilde{W}^+ \to (\mu\tilde{\mu}_\mathrm{L})(\mu\tilde{\nu}) \to 3\mu + \not{p}_\mathrm{T}$ (NC/3L)

$\widetilde{W}, \widetilde{H}$ → $\tilde{l}_\mathrm{L}, \tilde{\nu}$ → $\widetilde{B}$

Bino-stau coannihilation works if $m(\widetilde{B}) \simeq m(\tilde{\tau})$ ... excluded by NC/3L.

N.B. Exclusions at the "*obviously* 95%-CL excluded" criterion.
Slepton universality is assumed.

Masses set at low energy,
$\mu = M_2$, $\tan\beta = 40$, $\tilde{\chi}_1^0 = 100\,\mathrm{GeV}$, $A_{u,d,e} = 0$,
right-handed sleptons, squarks, gluinos, extra Higgses $\gg 1\,\mathrm{TeV}$.

SLSL: ATLAS [1908.08215], CMS [2012.08600].
CC/WW: ATLAS [1909.09226].
NC/3L: CMS [1709.05406], ATLAS [1803.02762].
Results to be analyzed: 2106.01676, 2108.07586.

SUSY now: DM and muon $g-2$

1. DM ⇔ $g-2$: tightly connected in MSSM
   - ➢ $\widetilde{W}$-LSP & $g-2$ = partial DM + LHC constraints
   - ➢ $\widetilde{H}$-LSP & $g-2$ = partial DM + direct det. constraints
   - ➢ $\widetilde{B}$-LSP & $g-2$ = too much DM + LHC constraints

extra DM?
non-simple cosmology?

coannihilation?
non-simple cosmology?

2. MSSM provides 4 scenarios for $g-2$.
   1. WHL: Coannihil. $\widetilde{B}$-DM 🚫 LHC searches (chargino-neutralino).
   2. BLR: Coannihil. $\widetilde{B}$-DM
   3. BHL/R:

3. Conclusion

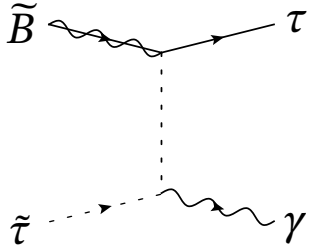
BLR scenario works well with coannihilation bino DM.

Endo, Hamaguchi, SI, Kitahara [2104.03217]

$(\tilde{e}_L, \tilde{\nu}_e)$, $(\tilde{\mu}_L, \tilde{\nu}_\mu)$, $(\tilde{\tau}_L, \tilde{\nu}_\tau)$, $\tilde{e}_R$, $\tilde{\mu}_R$, $\tilde{\tau}_R$, and $\widetilde{B}$ are light.

Bino-stau coannihilation

LSP (DM)

