University of Southampton

UNI BONN
bctp Bethe Center for Theoretical Physics

25/11/2024

Excesses in electroweak SUSY searches at the LHC

BASED ON : **2403.14759, 2112.01389**

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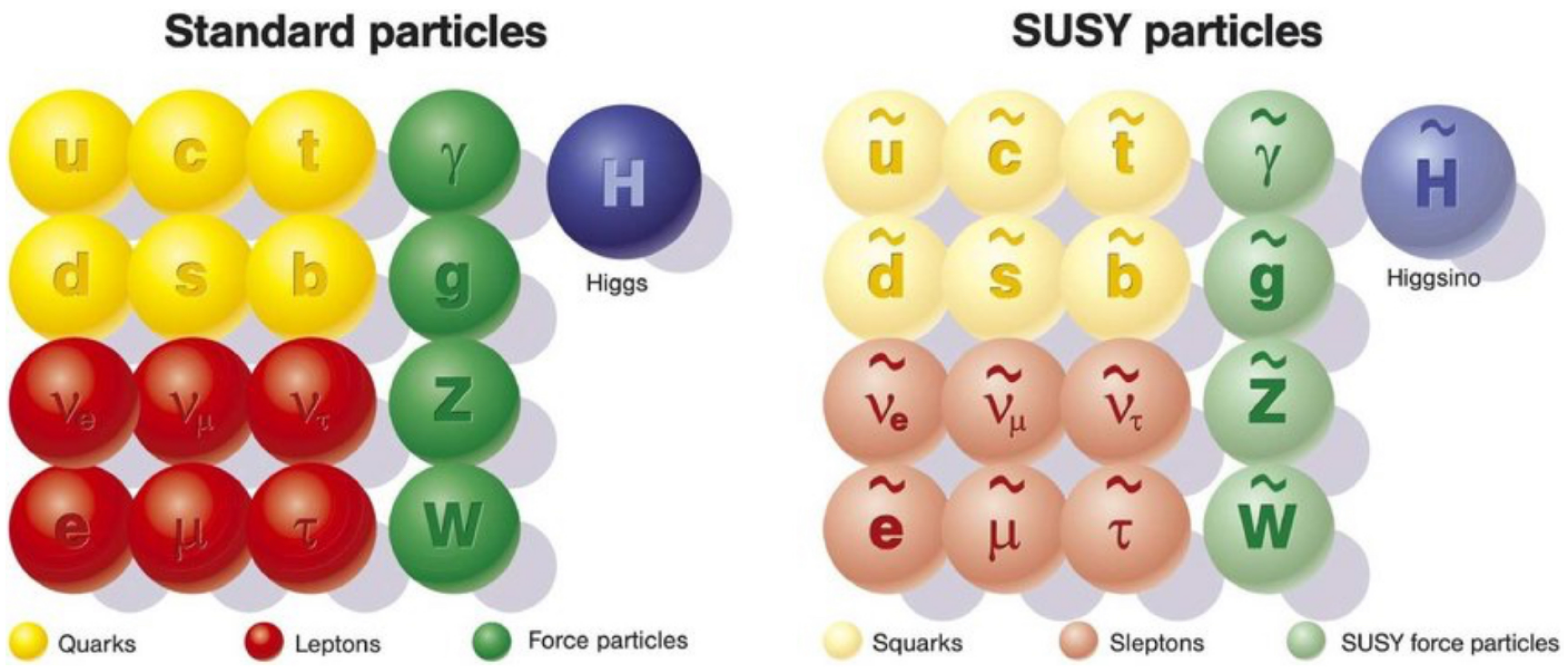
Manimala Chakraborti

Outline

- Brief recap of MSSM
- Latest status of the LHC searches for EW SUSY…
- … and muon g-2
- Results
- Summary

EW MSSM

MSSM particle content



Uncolored EW sector

- Charginos/ neutralinos
- Sleptons

Electroweak MSSM

- Modest production cross section, mass bounds from the LHC comparably weak
- May show up elsewhere : DM experiments, $(g-2)_\mu$
- Some interesting excesses

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	(same)
			$\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$	(same)
			$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	(same)
			$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	(same)
			$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	1/2	−1	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	−1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$
gluino	1/2	−1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)

EW sector may be hiding key to new physics!

MSSM Superpotential

$$W_{\text{MSSM}} = \bar{u} Y_u Q H_u - \bar{d} Y_d Q H_d - \bar{e} Y_e L H_d + \mu H_u H_d$$

Soft Breaking Terms

$$\mathscr{L}_{\text{soft}}^{\text{MSSM}} = -\frac{1}{2}\left(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B} + c.c\right)$$

$$-\left(\tilde{\bar{u}}\,\mathbf{a_u}\,\tilde{Q}H_u - \tilde{\bar{d}}\,\mathbf{a_d}\,\tilde{Q}H_d - \tilde{\bar{e}}\,\mathbf{a_e}\,\tilde{L}H_d + c.c\right)$$

$$-\tilde{Q}^\dagger \mathbf{m_Q^2}\,\tilde{Q} - \tilde{L}^\dagger\,\mathbf{m_L^2}\,\tilde{L} - \tilde{\bar{u}}\,\mathbf{m_{\bar{u}}^2}\,\tilde{\bar{u}}^\dagger - \tilde{\bar{d}}\,\mathbf{m_{\bar{d}}^2}\,\tilde{\bar{d}}^\dagger - \tilde{\bar{e}}\,\mathbf{m_{\bar{e}}^2}\,\tilde{\bar{e}}^\dagger$$

$$-m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - \left(bH_uH_d + c.c\right)$$

Neutralinos

Gauge eigenstate basis $(\tilde{B},\ \tilde{W}_3^0,\ \tilde{H}_u^0,\ H_d^0)$

Tree level neutralino mass matrix

$$M_N = \begin{pmatrix} M_1 & 0 & -M_Z\, c_\beta\, s_W & M_Z\, s_\beta\, s_W \\ 0 & M_2 & M_Z\, c_\beta\, cW & -M_Z\, s_\beta\, cW \\ -M_Z\, c_\beta\, s_W & M_Z\, c_\beta\, c_W & 0 & -\mu \\ M_Z\, s_\beta\, s_W & -M_Z\, s_\beta\, c_W & -\mu & 0 \end{pmatrix}$$

Mass diagonalisation : $N^* M_{\tilde{N}} N^{-1} = (m_{\tilde{\chi}_1^0},\ m_{\tilde{\chi}_2^0},\ m_{\tilde{\chi}_3^0},\ m_{\tilde{\chi}_4^0})$

Parameters → $M_1, M_2, \mu, \tan\beta$

Neutralinos

Gauge eigenstate basis $(\tilde{B},\ \tilde{W}_3^0,\ \tilde{H}_u^0,\ H_d^0)$

Tree level neutralino mass matrix

$$M_N = \begin{pmatrix} M_1 & 0 & -M_Z\, c_\beta\, s_W & M_Z\, s_\beta\, s_W \\ 0 & M_2 & M_Z\, c_\beta\, cW & -M_Z\, s_\beta\, cW \\ -M_Z\, c_\beta\, s_W & M_Z\, c_\beta\, c_W & 0 & -\mu \\ M_Z\, s_\beta\, s_W & -M_Z\, s_\beta\, c_W & -\mu & 0 \end{pmatrix}$$

$$N^* M_{\tilde{N}} N^{-1} = (m_{\tilde{\chi}_1^0},\ \ m_{\tilde{\chi}_2^0},\ \ m_{\tilde{\chi}_3^0},\ \ m_{\tilde{\chi}_4^0})$$

DM candidate

$$R_p \equiv (-1)^{3(B-L)+2S}$$

Parameters → $M_1, M_2, \mu, \tan\beta$

Charginos

Gauge eigenstate basis $(\tilde{W}^{\pm}, \tilde{H}^{\pm}_{u/d})$

Tree level chargino mass matrix

$$M_C = \begin{pmatrix} M_2 & \sqrt{2} M_W c_\beta \\ \sqrt{2} M_W s_\beta & \mu \end{pmatrix}$$

Mass diagonalisation : $U^* M_{\tilde{N}} V^{-1} = (m_{\tilde{\chi}_1^{\pm}}, \;\; m_{\tilde{\chi}_2^{\pm}})$

Parameters ➡ $M_2, \mu, \tan\beta$

Sleptons

Tree level slepton mass matrix

$$M_{\tilde{L}}^2 = \begin{pmatrix} m_l^2 + m_{LL}^2 & m_l X_l \\ m_l X_l & m_l^2 + m_{RR}^2 \end{pmatrix}$$

$$m_{LL}^2 = m_{\tilde{L}}^2 + (I_l^{3L} - Q_l s_w^2) M_z^2 c_{2\beta}$$

$$m_{RR}^2 = m_{\tilde{R}}^2 + Q_l s_w^2 M_z^2 c_{2\beta}$$

$$X_l = A_l - \mu(\tan\beta)^{2I_l^{3L}}$$

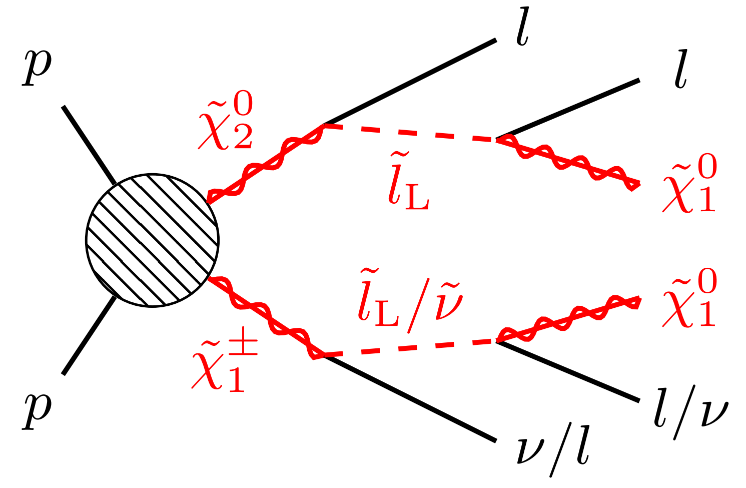
Parameters → $m_{\tilde{L}}\,, m_{\tilde{R}}, \mu, \tan\beta$

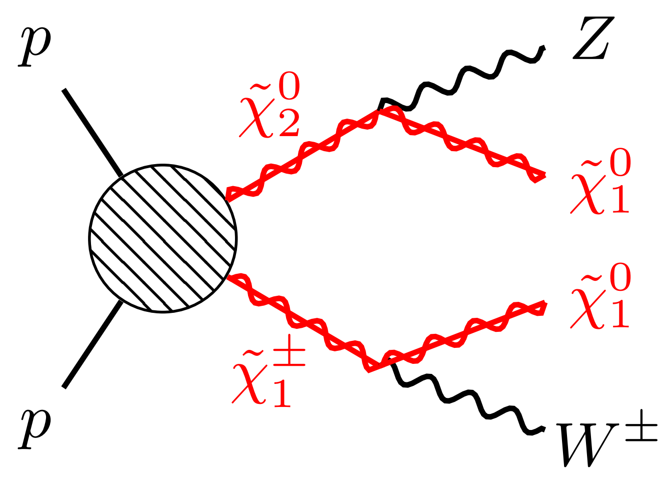
First two gens. $m_{\tilde{l}_1} \sim m_{LL}$ $\quad m_{\tilde{l}_2} \sim m_{RR}$

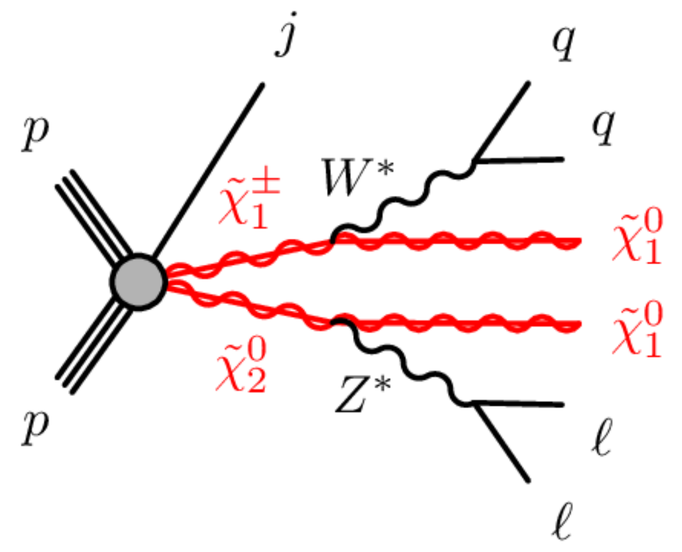
LHC searches

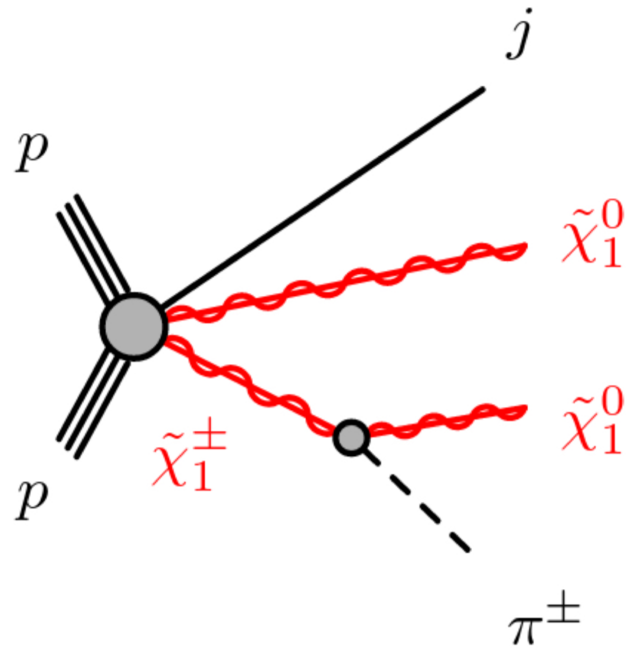
- Multilepton + missing E_T
  - Decay via sleptons
  - Decay via gauge/Higgs bosons (on-shell)
  - Decay via gauge bosons (off-shell)
- Disappearing/displaced track searches
  - Decay via pions (mass splitting ~ 100 MeV)
- Monojet searches
  - Pair production of DM

Mass splitting







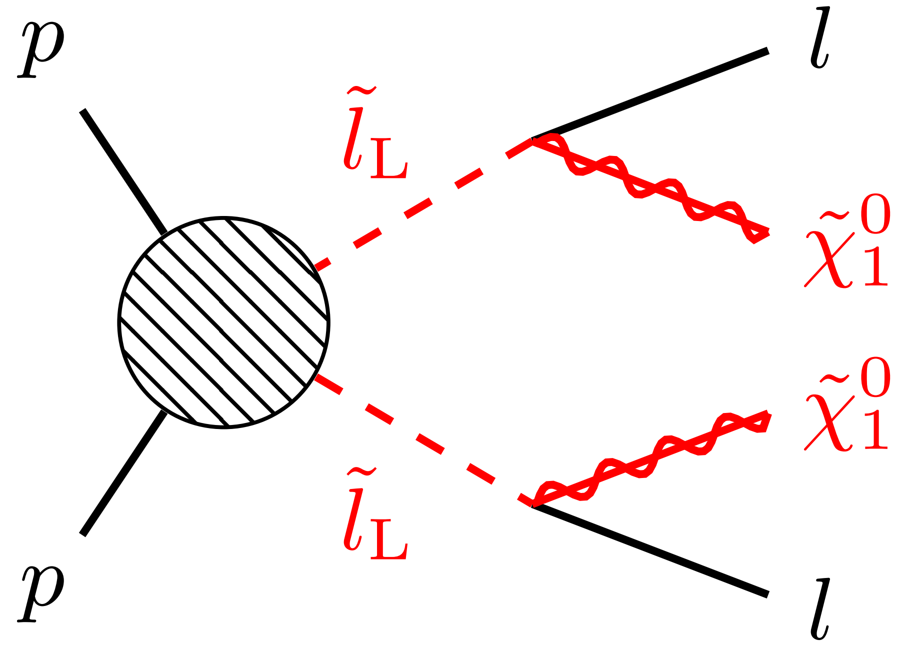


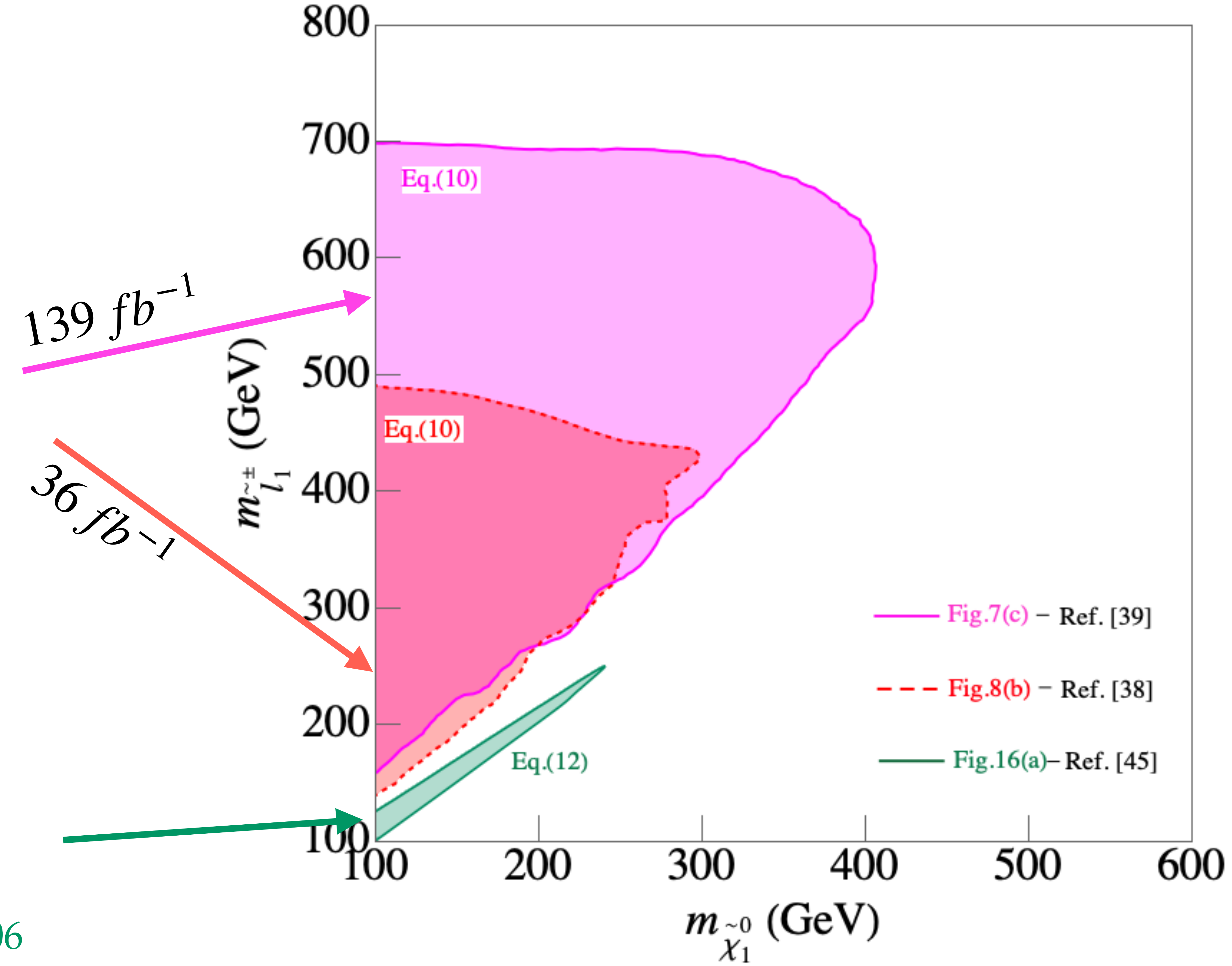
LHC searches

Slepton pair production

ATLAS [1908.08215]

