SUSY Phenomenology at the LHC

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2 Feb. 2021

ELFT Winter School *"Physics beyond the Standard Modeℓ: Modern Approaches"* @ ELTE & ONLINE

Cf.) Martin, "A Supersymmetry Primer" [hep-ph/9709356],

Web pages of ATLAS and CMS public results of SUSY searches,

Endo, Hamaguchi, Iwamoto, Kitahara [2001.11025]

1) Introduction (intentionally overlaps with Dezső's lecture)

- What is SUSY?
- Why SUSY?

  ... DM, GUT, Natural, $(g-2)_\mu$

2) LHC

- Review of SUSY searches

3) $(g-2)_\mu$-SUSY vs LHC

Endo, Hamaguchi, Iwamoto, Kitahara [2001.11025]

- in depth 1: Theory
- in depth 2: LHC
- Fight!

1) Introduction

(intentionally overlaps with Dezső's lecture)

- What is SUSY?
- Why SUSY?

  ... DM, GUT, Natural, $(g-2)_\mu$

~40min.

2) LHC

- Review of SUSY searches

~20min.

3) $(g-2)_\mu$-SUSY vs LHC

Endo, Hamaguchi, Iwamoto, Kitahara [2001.11025]

- in depth 1: Theory
- in depth 2: LHC
- Fight!

~30min. ... 90min?

Much time for questions.

Exercise for my ELFT2021 lecture

Sho Iwamoto

Answer **two of the three** courses and submit your report.

1 “Student” course: interrupt me

1. Interrupt me in the middle of my lecture. (not after!)
2. Ask some nice or stupid question.
3. Write the question (that you asked me during my lecture) on the report.

2 “Scientist” course: explain LHC

Imagine you have a German friend on Twitter, who is a lawyer and interested in the LHC because some of their tax is used for it. For her/him, briefly explain the LHC in ~ 4 tweets ($\simeq 1120$ letters).

3 “Theorist” course: count DOF

Degree of freedom (DOF) is a very important concept in all fields of physics. For example, the Hubble parameter of the early Universe (i.e., when the temperature T was $T \gg 100\,\mathrm{MeV} \simeq 10^{12}\,{}^\circ\mathrm{C}$) is approximately given by[*1]

$$H(T) = \frac{\mathrm{d}}{\mathrm{d}t} \log(\text{size of the Universe}) \approx \sqrt{\frac{\pi^2}{90} g_*(T)} \frac{T^2}{2.43 \times 10^{18}\,\mathrm{GeV}}; \qquad g_*(T) \approx n_\mathrm{B}(T) + \frac{7}{8} n_\mathrm{F}(T),$$

where $\{n_\mathrm{B}, n_\mathrm{F}\}(T)$ is the DOF of {bosons, fermions} which have mass smaller than T. Therefore, if we consider only the Standard Model (SM), the parameter g_* above the top-quark mass is given by

$$g_* = (\text{Bosonic DOF of the SM}) + \frac{7}{8}(\text{Fermionic DOF of the SM}) = 106.75.$$

Having this in mind, answer the following questions.

1. Verify the fermionic DOF of the SM is 90. (hint: quarks amount to 72, leptons to 18)
2. Verify the bosonic DOF of the SM is 28. (hint: it comes from Higgs and gauge bosons)
3. Confirm the above equation “$g_* = 106.75$”.
4. (OPTIONAL) If you want a challenging problem, count the bosonic DOF of the MSSM. Check that it is equal to the fermionic DOF of the MSSM. This equality is guaranteed by SUSY.

[*1] Derivation is given in many textbooks: Kolb–Turner “The Early Universe” §3, Weinberg “Cosmology” §3.1, etc.

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- SUSY = **super**symmetry

fermion ⇔ boson

- string theory + SUSY = superstring theory

... the theory of gravity?

- standard model + SUSY = **S**upersymmetric **S**tandard **M**odel
  - **M**inimal **SSM** ← our focus today
  - **N**ext-to-**M**inimal **SSM**
  - ...

- Standard Model

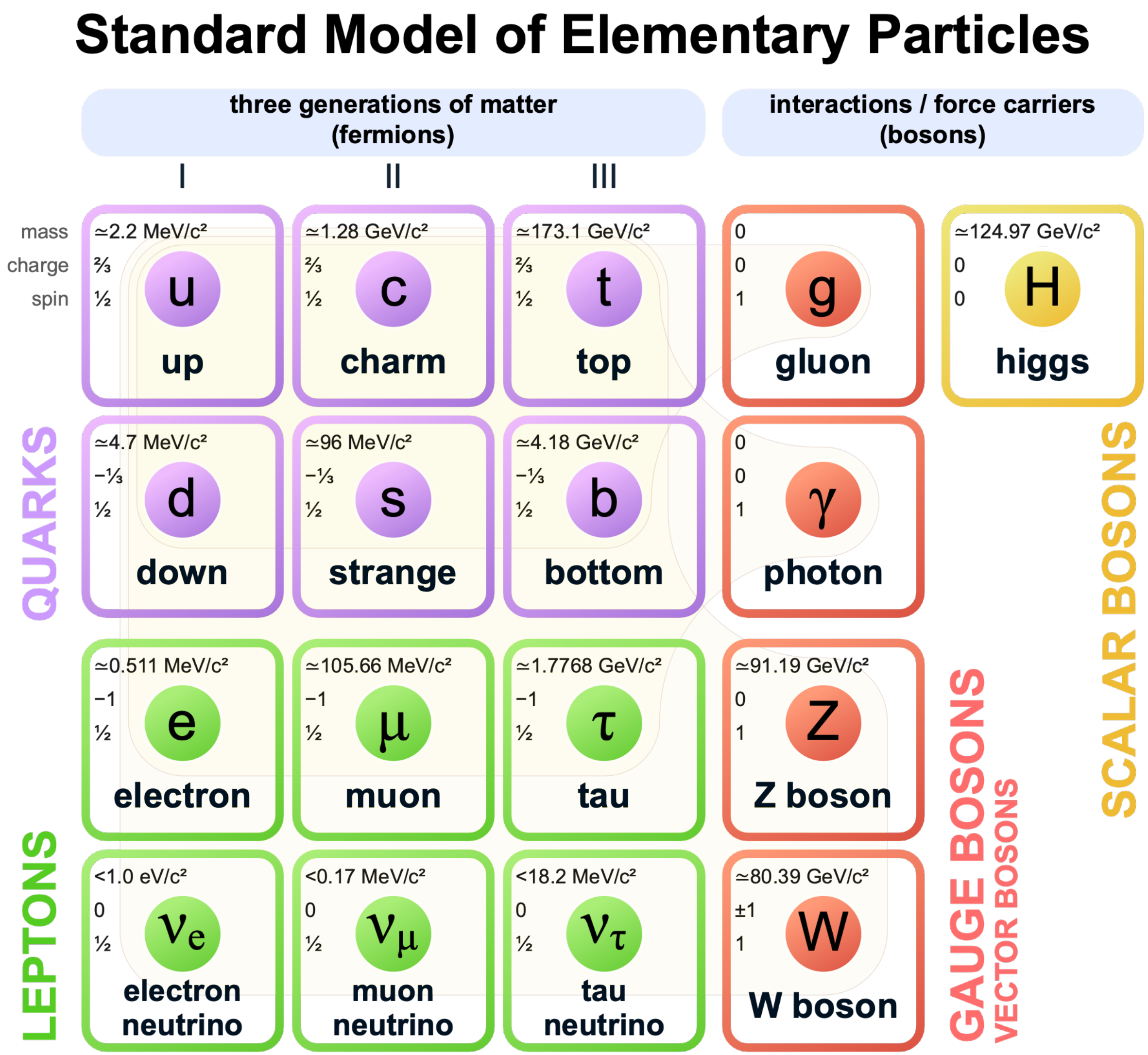

Image from Wikipedia

■ Standard Model

		$SU(3)_{color}$	$SU(2)_{weak}$	$U(1)_Y$	
matter (spinor) × 3 gen.	Q_L	3	2	1/6	$= (u_L, d_L)$
	U_R	3		2/3	$= u_R$
	D_R	3		−1/3	$= d_R$
	L_L		2	−1/2	$= (\nu_L, e_L)$
	E_R			−1	$= e_R$
gauge bosons	g	✓			(8 gluons)
	W		✓		(3 W-bosons)
	B			✓	
scalar boson	H		2	1/2	$= (\varphi_1 + i\,\varphi_2,\ h + i\,\varphi_3)$

ψ_u : up-type quarks

ψ_d : down-type quarks

ψ_ℓ : charged leptons

ν_L : neutrinos

(3 W-bosons) + B → $(W^+, W^-, Z) + \gamma$

Can you exercise "DOF counting"?

■ Standard Model

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ψ_u : up-type quarks

ψ_d : down-type quarks

ψ_ℓ : charged leptons

ν_L : neutrinos

(3 W-bosons), B → $(W^+, W^-, Z) + \gamma$

scalar: **real** = 1; **complex** = 2
spinor: **Weyl** (massless) = 2; **Dirac** (massive) = 4; **Majorana** (massive) = 2
vector: **massless** = 2; **massive** = 3

■ MSSM

		SU(3)$_{\text{color}}$	SU(2)$_{\text{weak}}$	U(1)$_Y$			
matter (spinor) × 3 gen.	$\boldsymbol{Q}_\mathrm{L}$	3	2	1/6	$= (u_\mathrm{L}, d_\mathrm{L})$	$(\tilde{u}_\mathrm{L}, \tilde{d}_\mathrm{L})$	
	$\boldsymbol{U}_\mathrm{R}$	3		2/3	$= u_\mathrm{R}$	$\tilde{u}_\mathrm{R}$	"Scalar quark"
	$\boldsymbol{D}_\mathrm{R}$	3		−1/3	$= d_\mathrm{R}$	+ $\tilde{d}_\mathrm{R}$	
	$\boldsymbol{L}_\mathrm{L}$		2	−1/2	$= (\nu_\mathrm{L}, e_\mathrm{L})$	$(\tilde{\nu}_\mathrm{L}, \tilde{e}_\mathrm{L})$	"Scalar lepton"
	$\boldsymbol{E}_\mathrm{R}$			−1	$= e_\mathrm{R}$	$\tilde{e}_\mathrm{R}$	
gauge bosons	$\boldsymbol{g}$	✓			(8 gluons)	$\tilde{g}$	"gluino" × 8
	$\boldsymbol{W}$		✓		(3 W-bosons)	+ $\widetilde{W}$	"wino" × 3
	$\boldsymbol{B}$			✓		$\widetilde{B}$	"bino" × 1
scalar bosons	$\boldsymbol{H}_\mathrm{u}$		2	1/2	$(H_\mathrm{u}^+, H_\mathrm{u}^0)$	+ $(\widetilde{H}_\mathrm{u}^+, \widetilde{H}_\mathrm{u}^0)$	
	$\boldsymbol{H}_\mathrm{d}$		2	−1/2	$(H_\mathrm{d}^0, H_\mathrm{d}^-)$	$(\widetilde{H}_\mathrm{d}^0, \widetilde{H}_\mathrm{d}^-)$	"Higgsinos"

Weyl **F.** ⇔ complex scalar **B.** "sfermion"

vector **B.** ⇔ Weyl **F.** "gauginos"

complex scalar **B.** ⇔ Weyl **F.**

scalar:	real	= 1
	complex	= 2
spinor:	Weyl (massless)	= 2
	Dirac (massive)	= 4
	Majorana (massive)	= 2
vector:	massless	= 2
	massive	= 3

MSSM: extra particles ⇨ search target @ LHC etc.

- extra Higgs bosons
  H^0, H^+, H^-, A^0
- colored SUSY particles
  $\tilde{g}$, $(\tilde{u}_\mathrm{L}, \tilde{d}_\mathrm{L}, \tilde{u}_\mathrm{R}, \tilde{d}_\mathrm{R})$ × 3 gen.
- **non-colored SUSY particles**
  - charged **s**leptons $(\tilde{e}_\mathrm{L}, \tilde{e}_\mathrm{R})$ × 3 gen.
  - **s**neutrinos $\tilde{\nu}_\mathrm{L}$ × 3 gen.
  - charg**inos** $(\widetilde{W}^\pm, \tilde{H}^\pm)$
  - neutral**inos** $(\tilde{B}, \widetilde{W}_3, \tilde{H}^0_\mathrm{d}, \tilde{H}^0_\mathrm{u})$

$(\tilde{u}_\mathrm{L}, \tilde{d}_\mathrm{L})$, $\tilde{u}_\mathrm{R}$, $\tilde{d}_\mathrm{R}$	"Scalar quark"
$(\tilde{\nu}_\mathrm{L}, \tilde{e}_\mathrm{L})$, $\tilde{e}_\mathrm{R}$	"Scalar lepton"
$\tilde{g}$	"gluino" × 8
$\widetilde{W}$	"wino" × 3
$\tilde{B}$	"bino" × 1
$(\tilde{H}^+_\mathrm{u}, \tilde{H}^0_\mathrm{u})$, $(\tilde{H}^0_\mathrm{d}, \tilde{H}^-_\mathrm{d})$	"Higgsinos"

$(H^+_\mathrm{u}, H^0_\mathrm{u})$
$(H^0_\mathrm{d}, H^-_\mathrm{d})$
⇩
h, $\boldsymbol{H^0, H^+, H^-, A^0}$ (& φ_{1-3})

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- Fight!

Problems in SM

- Neutrino mass = 0.
- No dark matter.
- No gravity / dark energy.
- No inflation.
- No baryon asymmetry.
- Non-unification of 3 forces.
- Unnatural Higgs mass.
- Unnatural θ_{QCD}.
- Discrepancies in expm:
  - muon $g-2$
  - $b \to s \mu \mu$
  - $R(D)$, $R(D^*)$
  - ......

Problems in SM

- Neutrino mass = 0. → introduce ν_R. ✓
- **No dark matter.** → **MSSM?**
- No gravity / dark energy.
- No inflation.
- No baryon asymmetry.

  → many models are proposed. (far above the collider energy)
- **Non-unification of 3 forces.**
- **Unnatural Higgs mass.**

  → **MSSM?**
- Unnatural θ_{QCD}. → introduce axion?
- Discrepancies in expm:
  - **muon g−2** → **MSSM?**
  - $b \to s\,\mu\,\mu$
  - $R(D)$, $R(D^*)$
  - ......

  → 3−4σ level; need efforts on expm/theory.

(cf. MSSM+ν_R+axion+inflaton+leptogenesis+.... would explain all these.)

■ Dark matter

- **necessary!!**
- maybe: New non-colored neutral stable particle? *or quasi-stable*
  - sneutrinos $\tilde{\nu}_{\rm L}$
  - neutralinos $(\widetilde{B}, \widetilde{W}_3, \widetilde{H}^0_{\rm d}, \widetilde{H}^0_{\rm u})$

non-colored SUSY particles
- charged sleptons $(\tilde{e}_{\rm L}, \tilde{e}_{\rm R})$ × 3 gen.
- sneutrinos $\tilde{\nu}_{\rm L}$ × 3 gen.
- charginos $(\widetilde{W}^{\pm}, \widetilde{H}^{\pm})$
- neutralinos $(\widetilde{B}, \widetilde{W}_3, \widetilde{H}^0_{\rm d}, \widetilde{H}^0_{\rm u})$

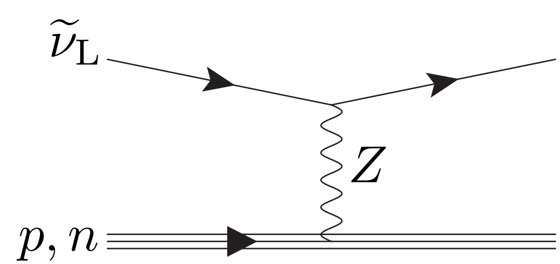
Requirements:

1) Stable. → **R-parity** "if R-parity is conserved, the Lightest SParticle become stable." **[next→]**

2) Density as observed.

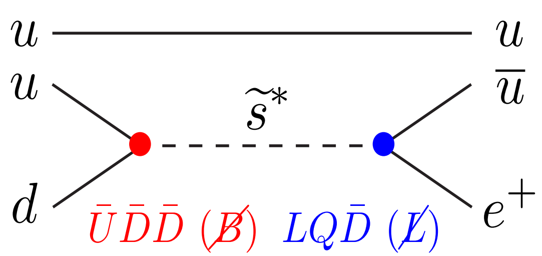
3) Avoiding constraints of DM searches.

→ depends on sparticle mass & couplings (→ later)
but $\tilde{\nu}_{\rm L}$ tends to fail.



- Nature: No proton decay.
- MSSM induces proton decay. ✗ ⇔ SM does not. ✓

"accidental conservation of baryon- & lepton-numbers"



→ Need to ensure proton stability

by introducing some artificial symmetry...

the most popular

"*R*-parity" { SM particles = even. SUSY particles = odd. ⇨ The LSP becomes stable.

nice biproduct!

- "MSSM + R-parity" keeps proton stable. ✓

and the LSP ➔ **DM candidate!** 😍

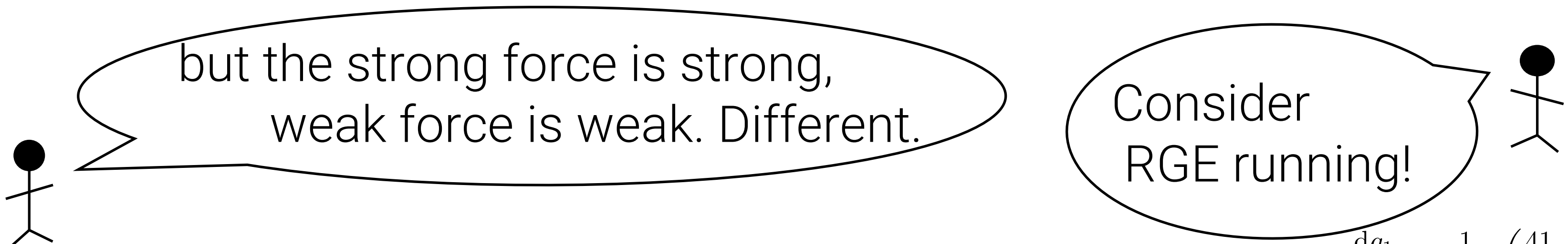
1) "MSSM + *R*-parity" has a **dark matter** candidate (the lightest neutralino).

- This **is** a good motivation.

(but there are much simpler models just for DM.)

- We[who?] believe the 3 forces are to be unified

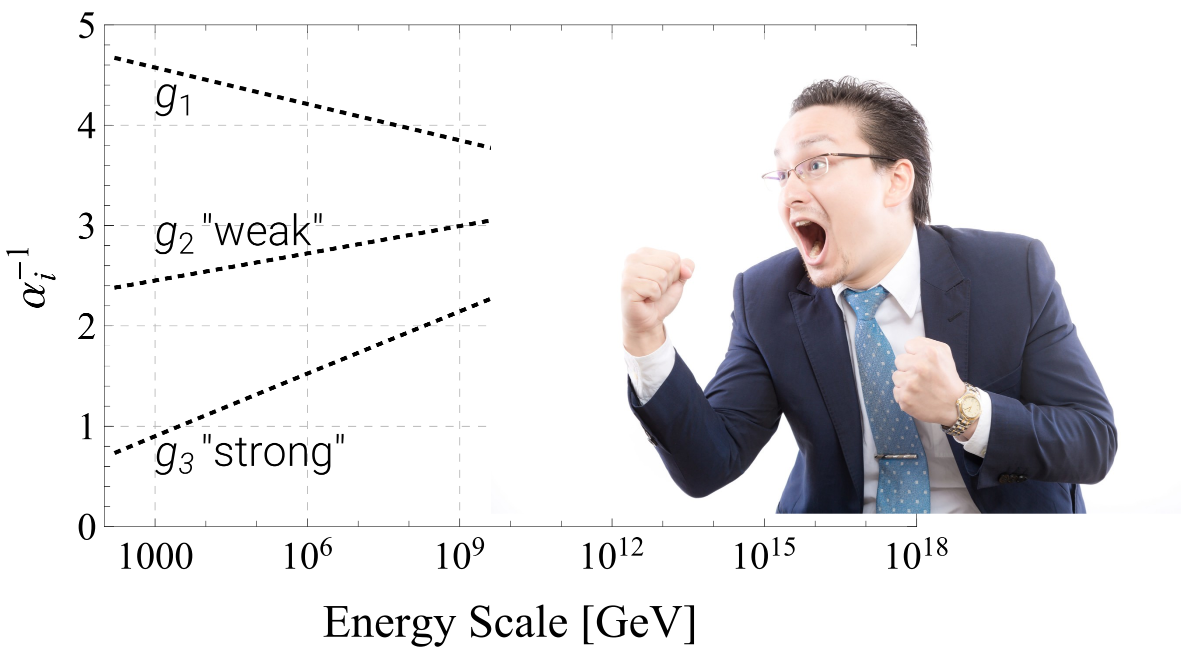
  ... "Grand Unification Theory".



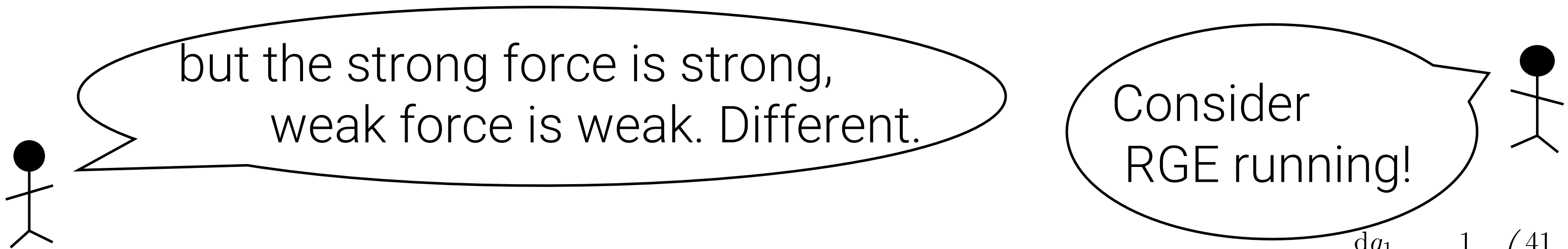
$$\frac{\mathrm{d}g_1}{\mathrm{d}t} \simeq \frac{1}{16\pi^2}\left(\frac{41}{10}g_1^3\right)$$
$$\frac{\mathrm{d}g_2}{\mathrm{d}t} \simeq \frac{1}{16\pi^2}\left(\frac{-19}{6}g_2^3\right)$$
$$\frac{\mathrm{d}g_3}{\mathrm{d}t} \simeq \frac{1}{16\pi^2}\left(-7g_3^3\right)$$
$$(\alpha_i = g_i^2/4\pi, \quad t = \log Q, \quad g_1 = \sqrt{5/3}g_Y)$$

(Cf. Machacek, Vaughn, Nucl. Phys. **B222** (1983) 83)

- Gauge couplings "run" because of renormalization.



- We[who?] believe the 3 forces are to be unified ... "Grand Unification Theory".



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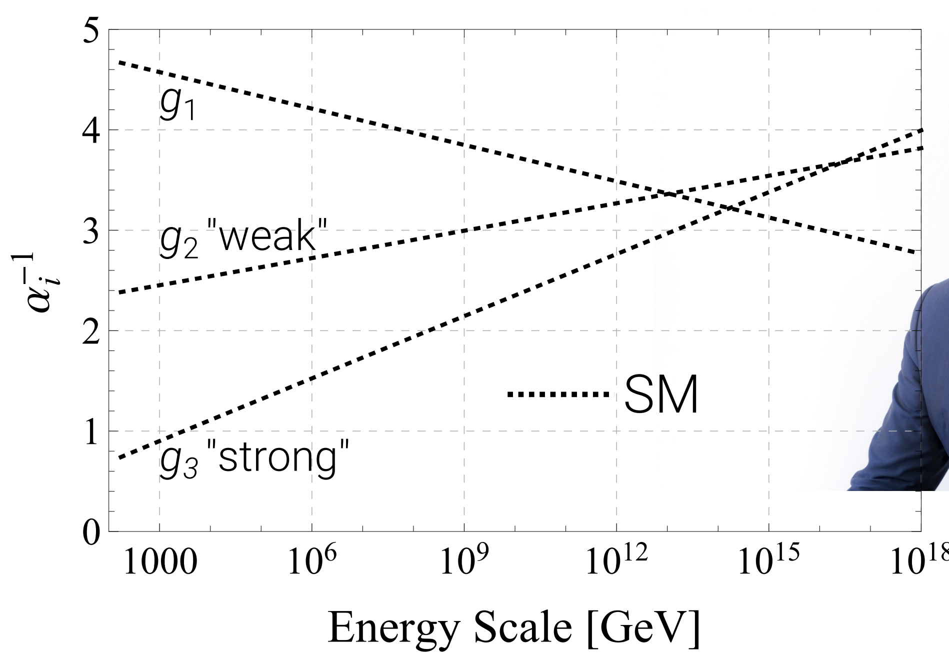
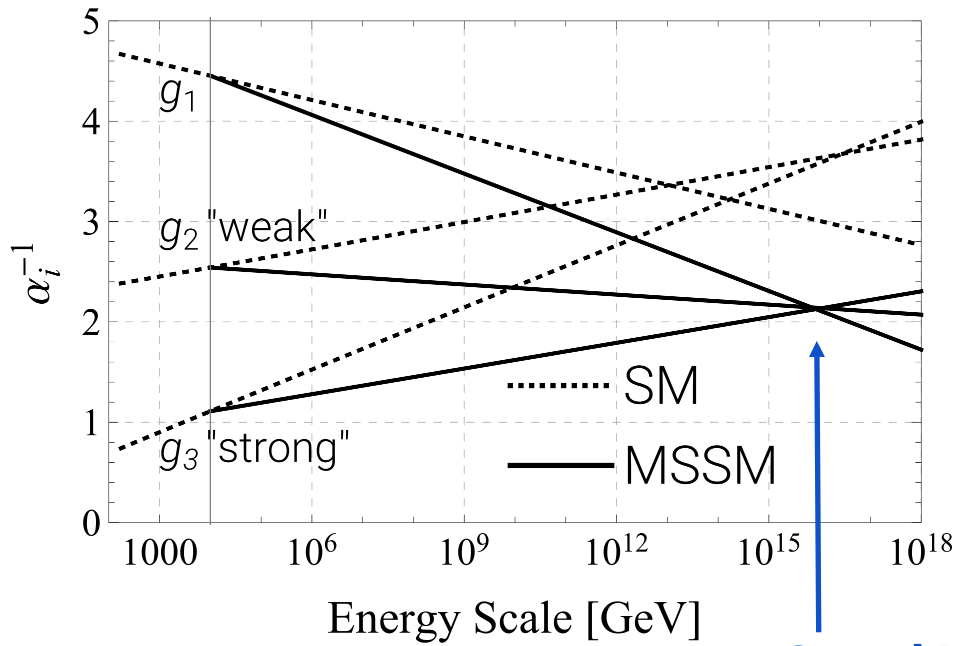


- We[who?] believe the 3 forces are to be unified
  ... "Grand Unification Theory".