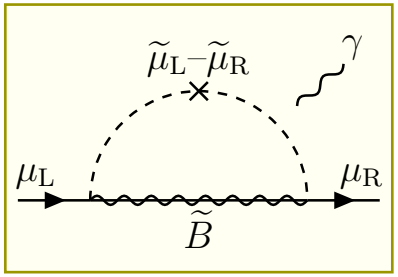


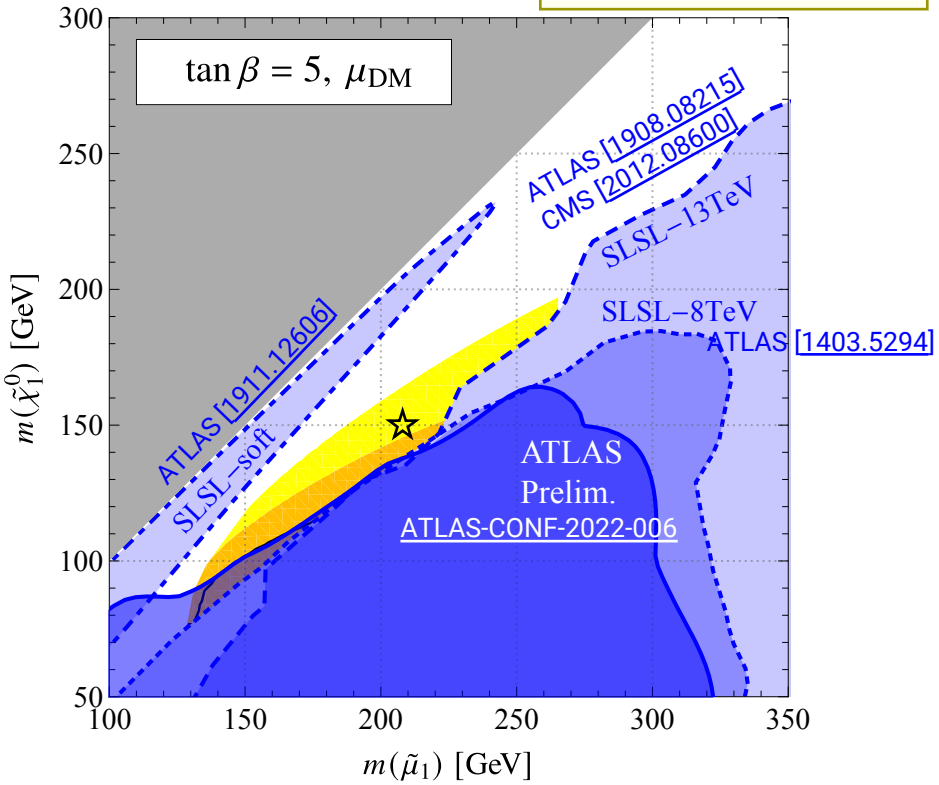
works if $m(\widetilde{B}) \simeq m(\tilde{\tau})$
(degenerate/compressed spectra).

... Elusive@LHC. (→ ILC searches)

(or, see Beresford, Liu [1811.06465])

BLR





$(\Omega h^2)_{\text{bino LSP}} = (\Omega h^2)^{\text{obs}}_{\text{DM}}$
on the whole plane (by tuned μ-parameter).

A benchmark point ☆ :

$\widetilde{\tau}_2$	: 242 GeV	μ	: 1922 GeV
$\widetilde{\mu}_2, \widetilde{e}_2$	: 207 GeV	$\tan\beta$	: 5
$\widetilde{\mu}_1, \widetilde{e}_1$	: 202 GeV	a_μ^{SUSY}	: 1.7×10^{-9}
$\widetilde{\nu}_{e,\mu,\tau}$	: 190 GeV	$(\Omega h^2)_{\text{bino}}$	: 0.12
$\widetilde{\tau}_1$	: 159 GeV		
$\widetilde{B}$	: 150 GeV		

Reminder: Prices for bino DM
= Avoid LHC && (DM reduction mechanism || non-simple cosmology)

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extra DM?
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coannihilation?
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2. MSSM provides 4 scenarios for $g-2$.
   1. WHL: Coannihil. $\widetilde{B}$-DM 🚫 LHC searches (chargino-neutralino).
   2. BLR: Coannihil. $\widetilde{B}$-DM = compressed ... 👍 still alive.
   3. BHL/R:

→ ee colliders.
$ee \to \tilde{\ell}\tilde{\ell}$

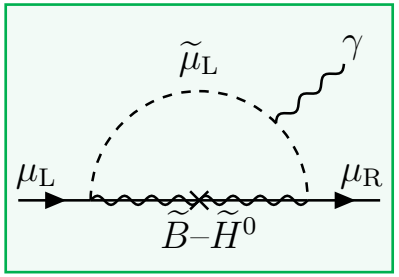
3. Conclusion

BHL & BHR: Waiting for HL-LHC and more direct detections.