13 TeV, 139 fb^{-1}

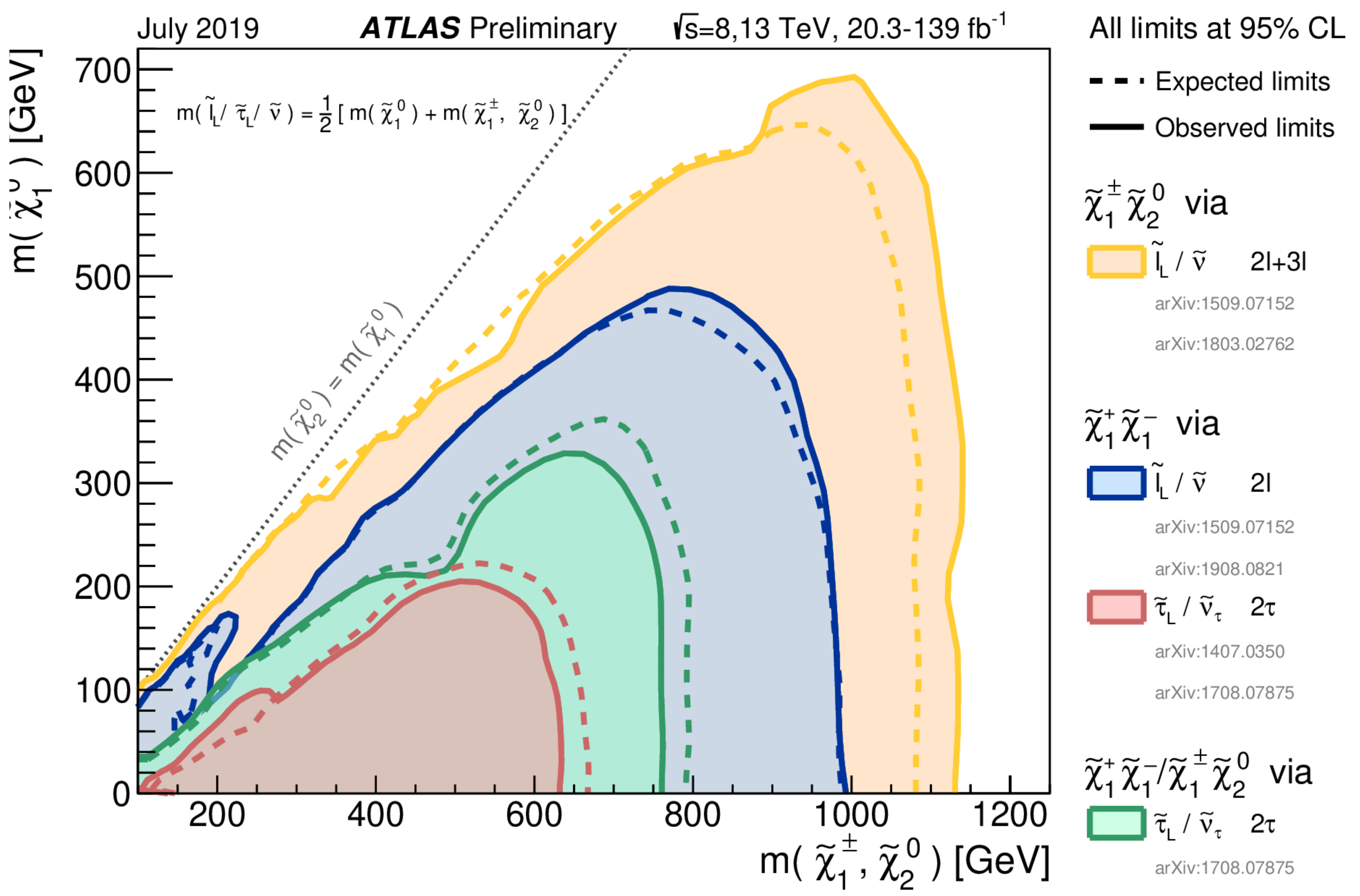


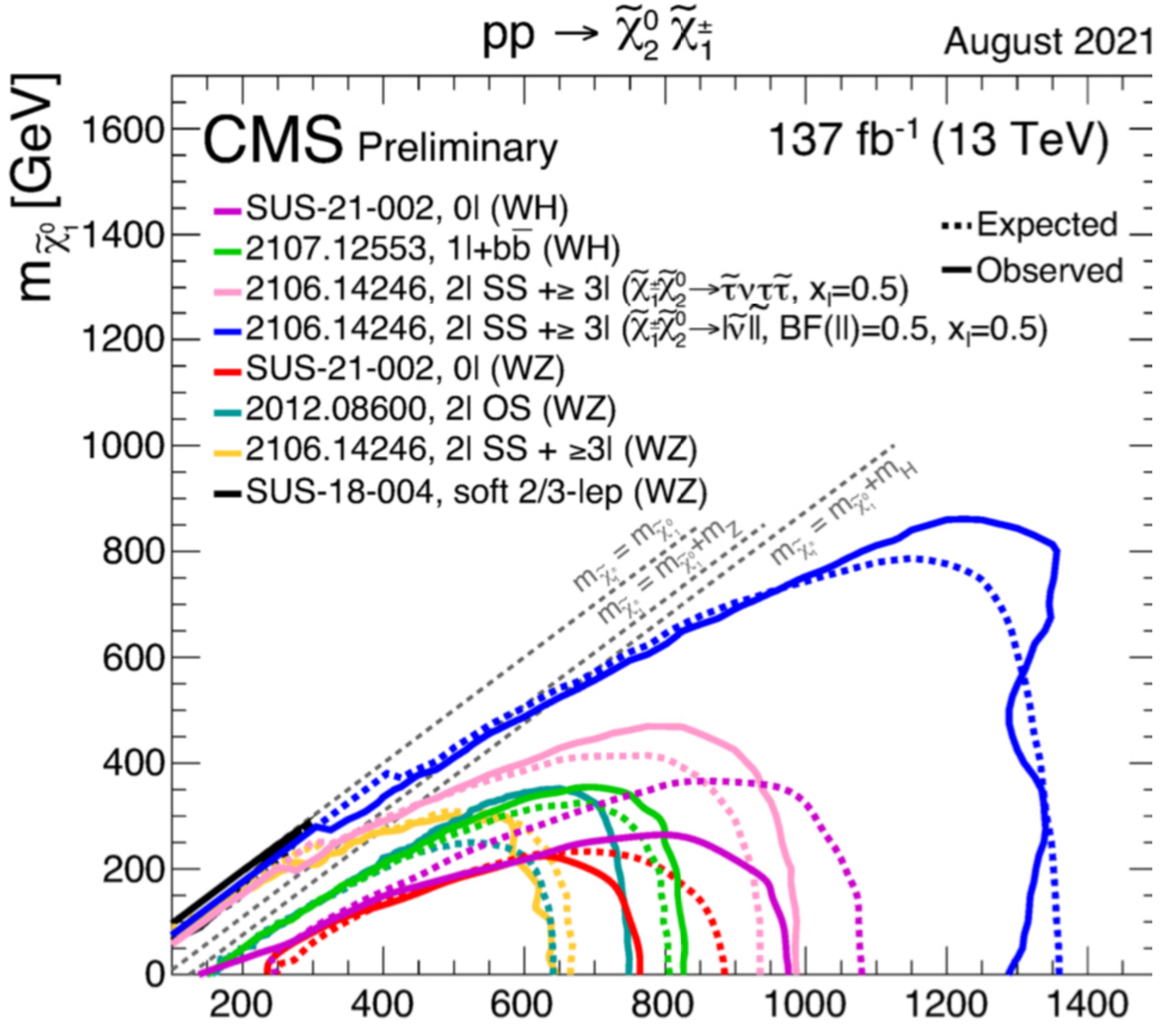


Compressed

ATLAS 1911.12606

What did the LHC exclude ?

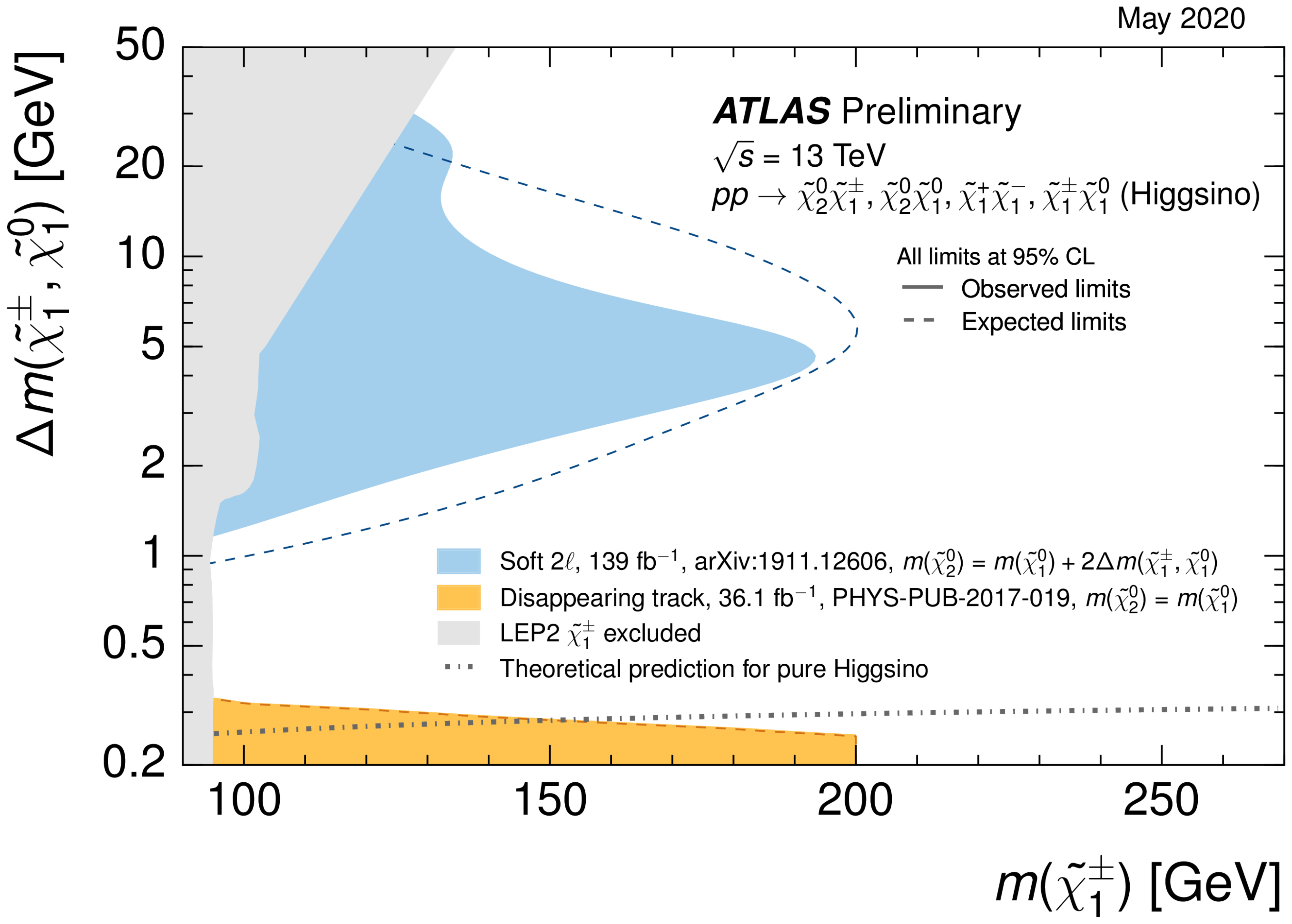


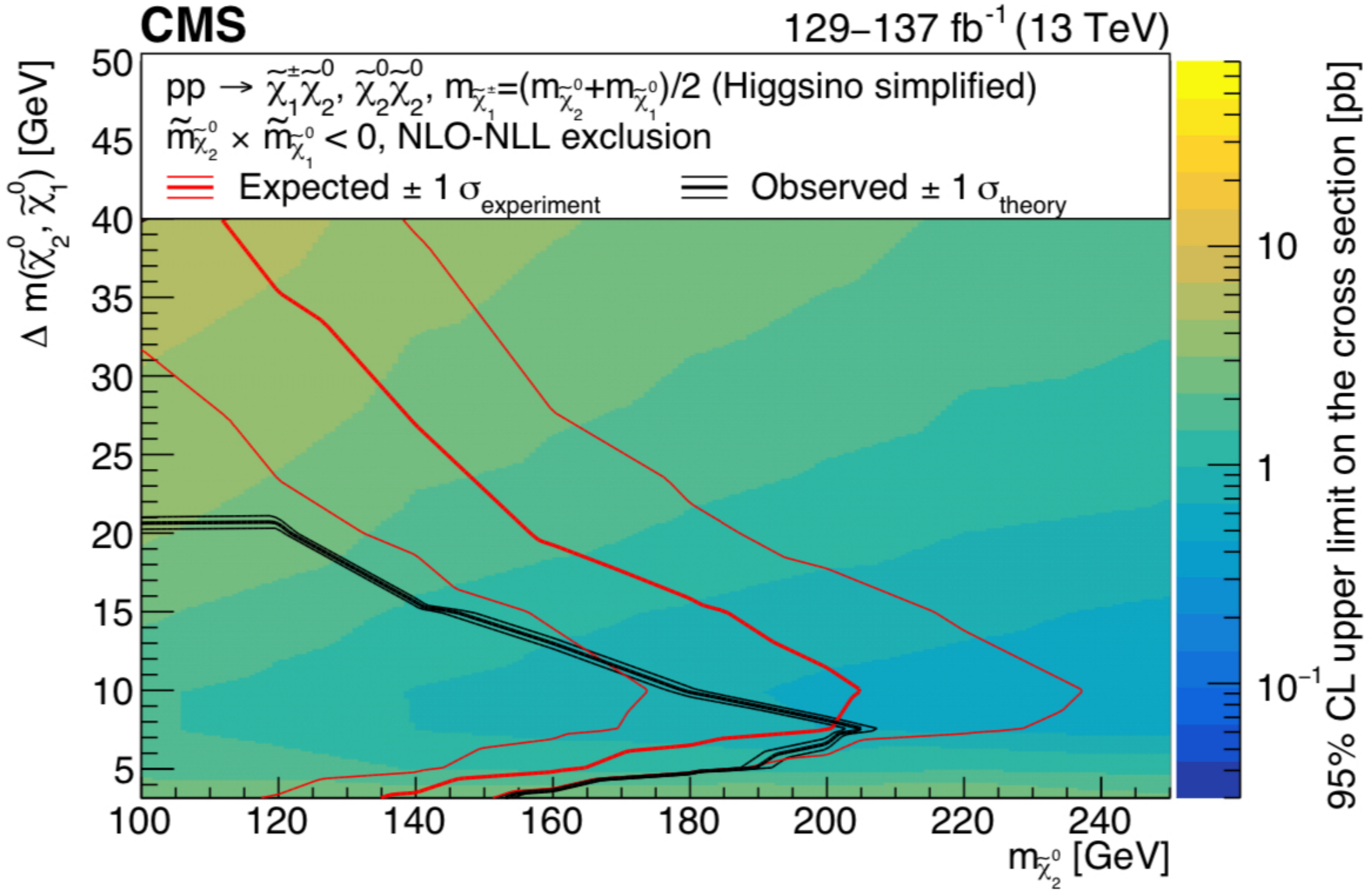


Impressive exclusion bounds for winos

- EW triplets
- Large mass splitting

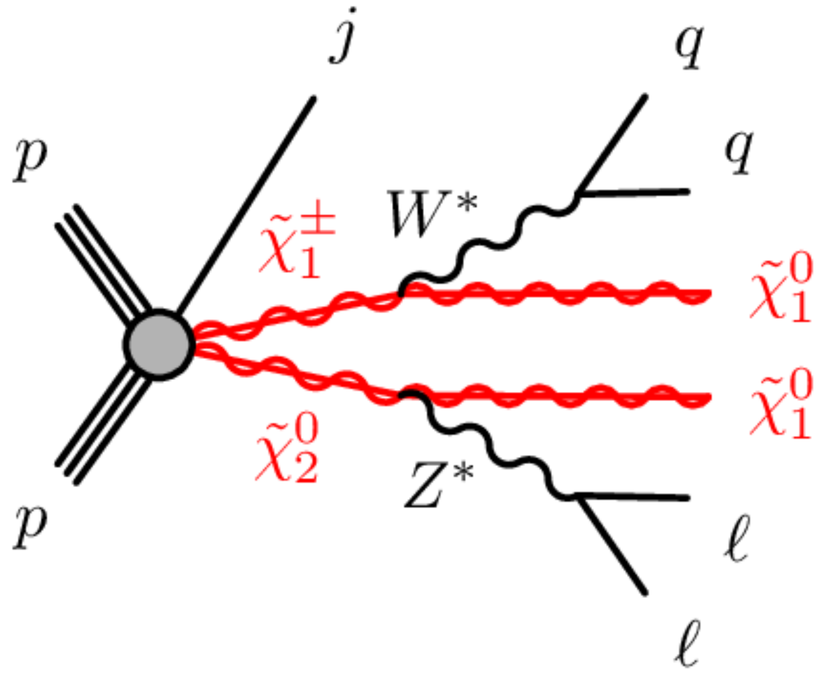
What did the LHC exclude ?



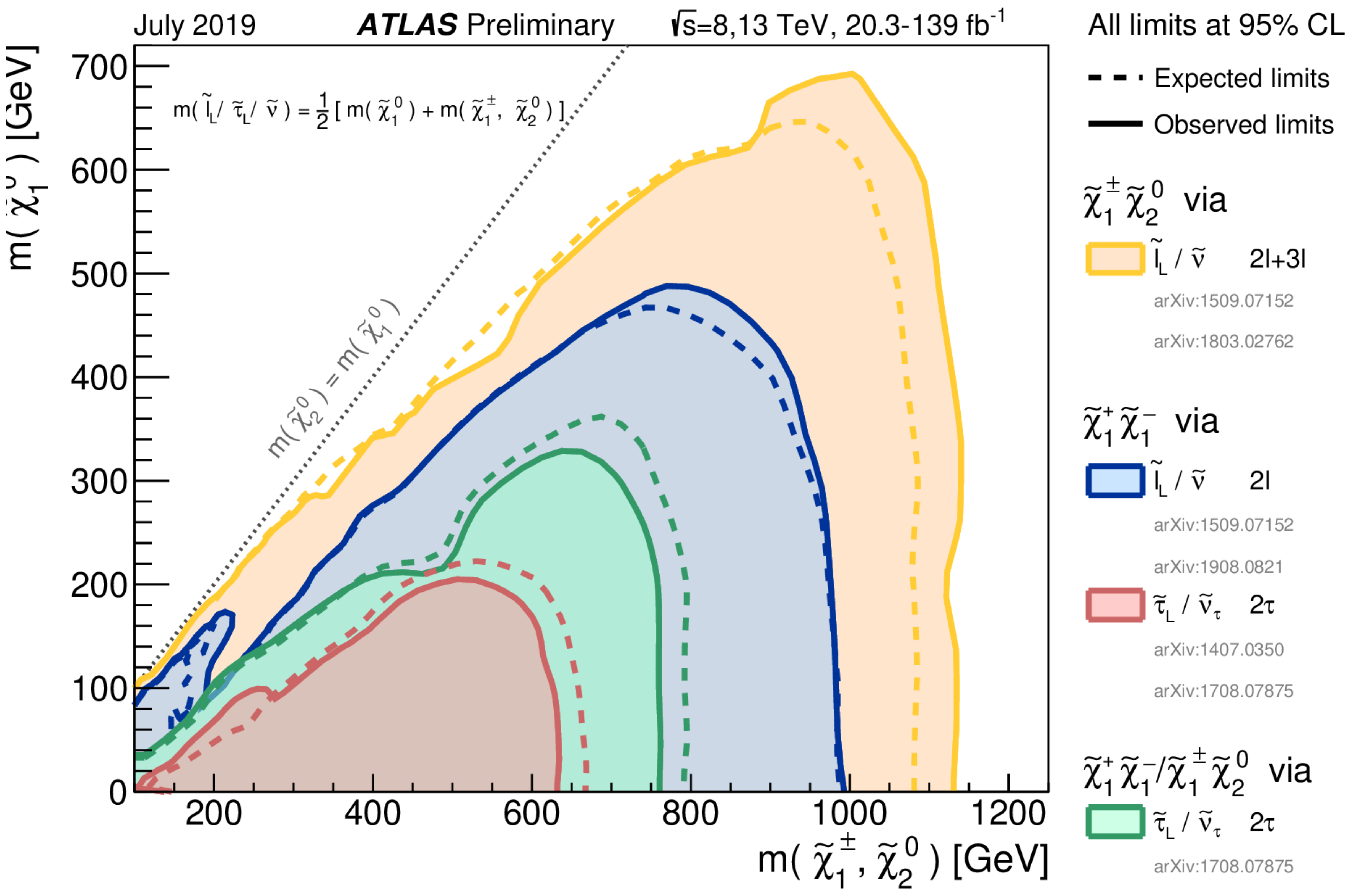


- Higgsino : $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0}$

- Small visible energy makes the searches challenging in the "compressed" region



Caution! Simplified models



Specific assumptions

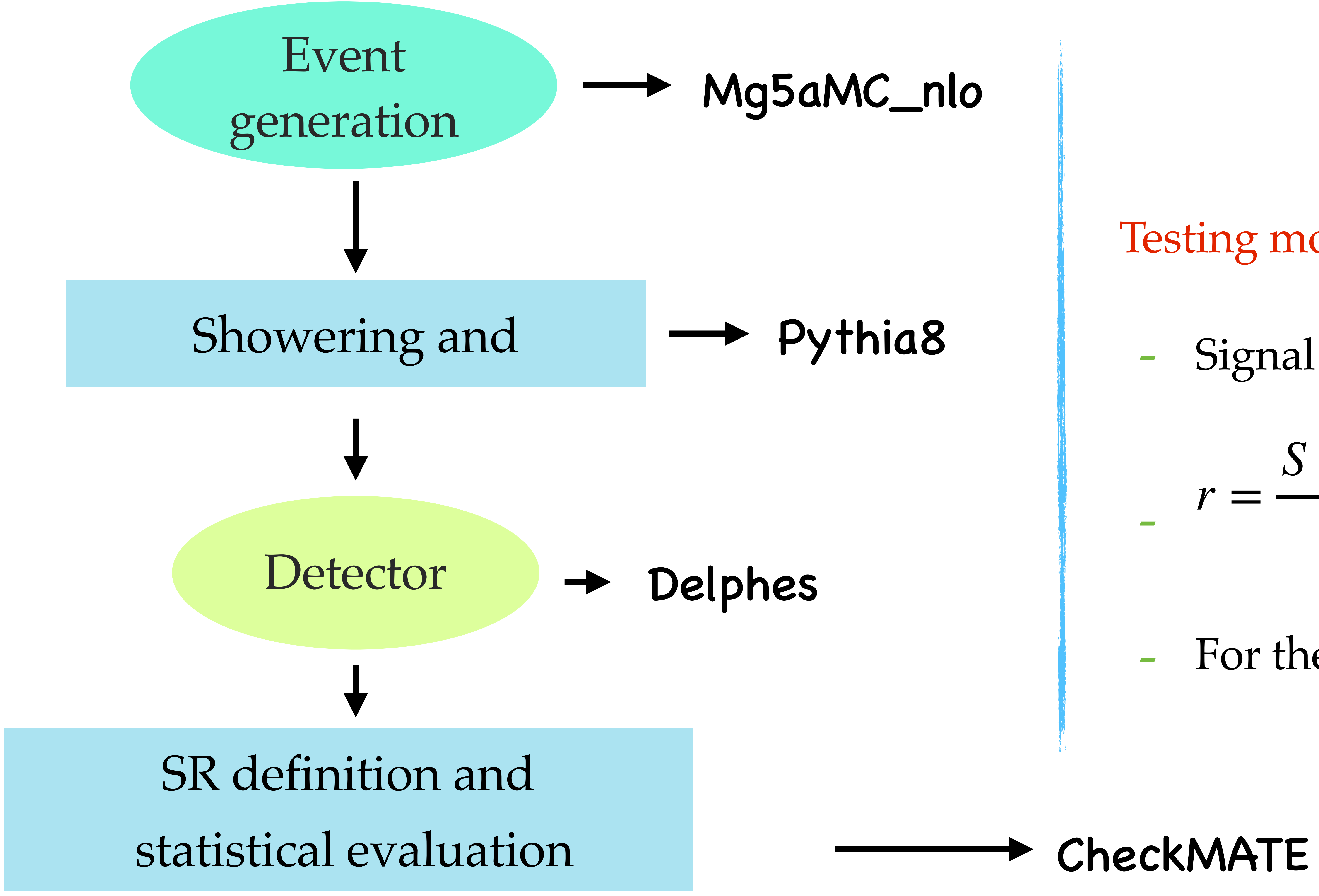
- Pure Wino decaying to pure bino
- 100% BR

Relax these assumptions and the limits change!