- Extra particles modify the renormalization group evolution:

if all **s**particle masses are 10^4 GeV



$$\frac{\mathrm{d}g_1}{\mathrm{d}t} \simeq \frac{1}{16\pi^2}\left(\frac{\mathbf{33}}{\mathbf{5}}g_1^3\right)$$
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$$(\alpha_i = g_i^2/4\pi, \quad t = \log Q, \quad g_1 = \sqrt{5/3}g_Y)$$

Grand Unification @ 10^{16} GeV!?

1) "MSSM + *R*-parity" has a **dark matter** candidate (the lightest neutralino).
   - ➢ This **is** a good motivation. (but there are much simpler models just for DM.)

2) helps **gauge coupling unification** if mass ~1–100 TeV.
   - ➢ This **is** a strong motivation. (but just a coincidence? Who believe in Grand Unification?)

■ Higgs mass is unnatural.

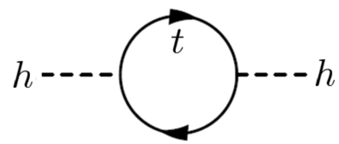
quantum correction

$$m_h^2 \simeq m_{\text{bare}}^2 + \Delta m_h^2$$

physical mass
10^4 GeV^2

Λ (cutoff) ~ Planck or GUT scale

$$\text{SM:} \quad \Delta m_h^2 \sim -\frac{3y_t^2}{4\pi^2}\Lambda^2 + \cdots$$



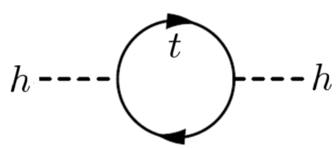
"naturalness problem"
"hierarchy problem"

<u>before 2012</u>

- ➢ No Higgs? (e.g., technicolor, extra dim., gauge-Higgs unif., ...)

- ➢ SUSY?

$$\text{MSSM:} \quad \Delta m_h^2 \sim -\frac{3y_t^2}{4\pi^2}\Lambda^2 + \frac{3y_t^2}{4\pi^2}\Lambda^2 + \cdots$$



"scalar top $\tilde{t}$" contribution

"Quadratic divergence" is cancelled out: Power of symmetry!

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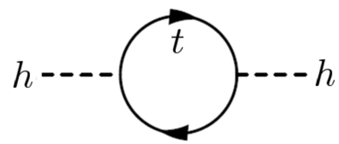


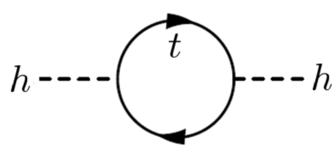
"naturalness problem"
"hierarchy problem"

4 July 2012: Higgs discovery

➢ ~~Non-Higgs? (e.g., technicolor, extra dim., gauge Higgs unif., ...)~~

➢ **SUSY!!!!**

$$\text{MSSM:} \quad \Delta m_h^2 \sim -\frac{3y_t^2}{4\pi^2}\Lambda^2 + \frac{3y_t^2}{4\pi^2}\Lambda^2 + \cdots$$



"scalar top $\tilde{t}$" contribution

"Quadratic divergence" is cancelled out: Power of symmetry!

Kitano, Nomura [hep-ph/0602096]

■ However....

$$\text{MSSM:}\quad \Delta m_h^2 \sim -\frac{3y_t^2}{4\pi^2}\Lambda^2 + \frac{3y_t^2}{4\pi^2}\Lambda^2 + \cdots$$

$$\sim -\frac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 \log\frac{\Lambda}{m_{\tilde{t}}} + \cdots$$

"Log divergence"

➢ if scalar-top mass is

$300\,\text{GeV}:$	$10^5 + (-10^5) \rightsquigarrow 10^4$	$[10\%]$	☺️	natural
$1000\,\text{GeV}:$	$10^6 + (-10^6) \rightsquigarrow 10^4$	$[1\%]$	😕	
$3000\,\text{GeV}:$	$10^7 + (-10^7) \rightsquigarrow 10^4$	$[0.1\%]$	👿	unnatural

(my subjective opinion)

- **We expected scalar quark at $\mathcal{O}$(0.1–1) TeV.** (motivation for 14 TeV LHC!)

After 2018 (LHC Run 2)

➢ **No SUSY yet.** Strong constraints on ~300 GeV squarks. [→ later]

➢ **SUSY fails to solve the hierarchy problem?????**

Kitano, Nomura [hep-ph/0602096]

■ Ho

Note

MSSM condition for EWSB:

$$\frac{m_Z^2}{2} = -\mu^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}$$

(little hierarchy problem on Higgsino mass μ)

Requirements for "natural SUSY"

Papucci, Ruderman, Weiler [1110.6926]

Higgsino mass

$$|\mu| \lesssim 200\,\mathrm{GeV}\left(\frac{\Delta^{-1}}{20\,\%}\right)^{-1/2}$$

scalar-top mass

$$\sqrt{m_{\tilde t_1}^2 + m_{\tilde t_2}^2} \lesssim 600\,\mathrm{GeV}\frac{\sin\beta}{\sqrt{1+\alpha^2}}\left(\frac{\log(\Lambda/\mathrm{TeV})}{3}\right)^{-1/2}\left(\frac{\Delta^{-1}}{20\,\%}\right)^{-1/2}$$

gluino mass

$$m_{\tilde g} \lesssim 900\,\mathrm{GeV}\cdot\sin\beta\left(\frac{\log(\Lambda/\mathrm{TeV})}{3}\right)^{-1/2}\left(\frac{\Delta^{-1}}{20\,\%}\right)^{-1/2}$$

ral

pinion)

After 2018 (LHC Run 2)

- ➢ **No SUSY yet.** Strong constraints on ~300 GeV squarks. [→ later]
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1) "MSSM + *R*-parity" has a **dark matter** candidate (the lightest neutralino).
   - ➢ This **is** a good motivation.

     (but there are much simpler models just for DM.)

2) helps **gauge coupling unification** if mass ~1–100 TeV.
   - ➢ This **is** a strong motivation.

     (but just a coincidence? Who believe in Grand Unification?)

3) solves **hierarchy problem** if scalar-top mass $\lesssim$ 1TeV.
   - ➢ This **was** the best-strongest motivation (because not much alternatives).

     (but "unnatural" is a problem? Nature can be unnatural.)
     (but scalar-top mass seems not so light....)

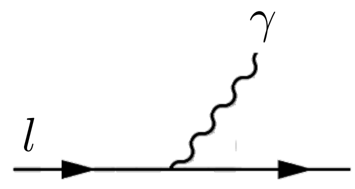
$$\boldsymbol{\mu} = g_l \frac{e}{2m_l}\boldsymbol{S}$$

[magnetic moment] [spin]

■ Muon g−2 anomaly

- lepton's g-factor

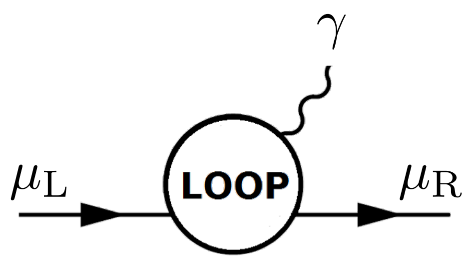
$$g_{e,\mu,\tau} \simeq 2 \longleftrightarrow \mathrm{Re}\Big(\quad \Big)$$



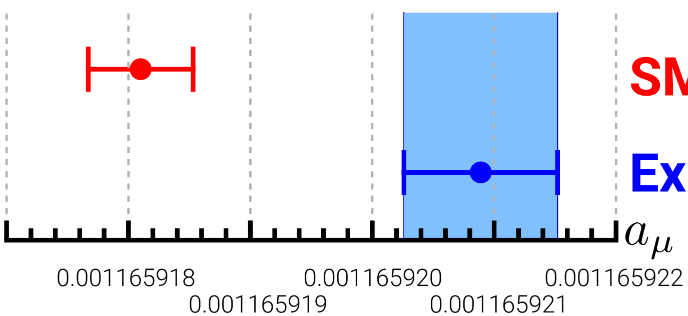
[tree level = classical]

- muon g−2 [anomalous magnetic moment]

$$a_\mu \equiv \frac{g_\mu - 2}{2} \longleftrightarrow \mathrm{Re}\Big(\quad \Big)$$



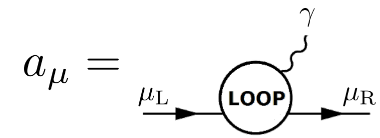
[loop level
= quantum correction]

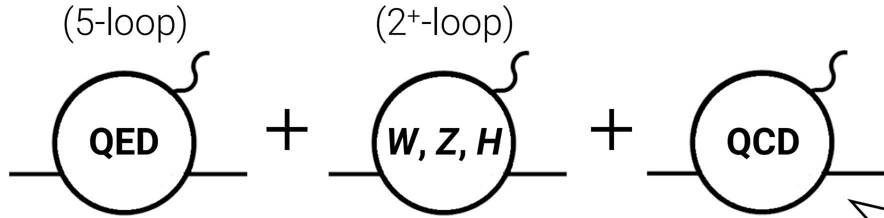


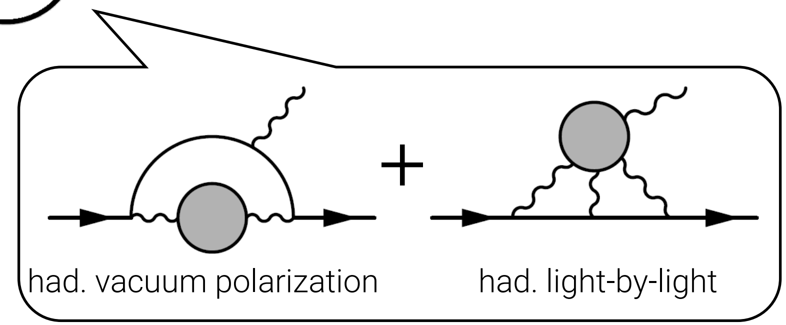
SM [theory] ("muon g−2 white paper" 2006.04822) [→ next slide]

Experiment @Brookhaven National Laboratory, 2004

3.6σ-level discrepancy!



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



$$a_\mu(\text{expm}) = (11\,659\,208.9 \pm 6.3) \times 10^{-10}$$ BNL '04 + 2018 CODATA

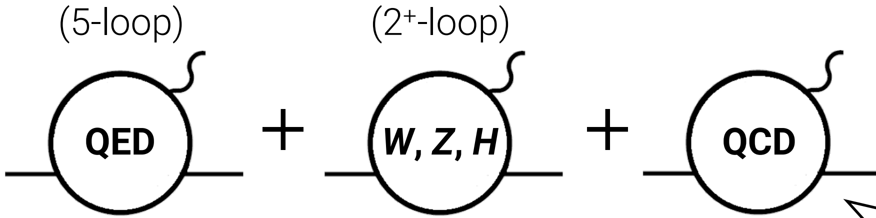
$$a_\mu(\text{SM}) = (11\,659\,181.0 \pm 4.3) \times 10^{-10}$$ "muon g−2 white paper" [2006.04822]

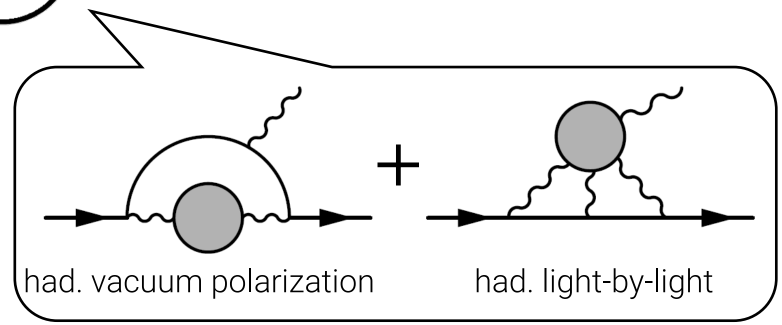
$$\text{QED} = (11\,658\,471.893 \pm 0.010) \times 10^{-10},$$
$$\text{EW} = (15.36 \pm 0.10) \times 10^{-10},$$
established!

$$\text{HVP} = (684.5 \pm 4.0) \times 10^{-10},$$
$$\text{HLbL} = (9.2 \pm 1.8) \times 10^{-10}.$$
need improvements / under discussion

expm: Muon g−2 collaboration [hep-ex/0602035]
QED: Aoyama, Hayakawa, Kinoshita, Nio [1205.5370] (cf. Atoms **7** (2019) 28)
EW: Gnendiger, Stöckinger, Stöckinger-Kim [1306.5546].
SM combination given in "Muon g−2 whitepaper" [2006.04822]

Lopez, Nanopoulos, Wang [ph/9308336]
Chattopadhyay, Nath [ph/9507386]
Moroi [ph/9512396]

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



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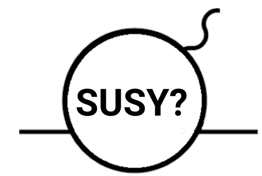
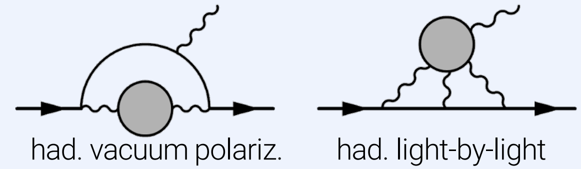
$$\boldsymbol{\Delta a_\mu = (\quad 27.9 \quad \pm 7.6 \quad) \times 10^{-10}}$$ **from new physics!?**



0th order estimation:

$$a_\mu^{\mathrm{NP}} \sim \frac{m_\mu^2}{16\pi^2}\frac{(\text{new coupling})^2}{(\text{new mass})^2} \Rightarrow \frac{\text{mass}}{\text{coupling}} \sim 150\,\mathrm{GeV}$$

100–500 GeV non-colored SUSY particles may explain this anomaly.



■ theory side: HVP and HLbL

"muon *g*−2 white paper" [2006.04822]

Contribution	Section	Equation	Value $\times 10^{11}$	References
Experiment (E821)		Eq. (8.13)	116 592 089(63)	Ref. [1]
HVP LO (e^+e^-)	Sec. 2.3.7	Eq. (2.33)	6931(40)	Refs. [2–7]
HVP NLO (e^+e^-)	Sec. 2.3.8	Eq. (2.34)	−98.3(7)	Ref. [7]
HVP NNLO (e^+e^-)	Sec. 2.3.8	Eq. (2.35)	12.4(1)	Ref. [8]
HVP LO (lattice, $udsc$)	Sec. 3.5.1	Eq. (3.49)	7116(184)	Refs. [9–17]
HLbL (phenomenology)	Sec. 4.9.4	Eq. (4.92)	92(19)	Refs. [18–30]
HLbL NLO (phenomenology)	Sec. 4.8	Eq. (4.91)	2(1)	Ref. [31]
HLbL (lattice, uds)	Sec. 5.7	Eq. (5.49)	79(35)	Ref. [32]
HLbL (phenomenology + lattice)	Sec. 8	Eq. (8.10)	90(17)	Refs. [18–30, 32]
QED	Sec. 6.5	Eq. (6.30)	116 584 718.931(104)	Refs. [33, 34]
Electroweak	Sec. 7.4	Eq. (7.16)	153.6(1.0)	Refs. [35, 36]
HVP (e^+e^-, LO + NLO + NNLO)	Sec. 8	Eq. (8.5)	6845(40)	Refs. [2–8]
HLbL (phenomenology + lattice + NLO)	Sec. 8	Eq. (8.11)	92(18)	Refs. [18–32]
Total SM Value	Sec. 8	Eq. (8.12)	116 591 810(43)	Refs. [2–8, 18–24, 31–36]
Difference: $\Delta a_\mu := a_\mu^{\rm exp} - a_\mu^{\rm SM}$	Sec. 8	Eq. (8.14)	279(76)	

Cited 16 refs. for HVP

Cited 15 refs. for HLbL

very involved...

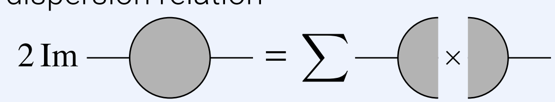
❖ Two methods to estimate HVP

1) dispersion rel. (e^+e^-) 693.1 ± 4.0

2) lattice calculation 711.6 ± 18.4 when the whitepaper was written

$\Rightarrow 708.7 \pm 5.3$ Borsanyi, Fodor, Guenther, et al. [2002.12347]

dispersion relation

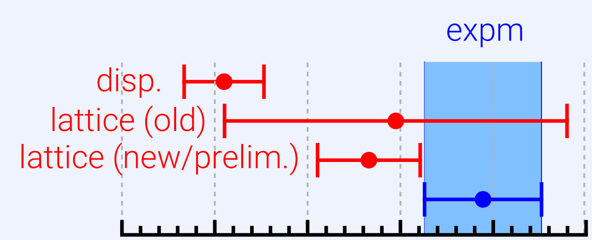


❖ Two methods to estimate HLbL

1) low-energy EFT 9.4 ± 1.9

2) lattice calculation 7.9 ± 3.5

lattice is improving!



under hot discussion...

■ experiment side: **New result is coming out!**

$$a_\mu(\mathrm{expm}) = (11\,659\,208.9 \pm 6.3) \times 10^{-10}$$
$$a_\mu(\mathrm{SM}) = (11\,659\,181.0 \pm 4.3) \times 10^{-10}$$

🡐 Only one experiment @ BNL.
& Uncertainty is *now* larger.

➢ New experiment @ Fermilab is Running since 2018.

$$a_\mu(\mathrm{Fermilab}) = (11\,659\,???.? \pm [\sim \mathbf{6}\ \ ]) \times 10^{-10}$$ in **SPRING** 2021

$$(11\,659\,???.? \pm [\sim \mathbf{1.5}]) \times 10^{-10}$$ in 202X

stay tuned!

Cf.) *Science* article (for public) on 27 Jan. 2021
[https://doi.org/10.1126/science.abg7862]

1) "MSSM + *R*-parity" has a **dark matter** candidate (the lightest neutralino).
   - This **is** a good motivation. (but there are much simpler models just for DM.)

2) helps **gauge coupling unification** if mass ~1−100 TeV.
   - This **is** a strong motivation. (but just a coincidence? Who believe in Grand Unification?)

3) solves **hierarchy problem** if scalar-top mass $\lesssim$ 1TeV.
   - This **was** the best-strongest motivation (because not much alternatives).

     (but "unnatural" is a problem? Nature can be unnatural.)
     (but scalar-top mass seems not so light....)

4) may explain the **Muon *g*−2 anomaly**.
   - Non-colored sparticle mass should be 100−500 GeV.
   - This **is** ONE motivation. Not much alternatives. (but it's only 3σ-level + many remarks.)

1) Introduction

- What is SUSY?
- Why SUSY?

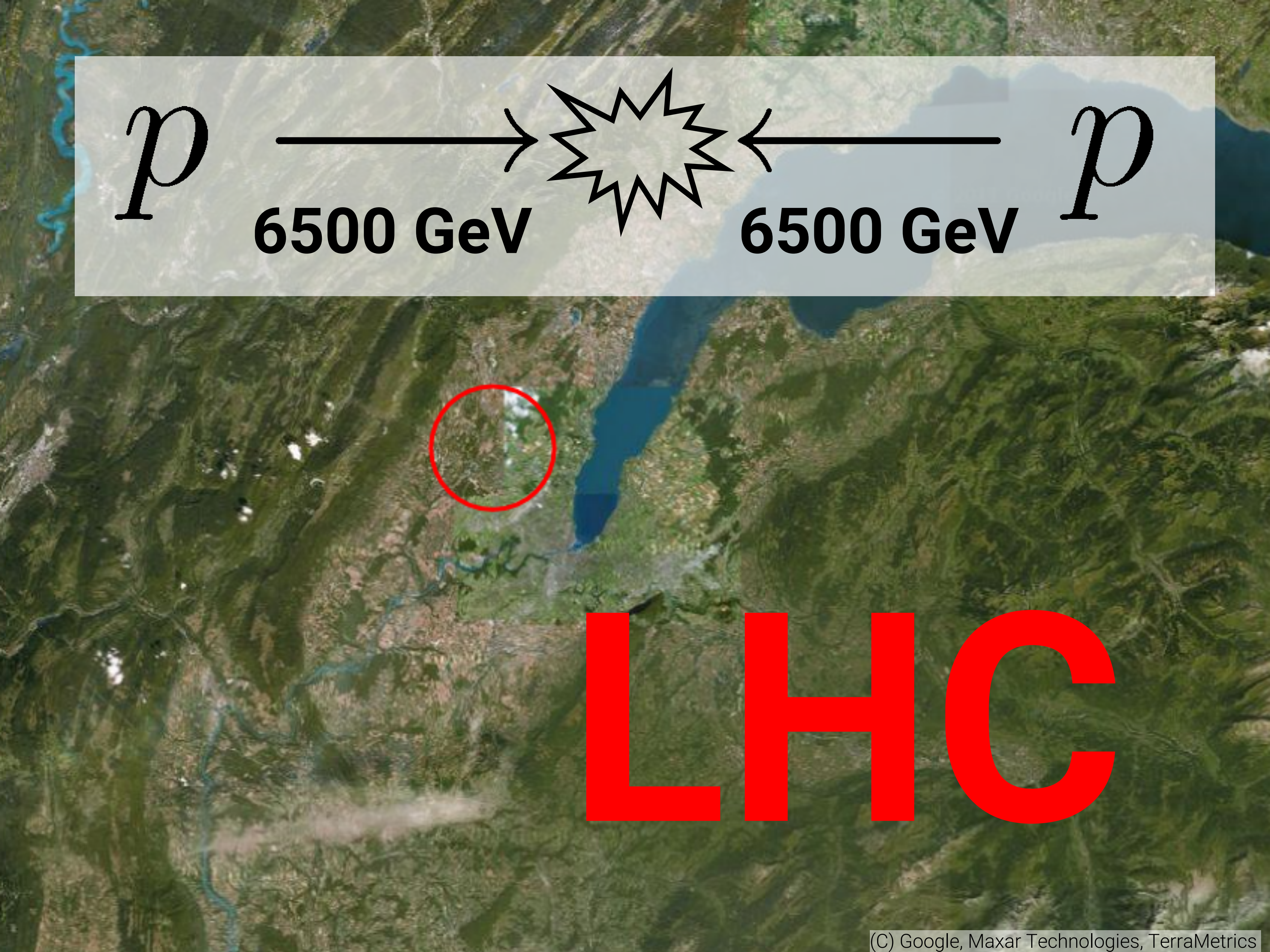
  ... DM, GUT, Natural, $(g-2)_\mu$

2) LHC

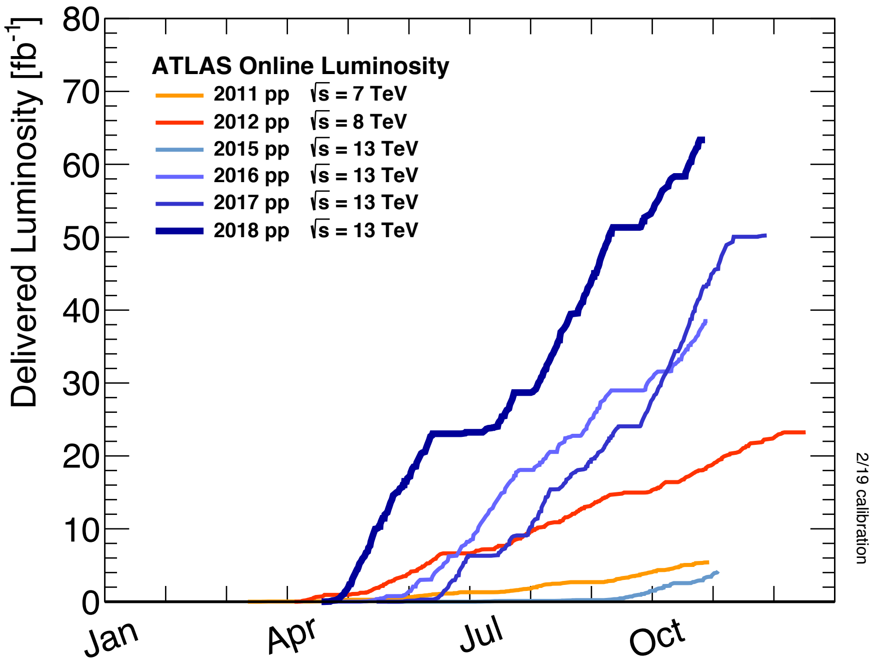
- Review of SUSY searches

3) $(g-2)_\mu$-SUSY vs LHC

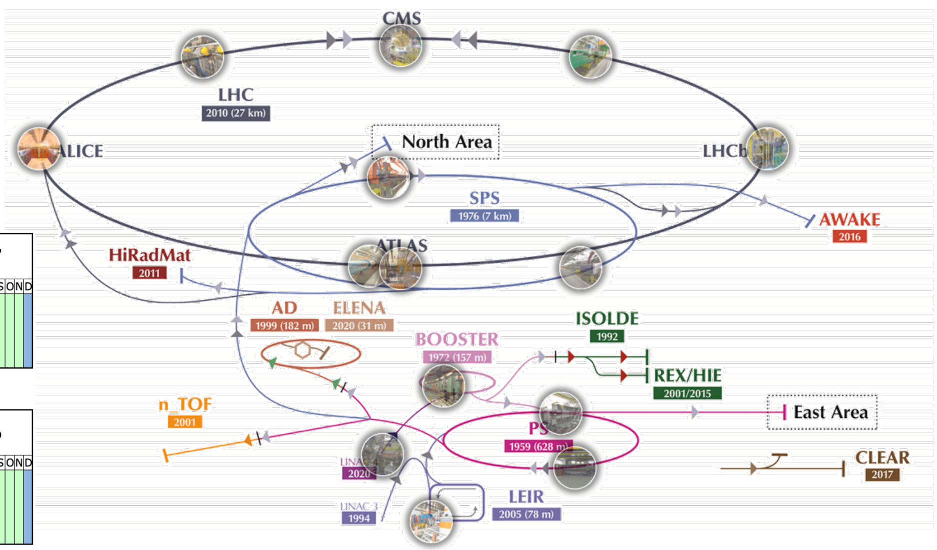
- in depth 1: Theory
- in depth 2: LHC
- Fight!