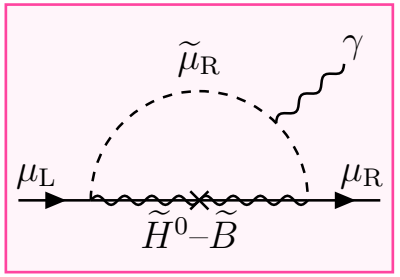
Endo, Hamaguchi, Iwamoto, Yanagi [1704.05287]

$\widetilde{B}, \widetilde{H}$, and ($\tilde{l}_{\rm L}$ or $\tilde{l}_{\rm R}$) are light. ⟸

BHL



BHR

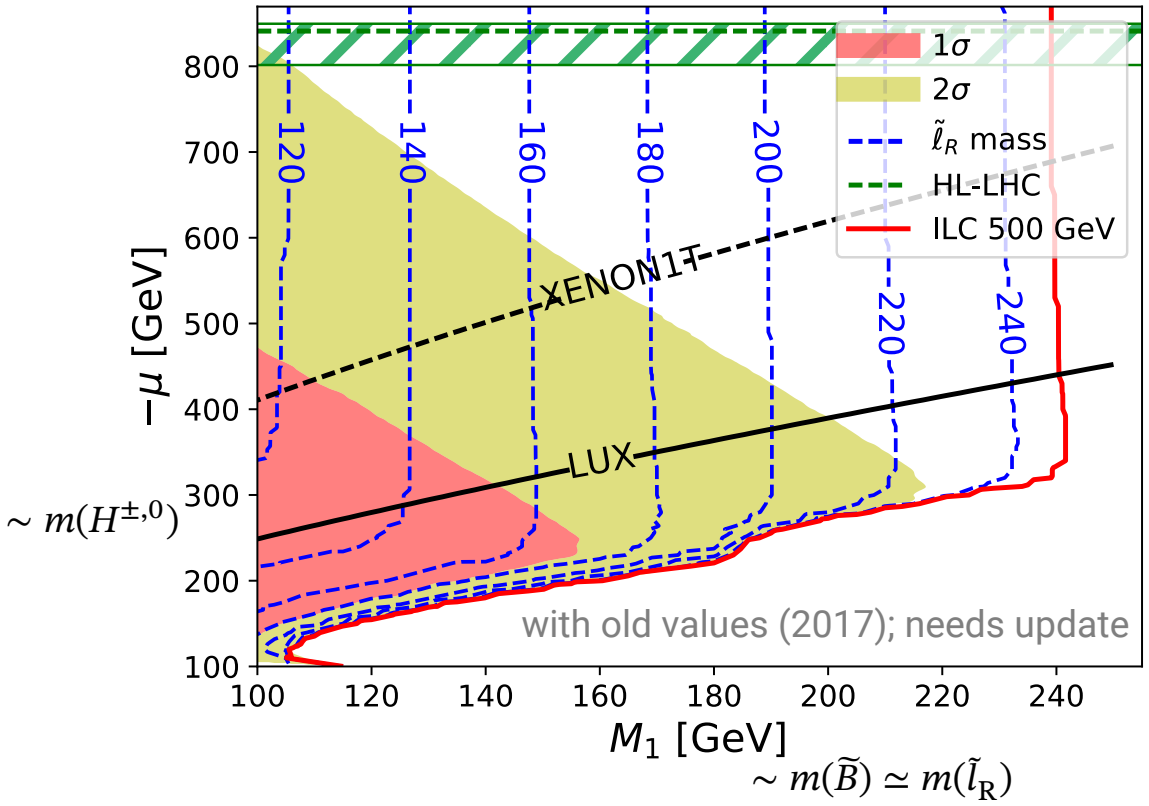


- ❖ $\widetilde{H}$-DM
- ❖ mixed DM

→ partial DM or direct detection

- ❖ $\widetilde{B}$-DM → Needs reduction ... Bino-stau coannihilation [$m(\widetilde{B}) \simeq m(\tilde{\tau})$]?

➢ BHR plane with coannihilation DM



$\widetilde{B}, \tilde{l}_{\rm R} < \widetilde{H}$

100–200 GeV 200–800 GeV

Whole region will be explored by

- ➢ DM direct detection,
- ➢ HL-LHC $(pp \to \widetilde{H}^+\widetilde{H}^0 \to 2\tau + \not{p}_{\rm T})$,
- ➢ ILC slepton searches.