Limits must be recast to be imposed on real parameter space

Recasting with CM

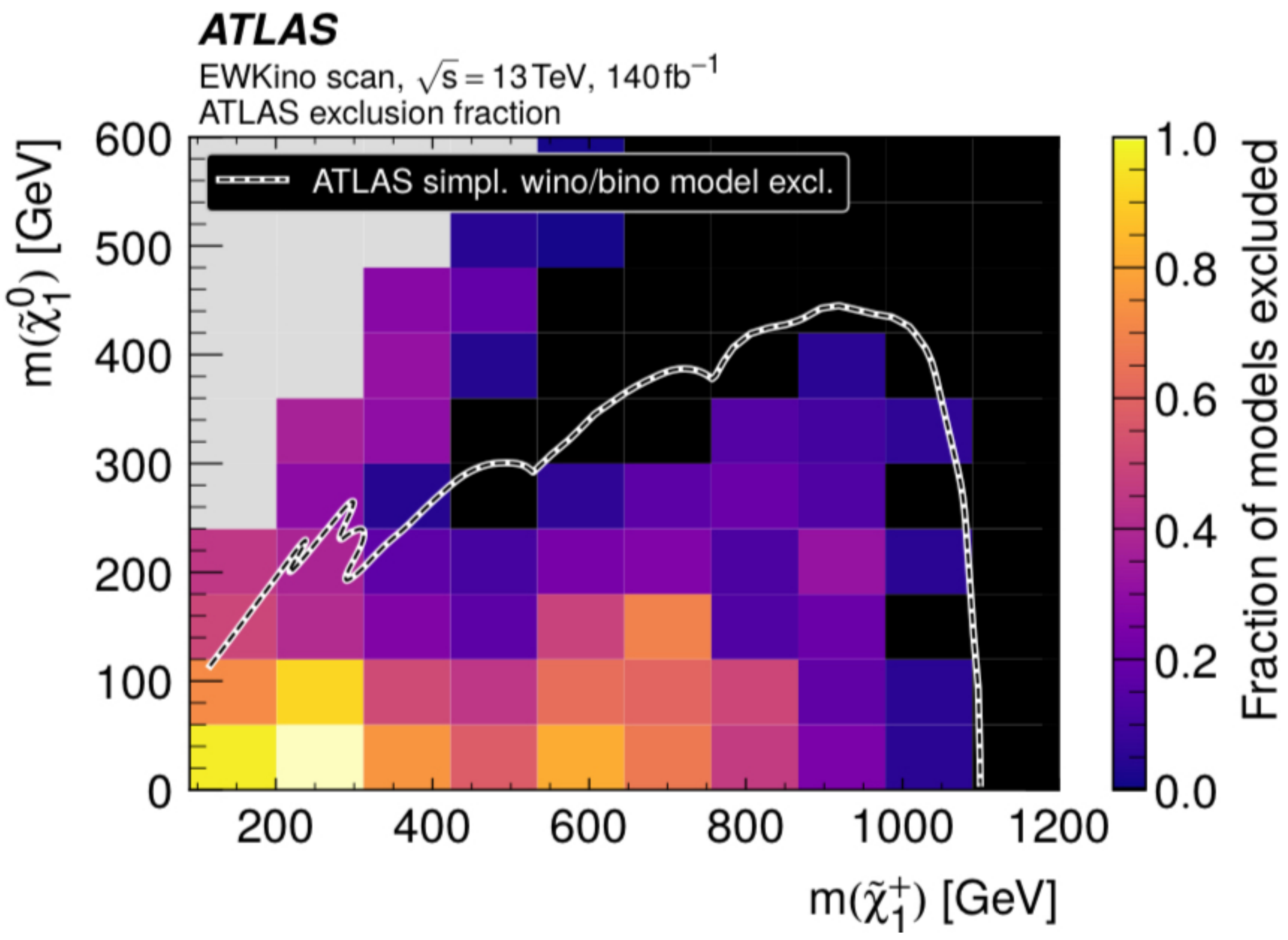
Drees, Dreiner, Schmeier, Tattersall, Kim ‘13
Kim, Schmeier, Tattersall, Rolbiecki ‘15
Dercks, Desai, Kim, Rolbiecki, Tattersall ‘16



Testing models against LHC analyses

- Signal events calculated for each SR
- $$r = \frac{S - 1.96 \times \Delta S}{S^{95}_{exp}}$$
- For the best SR, $r > 1$ ⟶ excluded!

What did the LHC actually exclude ?

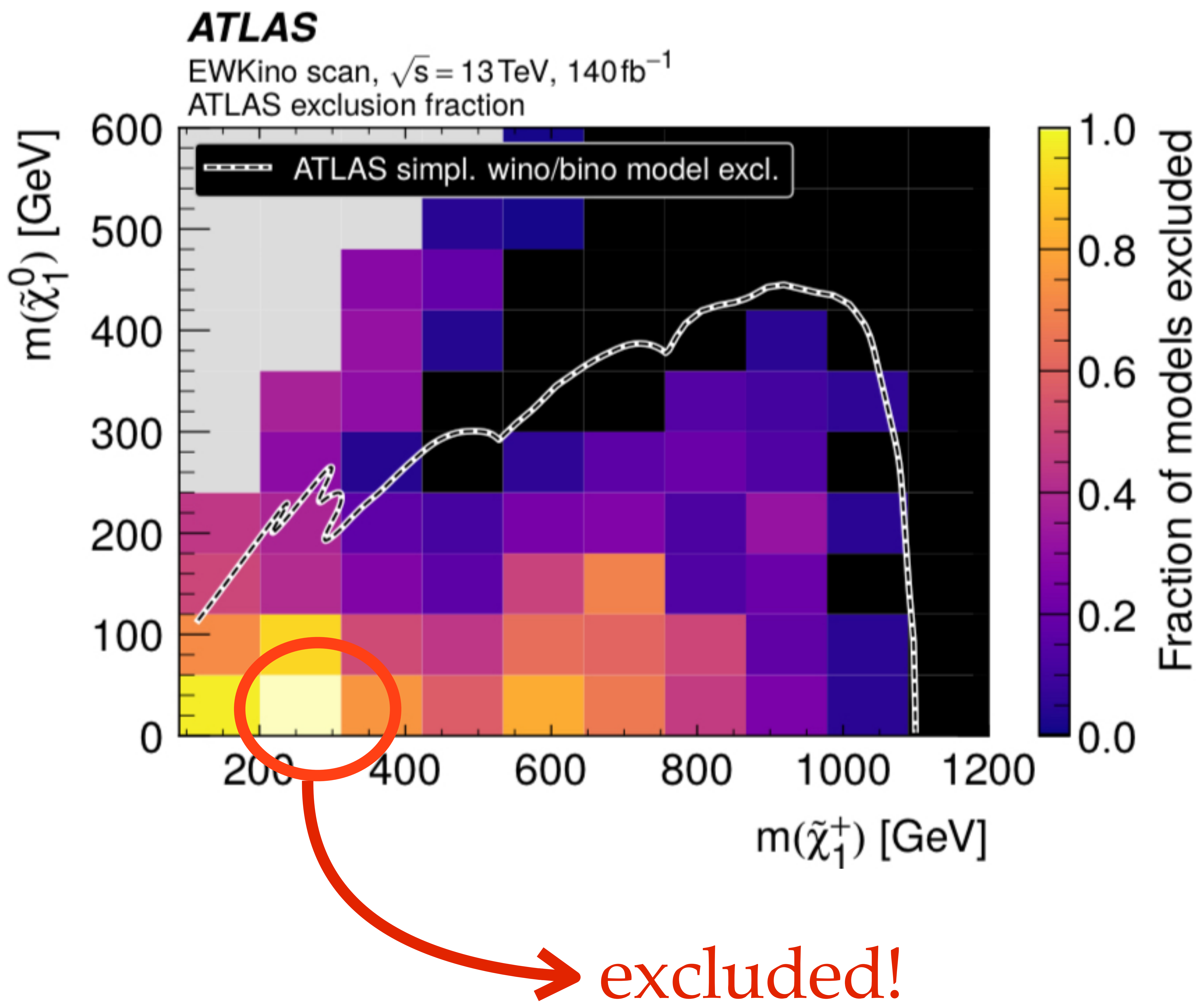


pMSSM scan with decoupled colored sector and sleptons

M_1	-2 TeV	2 TeV
M_2	-2 TeV	2 TeV
μ	-2 TeV	2 TeV
M_3	1 TeV	5 TeV
A_t	-8 TeV	8 TeV
A_b	-2 TeV	2 TeV
A_τ	-2 TeV	2 TeV
M_A	0 TeV	5 TeV
$\tan\beta$	1	60

2402.01392

What did the LHC actually exclude ?



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$\tan\beta$	1	60

2402.01392

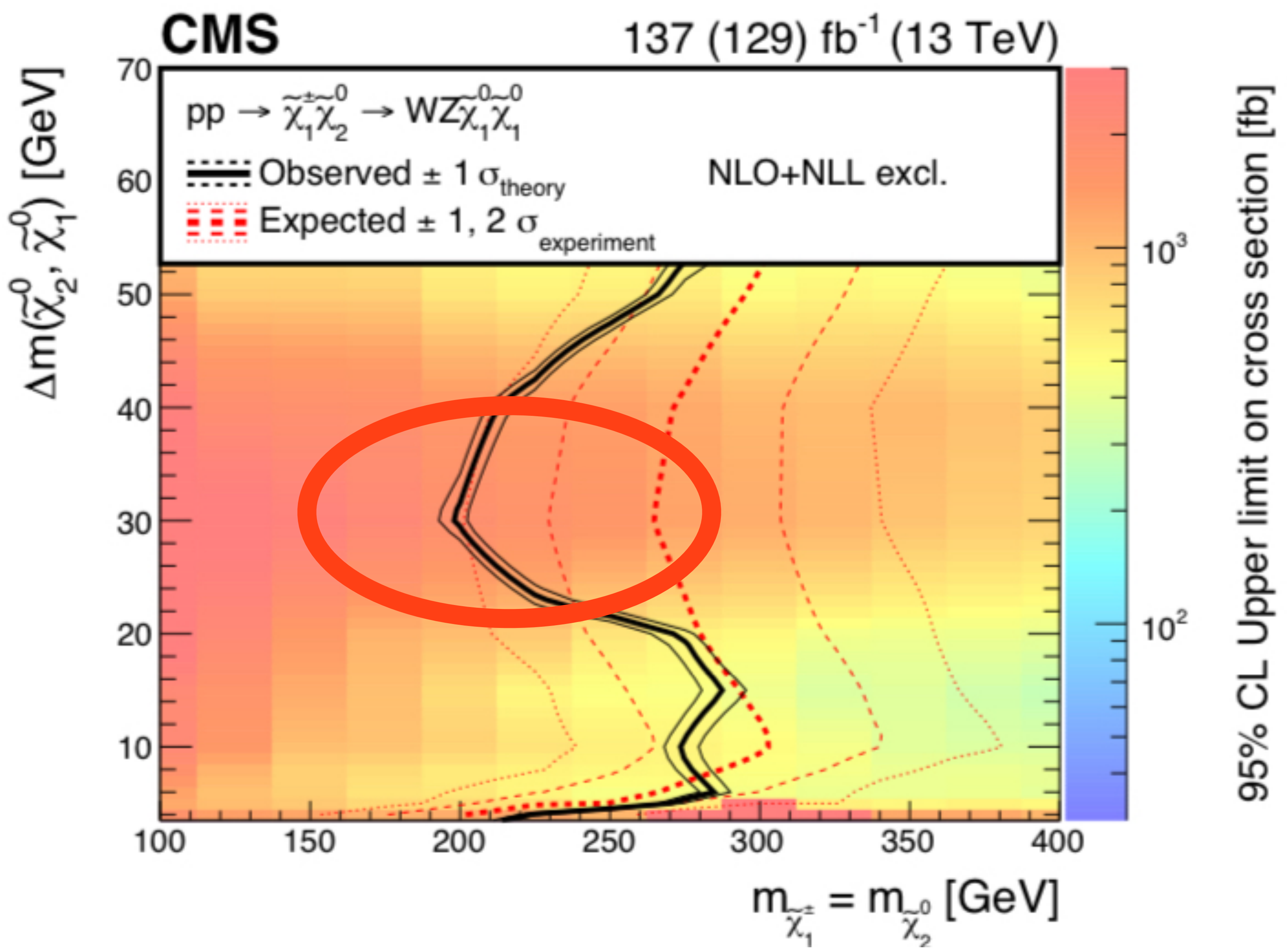
Generic lessons

- Much of MSSM parameter space still unexplored (even below ~ 1 TeV)
- "Simplified SUSY models" are not really SUSY
- To mitigate : Recast, reinterpret

LHC has not ruled out SUSY.

But when will it discover SUSY ?

Excesses ?



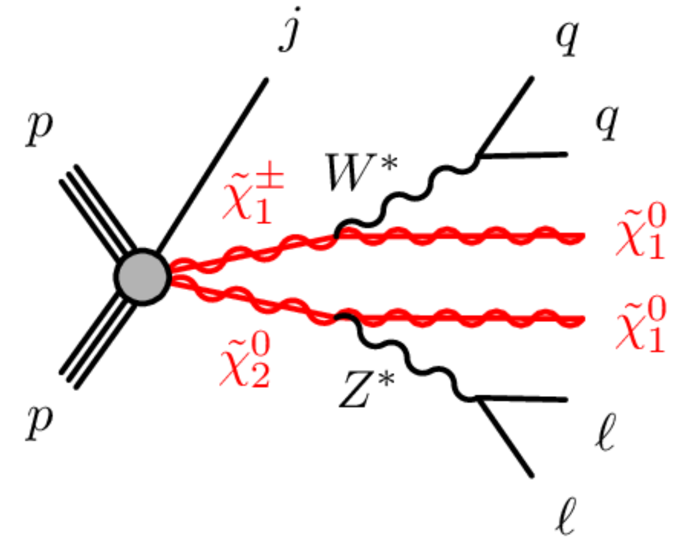
$2l/3l + E_T^{miss}$

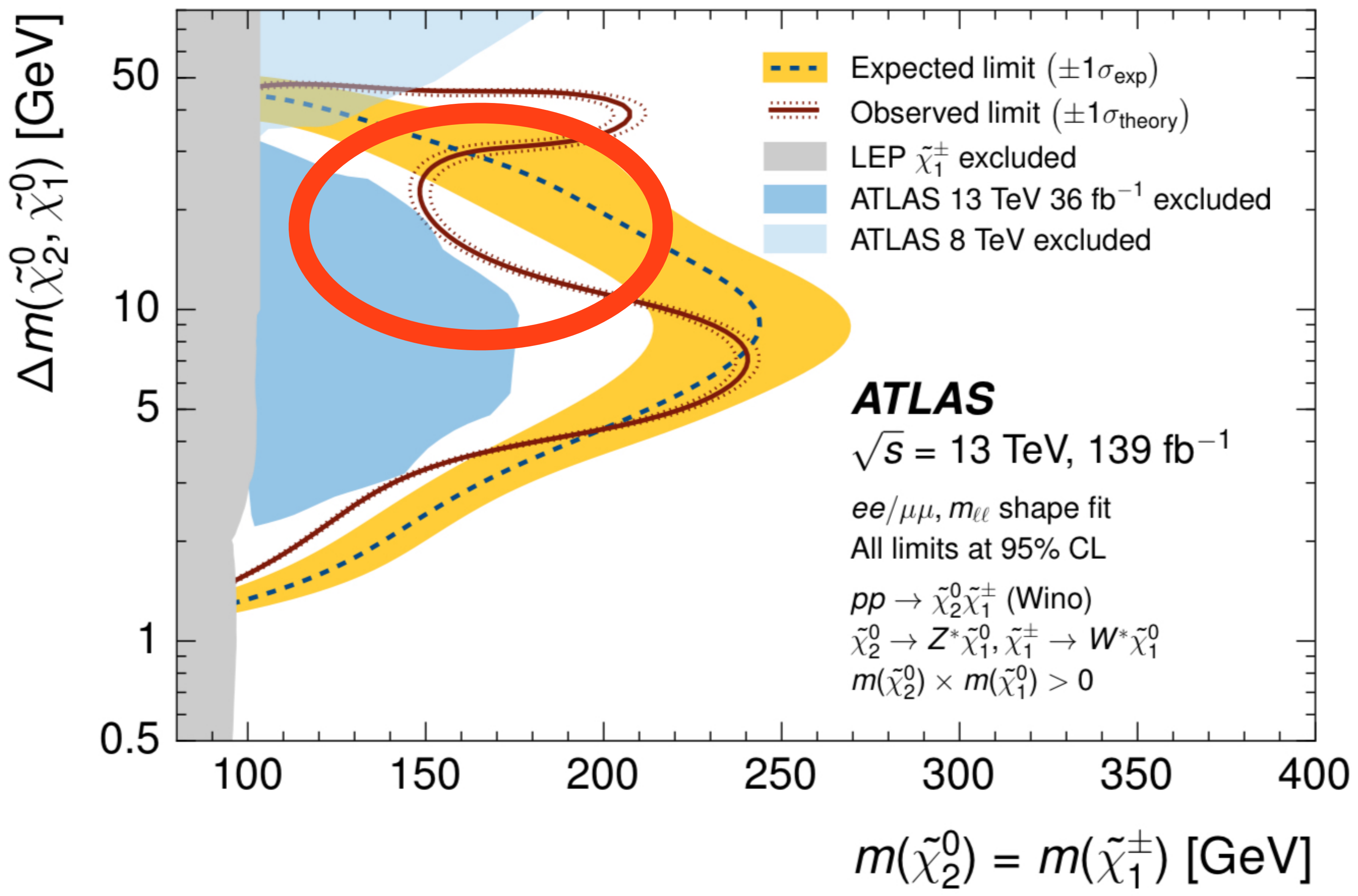
$\gtrsim 3l + E_T^{miss}$

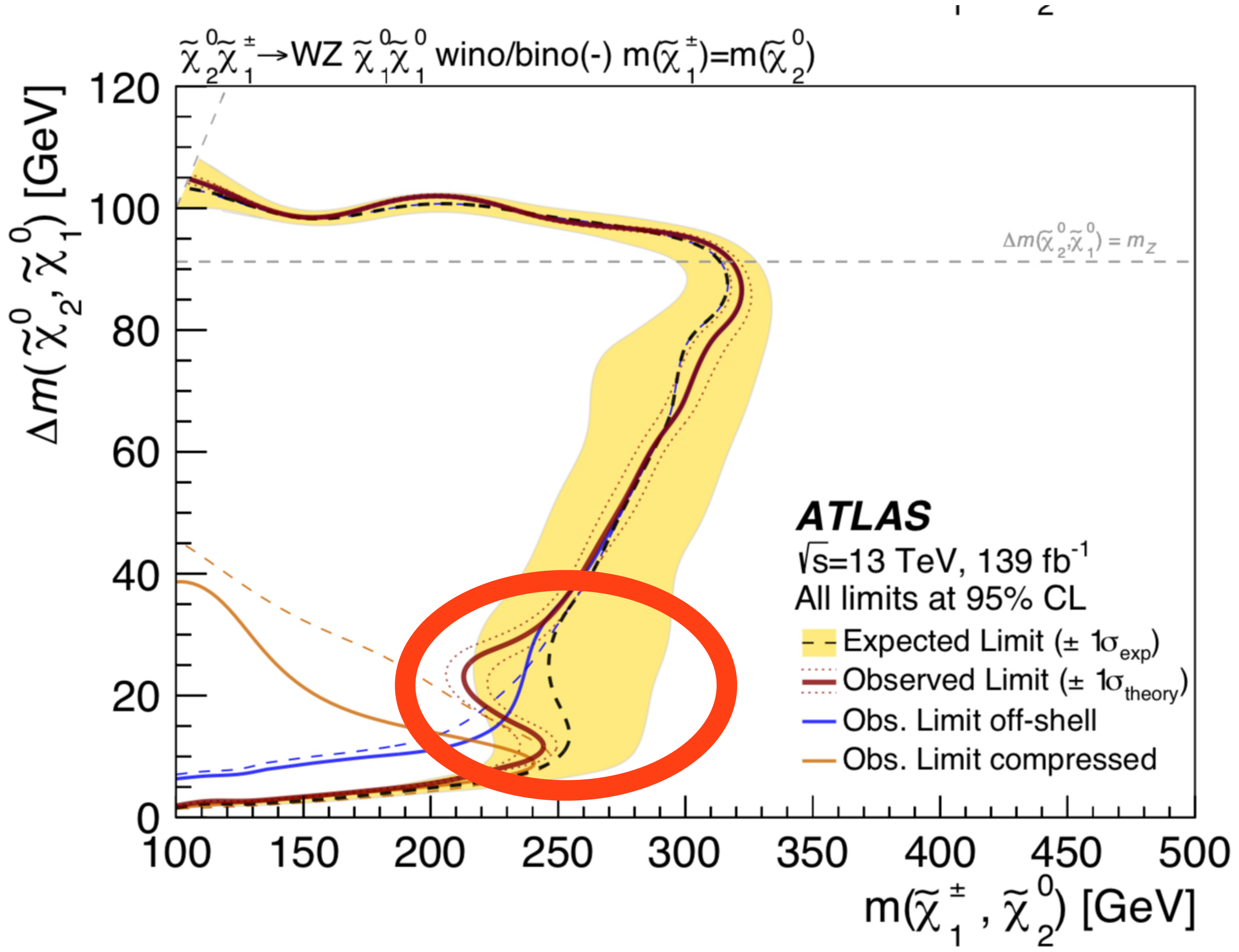
2402.01888

<u>Wino / Bino</u>

$\Delta m \equiv m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \sim 20$ GeV