p
6500 GeV
6500 GeV
p
LHC
(C) Google, Maxar Technologies, TerraMetrics

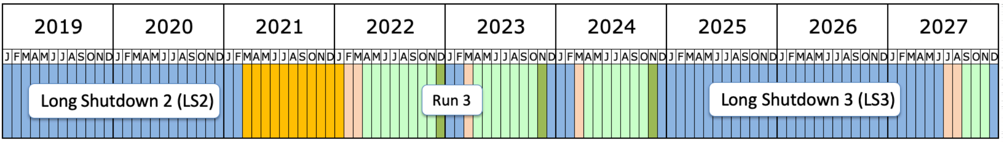
- LHC = proton collider



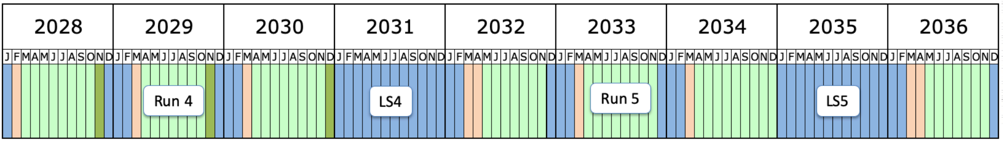
from LuminosityPublicResultsRun2



from CERN accelerating science webpage



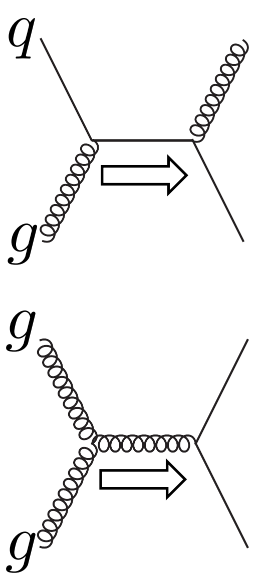
(delayed due to COVID-19)



Shutdown/Technical stop
Protons physics
Ions
Commissioning with beam
Hardware commissioning/magnet training

from CERN LHC-commissioning webpage

- LHC = proton collider
  → machine to produce **TeV-scale colored particles**.



colored particles

strong couplings

$(\widetilde{u}_{\rm L}, \widetilde{d}_{\rm L})$
$\widetilde{u}_{\rm R}$ "Scalar quark"
$\widetilde{d}_{\rm R}$

$(\widetilde{\nu}_{\rm L}, \widetilde{e}_{\rm L})$ "Scalar lepton"
$\widetilde{e}_{\rm R}$

$\widetilde{g}$ "gluino" × 8

$\widetilde{W}$ "wino" × 3
$\widetilde{B}$ "bino" × 1

$(\widetilde{H}_{\rm u}^{+}, \widetilde{H}_{\rm u}^{0})$
$(\widetilde{H}_{\rm d}^{0}, \widetilde{H}_{\rm d}^{-})$ "Higgsinos"

H^0, H^+, H^-, A^0
extra Higgs

- LHC = proton collider
  → machine to produce **TeV-scale colored particles**.

➢ 3 channels for colored-SUSY production

- $p + p \to \tilde{g} + \tilde{g}$
- $p + p \to \tilde{g} + \tilde{q}^{(*)}$
- $p + p \to \tilde{q} + \tilde{q}^{*}$

➢ Particles have many decay patterns

[→ next slide]

- $\tilde{t} \to t\,\tilde{\chi}_1^0$
- $\tilde{t} \to b\,\tilde{\chi}_1^+ \to bW^+\tilde{\chi}_1^0$
- $\tilde{t} \to t\,\tilde{\chi}_2^0 \to tZ\tilde{\chi}_1^0$
- $\tilde{t} \to t\,\tilde{\chi}_3^0 \to bW^+\tilde{\chi}_1^+ \to \cdots$
- $\cdots\cdots$

$(\tilde{u}_\mathrm{L}, \tilde{d}_\mathrm{L})$
$\tilde{u}_\mathrm{R}$ "Scalar quark"
$\tilde{d}_\mathrm{R}$

$(\tilde{\nu}_\mathrm{L}, \tilde{e}_\mathrm{L})$ "Scalar lepton"
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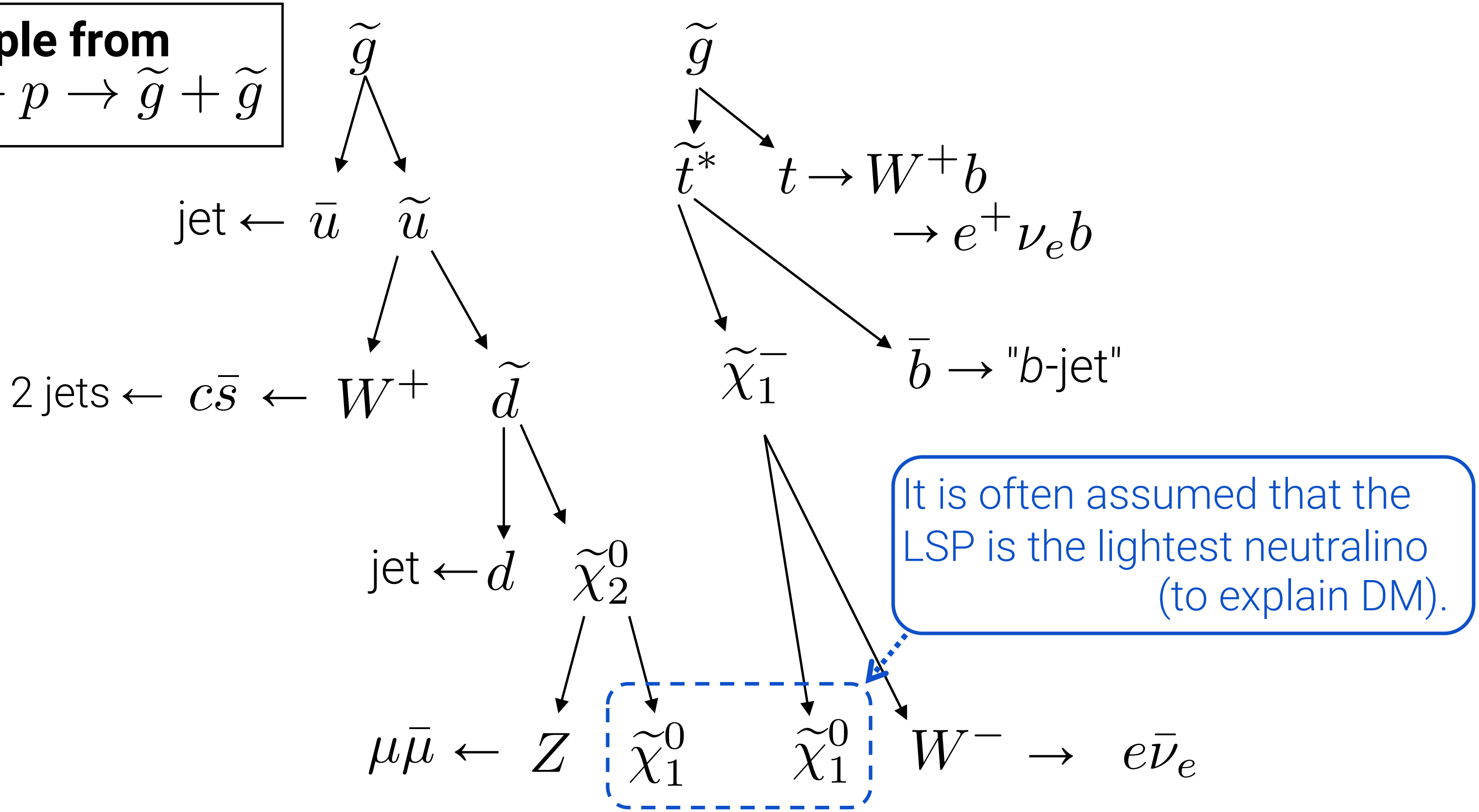
$\tilde{g}$ "gluino" × 8

$\widetilde{W}$ "wino" × 3
$\widetilde{B}$ "bino" × 1

$(\widetilde{H}_\mathrm{u}^+, \widetilde{H}_\mathrm{u}^0)$
$(\widetilde{H}_\mathrm{d}^0, \widetilde{H}_\mathrm{d}^-)$ "Higgsinos"

H^0, H^+, H^-, A^0
extra Higgs

an example from
$$p + p \to \tilde{g} + \tilde{g}$$



$$\tilde{g}\tilde{g} \to 4j2b(2e)^{\rm OS}(2\mu)^{\rm OS} + \not{E}_{\rm T} \text{ signature}$$

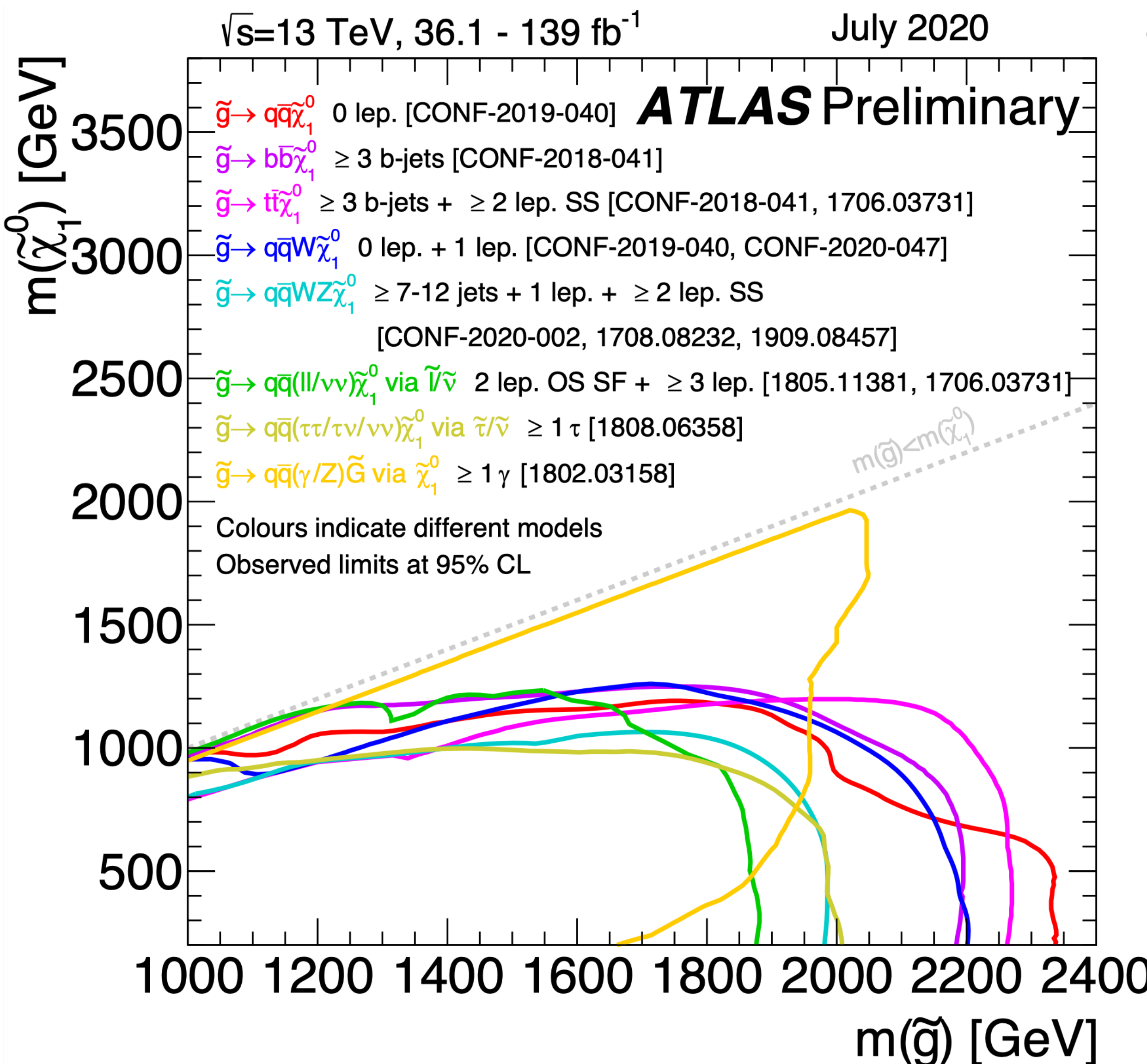
[opposite sign] [missing transverse energy]

Various decay pattern depending on mass spectrum.

➔ **We usually consider "simplified models."**

LHC Run 2 results on colored SUSY particle searches

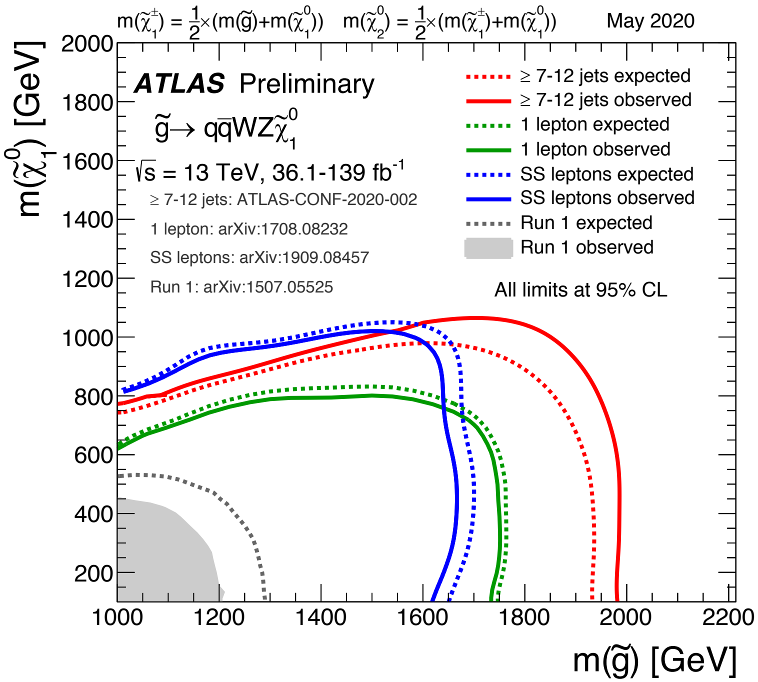
ATLAS, SUSY July 2020 Summary Plot Update

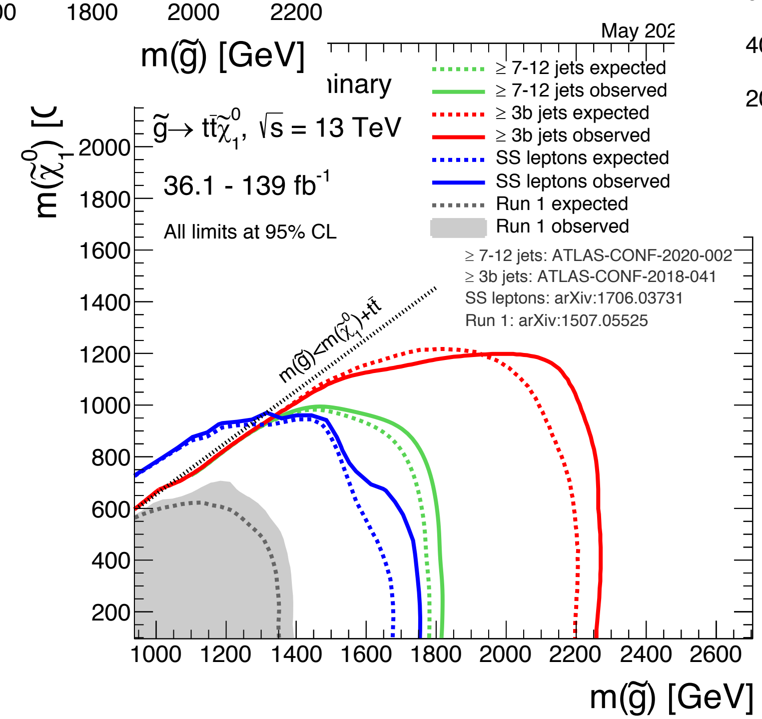


cf.) natural SUSY:

$$m_{\tilde{g}} \lesssim 900\,\mathrm{GeV}\cdot\sin\beta\left(\frac{\log(\Lambda/\mathrm{TeV})}{3}\right)^{-1/2}\left(\frac{\Delta^{-1}}{20\%}\right)^{-1/2}$$

LHC Run 2 results on colored SUSY particle searches





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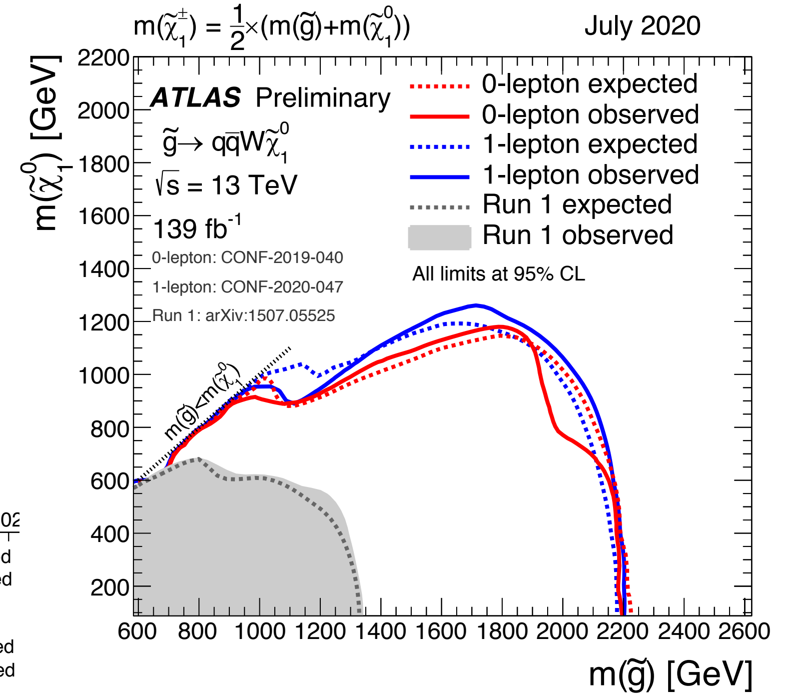
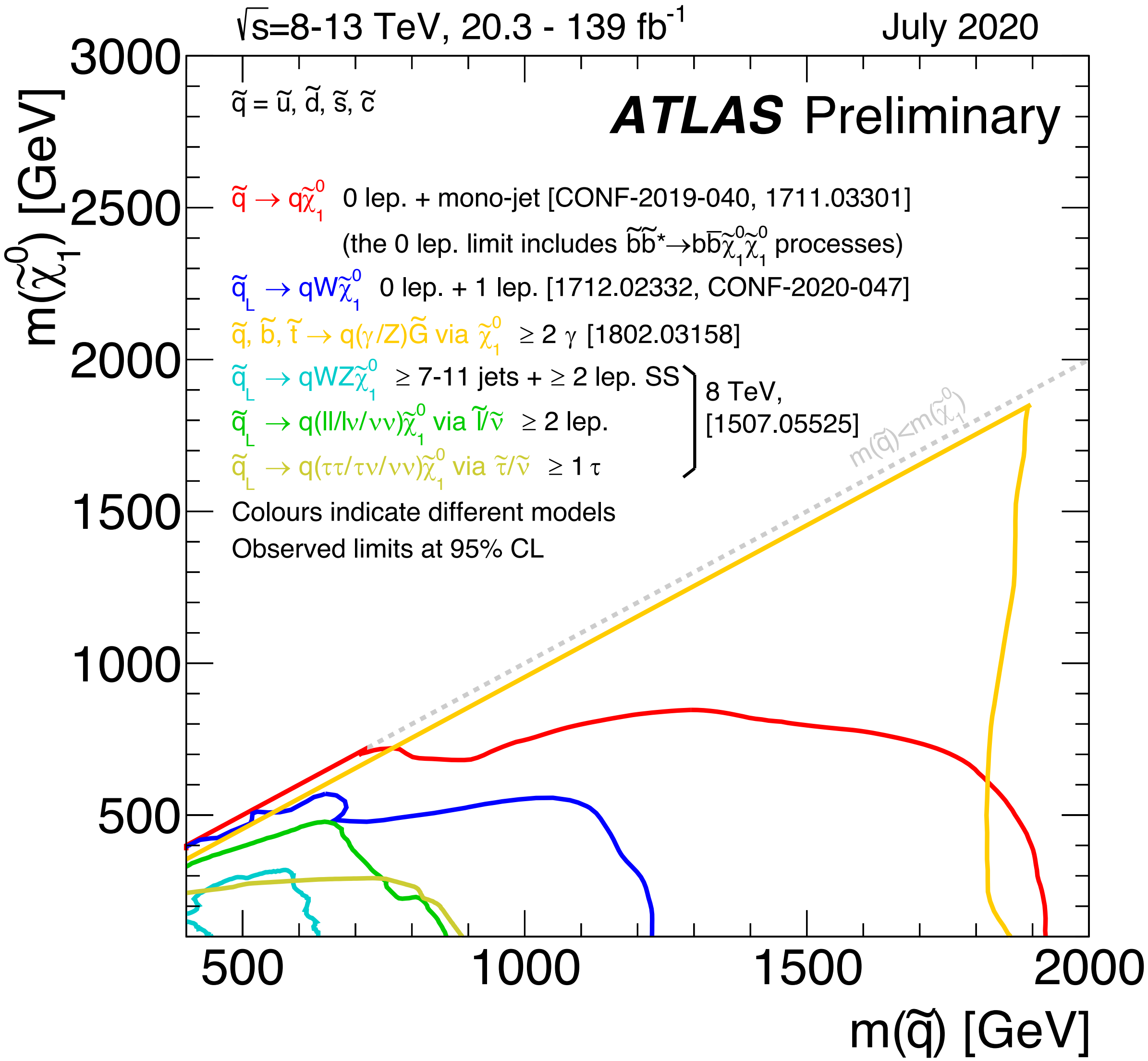
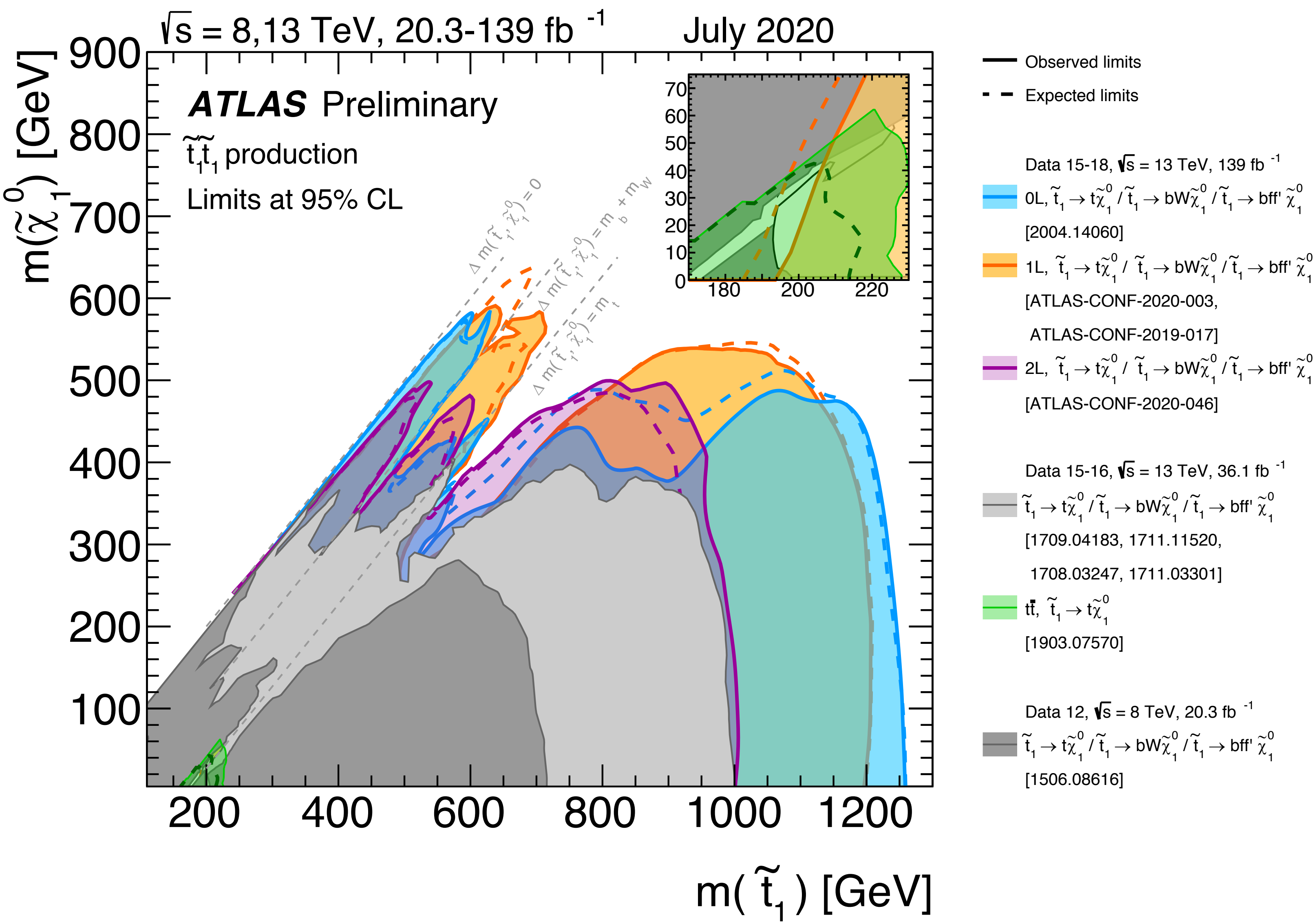