SUSY now: DM and muon $g-2$

1. DM ⇔ $g-2$: tightly connected in MSSM
   - ➢ $\widetilde{W}$-LSP & $g-2$ = partial DM + LHC constraints → extra DM? non-simple cosmology?
   - ➢ $\widetilde{H}$-LSP & $g-2$ = partial DM + direct det. constraints → coannihilation? non-simple cosmology?
   - ➢ $\widetilde{B}$-LSP & $g-2$ = too much DM + LHC constraints

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   2. BLR: Coannihil. $\widetilde{B}$-DM = compressed ... 👍 still alive. → ee colliders. $ee \to \tilde{\ell}\tilde{\ell}$
   3. BHL/R: $\tilde{B}$-$\tilde{H}$ mixed DM ... 🚫 direct det.
      Coannihil. $\widetilde{B}$-DM ... 👍 still alive. → direct det., HL-LHC, ee colliders. $2\tau + \not{p}_{\mathrm{T}}$ $ee \to \tilde{\ell}\tilde{\ell}$

3. Conclusion

Bad news to me: Non-discovery of non-colored SUSY particles @ LHC Run 2.

■ DM ⇔ $g-2$: tightly connected in MSSM

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extra DM?
non-simple cosmology?

coannihilation?
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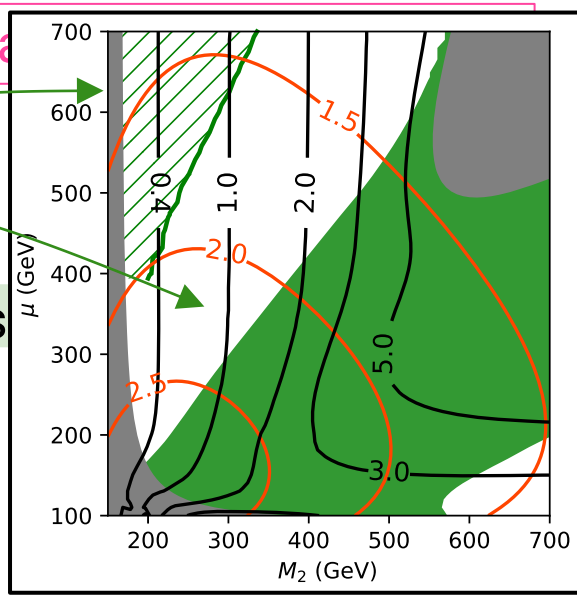
Coannihil. $\widetilde{B}$-DM ... 👍 still alive. → direct det., HL-LHC, ee colliders. $2\tau + \not{p}_{\mathrm{T}}$ $ee \to \tilde{\ell}\tilde{\ell}$

(N.B. There should always be loopholes / extensions.)

Bad news to me: Non-colored SUSY pa



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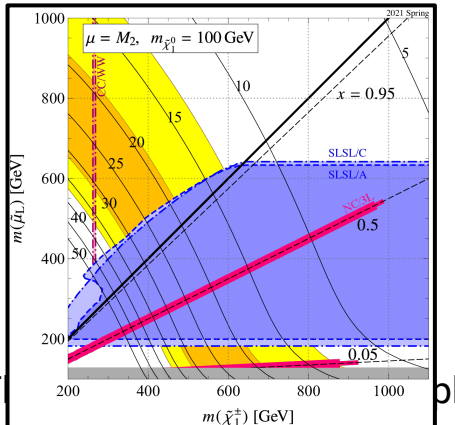
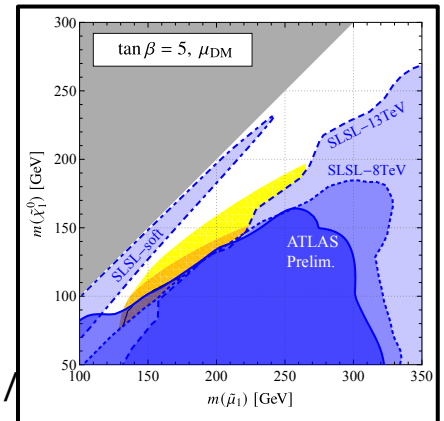
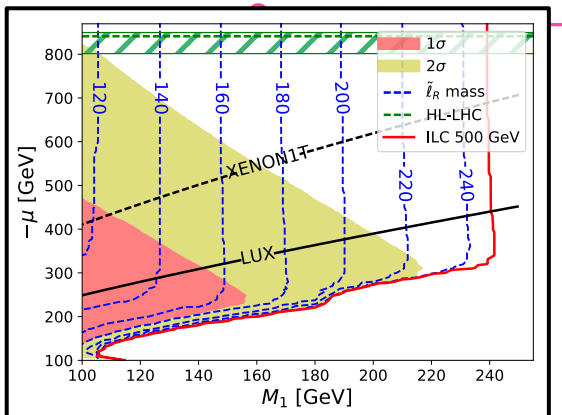
Coannihil. $\widetilde{B}$-DM ... 👍 still alive. → direct det., HL-LHC, ee colliders. → $\tilde{\ell}\tilde{\ell}$