$2l + E_T^{miss}$

$3l + E_T^{miss}$

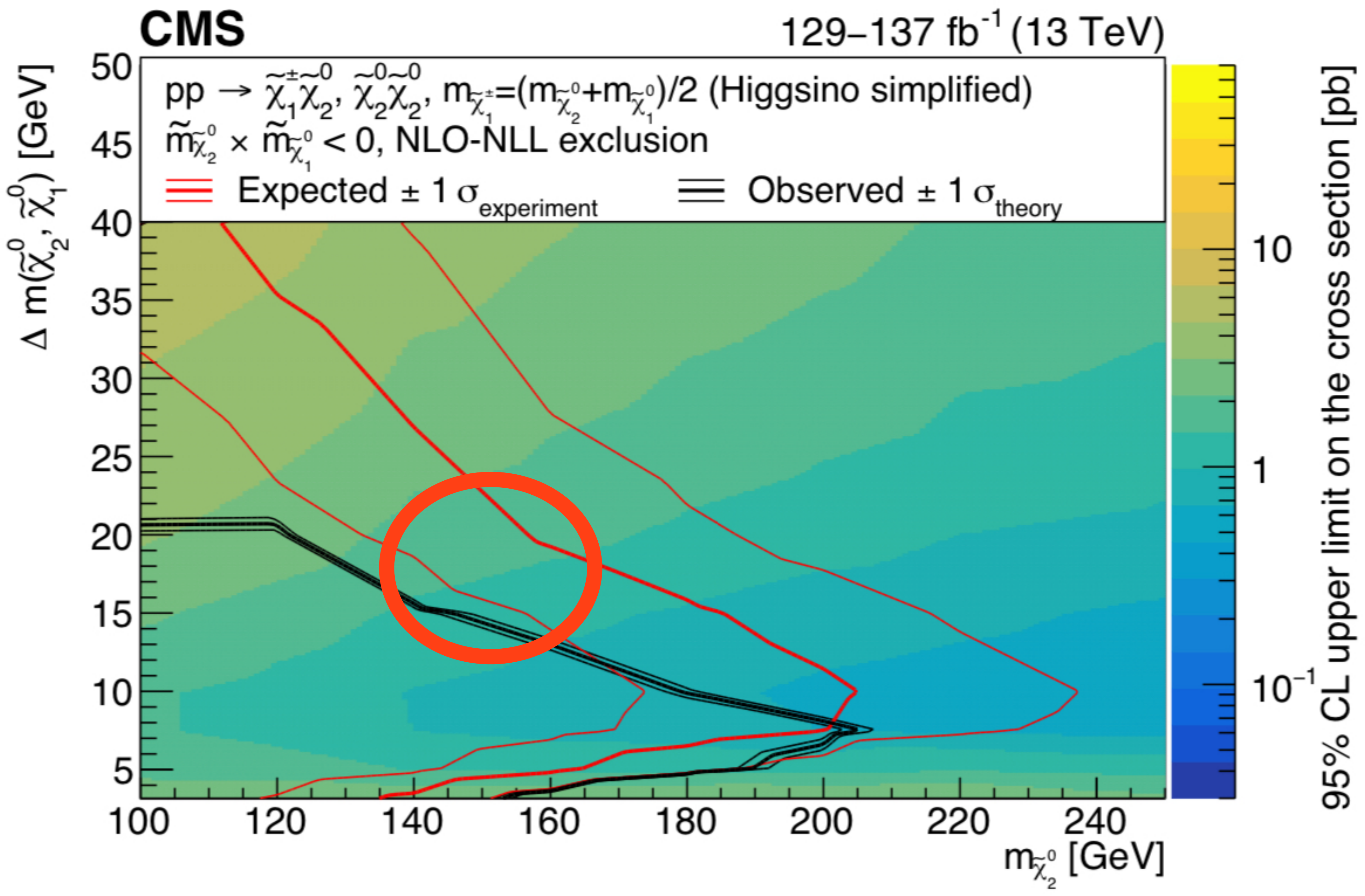
1911.12606

2106.01676

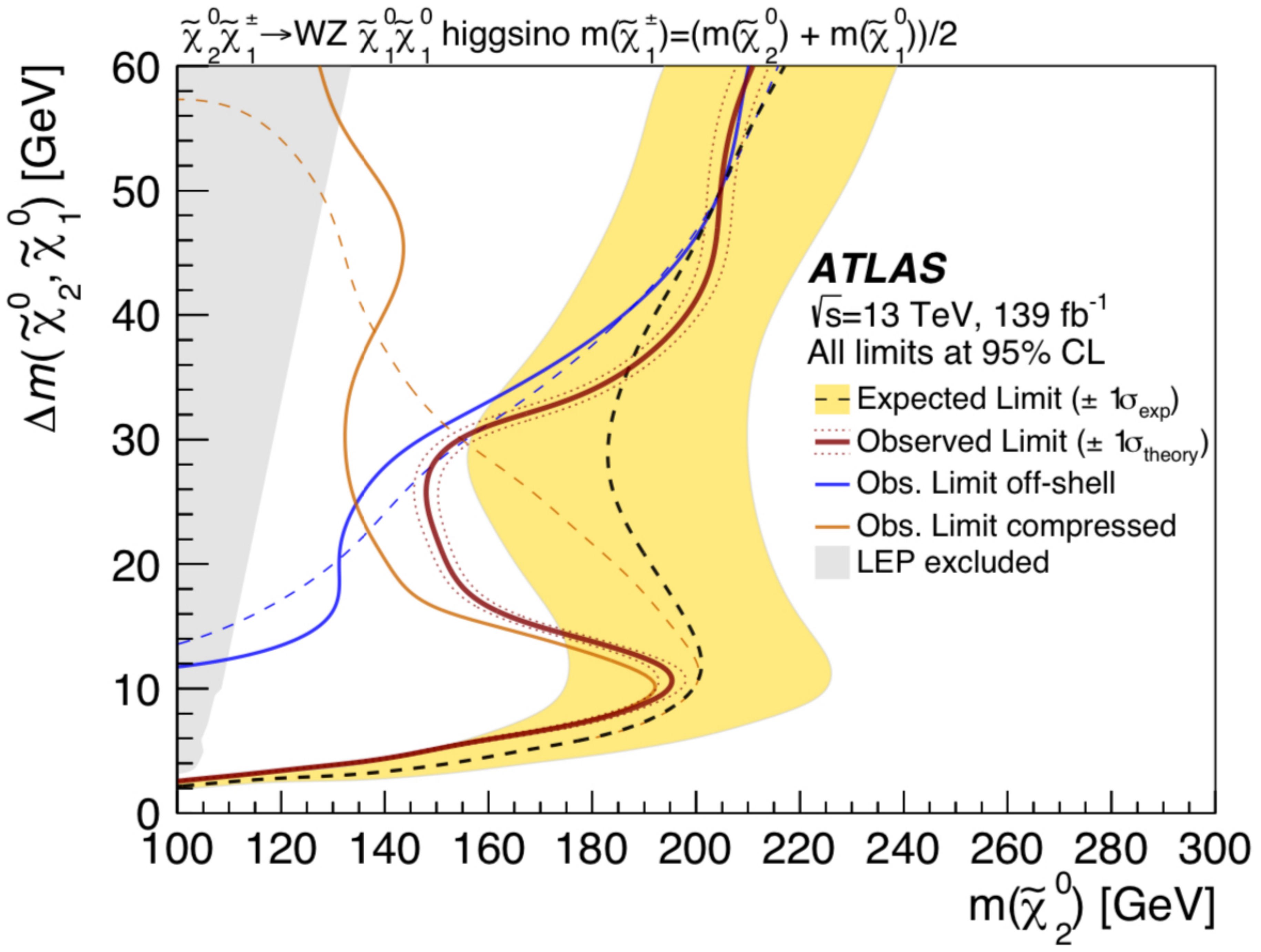
Excesses ?

Higgsino

$$\Delta m \equiv m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \sim 8 - 20\,\mathrm{GeV}$$



$2l/3l + E_T^{miss}$



$2l + E_T^{miss}$

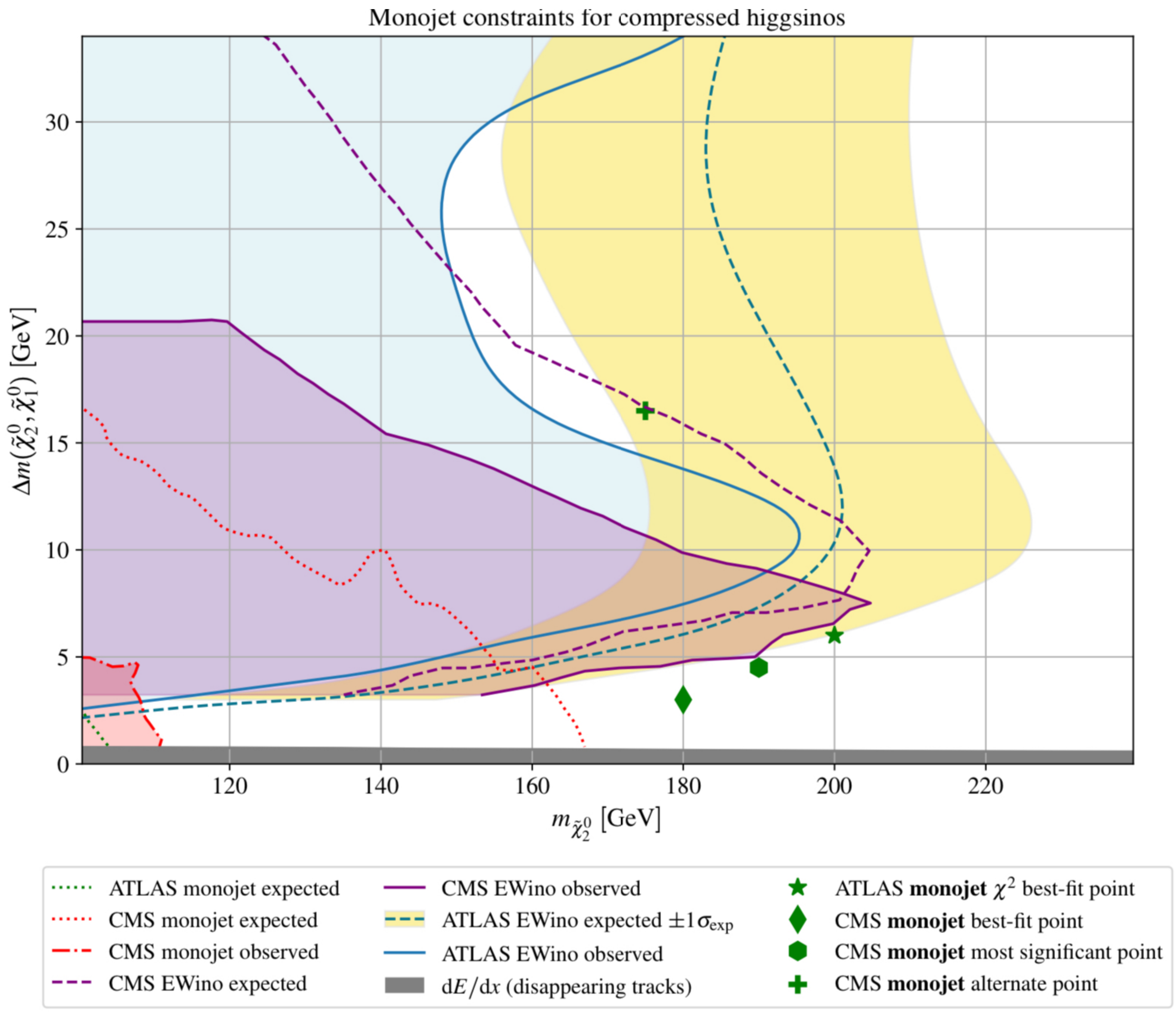
$3l + E_T^{miss}$

- searches with heavy sleptons : deficit in observed vs expected exclusion

2111.06296

2106.01676

Excesses ?



Higgsino

$$\Delta m \equiv m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \lesssim 20\,\mathrm{GeV}$$

Agin, Fuks, Goodsell, Murphy

2311.17149

Possible scenarios

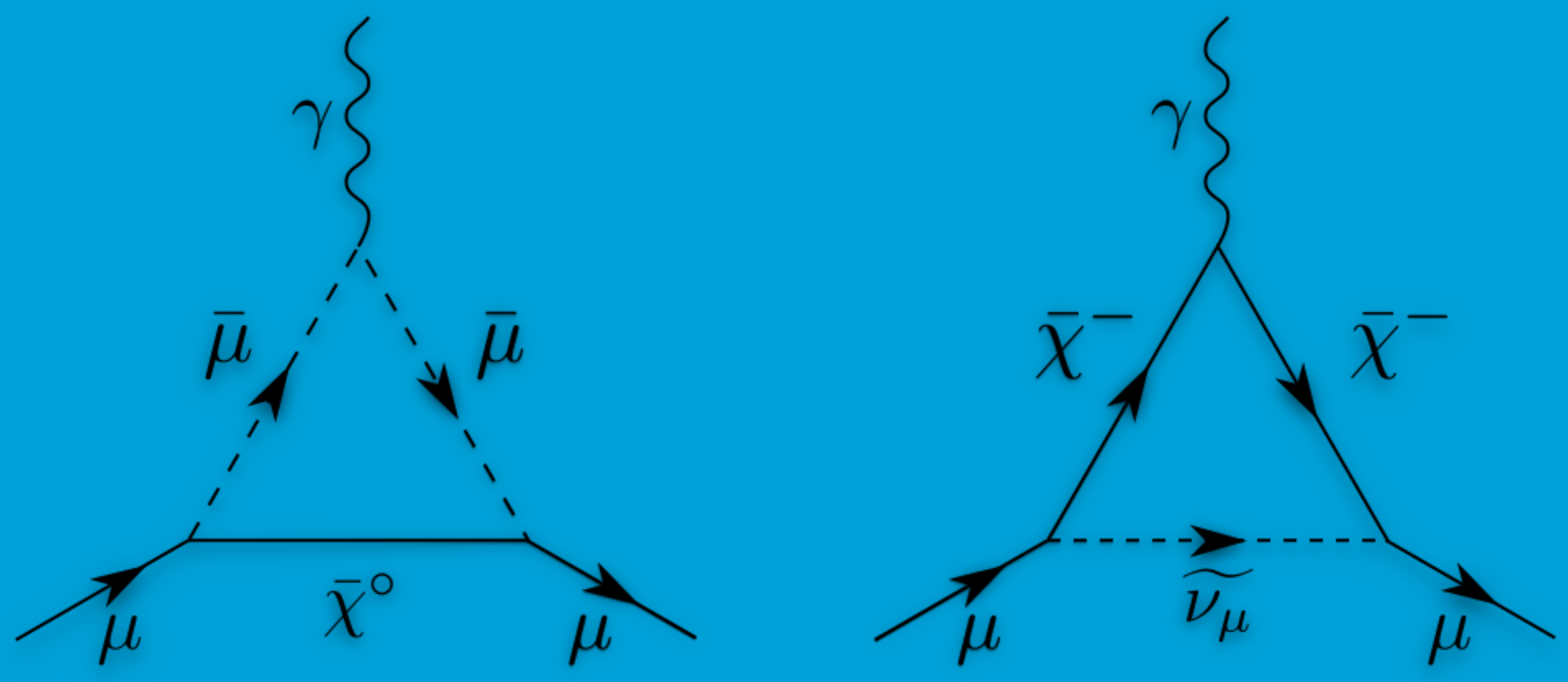
$$m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^\pm}$$

$$\Delta m \equiv m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \sim 20\ GeV$$

- Wino/Bino DM with chargino coannihilation.
    - $M_1 \approx M_2 < < \mu$
    - Relic density 100% saturated

- Higgsino DM with chargino coannihilation.
    - $\mu < < M_1, M_2$
    - Relic density partially saturated

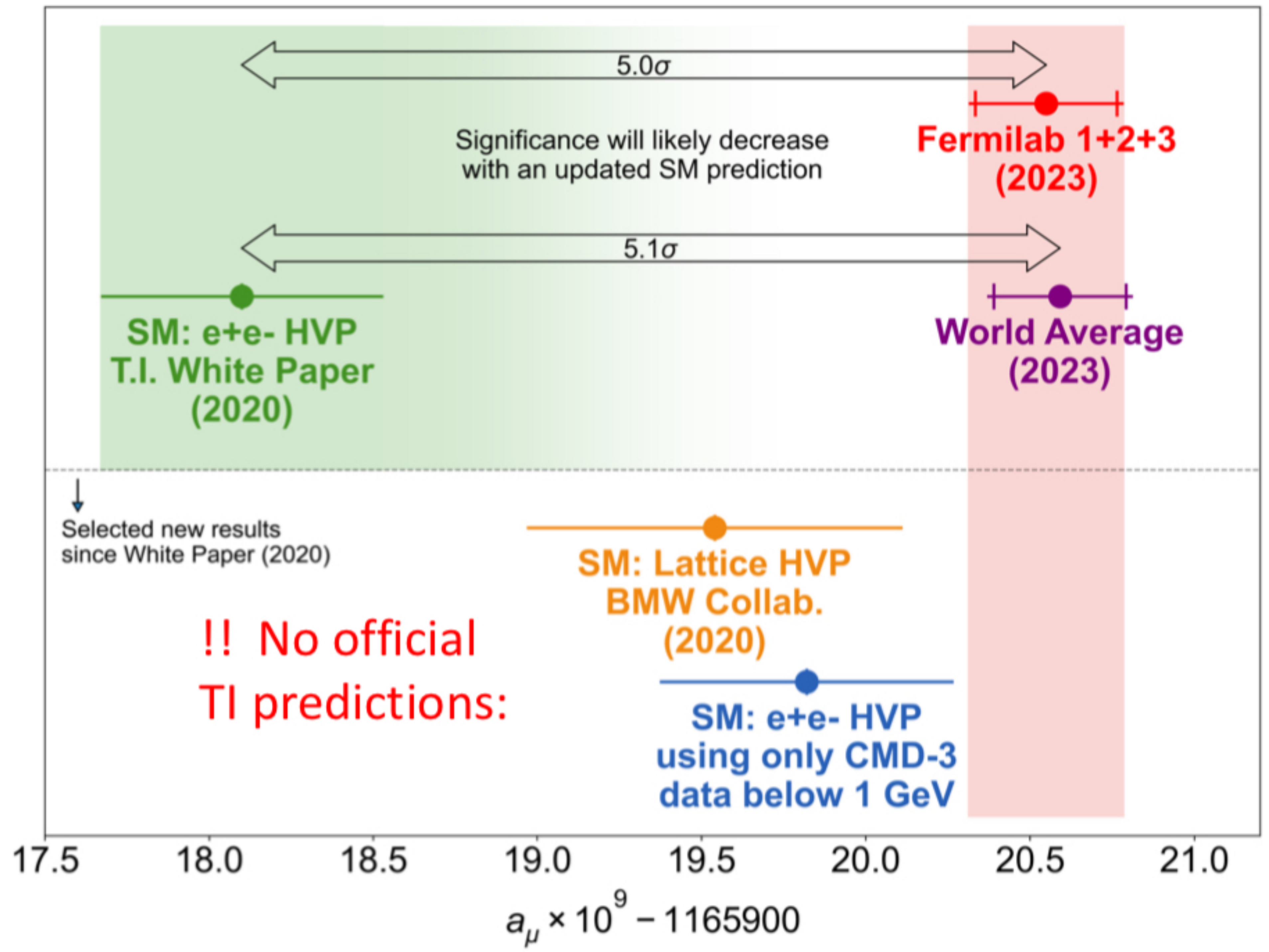
Muon (g-2) in MSSM



Muon (g-2) anomaly

Measurement of the Positive Muon Anomalous Magnetic Moment to **0.46 ppm**
[*Phys. Rev. Lett.* 126 (2021) 14, 141801]