√s=8-13 TeV, 20.3 - 139 fb^-1
July 2020
ATLAS Preliminary
q̃ = ũ, d̃, s̃, c̃
q̃ → qχ̃⁰₁ 0 lep. + mono-jet [CONF-2019-040, 1711.03301]
(the 0 lep. limit includes b̃b̃*→bb̄χ̃⁰₁χ̃⁰₁ processes)
q̃L → qWχ̃⁰₁ 0 lep. + 1 lep. [1712.02332, CONF-2020-047]
q̃, b̃, t̃ → q(γ/Z)G̃ via χ̃⁰₁ ≥ 2 γ [1802.03158]
q̃L → qWZχ̃⁰₁ ≥ 7-11 jets + ≥ 2 lep. SS
q̃L → q(ll/lν/νν)χ̃⁰₁ via l̃/ν̃ ≥ 2 lep.
q̃L → q(ττ/τν/νν)χ̃⁰₁ via τ̃/ν̃ ≥ 1 τ
8 TeV, [1507.05525]
Colours indicate different models
Observed limits at 95% CL
m(q̃)<m(χ̃⁰₁)
m(χ̃⁰₁) [GeV]
m(q̃) [GeV]
500
1000
1500
2000
2500
3000

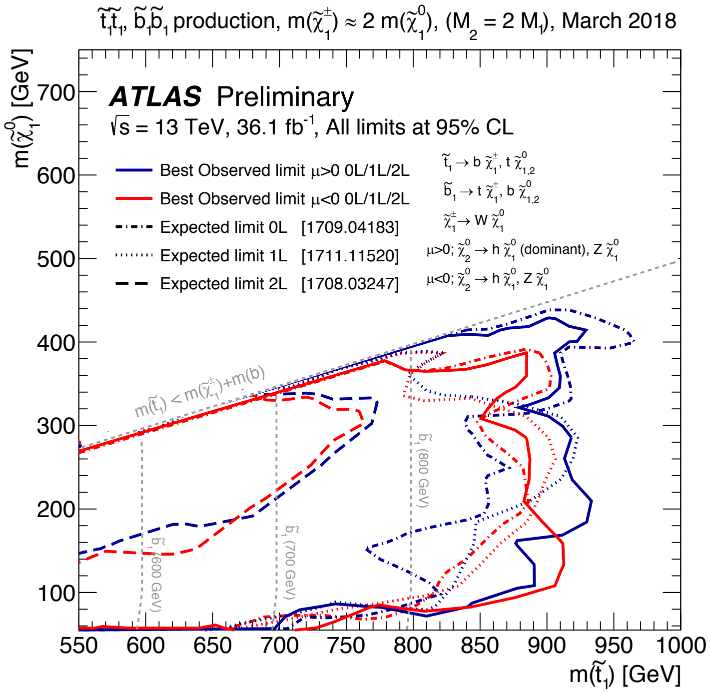
cf.) natural SUSY:

$$\sqrt{m_{\tilde{t}1}^2 + m_{\tilde{t}2}^2} \lesssim 600\,\mathrm{GeV}\frac{\sin\beta}{\sqrt{1+\alpha^2}}\left(\frac{\log(\Lambda/\mathrm{TeV})}{3}\right)^{-1/2}\left(\frac{\Delta^{-1}}{20\%}\right)^{-1/2}$$



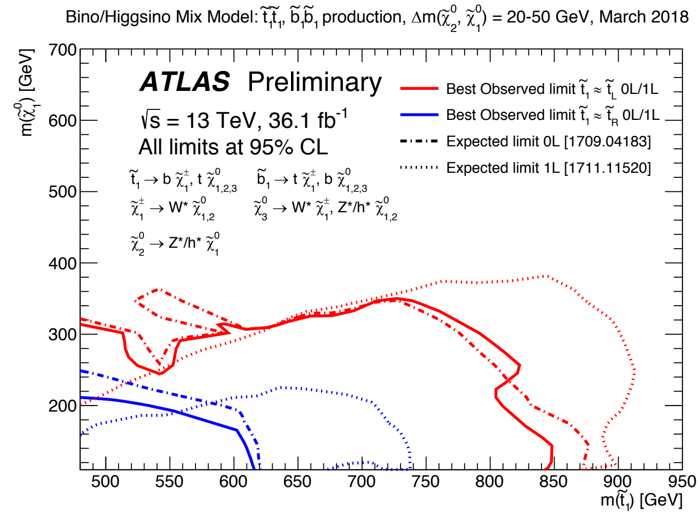
LHC Run 2 results on colored SUSY particle searches

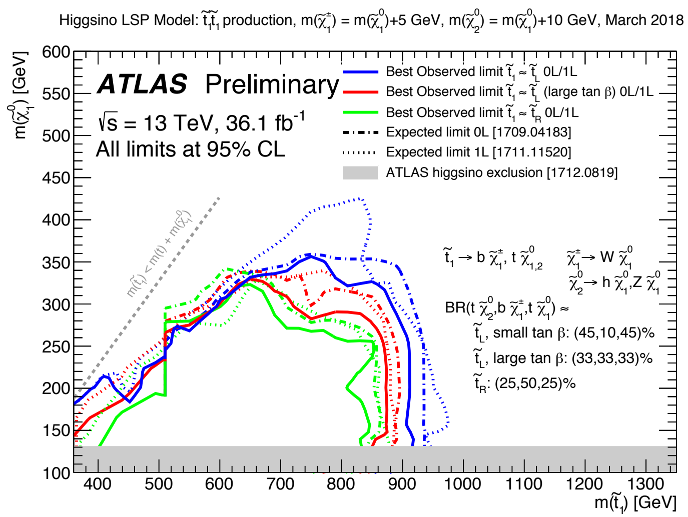
ATLAS, SUSY July 2020 Summary Plot Update

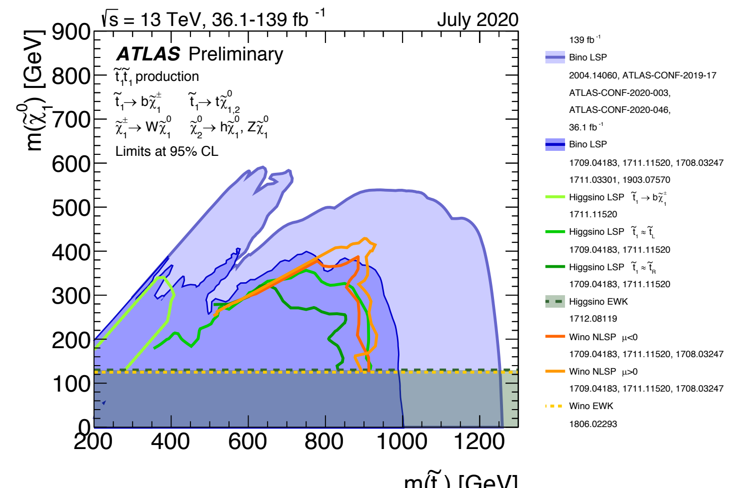


cf.) natural SUSY:

$$\sqrt{m^2_{\tilde{t}1} + m^2_{\tilde{t}2}} \lesssim 600\,\mathrm{GeV}\frac{\sin\beta}{\sqrt{1+\alpha^2}}\left(\frac{\log(\Lambda/\mathrm{TeV})}{3}\right)^{-1/2}\left(\frac{\Delta^{-1}}{20\%}\right)^{-1/2}$$







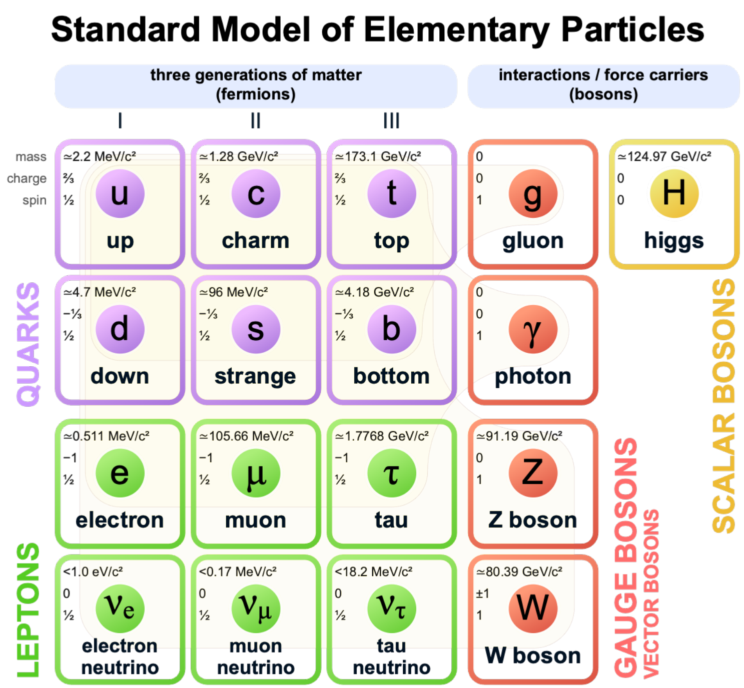
- You'd have noticed the biggest problem in MSSM....

many many many possibilities!!!!

[SUSY-breaking]

⇔ many (>100) unknown ~~SUSY~~ parameters.

- If SUSY is still a symmetry:



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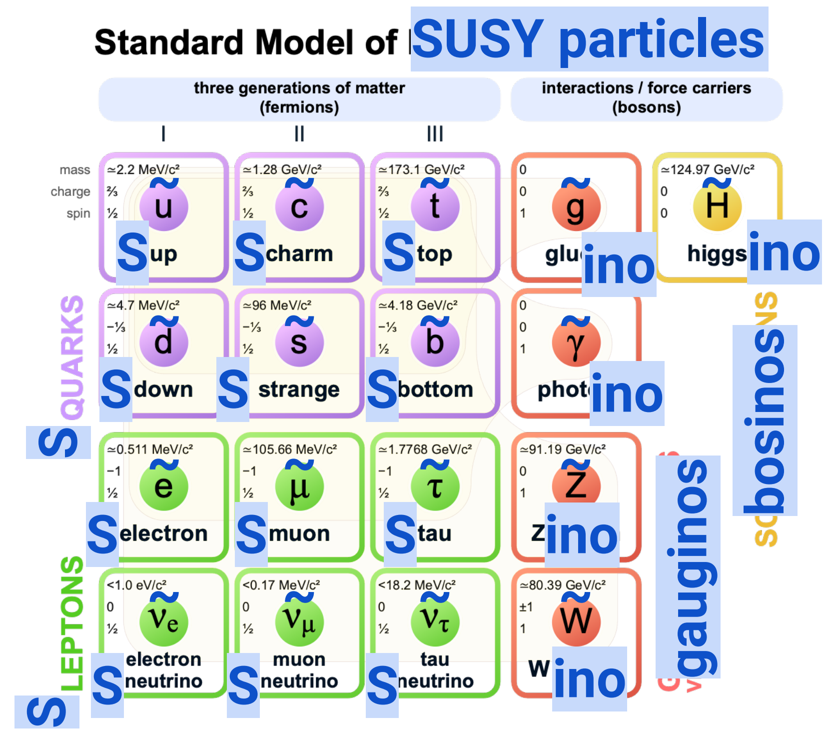


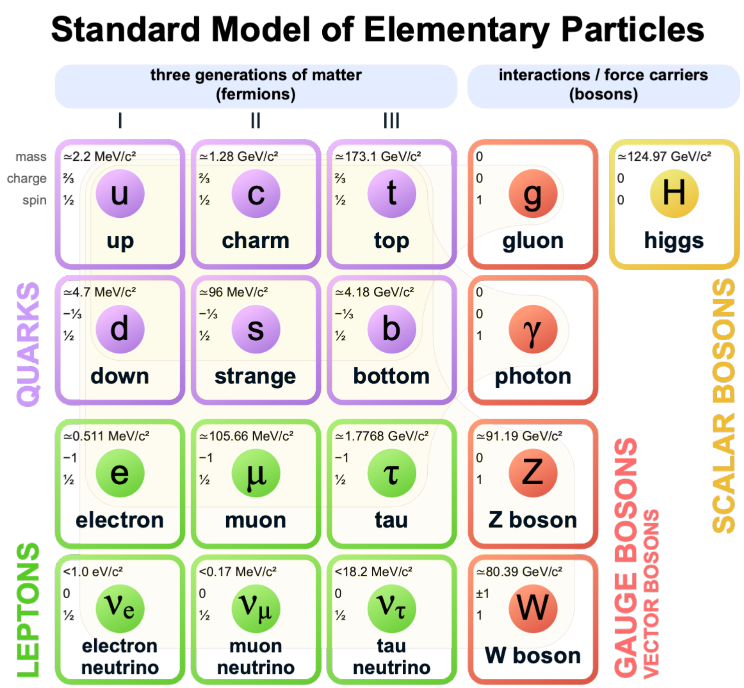
We know SM mass & parameters. → The same parameters in SUSY sector.

- You'd have noticed the biggest problem in MSSM....

many many many possibilities!!!!

⇔ many (>100) unknown ~~SUSY~~ [SUSY-breaking] parameters.

- If SUSY is still a symmetry:



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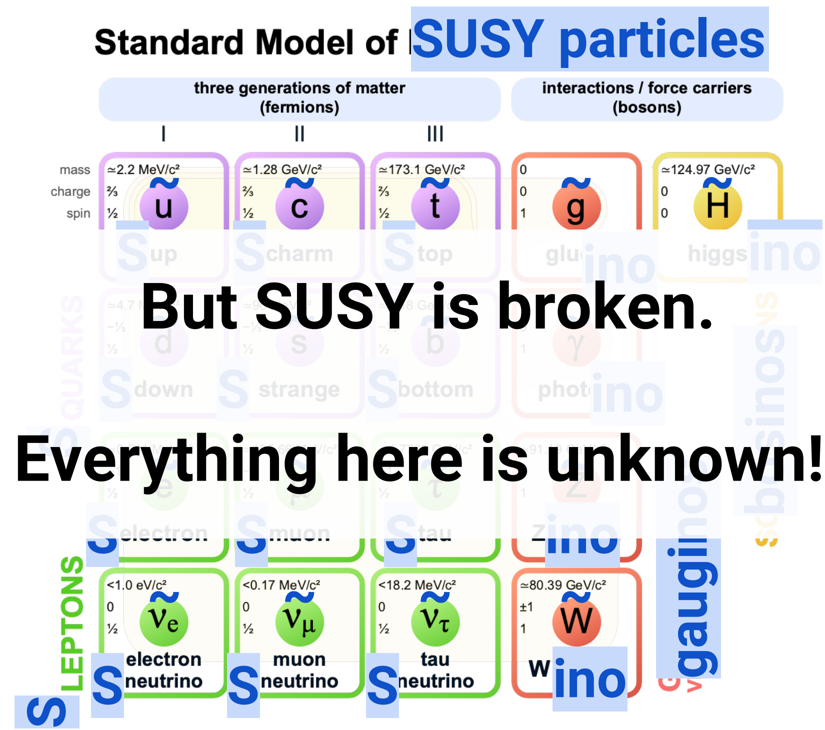

But SUSY is broken.

Everything here is unknown!!

We know SM mass & parameters. → The same parameters in SUSY sector.

■ Lagrangian of MSSM

R-parity violating terms
→ vanish if we impose *R*-parity.

$$W_{\mathrm{RPC}} = \mu H_{\mathrm{u}} H_{\mathrm{d}} - y_{\mathrm{u}ij} U^{\mathrm{c}}_i H_{\mathrm{u}} Q_j + y_{\mathrm{d}ij} D^{\mathrm{c}}_i H_{\mathrm{d}} Q_j + y_{\mathrm{e}ij} E^{\mathrm{c}}_i H_{\mathrm{d}} L_j,$$

$$W_{\mathrm{RPV}} = -\kappa_i L_i H_{\mathrm{u}} + \frac{1}{2}\lambda_{ijk} L_i L_j E^{\mathrm{c}}_k + \lambda'_{ijk} L_i Q_j D^{\mathrm{c}}_k + \frac{1}{2}\lambda''_{ijk} U^{\mathrm{c}}_i D^{\mathrm{c}}_j D^{\mathrm{c}}_k,$$

$$\mathcal{L}_{\not{\mathrm{SUSY}}} = -\frac{1}{2}\left(M_3 \tilde{g}_0 \tilde{g}_0 + M_2 \tilde{w}\tilde{w} + M_1 \tilde{b}\tilde{b} + \mathrm{H.c.}\right) - V_{\not{\mathrm{SUSY}}};$$

$$V^{\mathrm{RPC}}_{\not{\mathrm{SUSY}}} = \left(\tilde{q}^*_{\mathrm{L}} m^2_Q \tilde{q}_{\mathrm{L}} + \tilde{l}^*_{\mathrm{L}} m^2_L \tilde{l}_{\mathrm{L}} + \tilde{u}^*_{\mathrm{R}} m^2_{U^{\mathrm{c}}} \tilde{u}_{\mathrm{R}} + \tilde{d}^*_{\mathrm{R}} m^2_{D^{\mathrm{c}}} \tilde{d}_{\mathrm{R}} + \tilde{e}^*_{\mathrm{R}} m^2_{E^{\mathrm{c}}} \tilde{e}_{\mathrm{R}} + m^2_{H_{\mathrm{u}}}|h_{\mathrm{u}}|^2 + m^2_{H_{\mathrm{d}}}|h_{\mathrm{d}}|^2\right)$$
$$+ \left(-\tilde{u}^*_{\mathrm{R}} h_{\mathrm{u}} a_{\mathrm{u}} \tilde{q}_{\mathrm{L}} + \tilde{d}^*_{\mathrm{R}} h_{\mathrm{d}} a_{\mathrm{d}} \tilde{q}_{\mathrm{L}} + \tilde{e}^*_{\mathrm{R}} h_{\mathrm{d}} a_{\mathrm{e}} \tilde{l}_{\mathrm{L}} + b H_{\mathrm{u}} H_{\mathrm{d}} + \mathrm{H.c.}\right)$$
$$+ \left(+\tilde{u}^*_{\mathrm{R}} h^*_{\mathrm{d}} c_{\mathrm{u}} \tilde{q}_{\mathrm{L}} + \tilde{d}^*_{\mathrm{R}} h^*_{\mathrm{u}} c_{\mathrm{d}} \tilde{q}_{\mathrm{L}} + \tilde{e}^*_{\mathrm{R}} h^*_{\mathrm{u}} c_{\mathrm{e}} \tilde{l}_{\mathrm{L}} + \mathrm{H.c.}\right),$$

$$V^{\mathrm{RPV}}_{\not{\mathrm{SUSY}}} = \left(-b_i \tilde{l}_{\mathrm{L}i} H_{\mathrm{u}} + \frac{1}{2} T_{ijk} \tilde{l}_{\mathrm{L}i} \tilde{l}_{\mathrm{L}j} \tilde{e}^*_{\mathrm{R}k} + T'_{ijk} \tilde{l}_{\mathrm{L}i} \tilde{q}_{\mathrm{L}j} \tilde{d}^*_{\mathrm{R}k} + \frac{1}{2} T''_{ijk} \tilde{u}^*_{\mathrm{R}i} \tilde{d}^*_{\mathrm{R}j} \tilde{d}^*_{\mathrm{R}k} + \tilde{l}^*_{\mathrm{L}i} M^2_{\tilde{L}i} H_{\mathrm{d}} + \mathrm{H.c.}\right)$$
$$+ \left(C^1_{ijk} \tilde{l}^*_{\mathrm{L}i} \tilde{q}_{\mathrm{L}j} \tilde{u}^*_{\mathrm{R}k} + C^2_i h^*_{\mathrm{u}} h_{\mathrm{d}} \tilde{e}^*_{\mathrm{R}i} + C^3_{ijk} \tilde{d}_{\mathrm{R}i} \tilde{u}^*_{\mathrm{R}j} \tilde{e}^*_{\mathrm{R}k} + \frac{1}{2} C^4_{ijk} \tilde{d}_{\mathrm{R}i} \tilde{q}_{\mathrm{L}j} \tilde{q}_{\mathrm{L}k} + \mathrm{H.c.}\right),$$

SUSY parameters (we know!)

~~SUSY~~ parameters (unknown)

→ There are many "SUSY-breaking models" (to reduce #params).

[gauge mediation, anomaly mediation, ...]

1) Introduction

- What is SUSY?
- Why SUSY?

  ... DM, GUT, Natural, $(g-2)_\mu$

2) LHC

- Review of SUSY searches

3) $(g-2)_\mu$-SUSY vs LHC

- in depth 1: Theory
- in depth 2: LHC
- Fight!

- The previous section:

DM : lightest neutralino LSP ✓ ... but no discussion on relic density.

unification : 1–100 TeV SUSY ✓

naturalness : $\lesssim$ 1TeV colored (stop etc.) ← **our focus**

~~$(g-2)_\mu$: $\lesssim$ 500 GeV non-colored~~

- The next part: **"(g–2)-motivated MSSM vs LHC Run 2"**

based on

- Endo, Hamaguchi, Iwamoto, Yoshinaga [1303.4256]
- Endo, Hamaguchi, Iwamoto, Kitahara [2001.11025]

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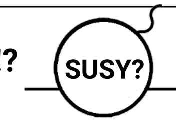
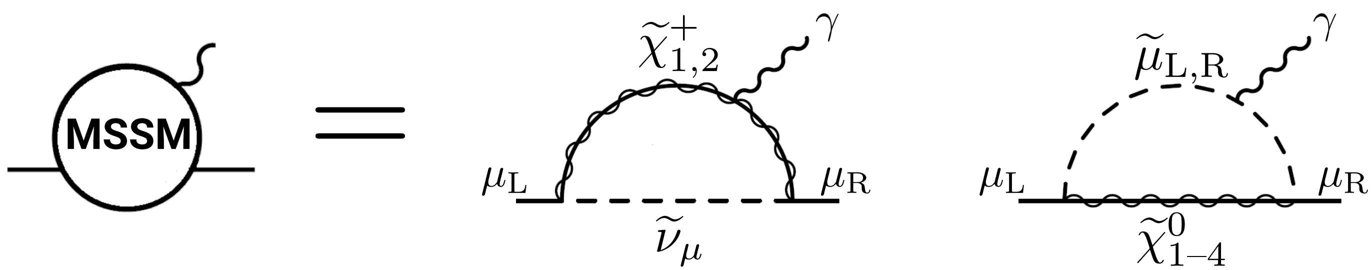
$\Delta a_\mu = (\quad 27.9 \quad \pm 7.6 \quad) \times 10^{-10}$ **from new physics!?**

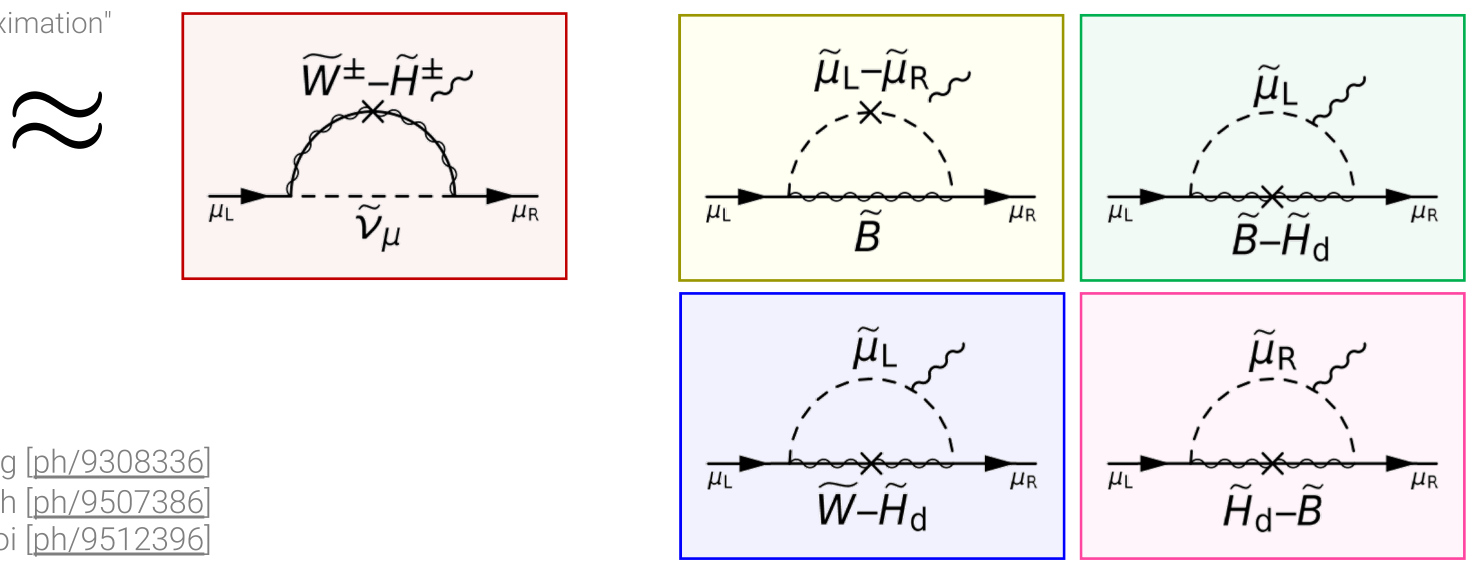


- What is this?