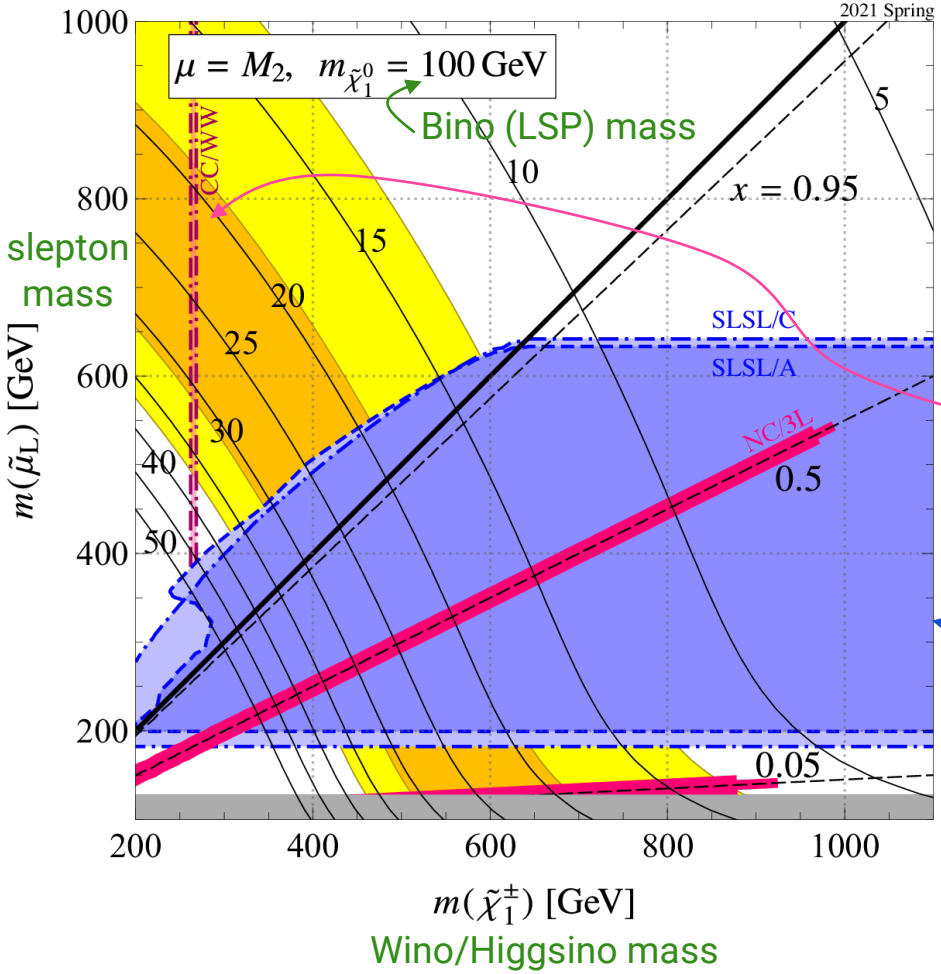


(N.B. T… …pholes /

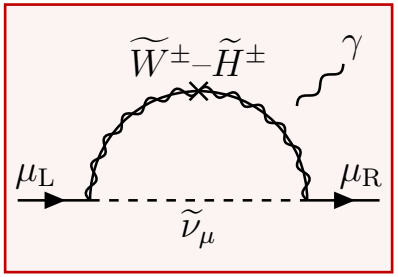
One topic I omitted from the mainstream of the talk

Example of WHL model with by-hand bino-LSP.