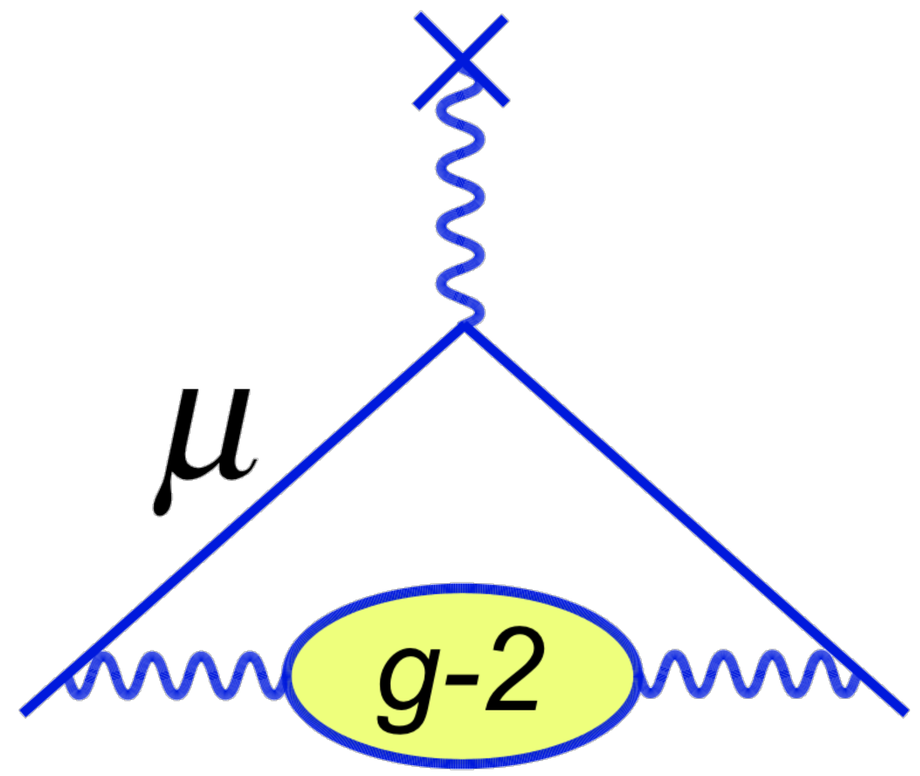
... **to 0.20 ppm** [*PRL* 131 (2023) 16, 161802]



Aoyama *et al* '20

Talk by Thomas Teubner, FPCP 2024

$$a_\mu^{exp} - a_\mu^{theo,SM} = (24.9 \pm 4.8) \times 10^{-10}$$

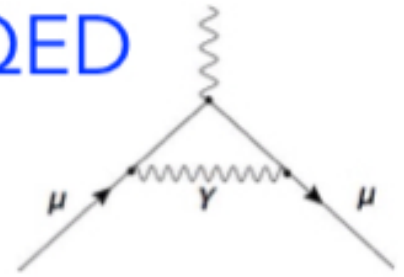
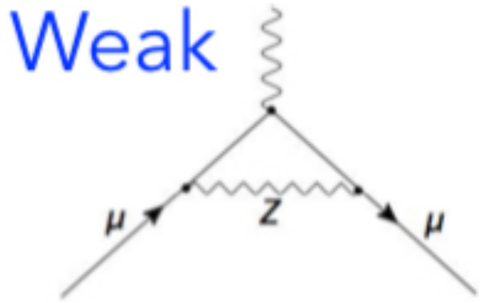
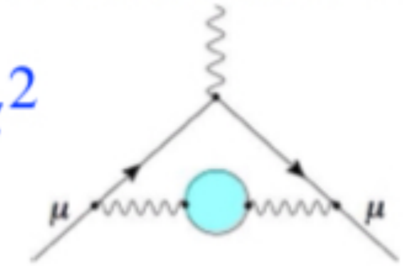
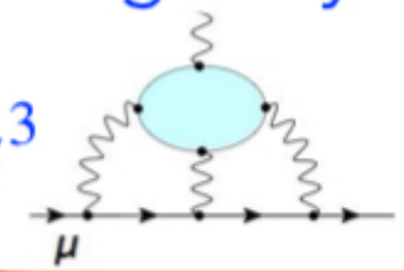


$$a_\mu = a_\mu^{\rm QED} + a_\mu^{\rm weak} + a_\mu^{\rm hadronic} + a_\mu^{\rm NP?}$$

Final result from Fermilab in 2025

Muon (g-2) anomaly

White Paper [T. Aoyama et al., *Phys. Rept.* 887 (2020) 1-166]

			0.37 ppm
QED	 $+\ldots$	$116\,584\,718.9\,(1) \times 10^{-11}$	0.001 ppm
Weak	 $+\ldots$	$153.6\,(1.0) \times 10^{-11}$	0.01 ppm
Hadronic…			
…Vacuum Polarization (HVP) α^2	 $+\ldots$	$6845\,(40) \times 10^{-11}$ [0.6%]	0.34 ppm
…Light-by-Light (HLbL) α^3	 $+\ldots$	$92\,(18) \times 10^{-11}$ [20%]	0.15 ppm

SM uncertainty dominated by HVP contribution

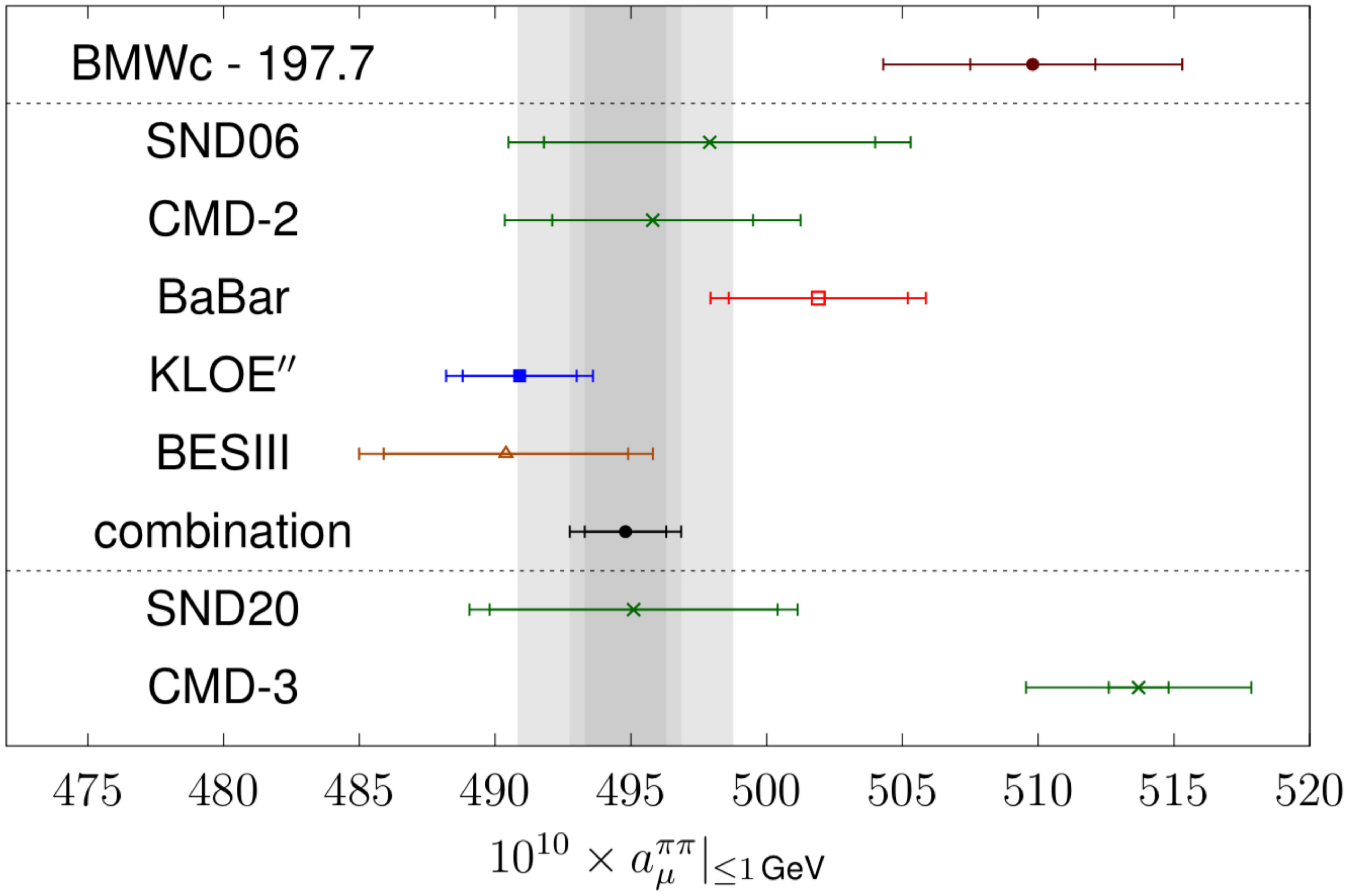
$$a_\mu = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{weak}} + a_\mu^{\mathrm{hadronic}} + a_\mu^{\mathrm{NP?}}$$

New theory WP expected soon !

Talk by Thomas Teubner, FPCP 2024

Muon (g-2) anomaly

F. Ignatov et al. (CMD-3), 2302.08834 [hep-ex]



Tensions between WP and CMD-3,BMW

New theory WP expected soon !

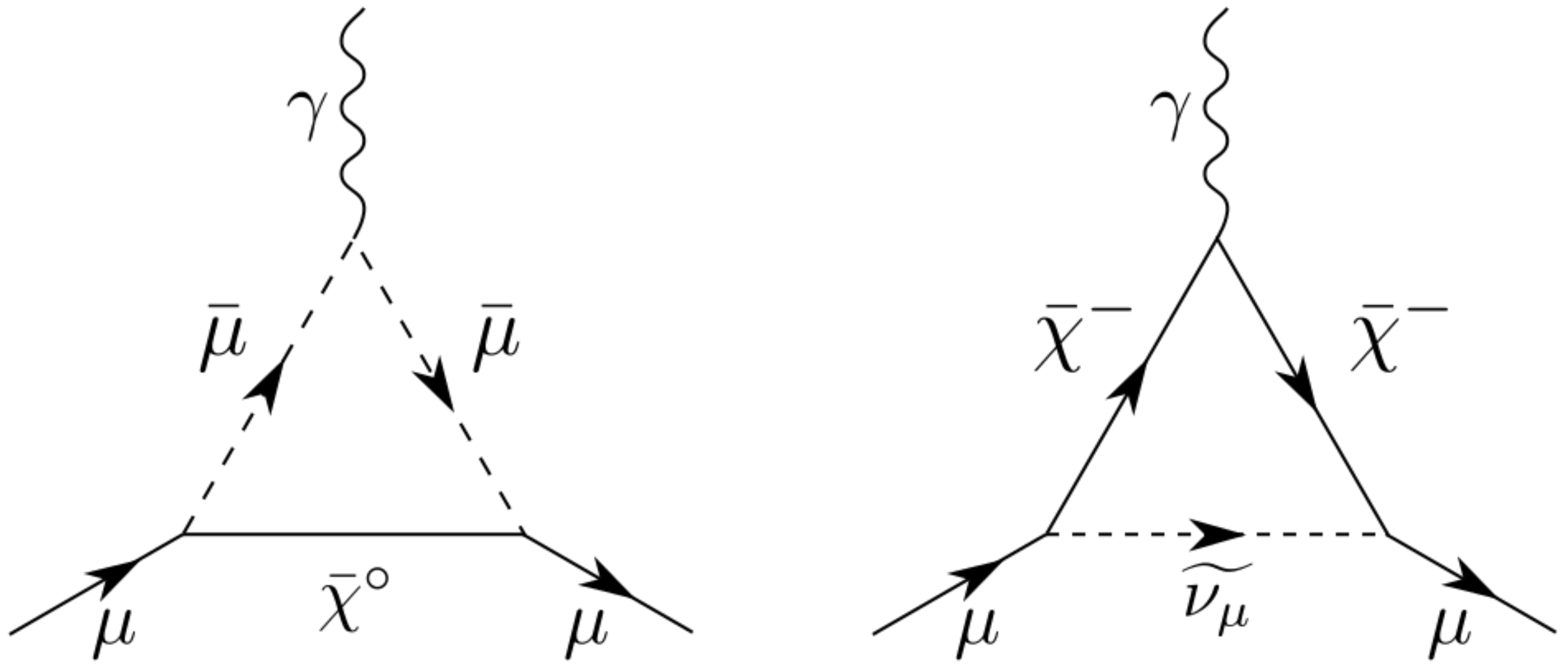
Talk by Thomas Teubner, FPCP 2024

Muon (g-2) in MSSM

We need very light BSM particles

OR

enhancement from couplings



$$\Delta a_\mu^{\mathrm{BSM}} \sim \Delta a^{\mathrm{SM,EW}} \cdot \left(\frac{m_W^2}{m_{\mathrm{BSM}}^2}\right) \cdot \left(\frac{g_{\mathrm{BSM}}}{g_{\mathrm{SM}}}\right)$$

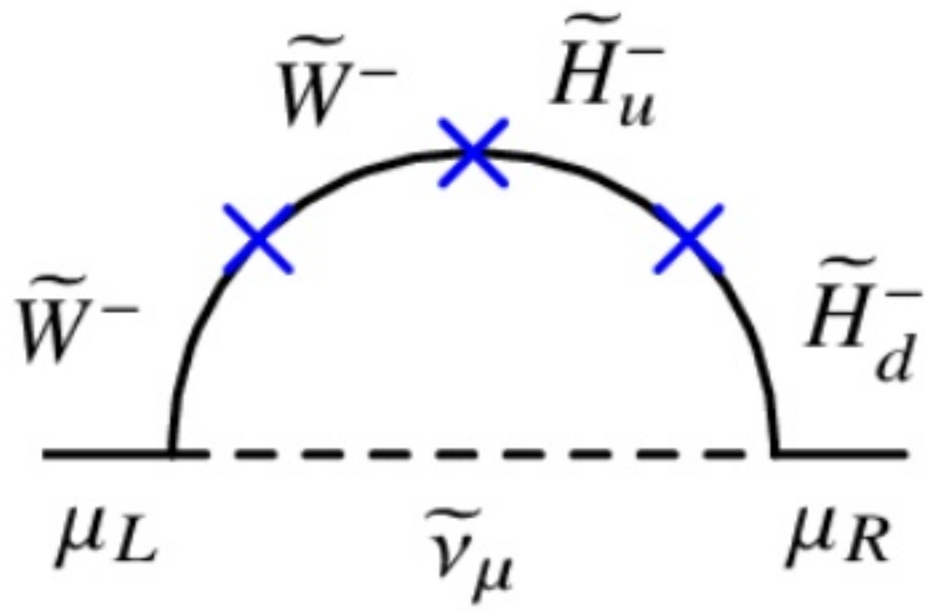
SM EW 1 loop : $\frac{\alpha}{\pi}\frac{m_\mu^2}{M_W^2}.$

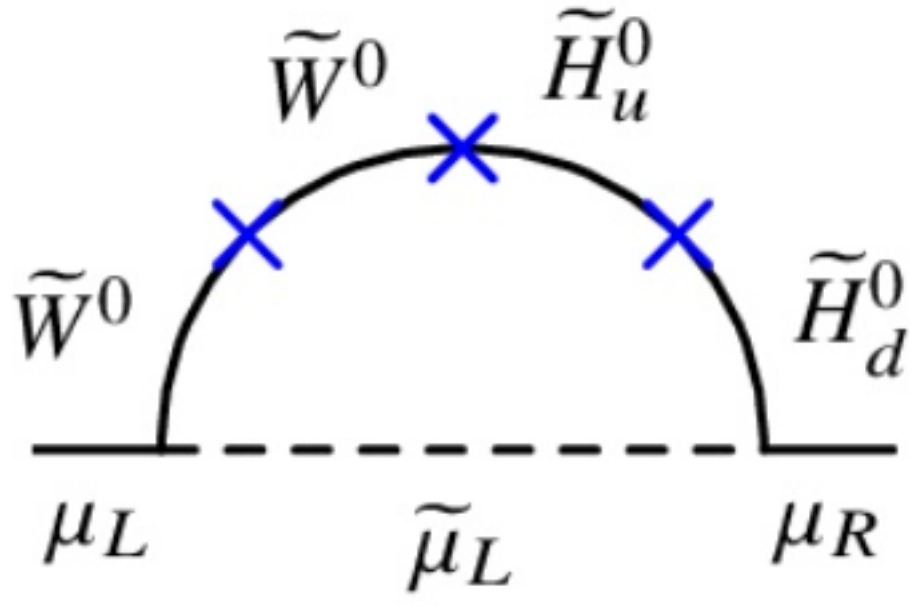
MSSM , 1 loop : $\frac{\alpha}{\pi}\frac{m_\mu^2}{M_{SUSY}^2} \times tan\beta$

MSSM can easily explain anomaly !

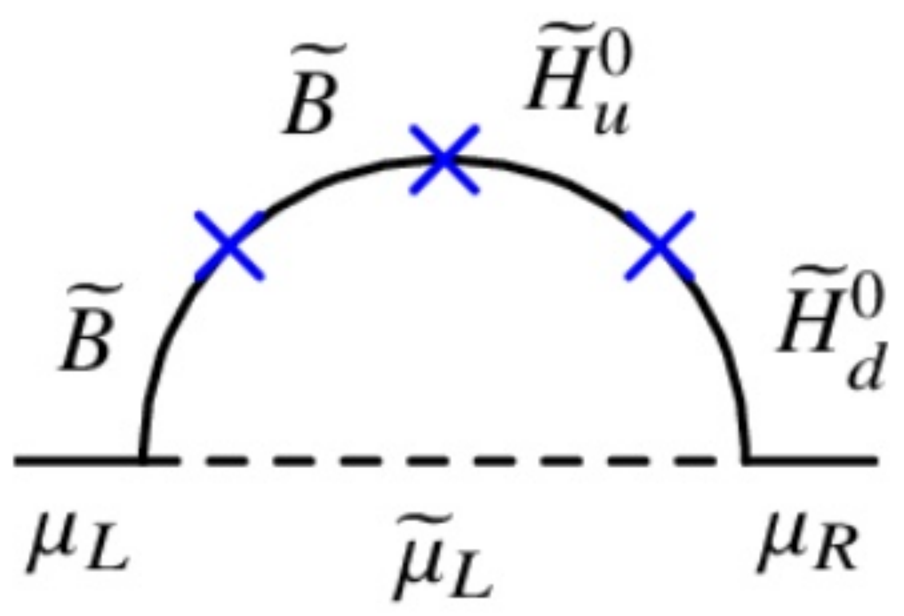
$\tan\beta \in [5-60] \rightarrow \quad m_{\mathrm{SUSY}} \in [200-600]\,\mathrm{GeV}$

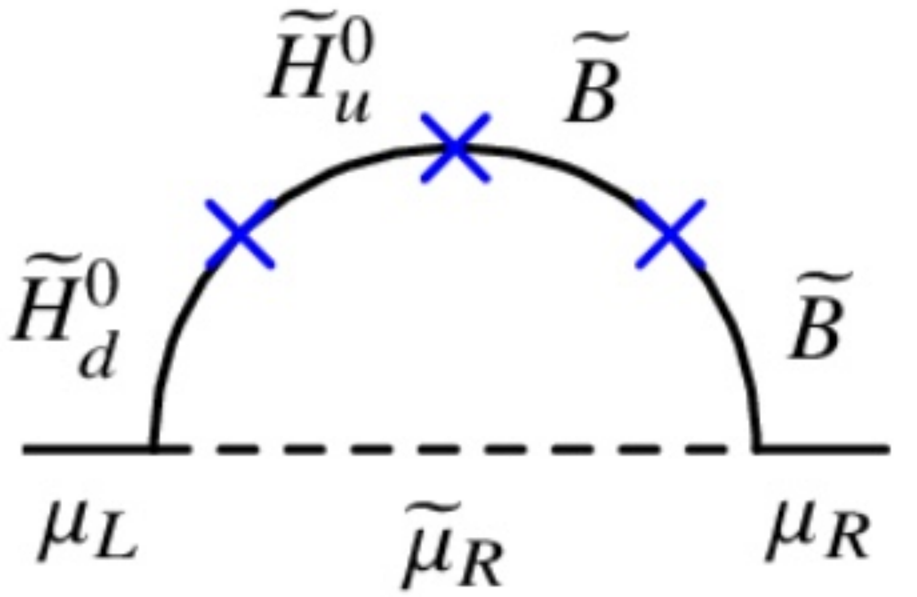
$$\Delta a_\mu^{\text{SUSY}} = \Delta a_\mu^{\text{WHL}} + \Delta a_\mu^{\text{BHL}} + \Delta a_\mu^{\text{BHR}} + \Delta a_\mu^{\text{BLR}}$$





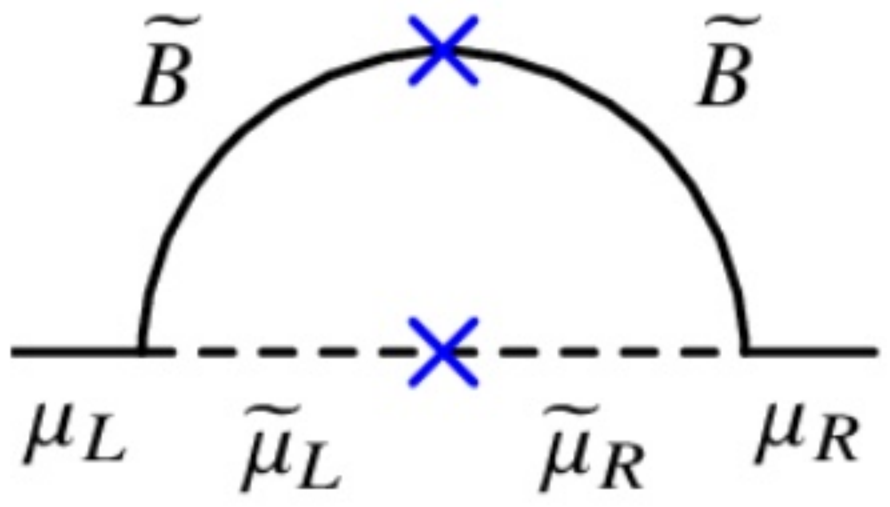
$$\Delta a_\mu^{\text{WHL}}(M_2, \mu, m_{\tilde{l}_L}) = \frac{\alpha_W}{8\pi}\frac{m_\mu^2}{M_2\mu}\tan\beta \cdot f_{\text{W}}(\{\mathbf{m}\})$$





$$\Delta a_\mu^{\text{BHL}}(M_1, \mu, m_{\tilde{l}_L}) = \frac{\alpha_Y}{8\pi}\frac{m_\mu^2}{M_1\mu}\tan\beta \cdot f_{\text{N}}(\{\mathbf{m}\})$$

$$\Delta a_\mu^{\text{BHR}}(M_1, \mu, m_{\tilde{l}_R}) = -\frac{\alpha_Y}{8\pi}\frac{m_\mu^2}{M_1\mu}\tan\beta \cdot f_{\text{N}}(\{\mathbf{m}\})$$



$$\Delta a_\mu^{\text{BLR}}(M_1, m_{\tilde{l}_L}, m_{\tilde{l}_R};\, \mu) = \frac{\alpha_Y}{4\pi}\frac{m_\mu^2 M_1 \mu}{m_{\mu_L}^2 m_{\mu_R}^2}\tan\beta \cdot f_{\text{BLR}}(\{\mathbf{m}\})$$