+ (2^{+}-loop)

"mass insertion approximation"



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

MSSM: extra particles

- extra Higgs bosons
  H^0, H^+, H^-, A^0
- colored SUSY particles
  $\tilde{g}$, $(\tilde{u}_\mathrm{L}, \tilde{d}_\mathrm{L}, \tilde{u}_\mathrm{R}, \tilde{d}_\mathrm{R})$ × 3 gen. → $\tilde{g}$; $(\tilde{u}_1, \tilde{u}_2, \tilde{u}_3, \tilde{u}_4, \tilde{u}_5, \tilde{u}_6)$, $(\tilde{d}_1, \tilde{d}_2, \tilde{d}_3, \tilde{d}_4, \tilde{d}_5, \tilde{d}_6)$
- **non-colored SUSY particles**
  - charged **s**leptons $(\tilde{e}_\mathrm{L}, \tilde{e}_\mathrm{R})$ × 3 gen. → $(\tilde{e}_1, \tilde{e}_2, \tilde{e}_3, \tilde{e}_4, \tilde{e}_5, \tilde{e}_6)$
  - **s**neutrinos $\tilde{\nu}_\mathrm{L}$ × 3 gen. → $(\tilde{\nu}_1, \tilde{\nu}_2, \tilde{\nu}_3)$
  - charg**ino**s $(\widetilde{W}^\pm, \widetilde{H}^\pm)$ → $(\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm)$
  - neutral**ino**s $(\widetilde{B}, \widetilde{W}_3, \widetilde{H}_\mathrm{d}^0, \widetilde{H}_\mathrm{u}^0)$ → $(\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0)$

gauge eigenstates ⟹ mass eigenstates

mix

because of off-diagonal mass terms

MSSM: extra particles

- extra Higgs bosons
  H^0, H^+, H^-, A^0
- colored SUSY particles
  $\tilde{g},\ (\tilde{u}_\mathrm{L}, \tilde{d}_\mathrm{L}, \tilde{u}_\mathrm{R}, \tilde{d}_\mathrm{R})$ × 3 gen. → $\tilde{g}$; $\tilde{u}_{1\text{–}6} \simeq (\tilde{u}_\mathrm{L}, \tilde{u}_\mathrm{R}, \tilde{c}_\mathrm{L}, \tilde{c}_\mathrm{R}, \tilde{t}_1, \tilde{t}_2)$; $\tilde{d}_{1\text{–}6} \simeq (\tilde{d}_\mathrm{L}, \tilde{d}_\mathrm{R}, \tilde{s}_\mathrm{L}, \tilde{s}_\mathrm{R}, \tilde{b}_1, \tilde{b}_2)$
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  - charged **s**leptons $(\tilde{e}_\mathrm{L}, \tilde{e}_\mathrm{R})$ × 3 gen. → $\tilde{e}_{1\text{–}6} \simeq (\tilde{e}_\mathrm{L}, \tilde{e}_\mathrm{R}, \tilde{\mu}_\mathrm{L}, \tilde{\mu}_\mathrm{R}, \tilde{\tau}_1, \tilde{\tau}_2)$
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The five diagrams of the MSSM contribution to the muon g−2.

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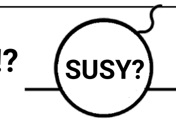
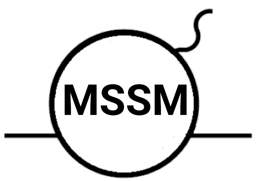


■ What is this?

mass eigen. to use in the actual calculation



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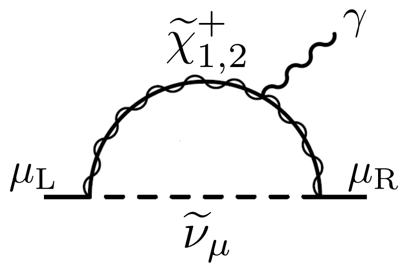
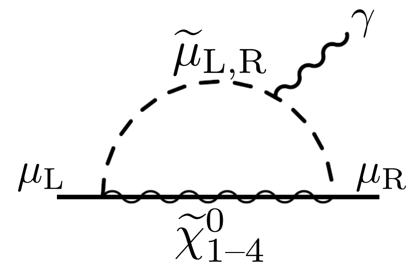


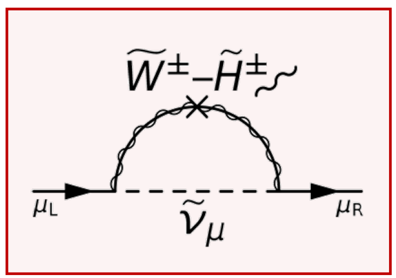


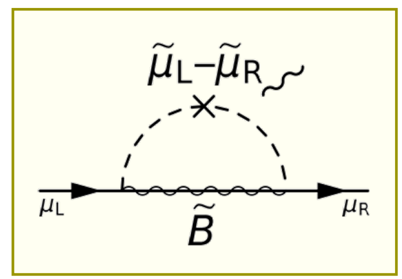
+ (2⁺-loop)

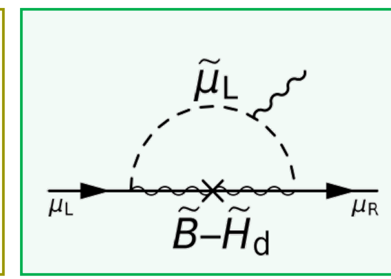
gauge eigen. for pheno discussion

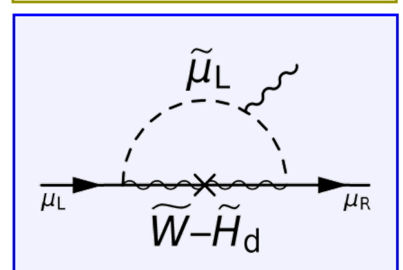
"mass insertion approximation"

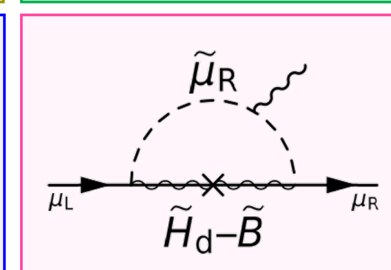
$\approx$











➢ **non-colored SUSY particles**

- charged **s**leptons $(\tilde{e}_L, \tilde{e}_R)$ × 3 gen. ⟶ $\tilde{e}_{1-6} \simeq (\tilde{e}_L, \tilde{e}_R, \tilde{\mu}_L, \tilde{\mu}_R, \tilde{\tau}_1, \tilde{\tau}_2)$
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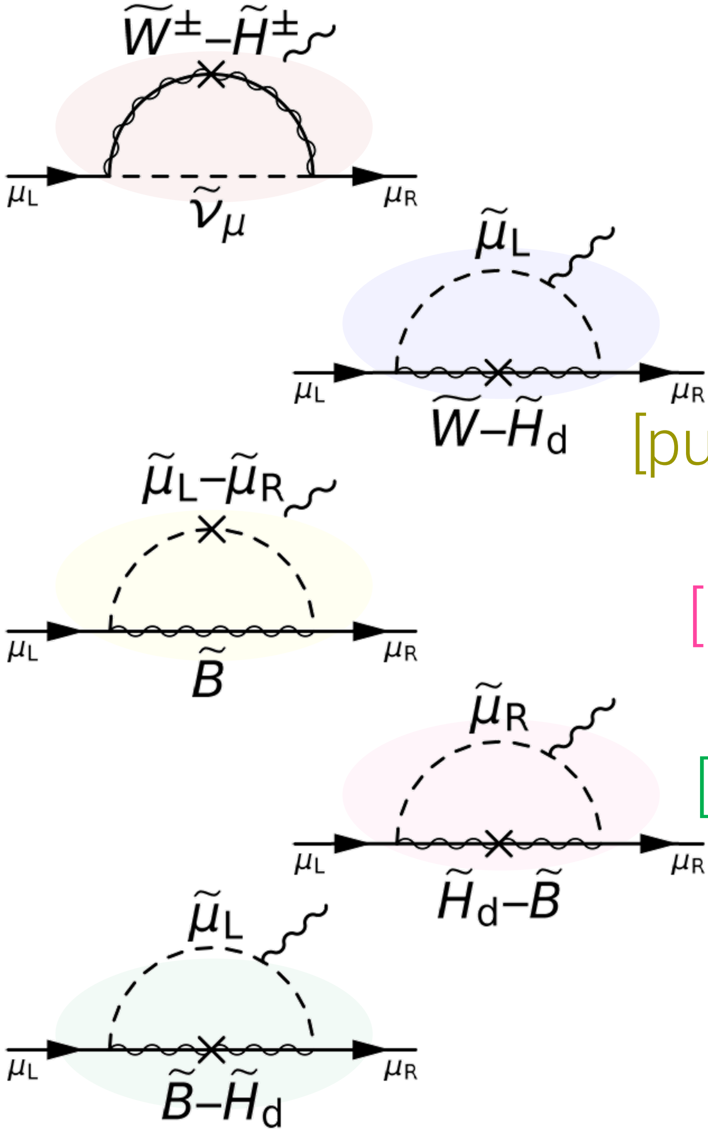

[W] $$\frac{g_2^2 m_\mu^2}{8\pi^2}\,\frac{M_2\mu\tan\beta}{m_{\tilde{\nu}_\mu}^4}\cdot F_a\left(\frac{M_2}{m_{\tilde{\nu}_\mu}},\frac{\mu}{m_{\tilde{\nu}_\mu}}\right)$$

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

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

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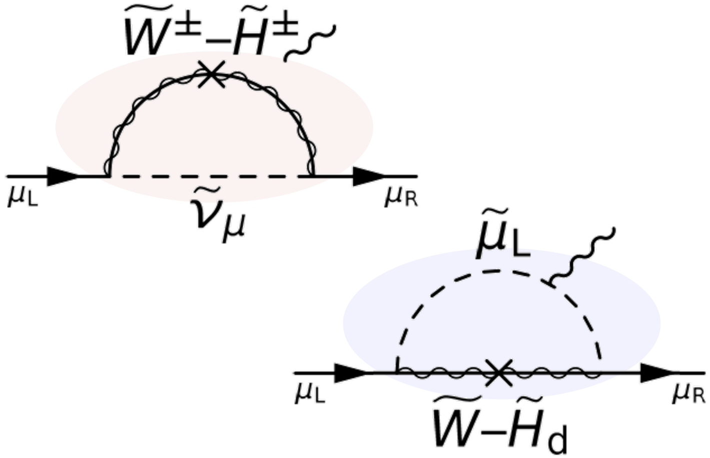
(cf. Cho et al. [1104.1769])

F_a, F_b are loop functions ($F > 0$):

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

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

Usually, the "Wino contribution" (first two diagrams) is the dominant one.



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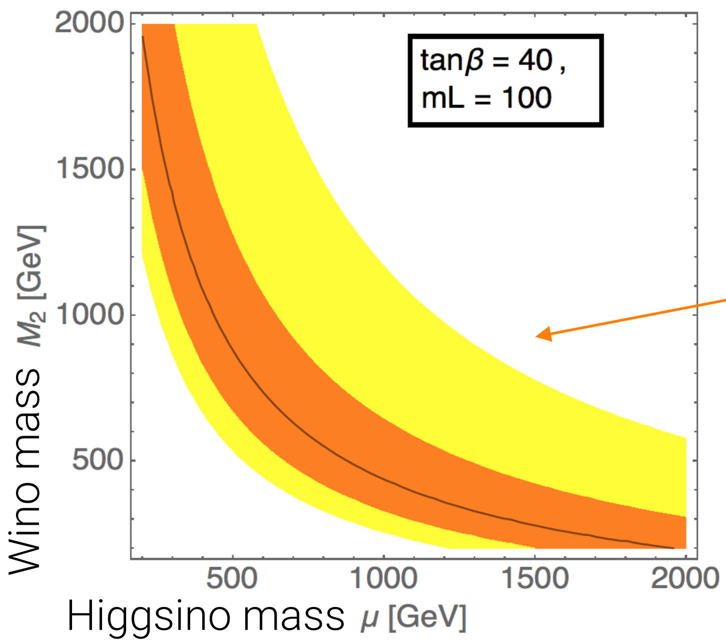
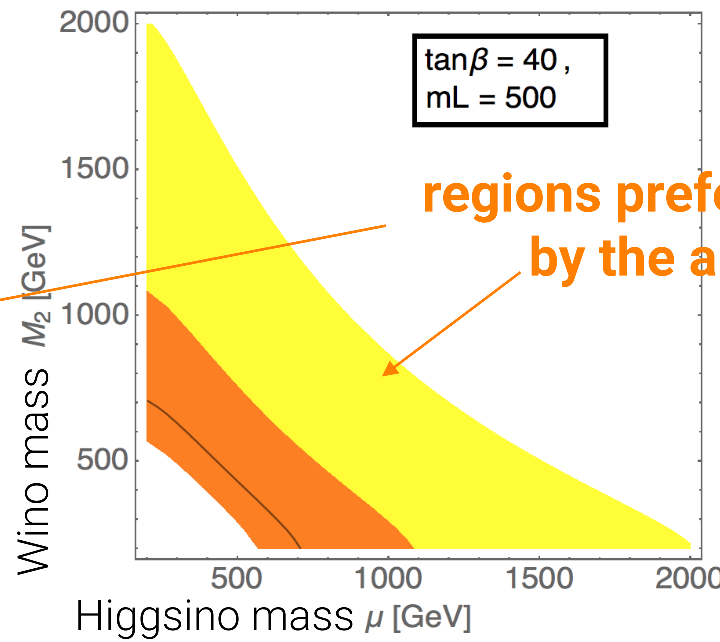
Wino contributions [red+blue; tree; slep=sneu]





regions preferred by the anomaly

→ We'll discuss LHC constraints on these parameter space.

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■ Production XS of [cross section]

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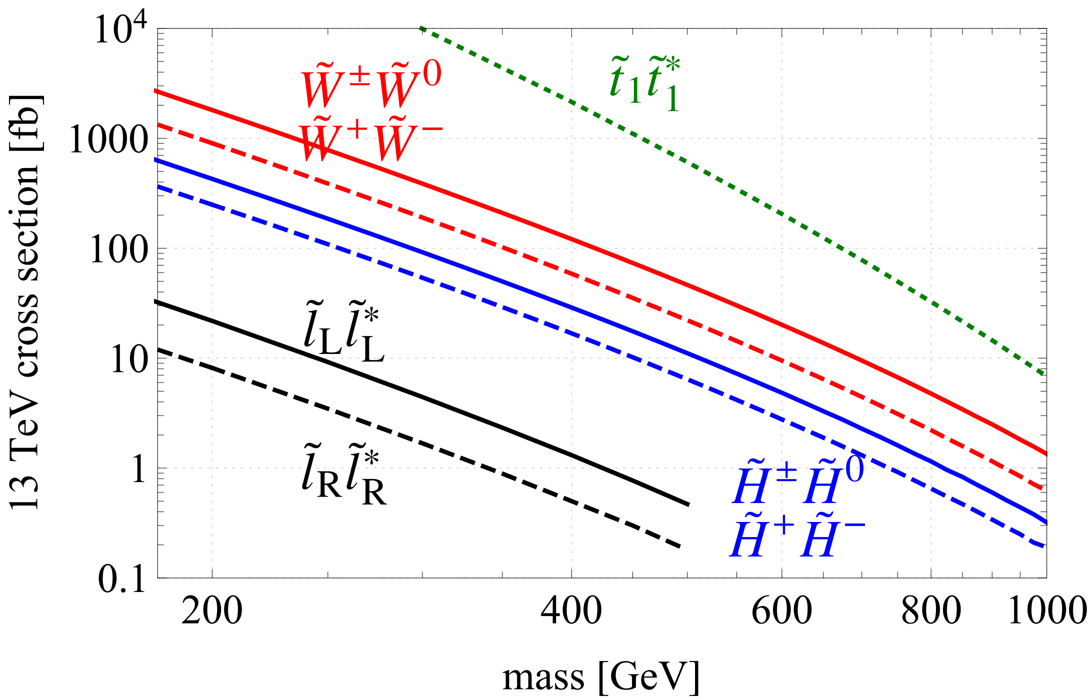
cf.) LHC Run 2:
Energy ~ 6.5 TeV × 2
Luminosity ~ 140 fb^{-1}



←140000ev

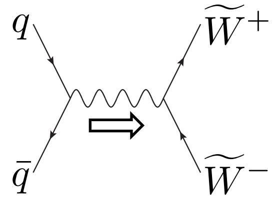
←1400ev

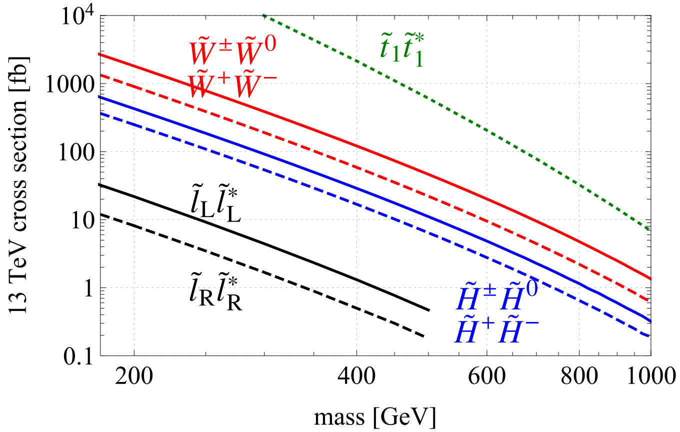
←14ev

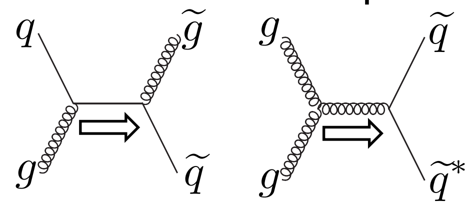
[The "actual" XS (e.g., $\sigma(pp \to \tilde{\chi}_2^0\tilde{\chi}_1^+)$) is "mixture" of these.]

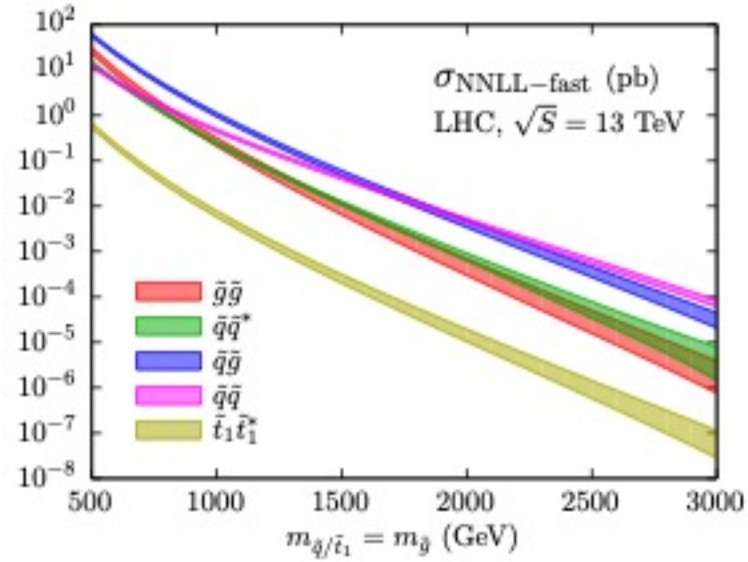
...Why so small?

■ Non-colored SUSY production ***vs.*** Colored SUSY production









Beenakker, Borschensky, et al. [1607.07741]

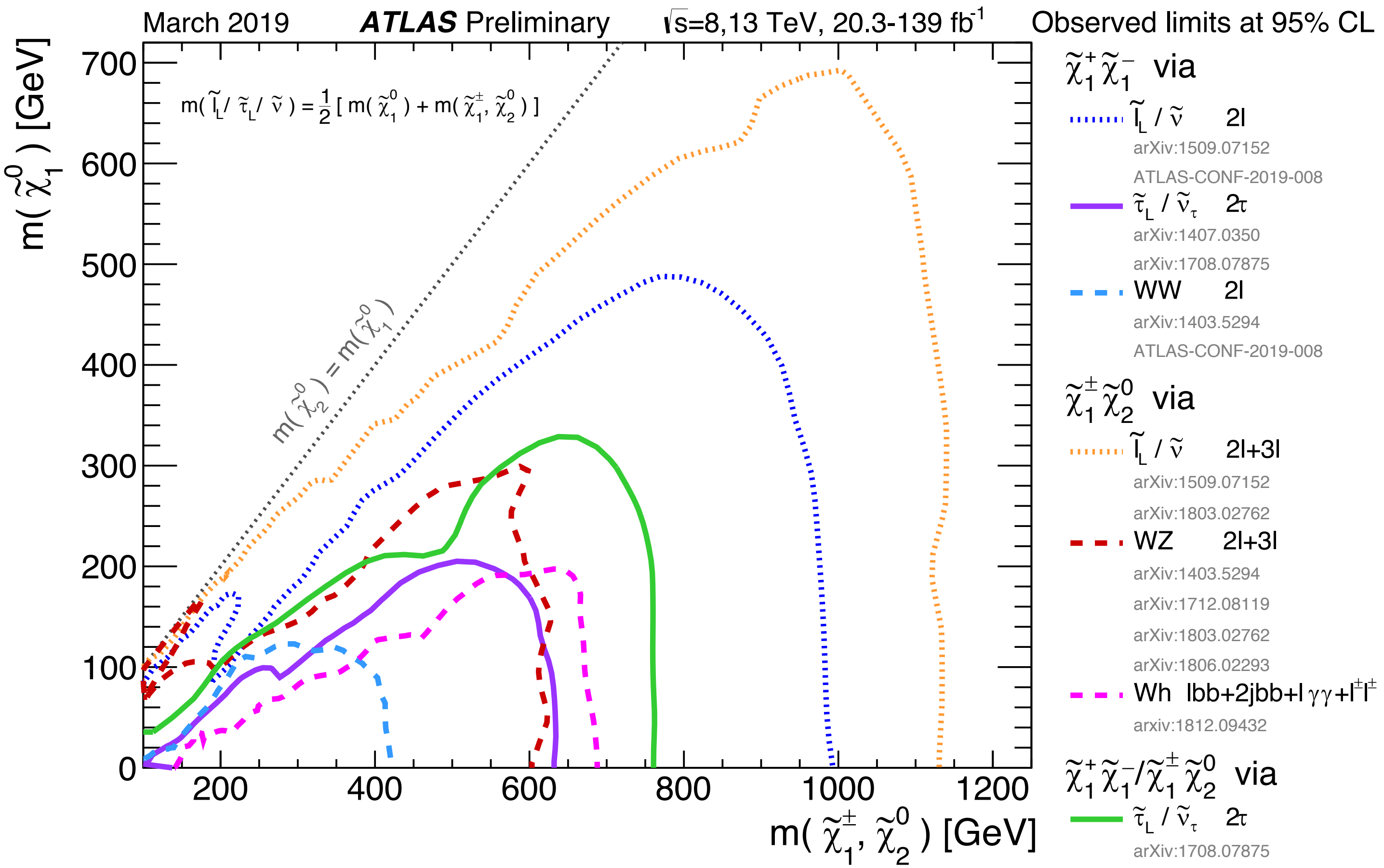
➢ Non-colored XS is smaller because

- Smaller couplings
- *s*-channel only
- Needs anti-quark from *p*

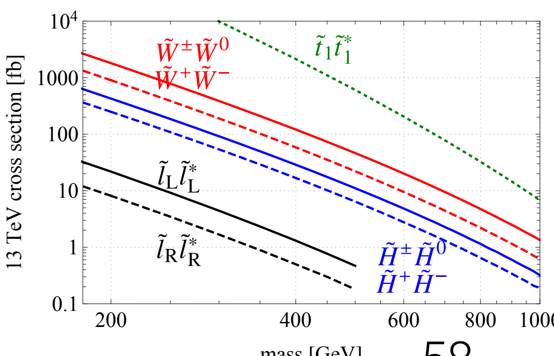
➢ $\tilde{g} \simeq \tilde{q} \gg \tilde{t} \simeq \tilde{b} \gg \widetilde{W} > \widetilde{H} \gg \tilde{l}_{\rm L} > \tilde{l}_{\rm R}$ if similar mass

LHC Run 2 results on NON-colored SUSY searches

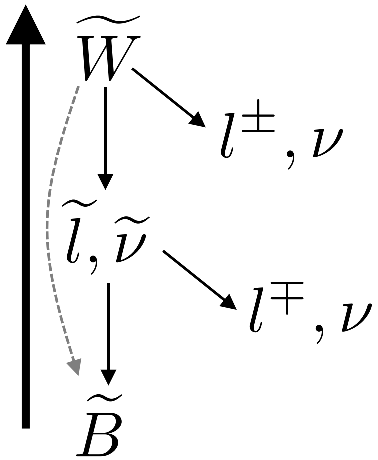
ATLAS, SUSY March 2019 Summary Plot



(They usually assume $\tilde\chi_2^0 \equiv \widetilde{W}^0$, $\tilde\chi_1^+ \equiv \widetilde{W}^+$.)