Endo, Hamaguchi, SI, Kitahara [2001.11025][2104.03217]



WHL



Various constraints @ LHC!

- $\tilde{\mu}_\mathrm{L} > \widetilde{W}^\pm, \widetilde{H}^\pm$

  $\widetilde{W}^+\widetilde{W}^- \to W^+W^- \not{p}_\mathrm{T}$ (CC/WW)

  $\widetilde{W}^0\widetilde{W}^+ \to ZW + \not{p}_\mathrm{T},\ HW + \not{p}_\mathrm{T}$ (NC/HW, NC/ZW)

- $\tilde{\mu}_\mathrm{L} < \widetilde{W}^\pm, \widetilde{H}^\pm$

  $\tilde{\mu}_\mathrm{L}\tilde{\mu}_\mathrm{L}^* \to 2\mu + \not{p}_\mathrm{T}$ (SLSL)

  $\widetilde{W}^0\widetilde{W}^+ \to (\mu\tilde{\mu}_\mathrm{L})(\mu\tilde{\nu}) \to 3\mu + \not{p}_\mathrm{T}$ (NC/3L)

(a bit of details in the next slide)

Stringent for $\mu_\mathrm{L} < \widetilde{W}^\pm, \widetilde{H}^\pm$.

N.B. Exclusions at the "*obviously* 95%-CL excluded" criterion.

Masses set at low energy,
$\mu = M_2$, $\tan\beta = 40$, $\tilde{\chi}_1^0 = 100\,\mathrm{GeV}$, $A_{u,d,e} = 0$,
right-handed sleptons, squarks, gluinos, extra Higgses $\gg 1\,\mathrm{TeV}$.

SLSL: ATLAS [1908.08215], CMS [2012.08600].
CC/WW: ATLAS [1909.09226].
NC/3L: CMS [1709.05406], ATLAS [1803.02762].
Results to be analyzed: 2106.01676, 2108.07586.

Endo, Hamaguchi, SI, Kitahara [2001.11025][2104.03217]

$\tilde{\mu}_{\rm L} < \tilde{W}^{\pm}, \tilde{H}^{\pm}$

cascade decay

$\tilde{W}, \tilde{H}$

$pp \to \tilde{\mu}_{\rm L}\tilde{\mu}_{\rm L}^{*} \to 2\mu + \not{p}_{\rm T}$

$\tilde{l}_{\rm L}, \tilde{\nu}$

$\tilde{B}$

Even though $\sigma(pp \to \tilde{\mu}_{\rm L}\tilde{\mu}_{\rm L}^{*}) \ll \sigma(pp \to \tilde{W}\tilde{W})$,
large luminosity in Run 2

→ **silver bullet** to kill models with
$\tilde{\mu}_{\rm L} < \tilde{W}^{\pm}, \tilde{H}^{\pm}$

(but not coannihil. region
→ next slide)

$\tilde{\mu}_{\rm L} > \tilde{W}^{\pm}, \tilde{H}^{\pm}$

$\tilde{l}_{\rm L}, \tilde{\nu}$

$\tilde{W}, \tilde{H}$

$\tilde{B}$

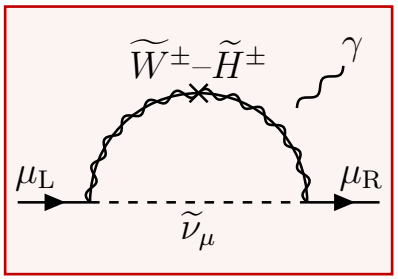
$(HW\,|\,ZW\,|\,WW) + \not{p}_{\rm T}$

Looks simple, but subtle.