[Borrowed from Kazuki Sakurai]

Summary of g-2 in MSSM

$$\Delta a_\mu^{\rm SUSY} = \Delta a_\mu^{\rm WHL} + \Delta a_\mu^{\rm BHL} + \Delta a_\mu^{\rm BHR} + \Delta a_\mu^{\rm BLR}$$

$\Delta a_\mu^{\rm WHL}(M_2, \mu, m_{\tilde{l}_L})$

$\Delta a_\mu^{\rm BHL}(M_1, \mu, m_{\tilde{l}_L})$

$\Delta a_\mu^{\rm BHR}(M_1, \mu, m_{\tilde{l}_R})$

Higgsino, one gaugino, one slepton all must be light:

⇨ **LHC constraint with large $E_T\!\!\!\!/$**

gaugino-Higgsino mixing ⇨ **DM direct detection**

$\Delta a_\mu^{\rm BLR}(M_1, m_{\tilde{l}_L}, m_{\tilde{l}_R};\ \mu)$

↑ large (μ)

Bino and both L and R sleptons must be light:

⇨ **LHC constraint with large $E_T\!\!\!\!/$**

⇨ **Bino abundance** $\Omega_{\tilde{\chi}_1^0} < \Omega_{\rm DM}$

⇨ **Charged LSP, Vacuum stability**

[Borrowed from Kazuki Sakurai]

Results

Analysis flow

- **SuSpect** → Spectrum generation
- **GM2Calc** → $(g-2)_\mu$ @ 2 loop
- **MicrOMEGAS** → DM observables
- **CheckMATE** → LHC constraints

- $\Delta a_\mu = (24.9 \pm 4.8) \times 10^{-10}$
- $\Omega_{CDM} h^2 = 0.120 \pm 0.001$
- Direct detection SI bounds from LZ

Squarks and gluinos decoupled

DM choices

Muon g-2 @ 5σ

- ✦ Bino/wino DM with chargino coannihilation
  - $M_1 \sim M_2 < \mu$ (Relic density 100% satisfied)

$m_{(N)LSP} \lesssim 650 \ (700)$ GeV

- ✦ Bino DM with slepton coannihilation
  - $M_1 \sim m_{\tilde{l}} < M_2, \mu$ (Relic density 100% satisfied)

$m_{(N)LSP} \lesssim 550 \ (600)$ GeV

- ✦ Higgsino DM
  - $\mu < M_1, M_2$ (underabundant upto ~ 1 TeV)

$m_{(N)LSP} \lesssim 500$ GeV

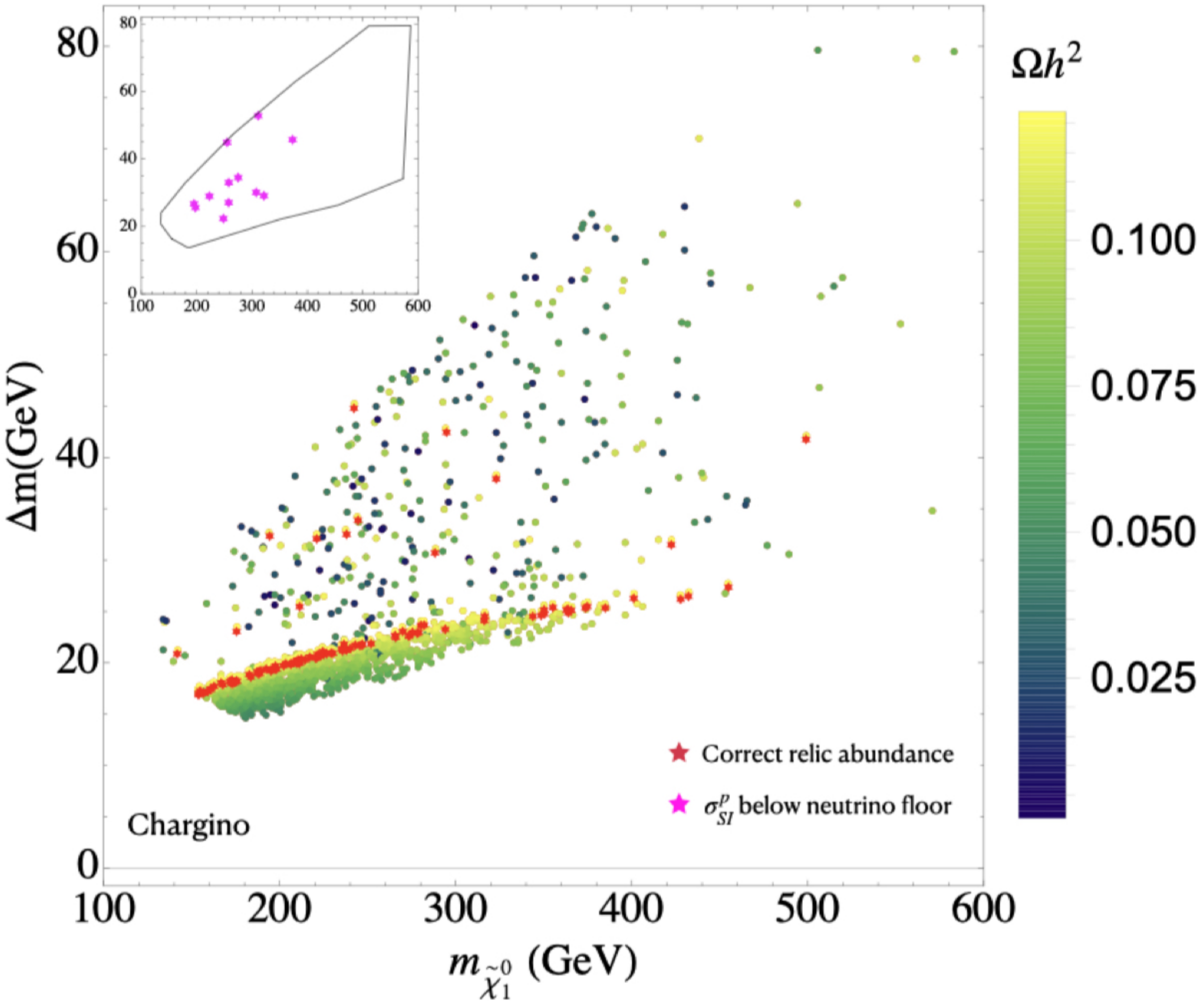
- ✦ Wino DM
  - $M_2 < M_1, \mu$ (underabundant upto ~ 3 TeV)

$m_{(N)LSP} \lesssim 600$ GeV

Bino/higgsino DM : tension between DM & g-2

MC, Heinemeyer, Saha' 20/21

Wino/Bino(+) DM



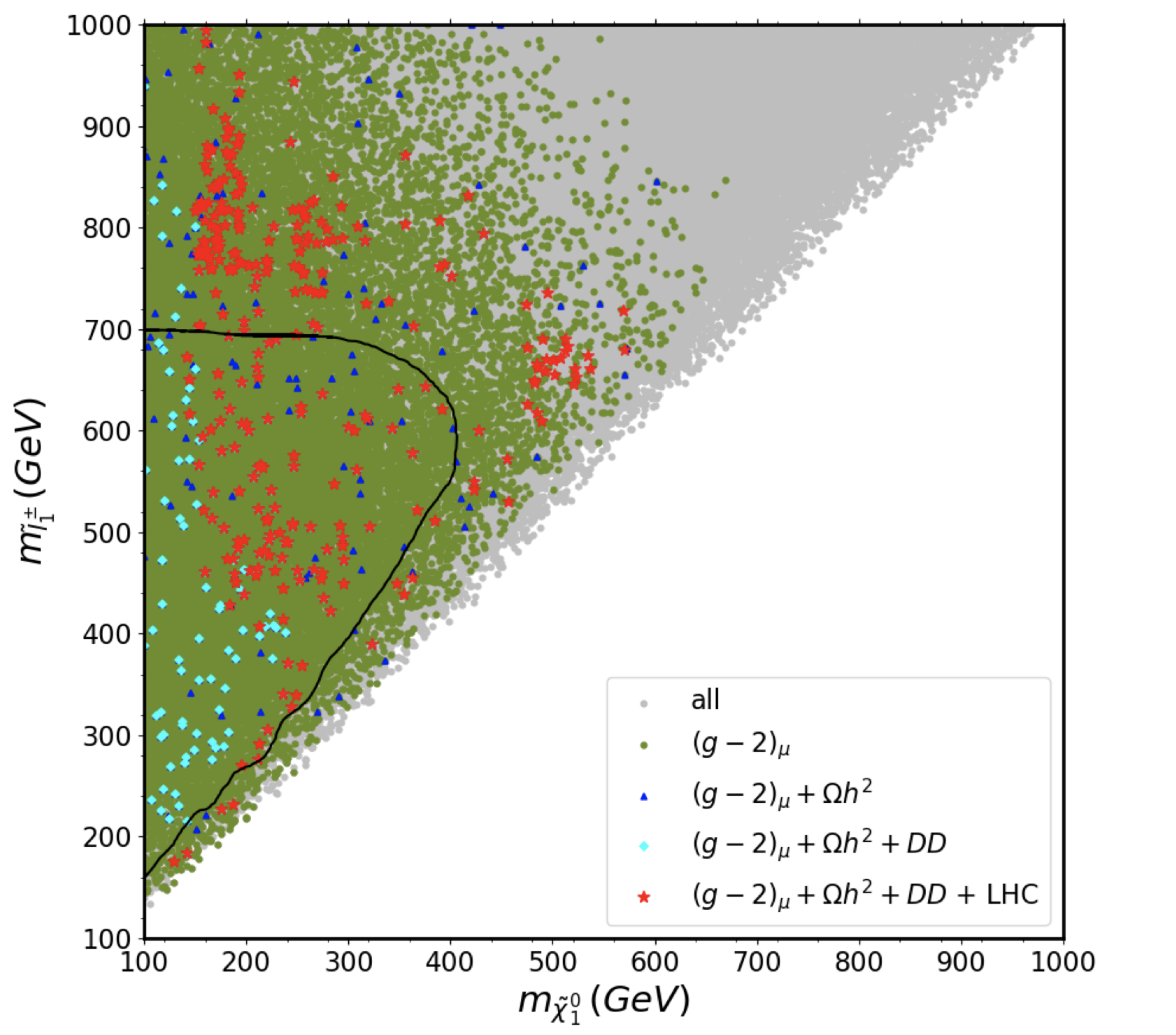
$$100\ \text{GeV} \leq M_1 \leq 1000\ \text{GeV}\ , \quad M_1 \leq M_2 \leq 1.1 M_1\ ,$$
$$1.1 M_1 \leq \mu \leq 10 M_1, \quad 5 \leq \tan\beta \leq 60,$$
$$100\ \text{GeV} \leq m_{\tilde{l}_L} \leq 1500\ \text{GeV}, \quad m_{\tilde{l}_R} = m_{\tilde{l}_L}\ .$$

Upper and lower bounds from $(g-2)_\mu$ and

LHC searches

MC, Heinemeyer, Saha, Schappacher' 22

Wino/Bino(+) DM



Green : $(g-2)_\mu$ but not DM, LHC

Blue : $(g-2)_\mu$ + DM, but not LHC

Red : all

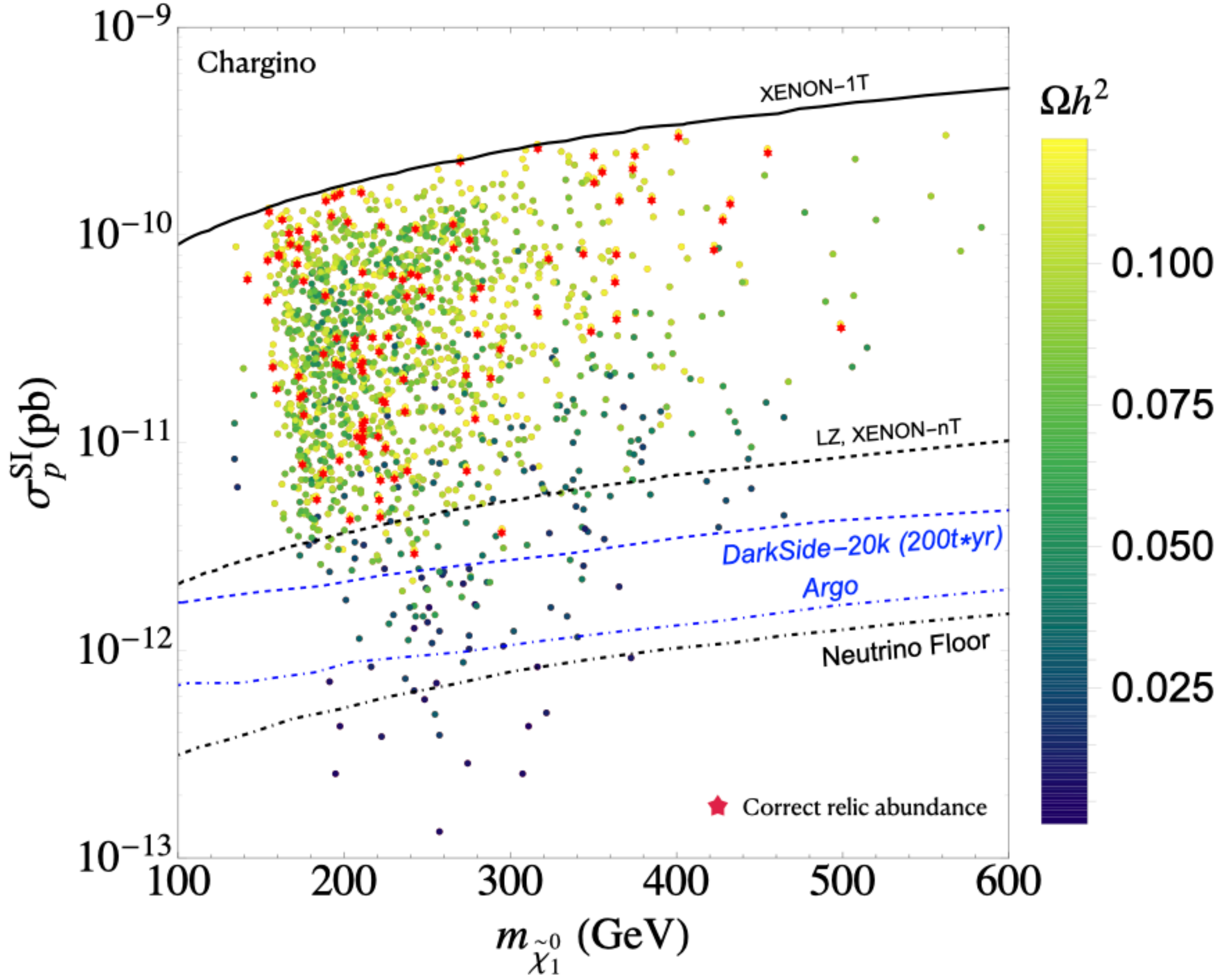
- Slepton-pair production →(2*l* + missing E_T) provides important search channel .

- Considerable BR for $\tilde{e}_L(\tilde{\mu}_L) \to \tilde{\chi}_1^\pm \nu_l$

  ATLAS : $\tilde{e}_L(\tilde{\mu}_L) \to \tilde{\chi}_1^0 l$

➡ Less no. of signal leptons.

Wino/Bino(+) DM

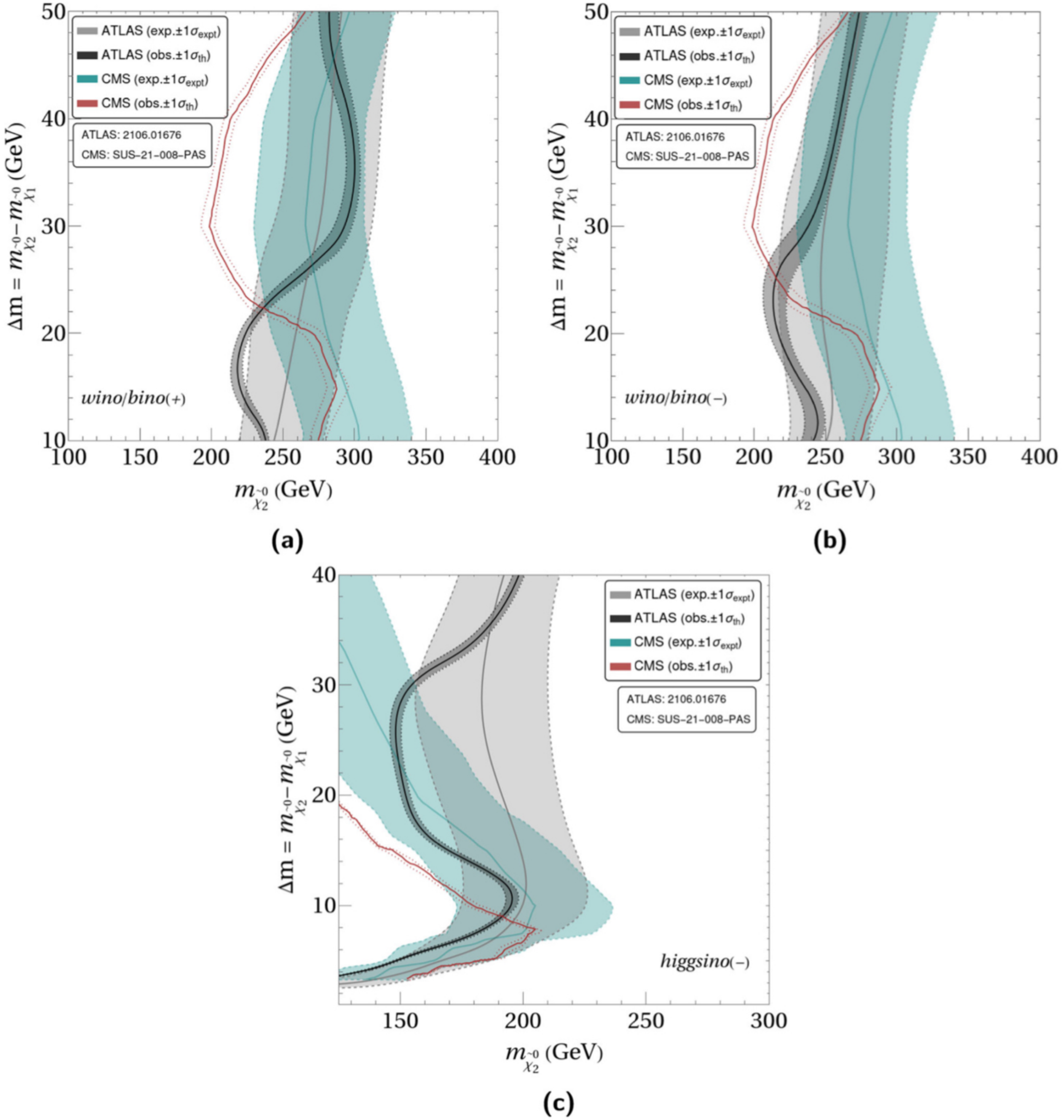


New LZ bound partially covers the parameter space

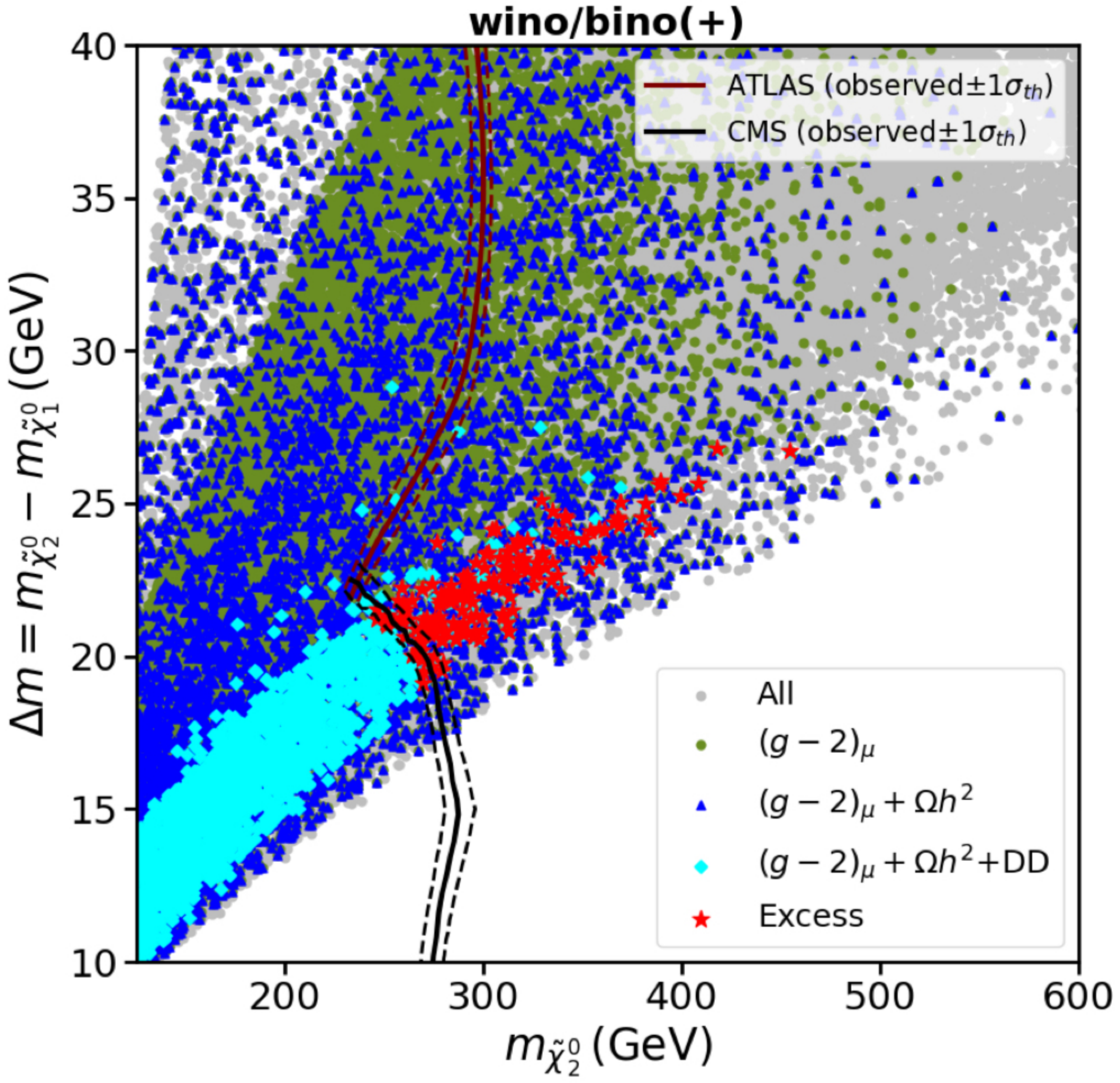
2410.17036

MC, Heinemeyer, Saha, Schappacher' 22

Wino/Bino(+) DM


ATLAS (exp.±1σexpt)
ATLAS (obs.±1σth)
CMS (exp.±1σexpt)
CMS (obs.±1σth)
ATLAS: 2106.01676
CMS: SUS-21-008-PAS
wino/bino(+)
wino/bino(−)
higgsino(−)
Δm = m χ̃2⁰ − m χ̃1⁰ (GeV)
m χ̃2⁰ (GeV)
(a)
(b)
(c)