■ Wino > sleptons



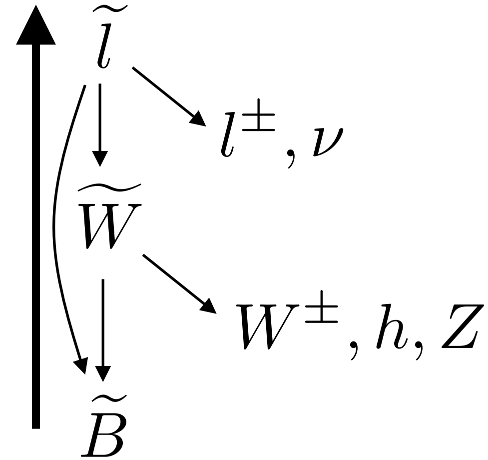
$$\widetilde{W}^+\widetilde{W}^0 \to (l^+\nu\widetilde{B})(l^-l^+\widetilde{B}) = 3\ell + \not{E}_{\mathrm{T}}$$

$$\widetilde{l}\widetilde{l}^* \to (l^-\widetilde{B})(l^+\widetilde{B}) = 2\ell + \not{E}_{\mathrm{T}}$$

➢ Search targets:

- Wino pair → 2–3 lepton + mET
- slepton pair → 2 lepton + mET

■ Wino < sleptons



$$\widetilde{W}^+\widetilde{W}^0 \to (W^+\widetilde{B})([Z \text{ or } h]\widetilde{B})$$

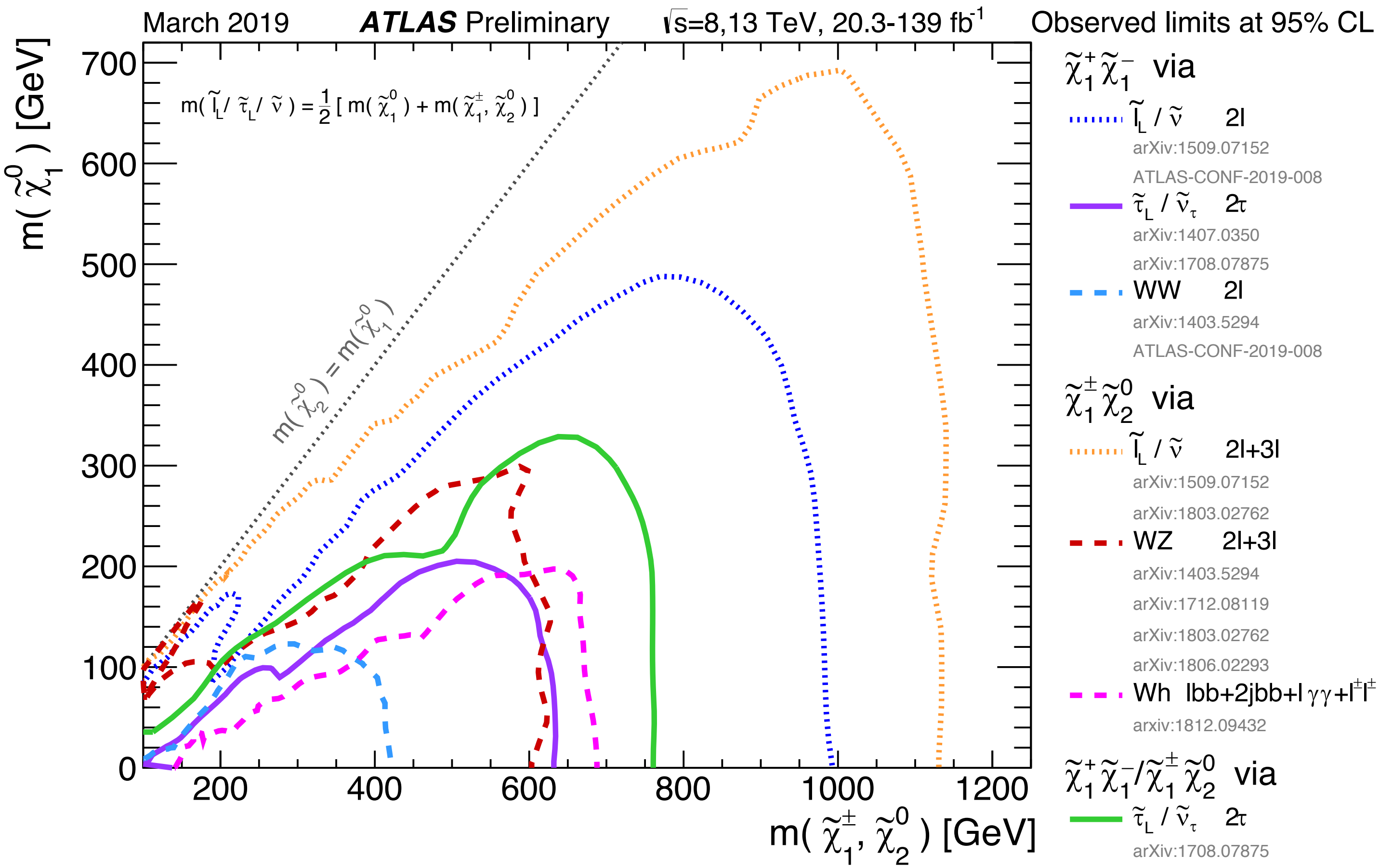
[no need to rely on slepton production]

➢ Search targets:

- Wino pair → WZ + mET
- Wino pair → Wh + mET

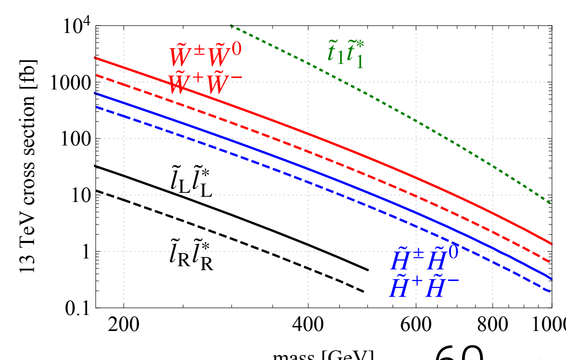
LHC Run 2 results on NON-colored SUSY searches

ATLAS, SUSY March 2019 Summary Plot



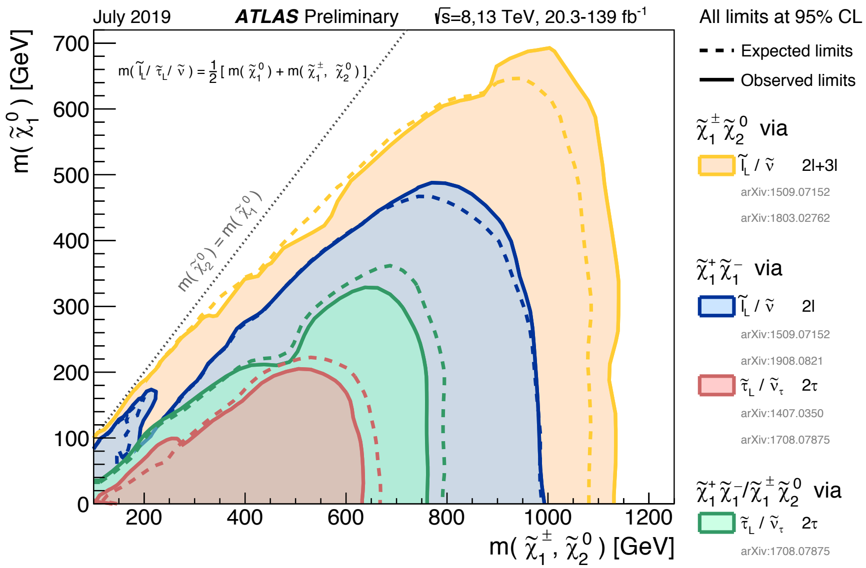
(They usually assume $\tilde\chi^0_2 \equiv \widetilde{W}^0$, $\tilde\chi^+_1 \equiv \widetilde{W}^+$.)

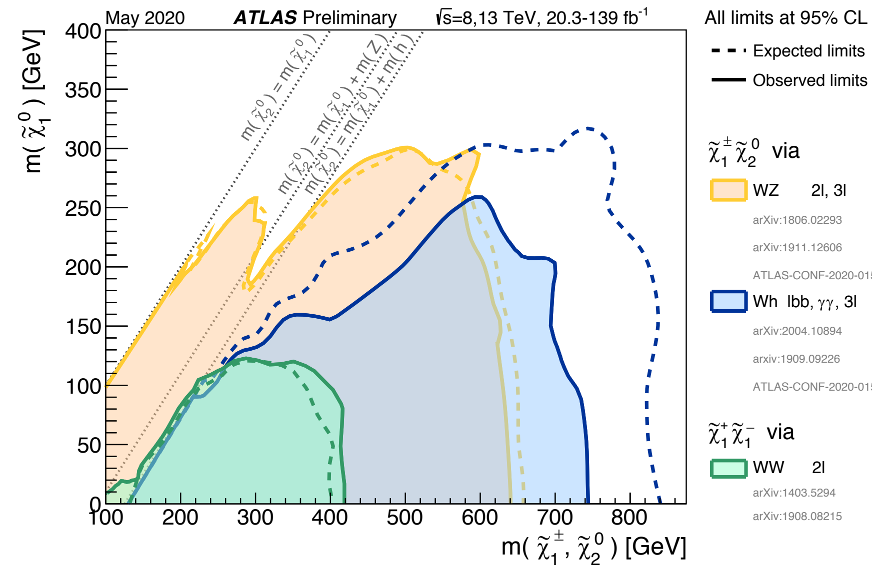
$\mathrm{Br}(Z \to \mathrm{had}) = 69.911(56)\%$
$\mathrm{Br}(Z \to b\bar b) = 15.12(5)\%$
$\mathrm{Br}(Z \to e, \mu, \tau) \simeq 10.10\%$
$\mathrm{Br}(Z \to \mathrm{inv}) = 20.000(55)\%$
$\mathrm{Br}(W \to \mathrm{had}) = 67.41(27)\%$

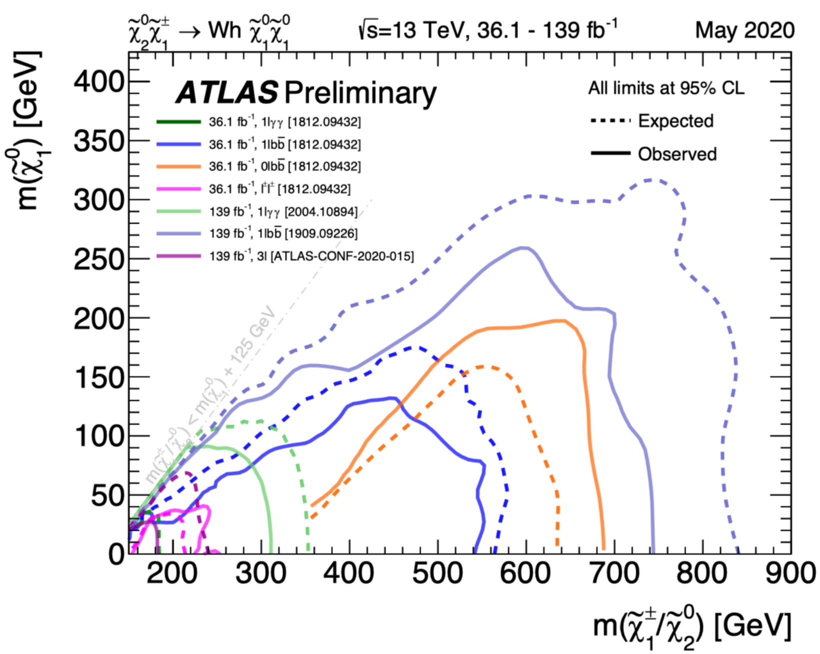


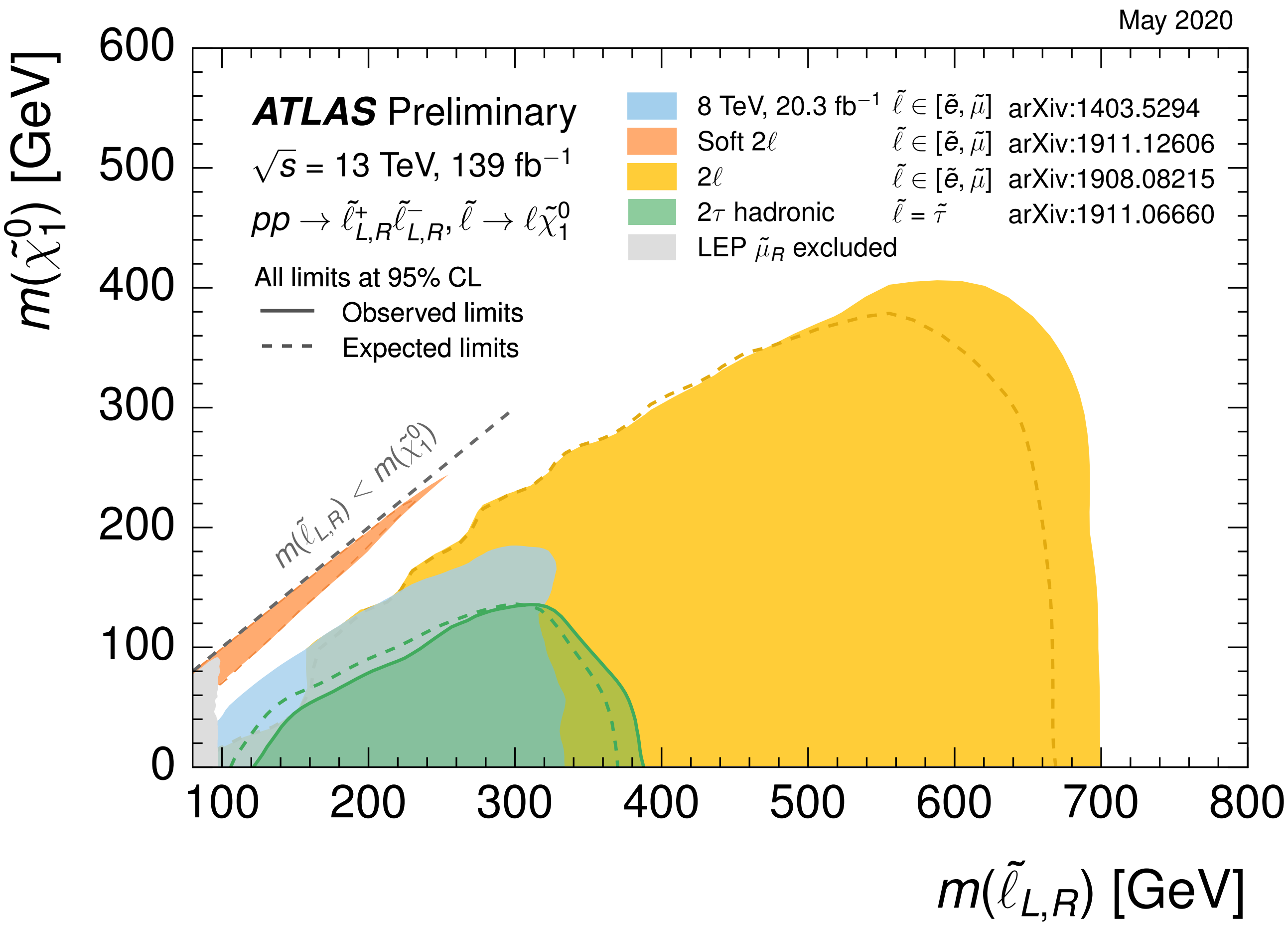
LHC Run 2 results on NON-colored SUSY searches

ATLAS, SUSY July 2020 Summary Plot Update

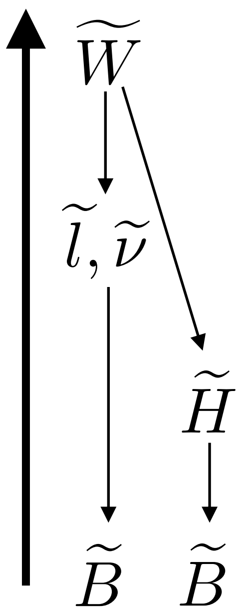




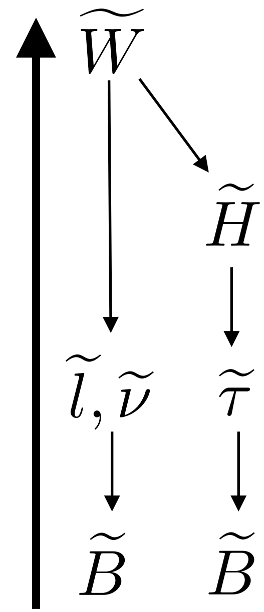



May 2020
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
$pp \to \tilde{\ell}^+_{L,R}\tilde{\ell}^-_{L,R}, \tilde{\ell} \to \ell\tilde{\chi}^0_1$
All limits at 95% CL
Observed limits
Expected limits
8 TeV, 20.3 fb^{-1} $\tilde{\ell} \in [\tilde{e}, \tilde{\mu}]$ arXiv:1403.5294
Soft 2ℓ $\tilde{\ell} \in [\tilde{e}, \tilde{\mu}]$ arXiv:1911.12606
2ℓ $\tilde{\ell} \in [\tilde{e}, \tilde{\mu}]$ arXiv:1908.08215
2τ hadronic $\tilde{\ell} = \tilde{\tau}$ arXiv:1911.06660
LEP $\tilde{\mu}_R$ excluded
$m(\tilde{\ell}_{L,R}) < m(\tilde{\chi}^0_1)$
$m(\tilde{\chi}^0_1)$ [GeV]
$m(\tilde{\ell}_{L,R})$ [GeV]
0
100
200
300
400
500
600
700
800

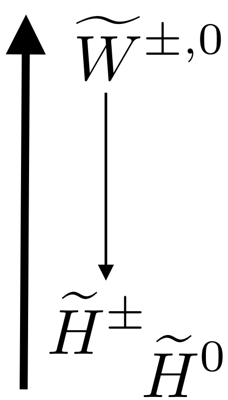
- Wino > sleptons > Higgsino



- Wino > Higgsino > sleptons



- Higgsino LSP



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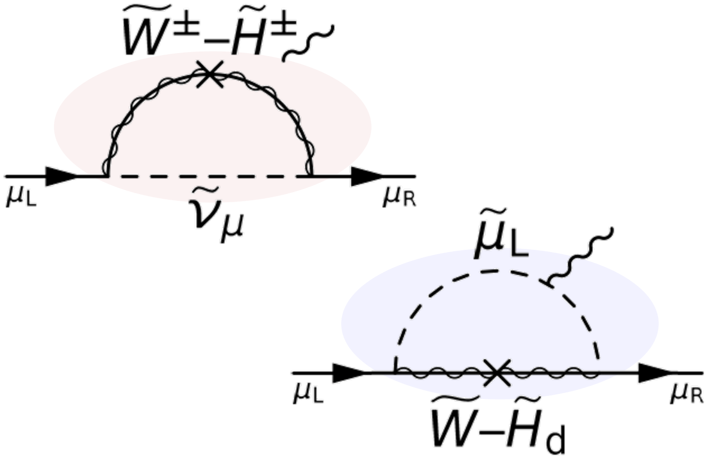
The "Wino (WHL)-dominant scenario" has five important parameters.



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- The relevant parameters: → our simplification:

$$\tan\beta := \langle H_u\rangle/\langle H_d\rangle \qquad \tan\beta = 40$$

"ino" mass:

$$M_1 \approx \widetilde{B}\text{-mass} \qquad M_1 = 100\,\text{GeV or } 0.5M_2$$

$$\mu \approx \widetilde{H}\text{-mass} \qquad \mu = 1.0M_2 \text{ or } 2.0M_2$$

$$M_2 \approx \widetilde{W}\text{-mass}$$

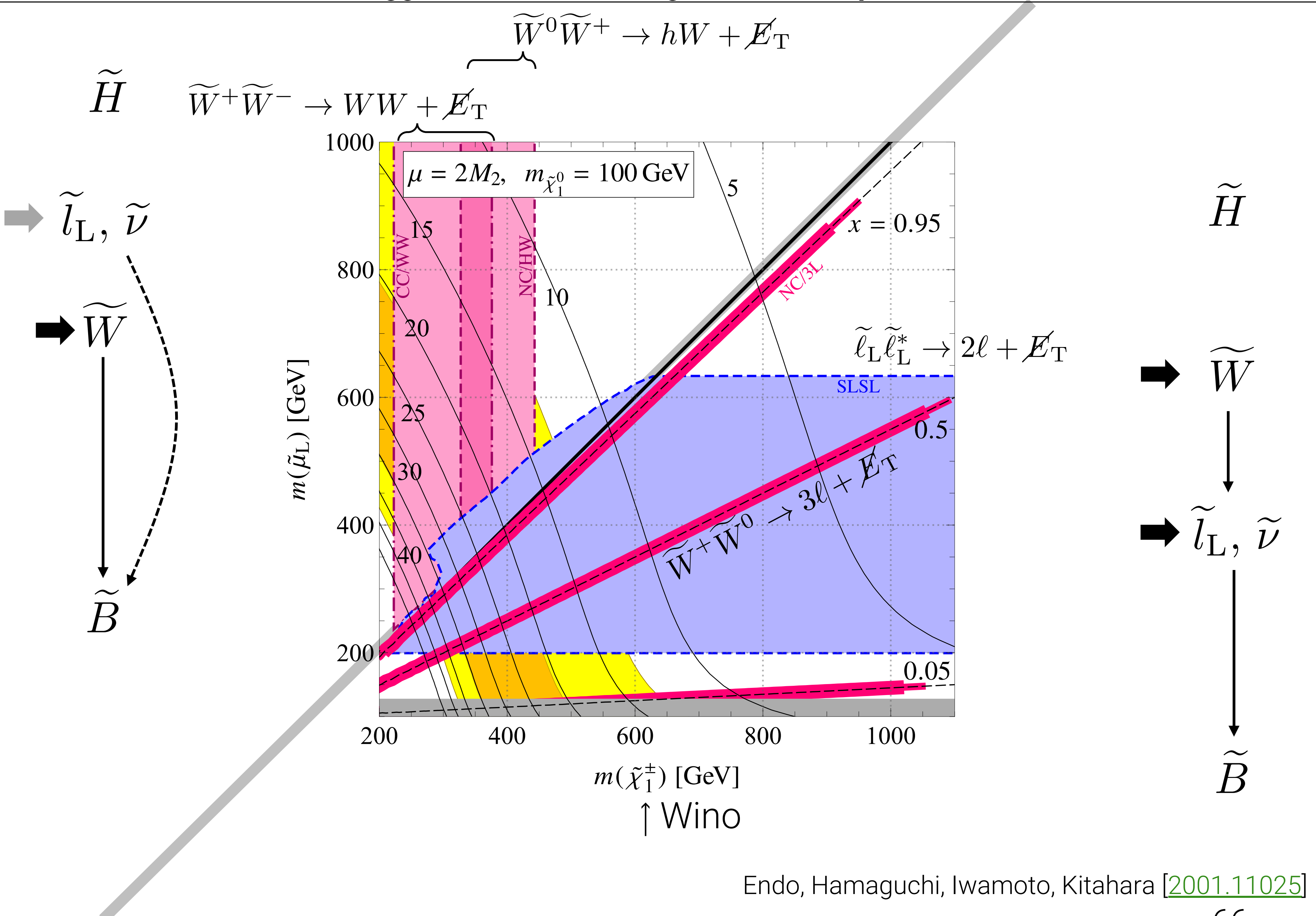
slepton mass:

$$m_L^2 \approx \widetilde{l}_L\text{-mass}$$

and we draw on $(\widetilde{\chi}_1^\pm, \widetilde{l}_L)$-mass plane.

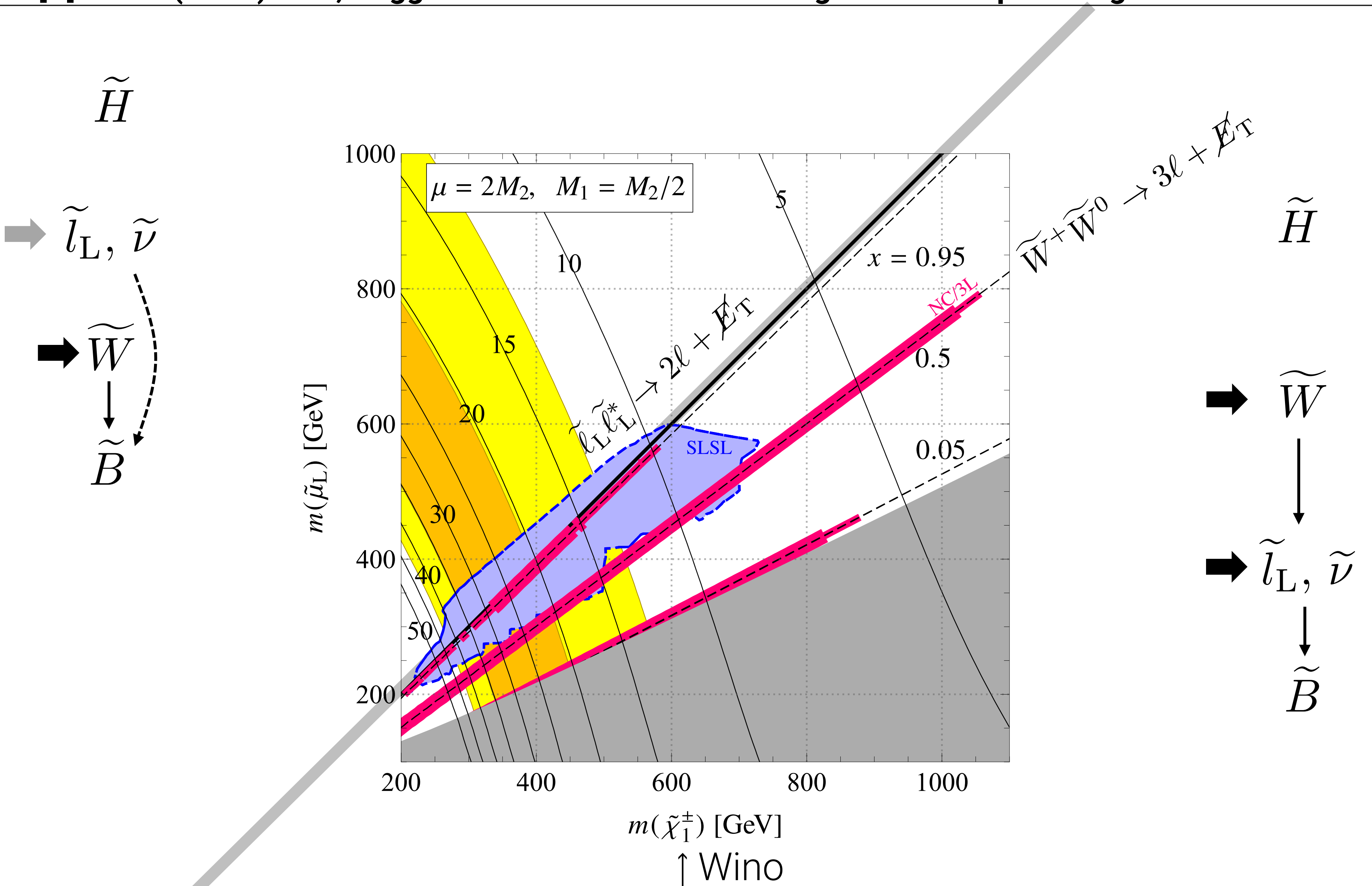
(lighter chargino, left-handed slepton)

[A] LSP = 100GeV bino, Higgsino is heavier. Large wino XS helps LHC searches.