- **destructive** interference:
  $\sigma(pp \to \tilde{\chi}\tilde{\chi})$ gets smaller
  if squarks are not decoupled.
  Liu, McGinnis, Wagner, Wang [2008.11847]
- multiple types of final states:
  needs to combine HW + ZW.
  (cf. ATLAS [2108.07586])

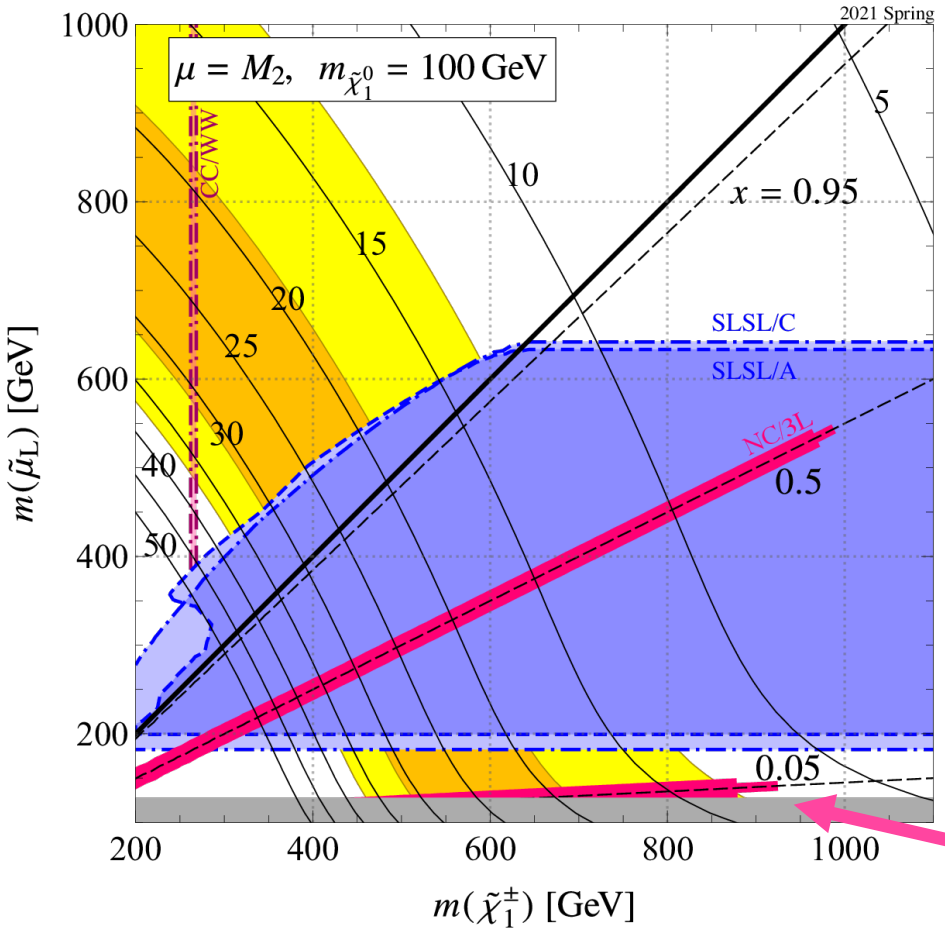
→ **yet to** discuss/analyze.

WHL



How about coannihilation region?

Endo, Hamaguchi, SI, Kitahara [2001.11025][2104.03217]



WHL + coannihil. $\widetilde{B}$-DM

$\widetilde{W}, \widetilde{H}$

$\downarrow$

$\tilde{l}_\mathrm{L}, \tilde{\nu}$

$\downarrow$

$\widetilde{B}$

$pp \to \widetilde{W}^+\widetilde{W}^0 \to \ell\ell\ell^{\mathrm{soft}} + \not{p}_\mathrm{T}$

- $\tilde{\mu}_\mathrm{L} < \widetilde{W}^\pm, \widetilde{H}^\pm$

$\tilde{\mu}_\mathrm{L}\tilde{\mu}_\mathrm{L}^* \to 2\mu + \not{p}_\mathrm{T}$	(SLSL)
$\widetilde{W}^0\widetilde{W}^+ \to (\mu\tilde{\mu}_\mathrm{L})(\mu\tilde{\nu}) \to 3\mu + \not{p}_\mathrm{T}$	(NC/3L)

⟶ Coannihilation region looks dead : **WHL & DM = difficult.**

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