Wino/Bino(+) excess



Wino/Bino (+) : $M_1 \times M_2 > 0$

Parameter scan range

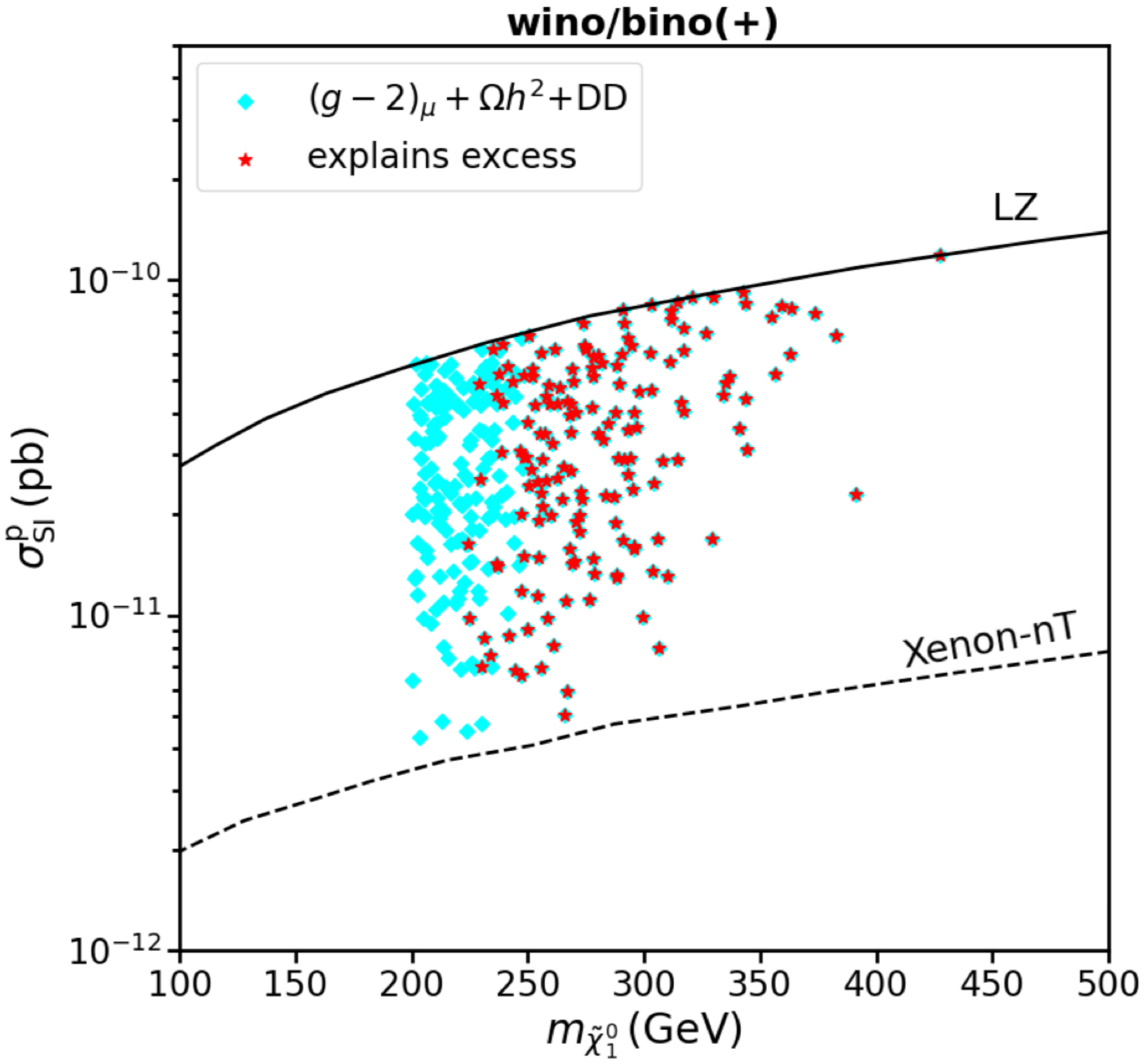
$$100\ \text{GeV} \leq M_1 \leq 400\ \text{GeV}\ , \quad |M_1| \leq M_2 \leq 1.1\,|M_1|\ ,$$
$$1.1|M_1| \leq \mu \leq 10|M_1|, \quad 2 \leq \tan\beta \leq 60\ ,$$
$$100\ \text{GeV} \leq m_{\tilde{l}_L} = m_{\tilde{l}_R} \leq 1.5\ \text{TeV}\ , \quad M_A = 1.5\ \text{TeV}\ .$$

Only points with : $m_{\tilde{l}} > m_{\tilde{\chi}_2^0}$

Excesses do not overlap well

Many good points at $\Delta m \approx 20$ GeV

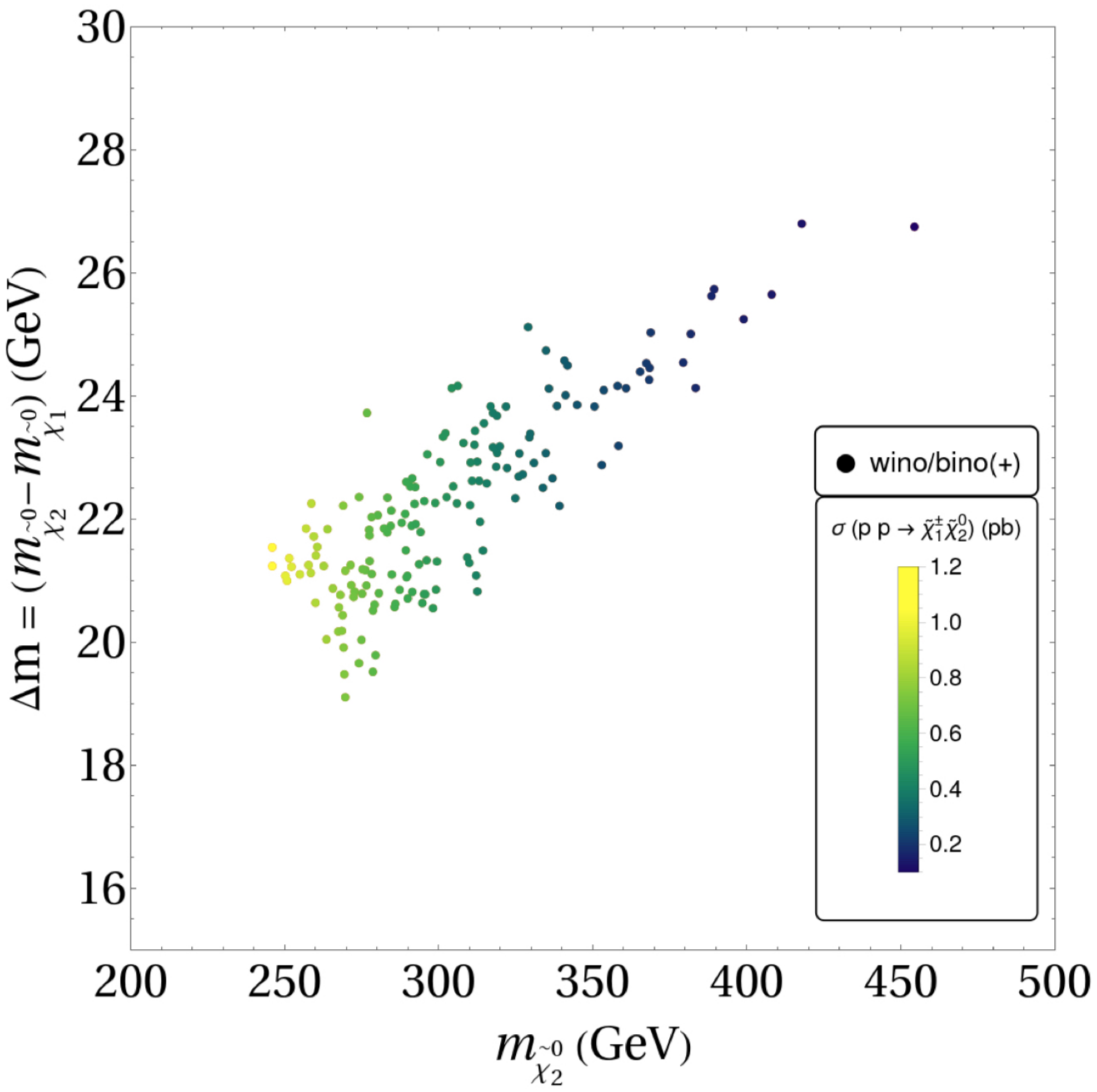
Wino/Bino(+) excess



- ✦ DD can be complementary
- ✦ New LZ bound partially covers the parameter space

2410.17036

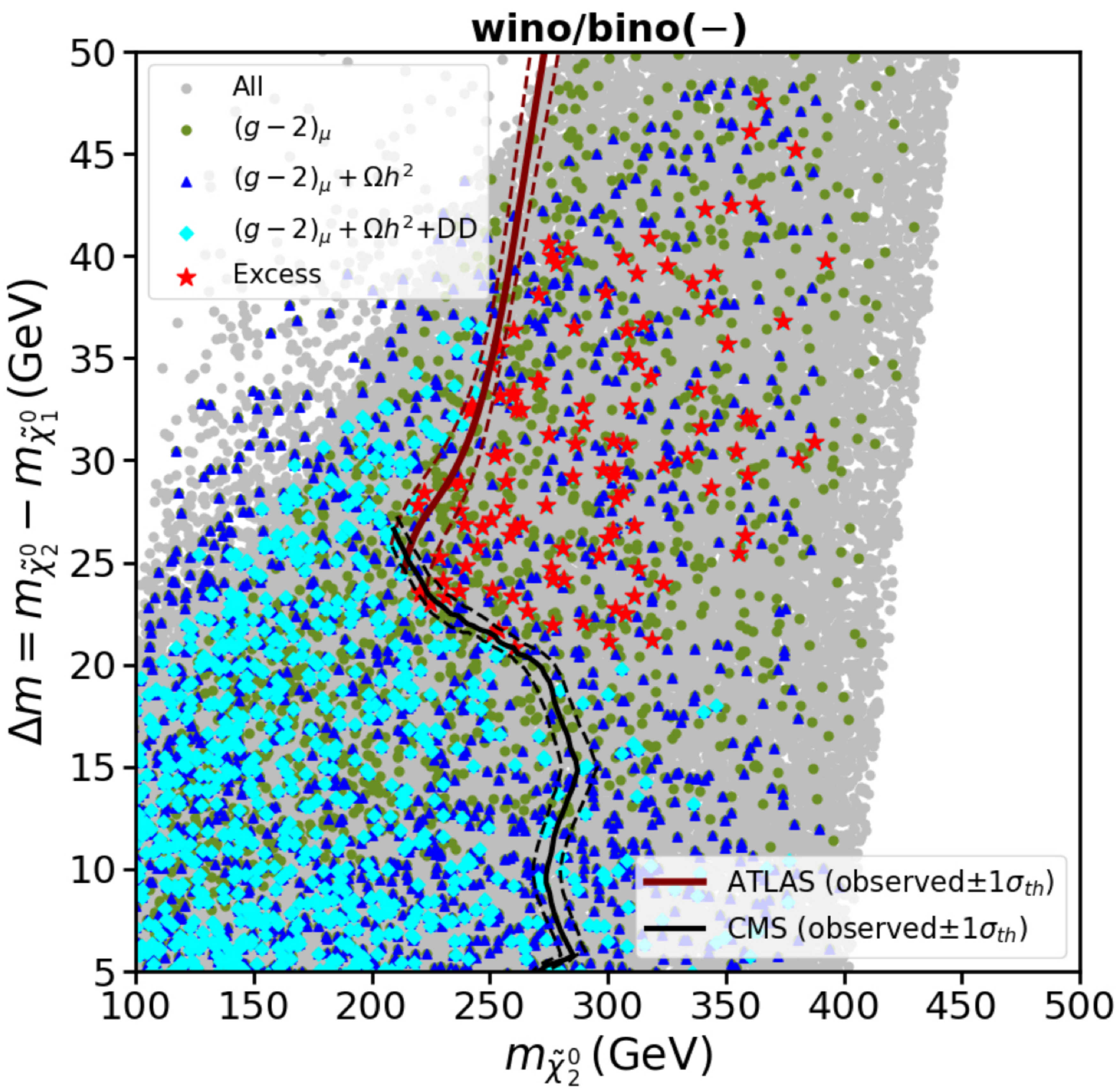
Wino/Bino(+) excess



Cross section roughly in the correct range considering the difference between expected and observed limits

NLO+NLL Resummino

Wino/Bino(-) DM



ATLAS and CMS overlap better

Wino/Bino (-) : $M_1 \times M_2 < 0$

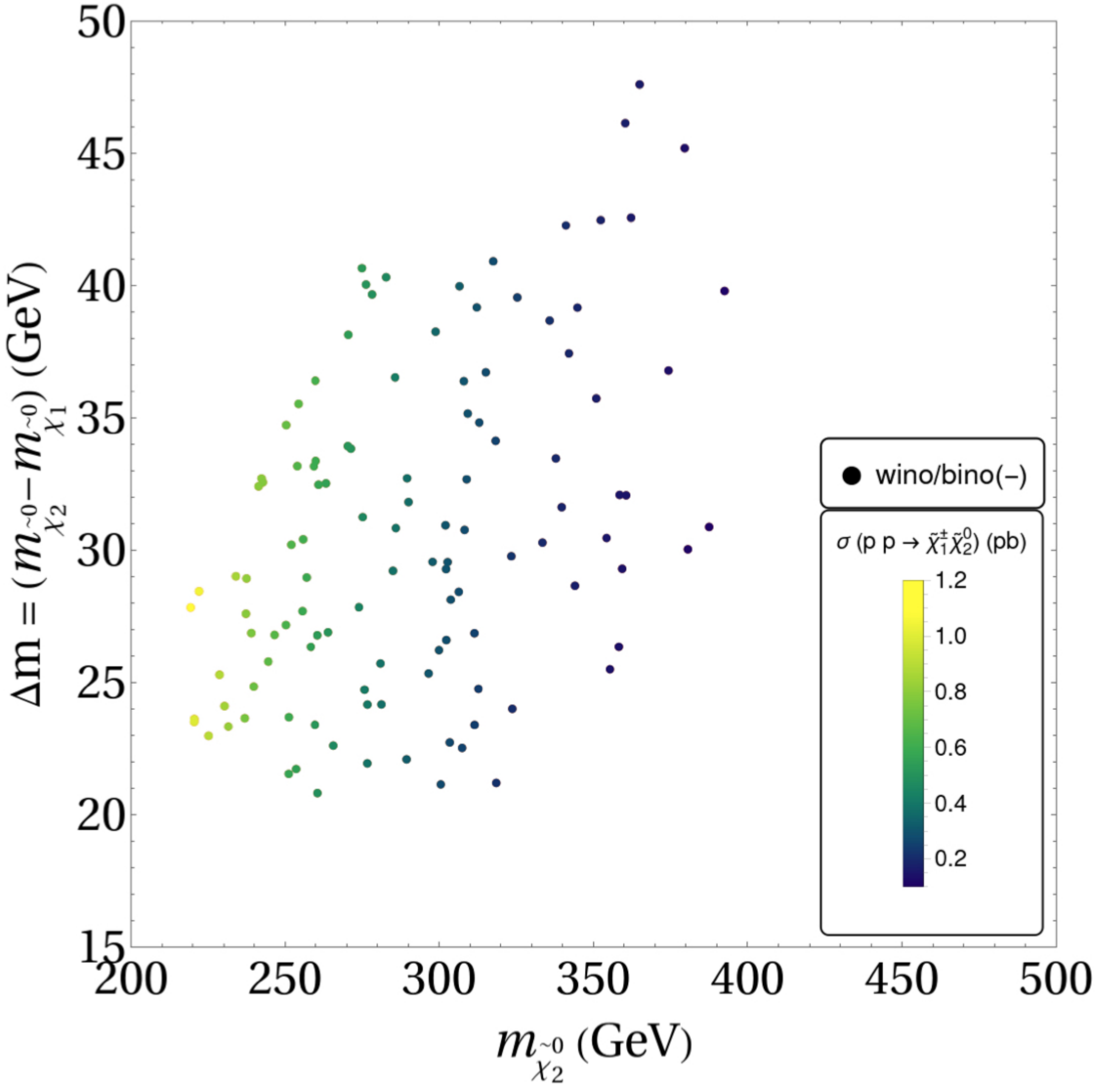
Parameter scan range

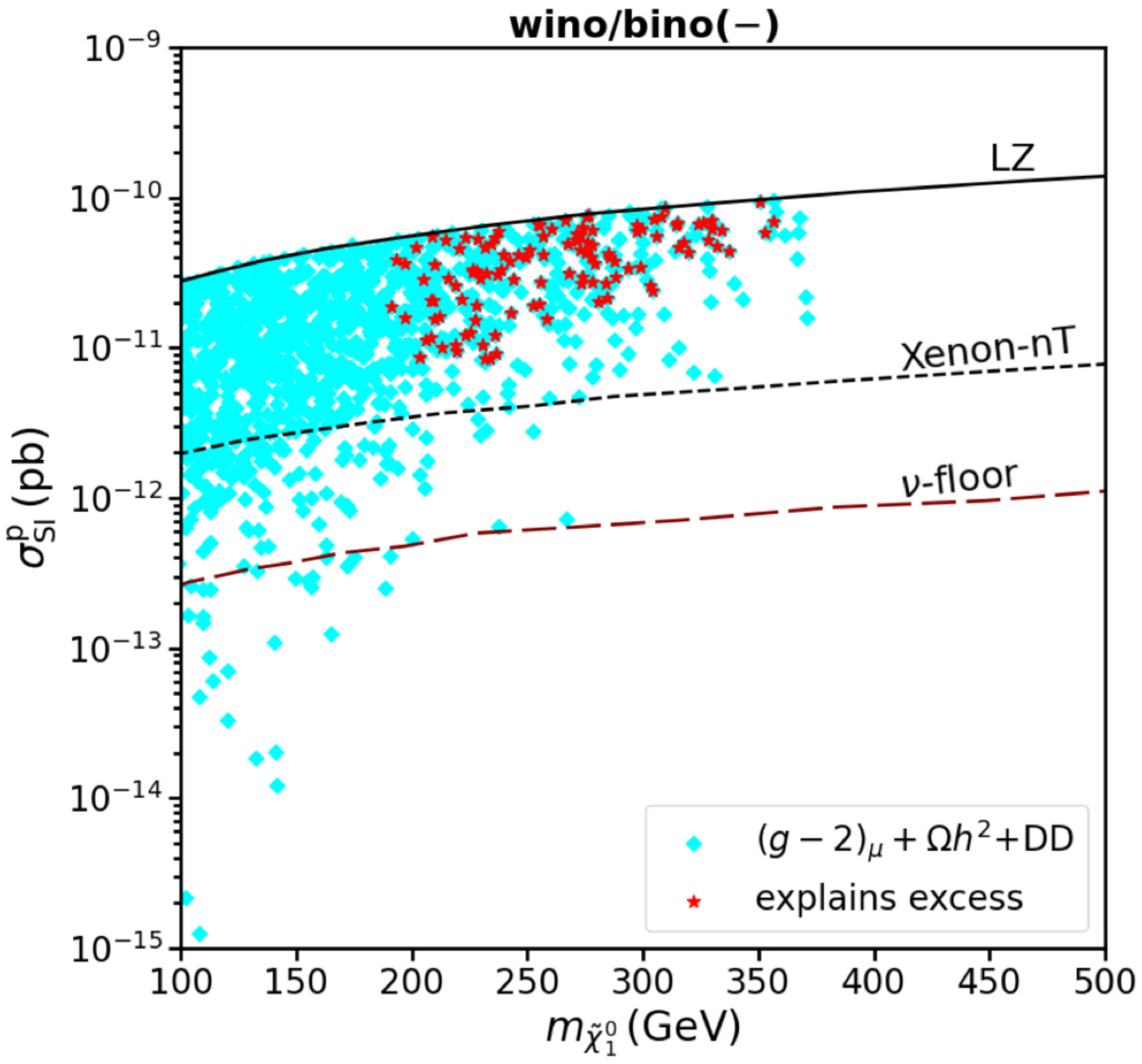
$$100\ \text{GeV} \le -M_1 \le 400\ \text{GeV}\,, \quad |M_1| \le M_2 \le 1.4\,|M_1|\,,$$
$$1.2\,|M_1| \le \mu \le 2\ \text{TeV}\,, \quad 2 \le \tan\beta \le 60\,,$$
$$100\ \text{GeV} \le m_{\tilde{l}_L} = m_{\tilde{l}_R} \le 1.5\ \text{TeV}\,, \quad M_A = 3\ \text{TeV}\,.$$