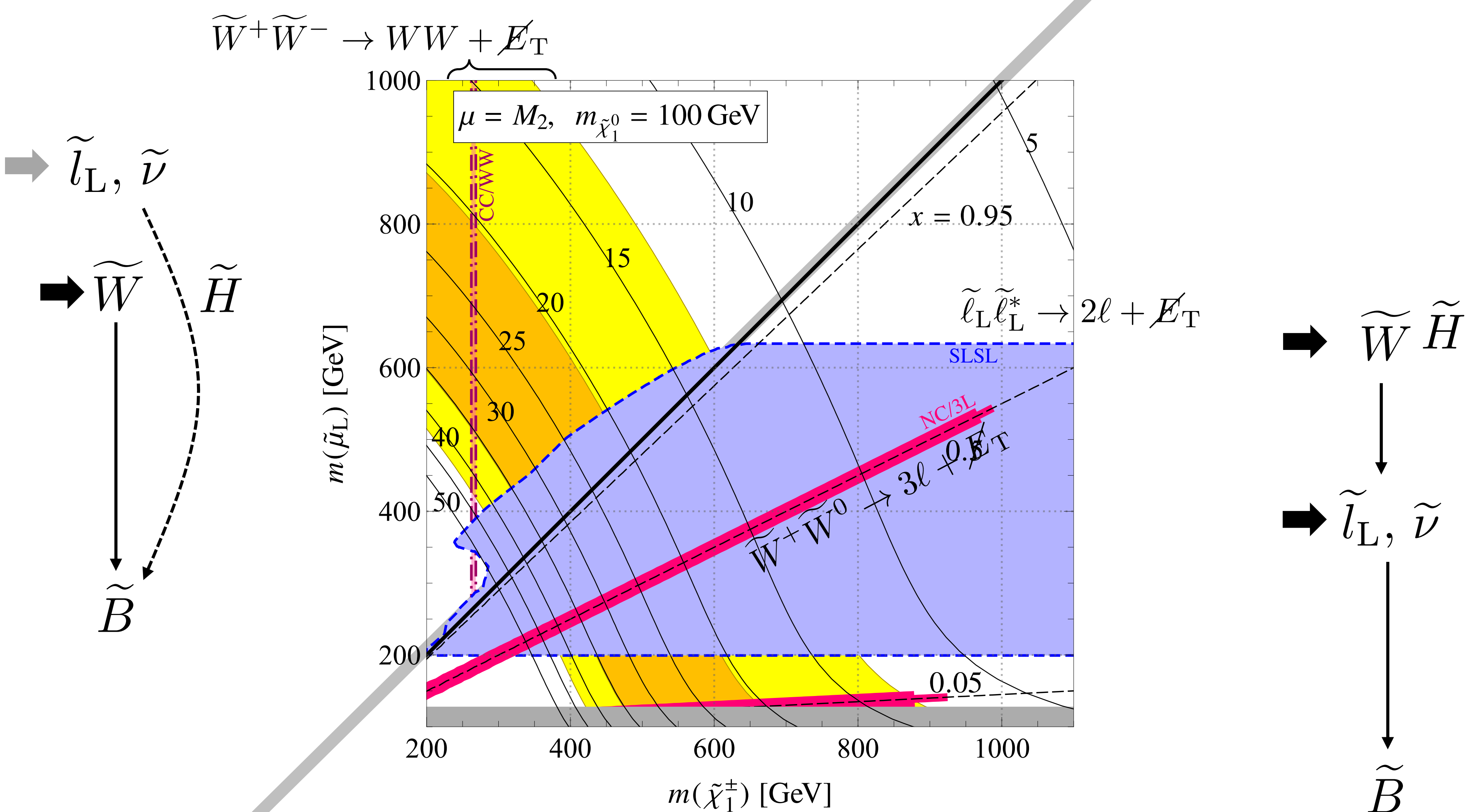
Endo, Hamaguchi, Iwamoto, Kitahara [2001.11025]

[B] LSP = (M2/2) bino, Higgsino is heavier. Wino has large XS but is quasi-degenerate with Bino.



Endo, Hamaguchi, Iwamoto, Kitahara [2001.11025]

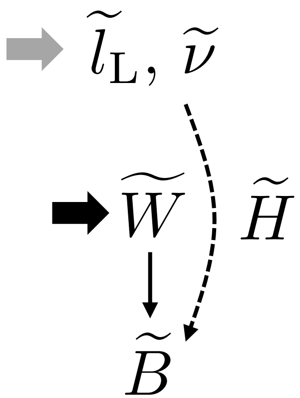
[C] LSP = 100GeV bino, with Higgsino/Wino mixing. Smaller neutralino-chargino production XS.

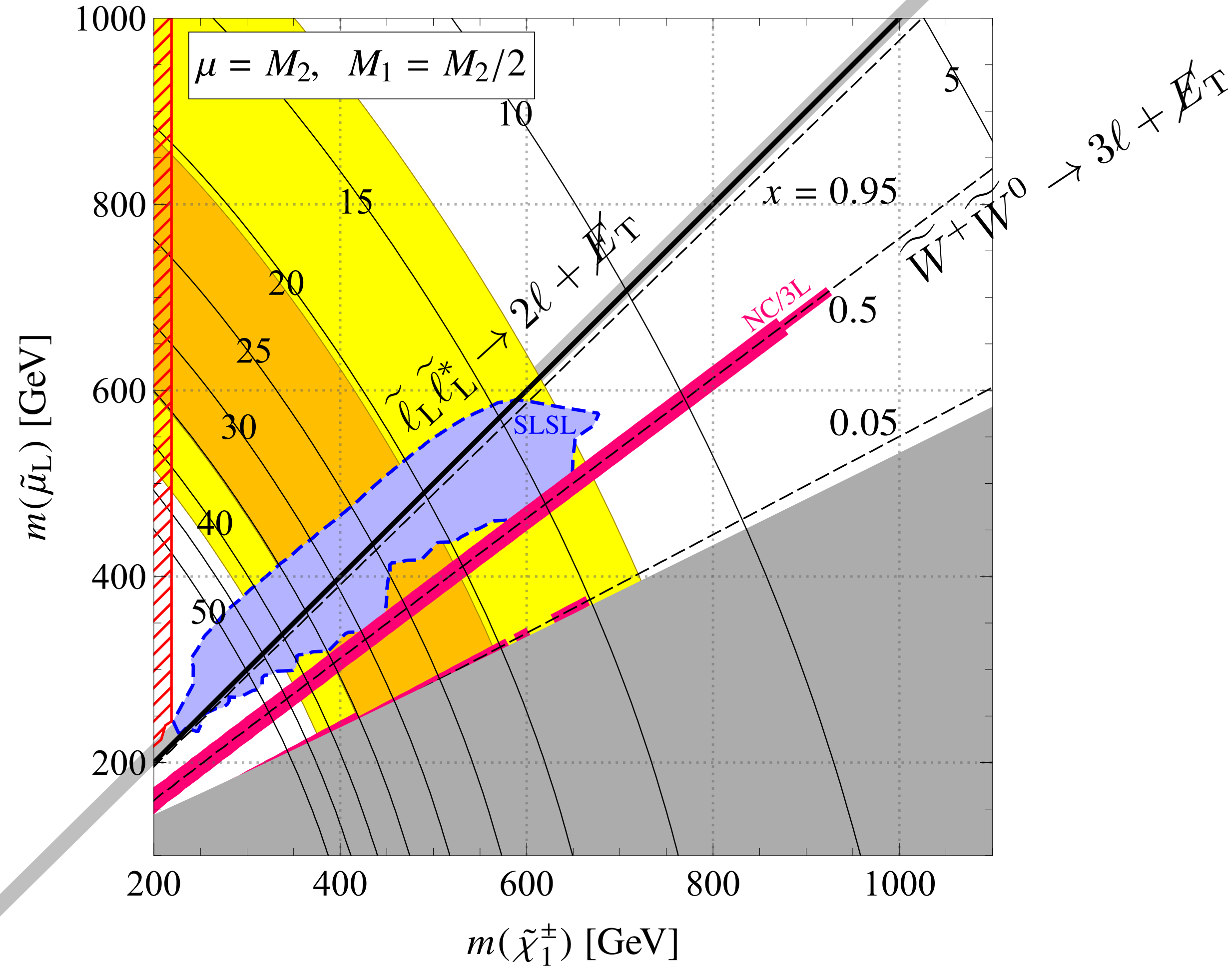


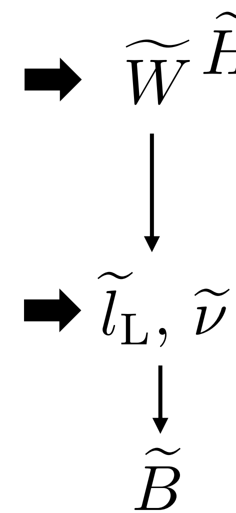
↑ Wino/Higgsino mixed

Endo, Hamaguchi, Iwamoto, Kitahara [2001.11025]

[D] LSP = (M2/2) bino, with Higgsino/Wino mixing. Smaller neutralino-chargino production XS.



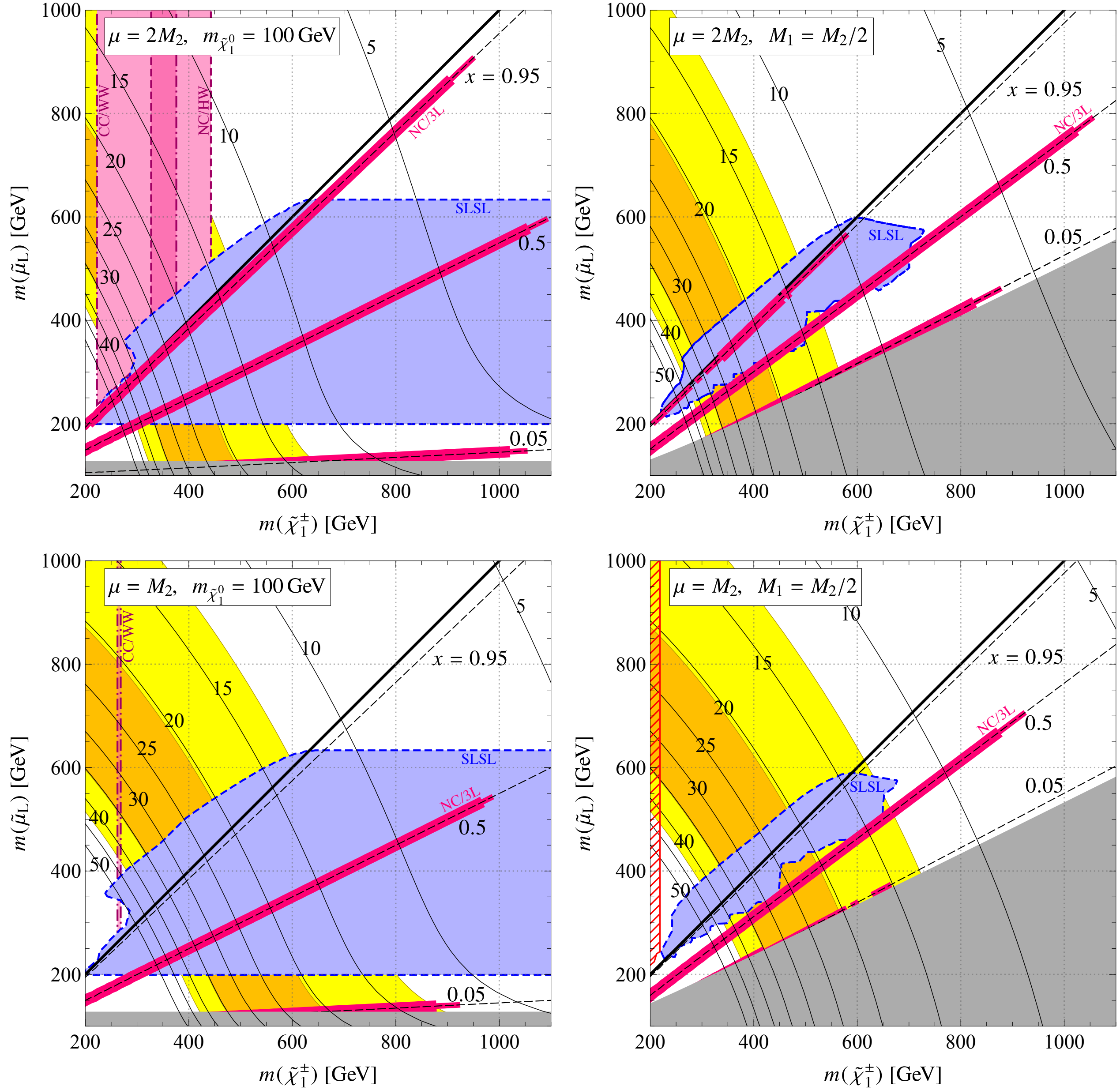




↑ Wino/Higgsino mixed

Endo, Hamaguchi, Iwamoto, Kitahara [2001.11025]

Summary of the four figures.



■ $\widetilde{W} > \widetilde{l}_L$

→ almost excluded due to

$$\widetilde{W}^+\widetilde{W}^0 \to 3\ell + \not{E}_T$$
$$\widetilde{\ell}_L\widetilde{\ell}_L^* \to 2\ell + \not{E}_T$$

■ $\widetilde{W} < \widetilde{l}_L$

→ excluded only if LSP is very light & Higgsino is heavy.

Endo, Hamaguchi, Iwamoto, Kitahara [2001.11025]

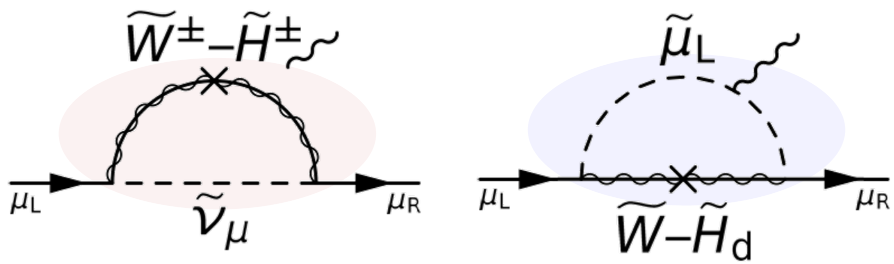
■ Problems in SM

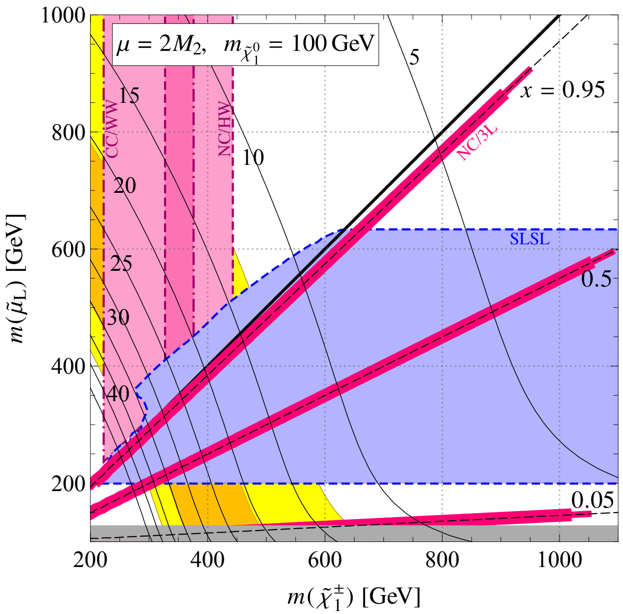
- Neutrino mass = 0. → introduce ν_R. ✓
- **No dark matter.** → **SUSY + R-parity: stable neutralino LSP.**
- No gravity / dark energy.
- No inflation.
- No baryon asymmetry.

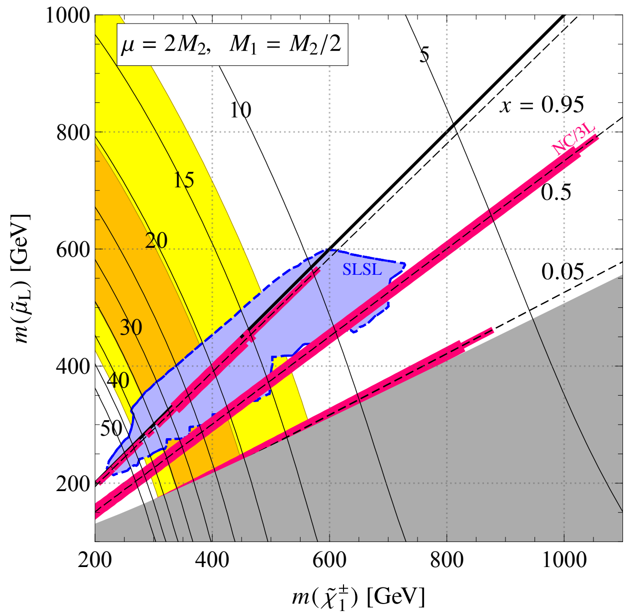
  → many models are proposed. (far above the collider energy)
- **Non-unification of 3 forces.** → **MSSM** ✓
- **Unnatural Higgs mass.** → **If scalar-top will be found below 1TeV... (but only narrow region remains).**
- Unnatural θ_{QCD}. → introduce axion?
- Discrepancies in expm:
  - **muon *g*−2**
  - $b \to s\,\mu\,\mu$, $R(D)$, $R(D^*)$, ...

  → **Non-colored SUSY particle may explain. ... but LHC constraints?** **[→next page]** [most reasonable] [easiest to detect]

"Wino-contribution dominating scenario"







- $\widetilde{W} > \tilde{l}_L$

→ **almost excluded**
due to
$$\widetilde{W}^+\widetilde{W}^0 \to 3\ell + \not{E}_T$$
$$\tilde{\ell}_L\tilde{\ell}^*_L \to 2\ell + \not{E}_T$$

- $\widetilde{W} < \tilde{l}_L$

→ excluded **only if LSP is very light & Higgsino is heavy.**

Note! DM relic density not discussed here at all.

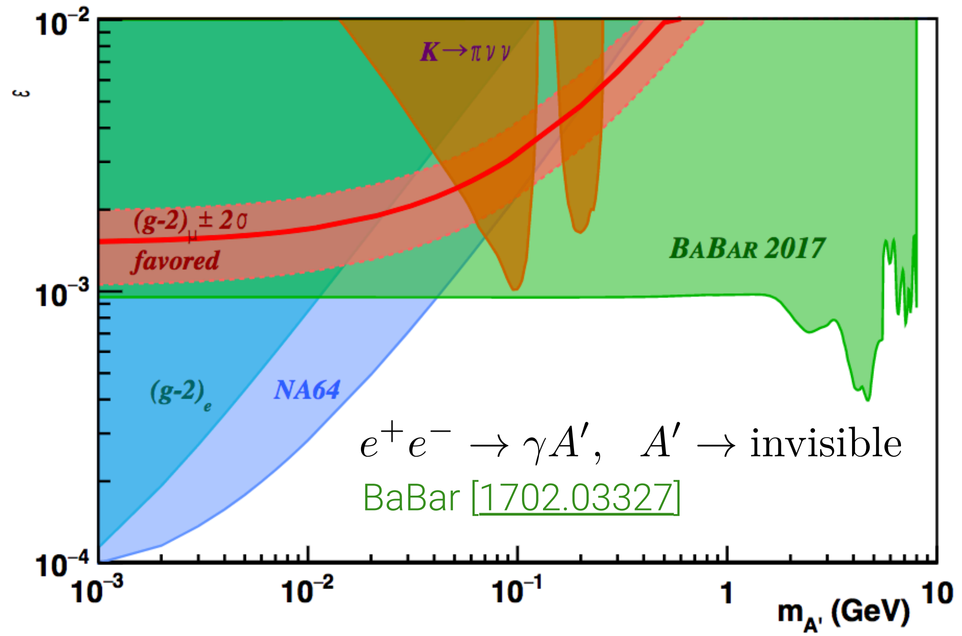
Appendix) other models for Δa_μ

$$a_\mu^{\rm NP} \sim \frac{m_\mu^2}{16\pi^2}\frac{(\text{new coupling})^2}{(\text{new mass})^2} \Rightarrow \frac{\text{mass}}{\text{coupling}} \sim 150\,\text{GeV}$$

$$a_\mu(\text{expm}) = (11\,659\,208.9 \pm 6.3) \times 10^{-10}$$
$$a_\mu(\text{SM}) = (11\,659\,181.0 \pm 4.3) \times 10^{-10}$$
$$\boldsymbol{\Delta a_\mu = (27.9 \pm 7.6) \times 10^{-10}}$$

- MSSM: (coupling, mass) ~ (1, 200GeV)
- light Z' models: (coupling, mass) ~ (tiny, tiny)

	$U(1)_Y$	**"dark photon"**
Q_L	1/6	(1/6)ε
U_R	2/3	(2/3)ε
D_R	−1/3	(−1/3)ε
L_L	−1/2	(−1/2)ε
E_R	−1	(−1)ε
B	✓	
A'		✓
H	1/2	(1/2)ε



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

BaBar [1702.03327]

⇨ **excluded (as a Δa_μ solution)**

$$a_\mu^{\rm NP} \sim \frac{m_\mu^2}{16\pi^2}\frac{(\text{new coupling})^2}{(\text{new mass})^2} \Rightarrow \frac{\text{mass}}{\text{coupling}} \sim 150\,\text{GeV}$$

$$a_\mu(\text{expm}) = (11\,659\,208.9 \pm 6.3) \times 10^{-10}$$
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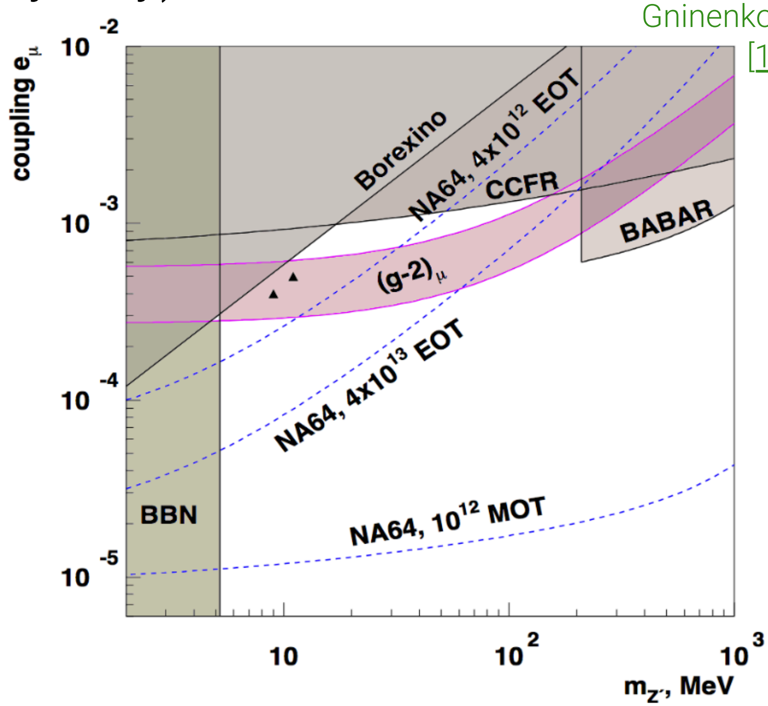
$$\Delta a_\mu = (27.9 \pm 7.6) \times 10^{-10}$$

- MSSM: (coupling, mass) ~ (1, 200GeV)
- light Z' models: (coupling, mass) ~ (tiny, tiny)

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

Gninenko, Krasnikov [1801.10448]

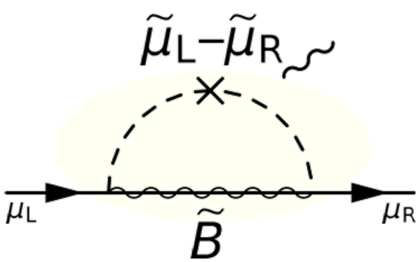


⇨ **another valid solution**

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

Appendix) Pure-Bino and BHL/R

- "pure-Bino contribution": Bino and $\tilde{\mu}_{\rm L}, \tilde{\mu}_{\rm R}$ must be $\mathcal{O}(100)$GeV.
  - Higgsino and Wino can be any heavy.
- $\propto \mu \tan\beta$ → heavier Higgsino gives larger contribution.

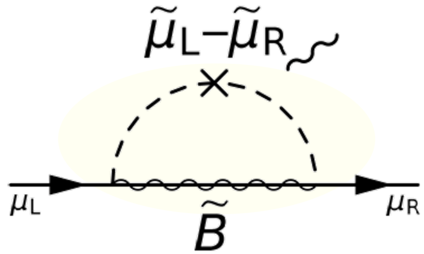


[pure-B]
$$\frac{g_Y^2 m_\mu^2}{8\pi^2} \frac{\mu \tan\beta}{M_1^3} \cdot F_b\left(\frac{m_{\tilde{\mu}_{\rm L}}}{M_1}, \frac{m_{\tilde{\mu}_{\rm R}}}{M_1}\right)$$

F_a, F_b are loop functions and positive.

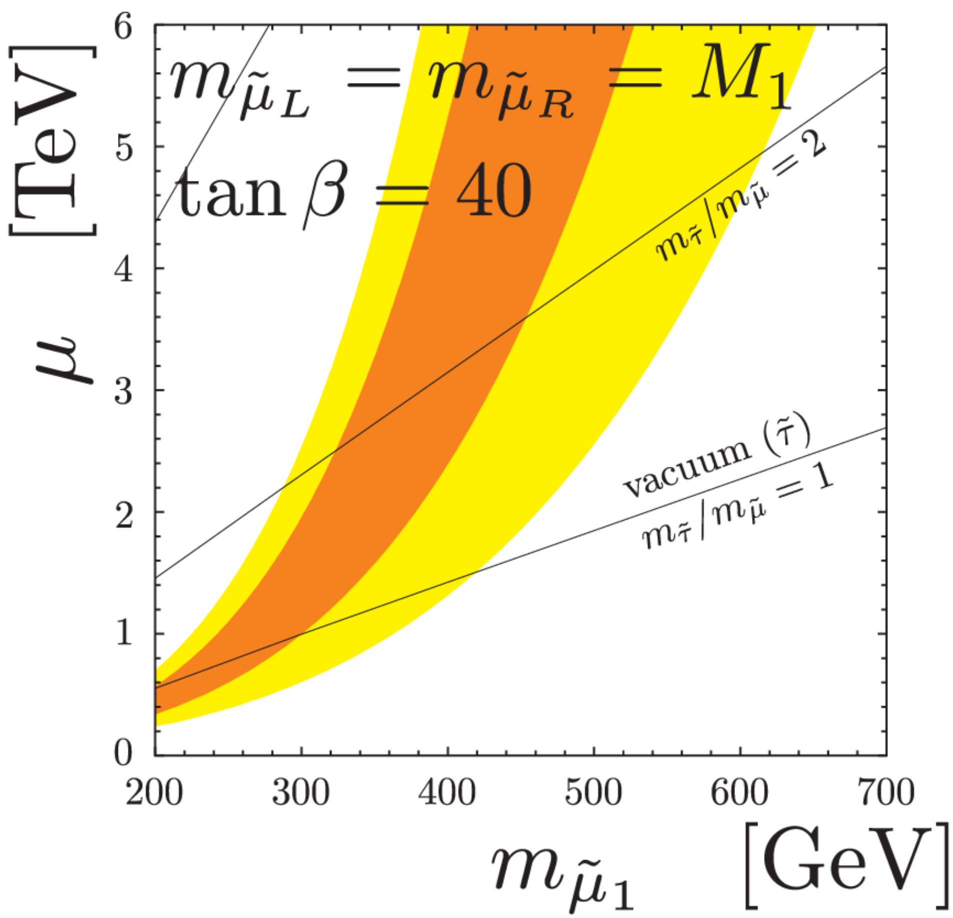
$$F_a(x,y) = \frac{1}{2}\frac{C_1(x^2) - C_1(y^2)}{x^2 - y^2}, \qquad F_b(x,y) = -\frac{1}{2}\frac{N_2(x^2) - N_2(y^2)}{x^2 - y^2};$$

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



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

from $M^2_{\tilde{\mu}} = \begin{pmatrix} m(l_L)^2 & m_\mu(A^*_\mu - \mu\tan\beta) \\ m_\mu(A^*_\mu - \mu\tan\beta) & m(l_R)^2 \end{pmatrix}$



μ tanβ has upper bounds:

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

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

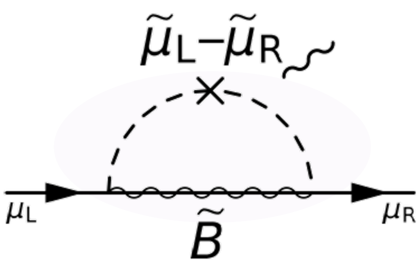
$= 1 \Rightarrow m_{\tilde{\mu}} \lesssim 300(420)$ GeV

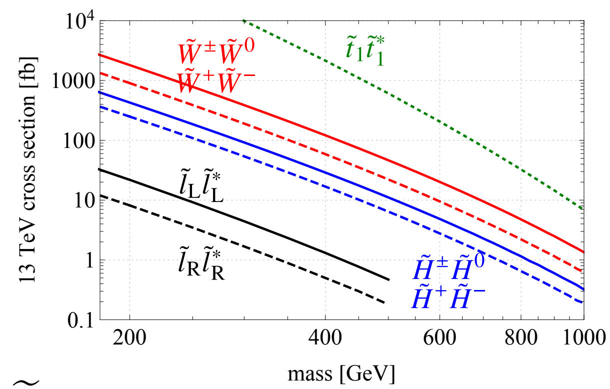
$= 2 \Rightarrow \lesssim 440(620)$ GeV

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

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

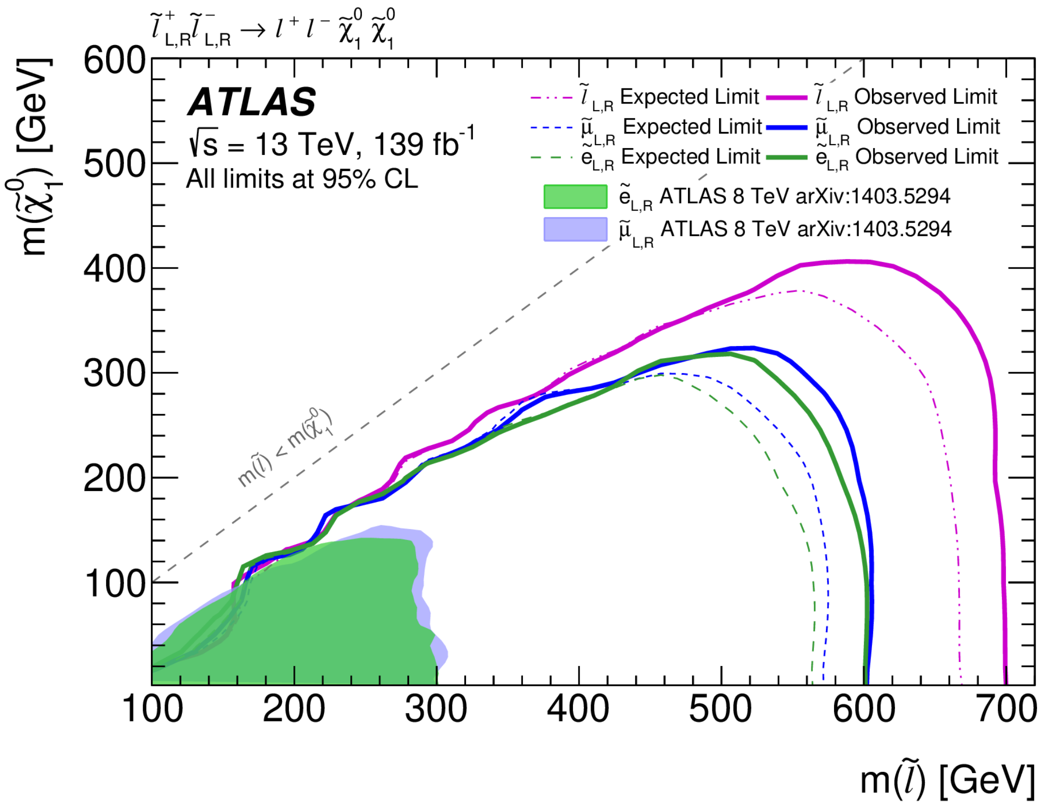
$$\frac{g_Y^2 m_\mu^2}{8\pi^2}\frac{\mu\tan\beta}{M_1^3}\cdot F_b\left(\frac{m_{\tilde{\mu}_L}}{M_1},\frac{m_{\tilde{\mu}_R}}{M_1}\right)$$



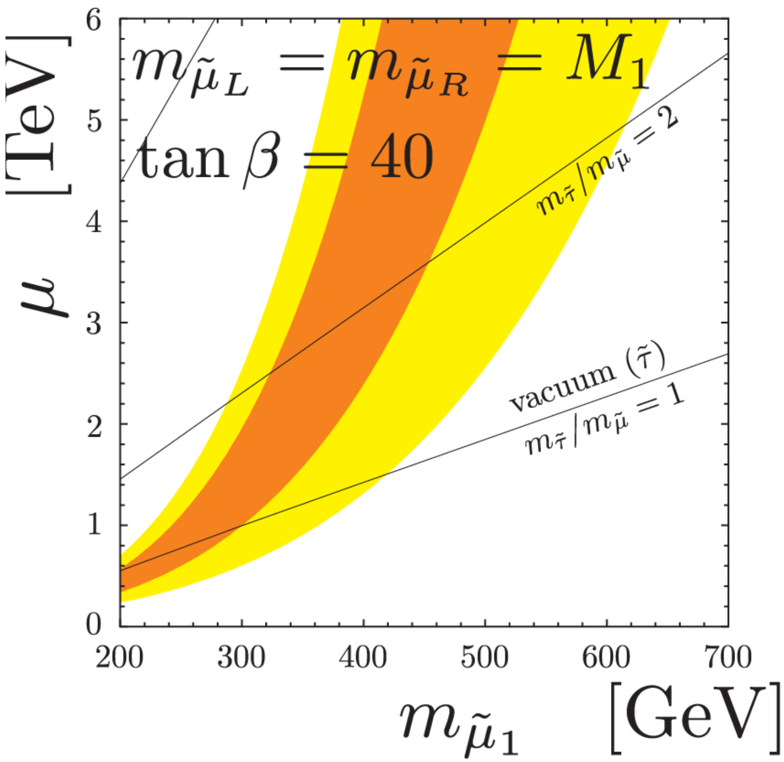


- ➢ LHC: only slepton pair-production
  - small cross section: $0.47\,(0.18)$ fb for $500\,\mathrm{GeV}$ $\tilde{\ell}_L\ (\tilde{\ell}_R)$
  - "di-lepton + missing" signature ... not easy.

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



ATLAS [1908.08215]

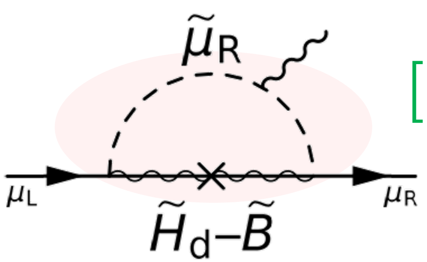


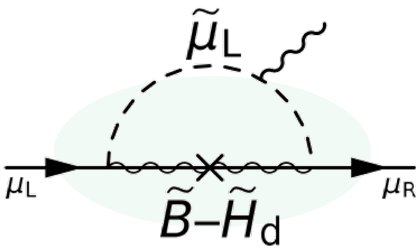
Endo, Hamaguchi, Kitahara, Yoshinaga [1309.3065]

- "BHR contribution" (Bino, Higgsino, $\tilde{\mu}_{\mathrm{R}}$ must be $\mathcal{O}(100)$GeV)
  - If μ-parameter < 0, this is the only viable contribution.
    (Higgsino-mass parameter)
- "BHL contribution" (Bino, Higgsino, $\tilde{\mu}_{\mathrm{L}}$ must be $\mathcal{O}(100)$GeV)
  - nothing special.
- $\propto g_Y^2$

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

[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.

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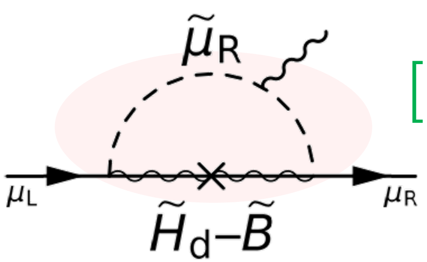
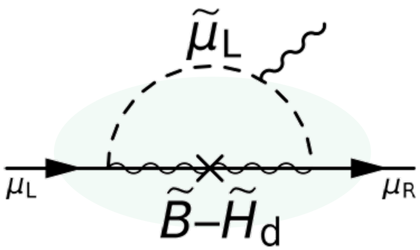
- Wino >> TeV & Higgsino < TeV → BHL or BHR scenario.
  $(\mu > 0)$ $(\mu < 0)$
  - $\propto g_Y^2$ → relevant particles ≲ 500 GeV
  - LHC: $pp \to \widetilde{H}^+\widetilde{H}^0,\ \widetilde{H}^+\widetilde{H}^-$ "not much, but enough"
  - DM: ~~Bino–Higgsino mixing~~, bino–slepton co-annihilation.
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



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

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



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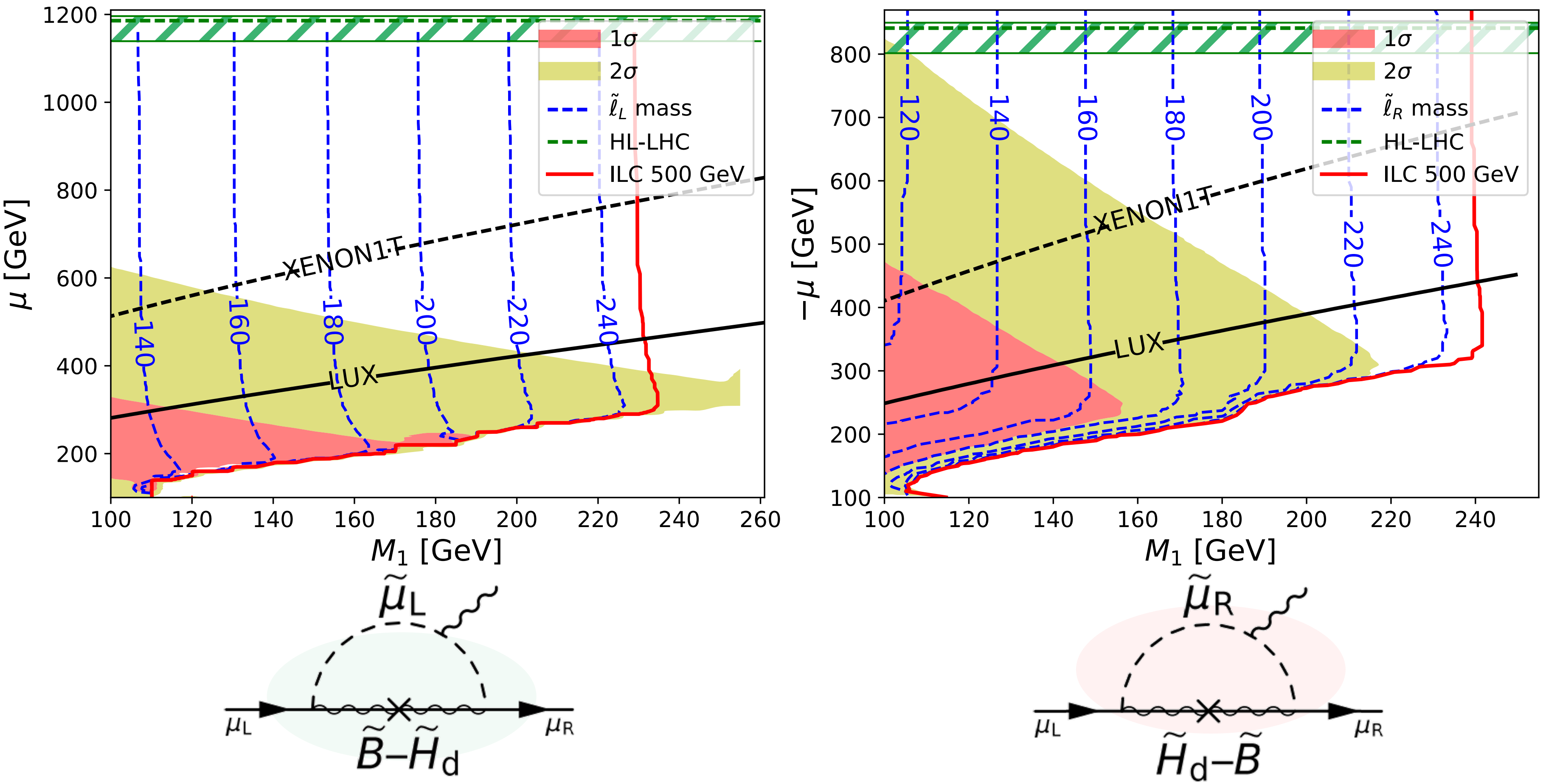
$$C_1(x) = \frac{3-4x+x^2+2\log x}{(1-x)^3}, \qquad N_2(x) = \frac{1-x^2+2x\log x}{(1-x)^3}.$$

■ Wino >> TeV & Higgsino < TeV → BHL or BHR scenario. $(\mu > 0)$ $(\mu < 0)$

- $\propto g_Y^2$ → relevant particles ≲ 500 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.



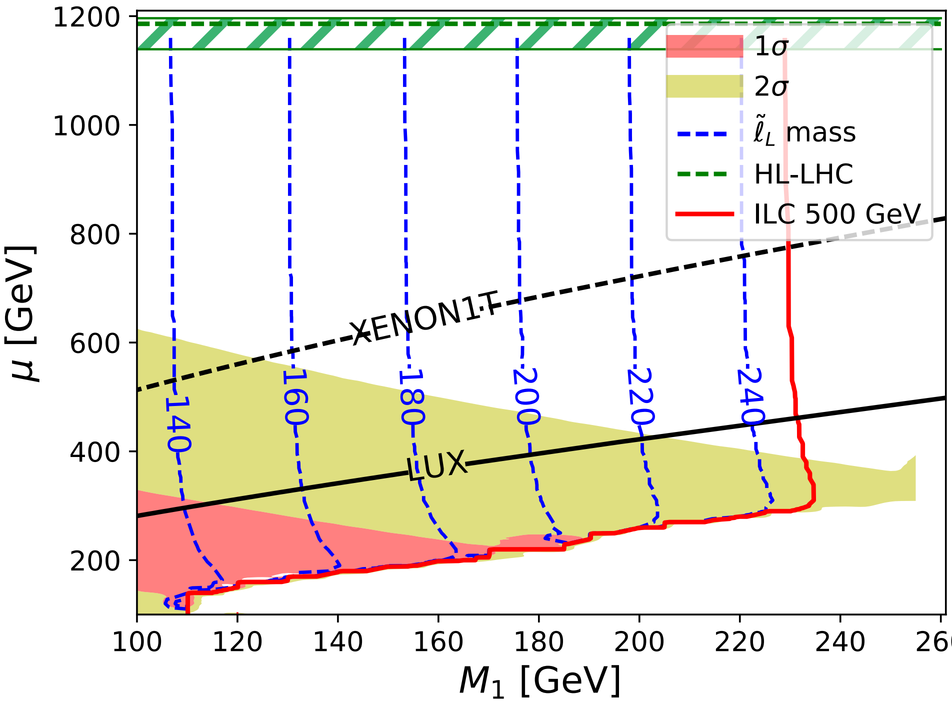
- Bino−slepton (stau) co-annihilation → $m_{\tilde{\nu}_\tau}$ (or $m_{\tilde{\tau}_R}$) $\simeq m_{\widetilde{B}}$

.

- We assumed:
  - ➢ slepton universality,
  - ➢ DM density is realized at each point in the plots.

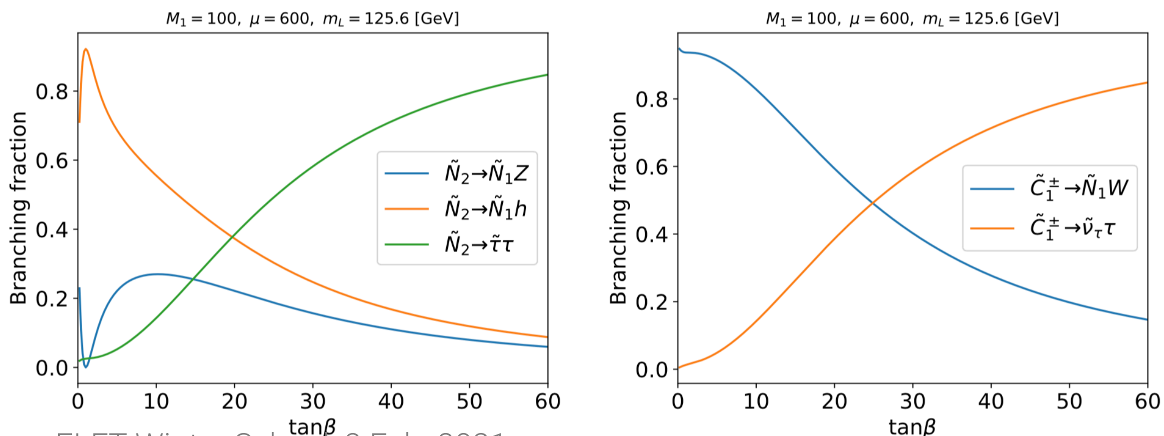
    → $m_{\widetilde{B}} \lesssim m_{\tilde{\mu}} < m_{\widetilde{H}}$

    ($\sim M_1$) ($\sim \mu$)



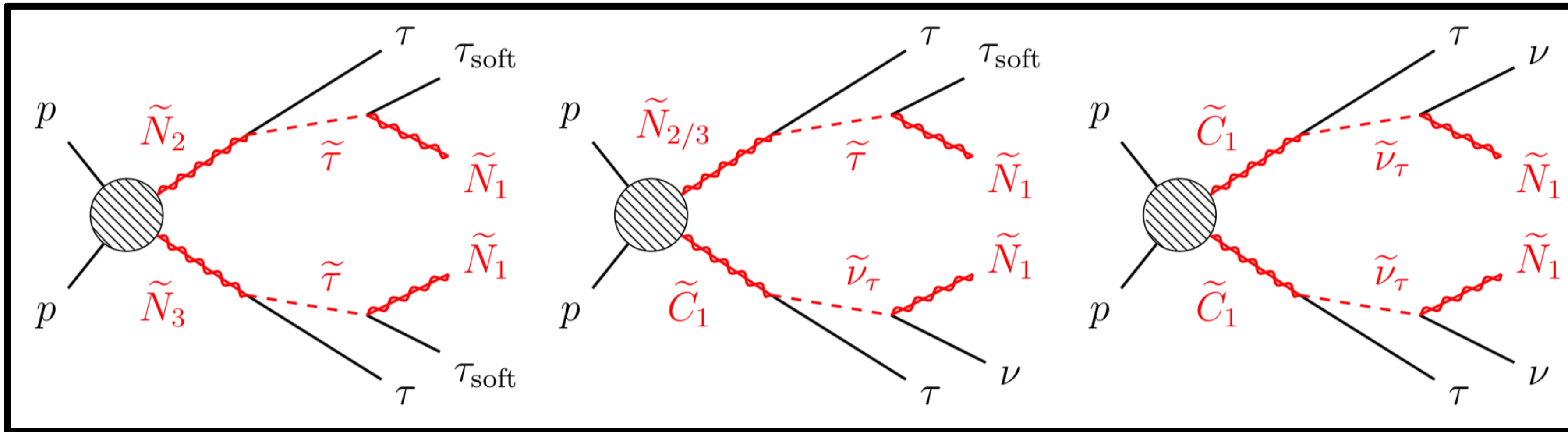
- HL-LHC?
  - ➢ $pp \to \widetilde{H}^+ \widetilde{H}^0,\ \widetilde{H}^+ \widetilde{H}^-$
  - ➢ $\widetilde{H}^0 \to \tau\tilde{\tau},\ \ \widetilde{H}^+ \to \tau\tilde{\nu}_\tau$ because of tanβ.

    → multi-tau signature



"BHR"/"BHL": Higgsino provides multi-τ signature.

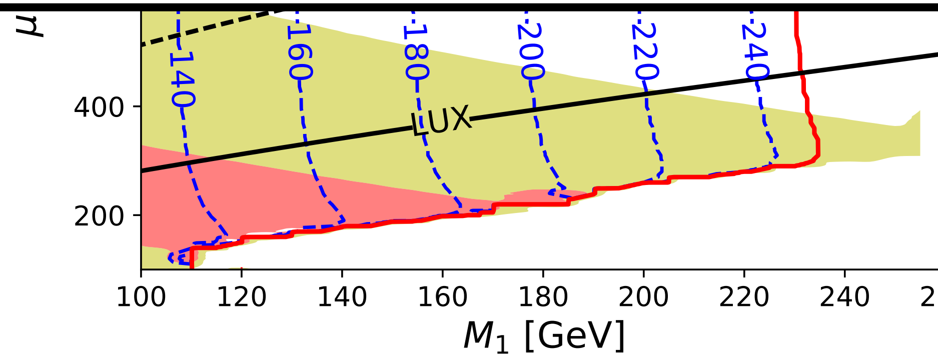
Endo, Hamaguchi, Iwamoto, Yanagi [1704.05287]



each point in the plots.

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

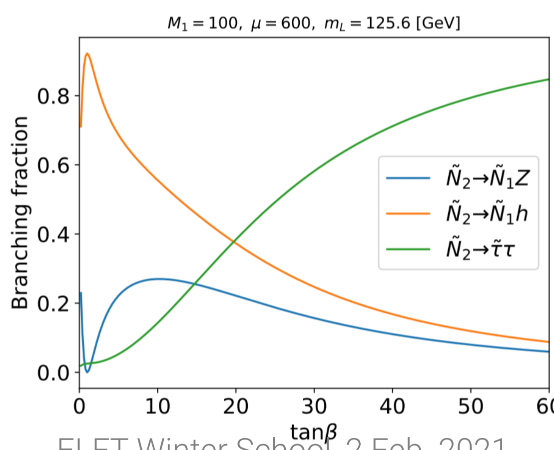
(~M_1) (~μ)

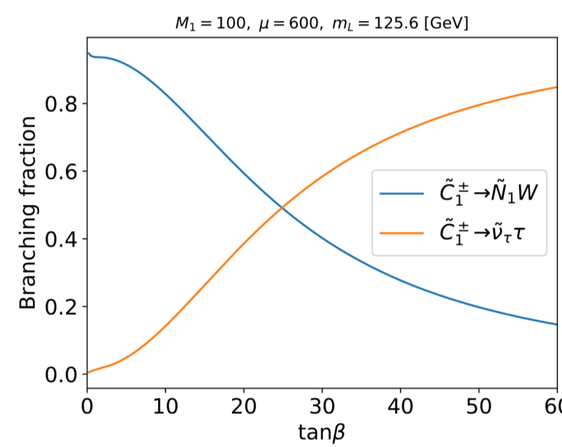


■ HL-LHC?

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

→ multi-tau signature **"2τ** (+ soft) **+ missing"**





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