Only points with : $m_{\tilde{l}} > m_{\tilde{\chi}_2^0}$

Many good points at $\Delta m \approx 25$ GeV

Wino/Bino(-) DM





LHC cross section in the right range

DD can be complementary

Higgsino(+) DM

Higgsino(+) : $\mu \times M_1 > 0$

- $SU(2)_L$ doublet favored by naturalness
- Under-abundant upto ~ 1 TeV
- Compressed spectra with $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0}$

$\Omega_{CDM} h^2 \leq 0.122$

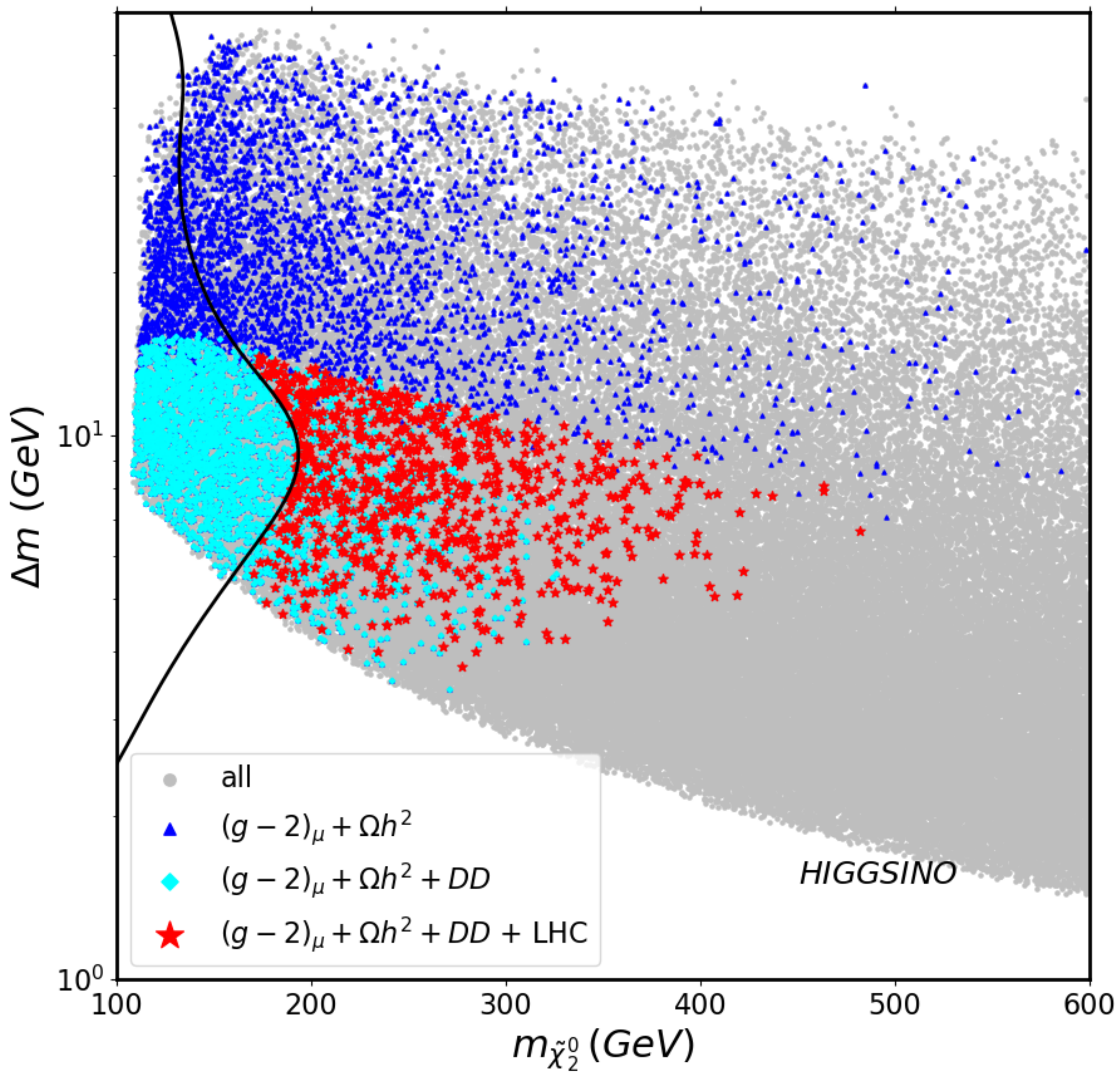
Parameter scan range

$$100 \text{ GeV} \leq \mu \leq 1.2 \text{ TeV} , \quad 1.1\mu \leq M_1 \leq 10\mu ,$$
$$1.1\mu \leq M_2 \leq 10\mu, \quad 5 \leq \tan\beta \leq 60,$$
$$100 \text{ GeV} \leq m_{\tilde{l}_L}, m_{\tilde{l}_R} \leq 2 \text{ TeV} .$$

Higgsino(+) DM

Higgsino(+) : $\mu \times M_1 > 0$

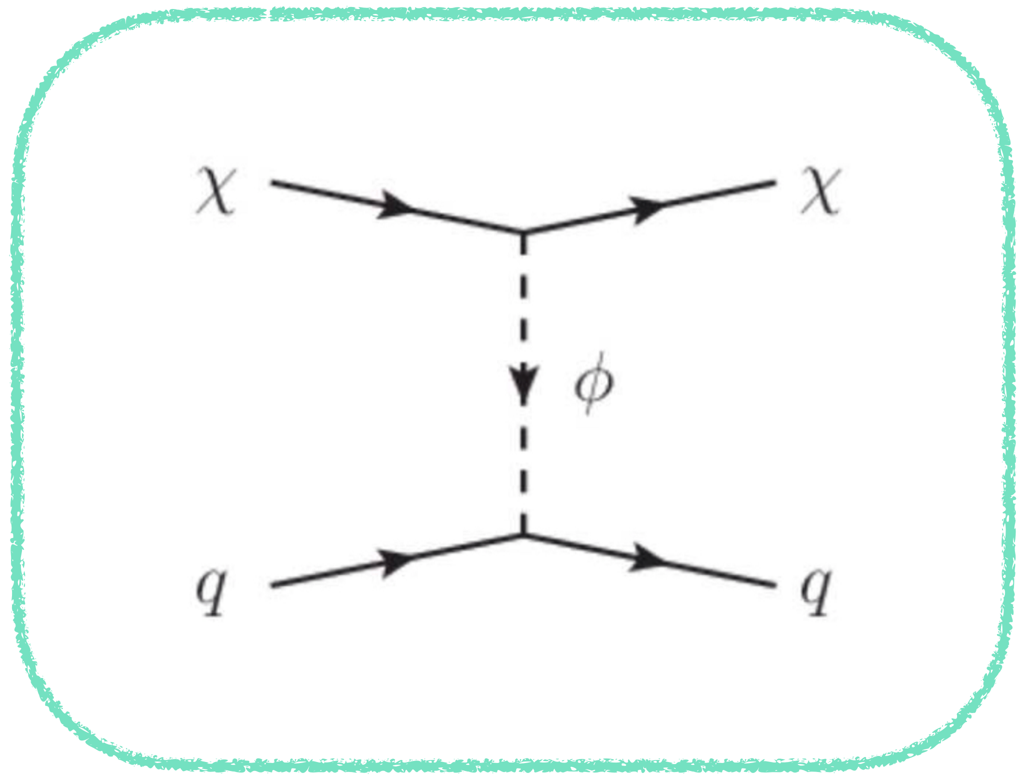
$m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0}$



Direct detection cuts away higher Δm

- Compressed spectra searches most important.
- $\Delta m \sim \mathcal{O}(10)$ GeV → Disappearing track searches not sensitive

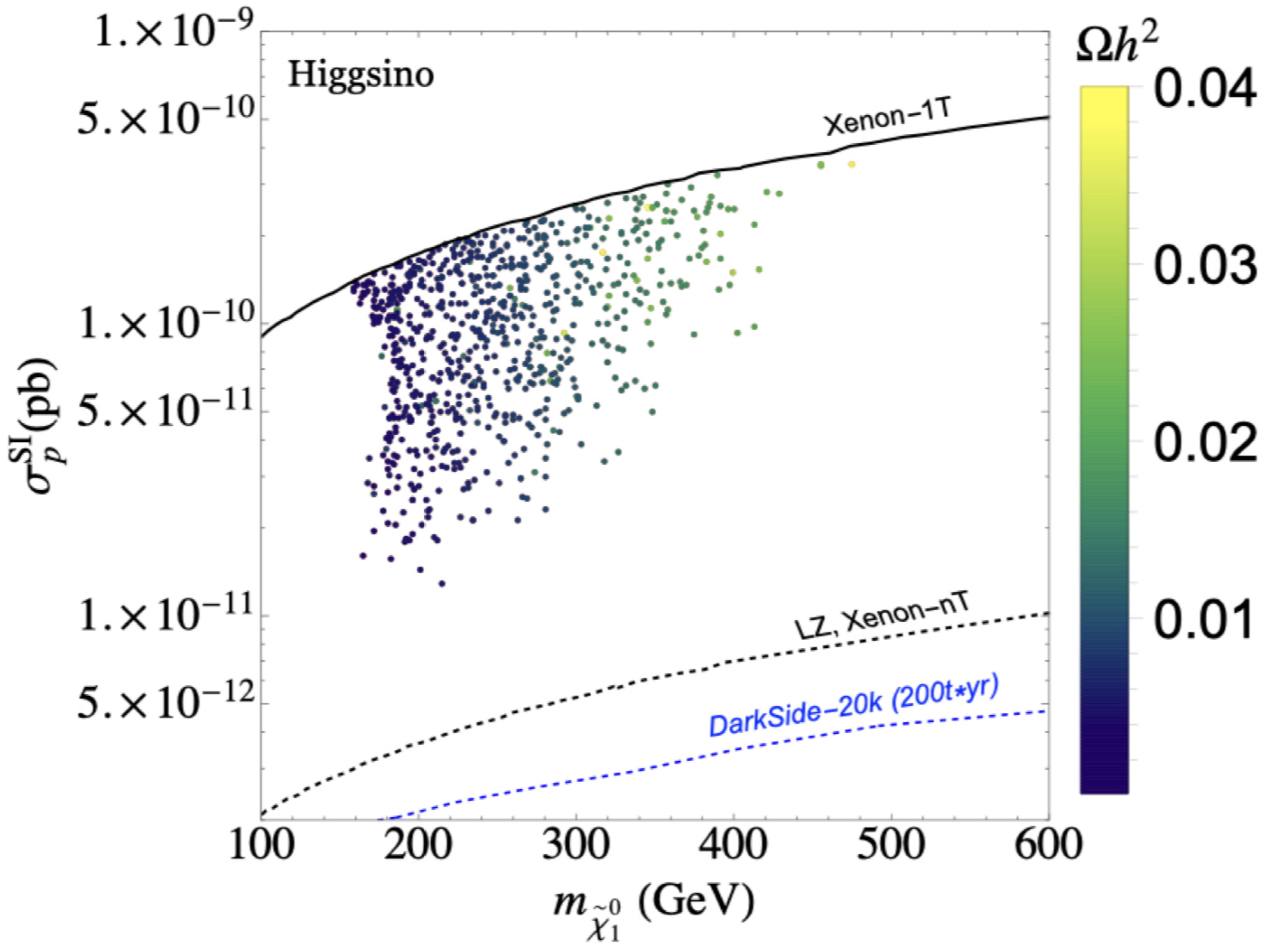
$$c_{h\tilde{\chi}_1^0\tilde{\chi}_1^0} \simeq -\frac{1}{2}(1+\sin 2\beta)\left(\tan^2\theta_{\rm w}\frac{M_W}{M_1-\mu}+\frac{M_W}{M_2-\mu}\right)$$

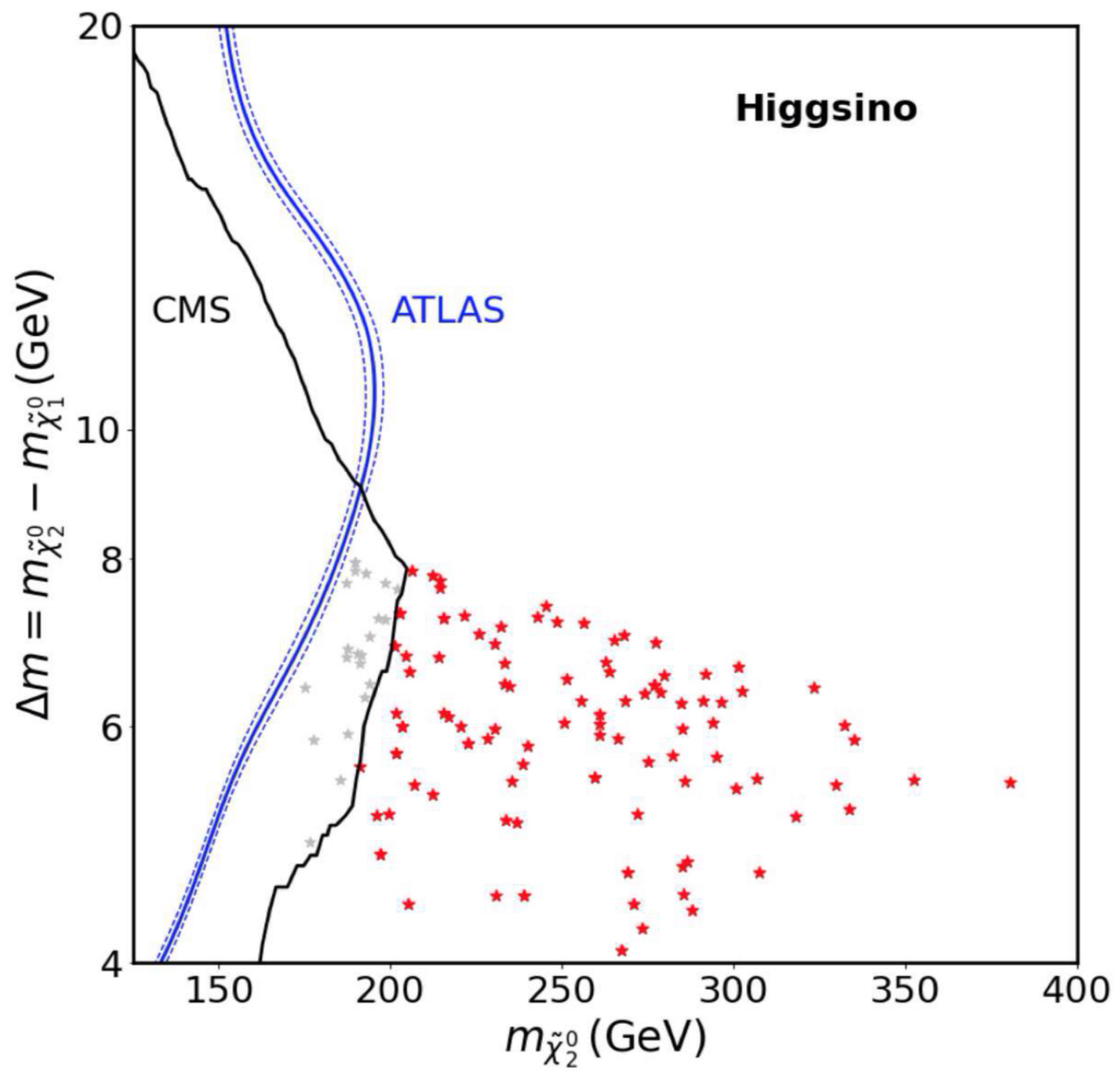


Drees, Ghaffari '21

Higgsino(+) DM

Higgsino(+) : $\mu \times M_1 > 0$





With LZ 2022

$m_{\tilde{l}} > m_{\tilde{\chi}_2^0}$

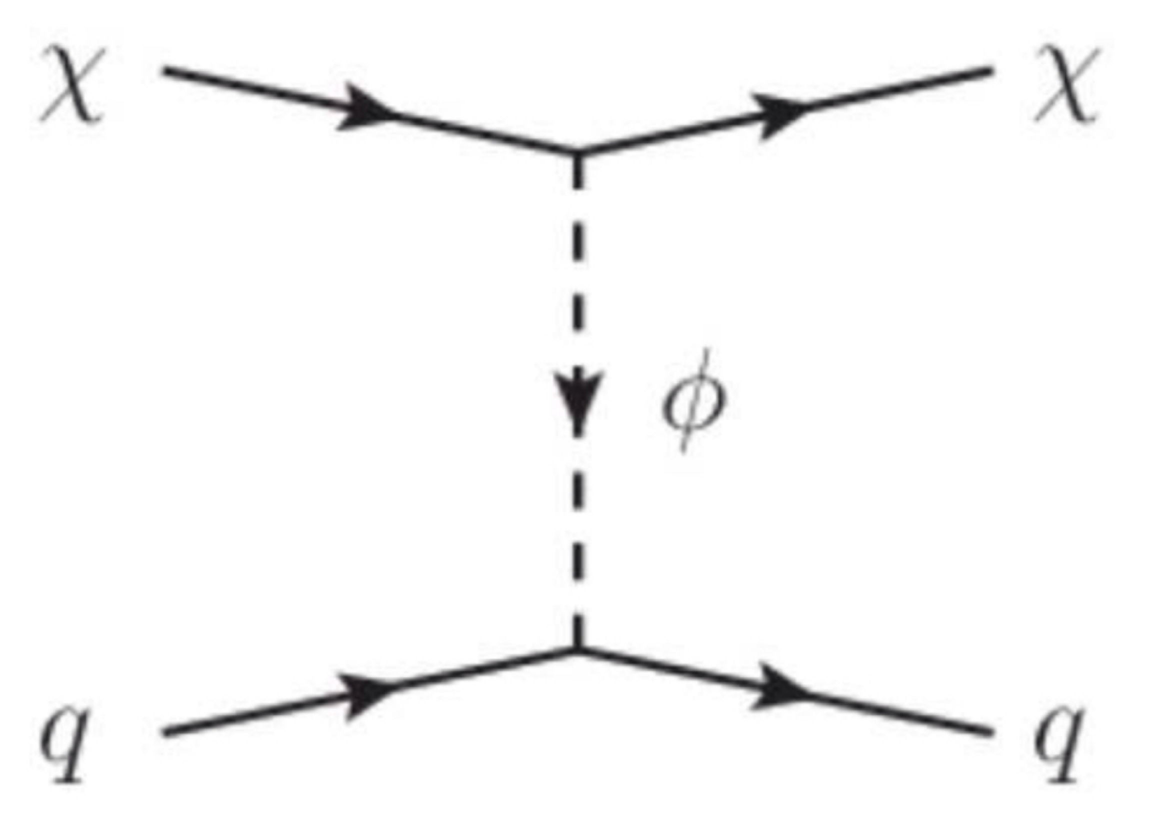
Direct detection cuts away higher Δm

Higgsino(-) DM

SI scattering amplitude

$$\mathcal{M}_p^{\rm SI} \propto \frac{v}{\mu^2}\left[2\frac{(M_1+\mu\sin 2\beta)}{m_h^2} - \frac{\mu\cos 2\beta\tan\beta}{m_H^2}\right]$$

$$\approx \frac{v}{\mu^2}\left[2\frac{(M_1+2\mu/\tan\beta)}{m_h^2} + \frac{\mu\tan\beta}{m_H^2}\right]$$



Cancellation possible for $\mu \times M_1 < 0$

- within the first term : Bino LSP
- between h and H exchange : light $M_H \approx M_A$

Huang, Wagner'14, Baum et al '23

Higgsino(-) DM

Higgsino(-) : $\mu \times M_1 < 0$

Parameter scan range

$$
\begin{aligned}
190\ \text{GeV} \leq -M_1 \leq 1500\ \text{GeV}\ , \quad M_2 = 3\ \text{TeV}\ , \\
\frac{-2M_1 \tan\beta}{4 + M_h^2/M_H^2 \tan^2\beta} \leq \mu \leq |M_1|\ , \\
1 \leq \tan\beta \leq 50\ , \\
m_{\tilde{l}_L} = m_{\tilde{l}_R} = 1.5\ \text{TeV}\ , \\
190\ \text{GeV} \leq M_A \leq 1.5\ \text{TeV}\ .
\end{aligned}
$$

We take $M_1 < 0$

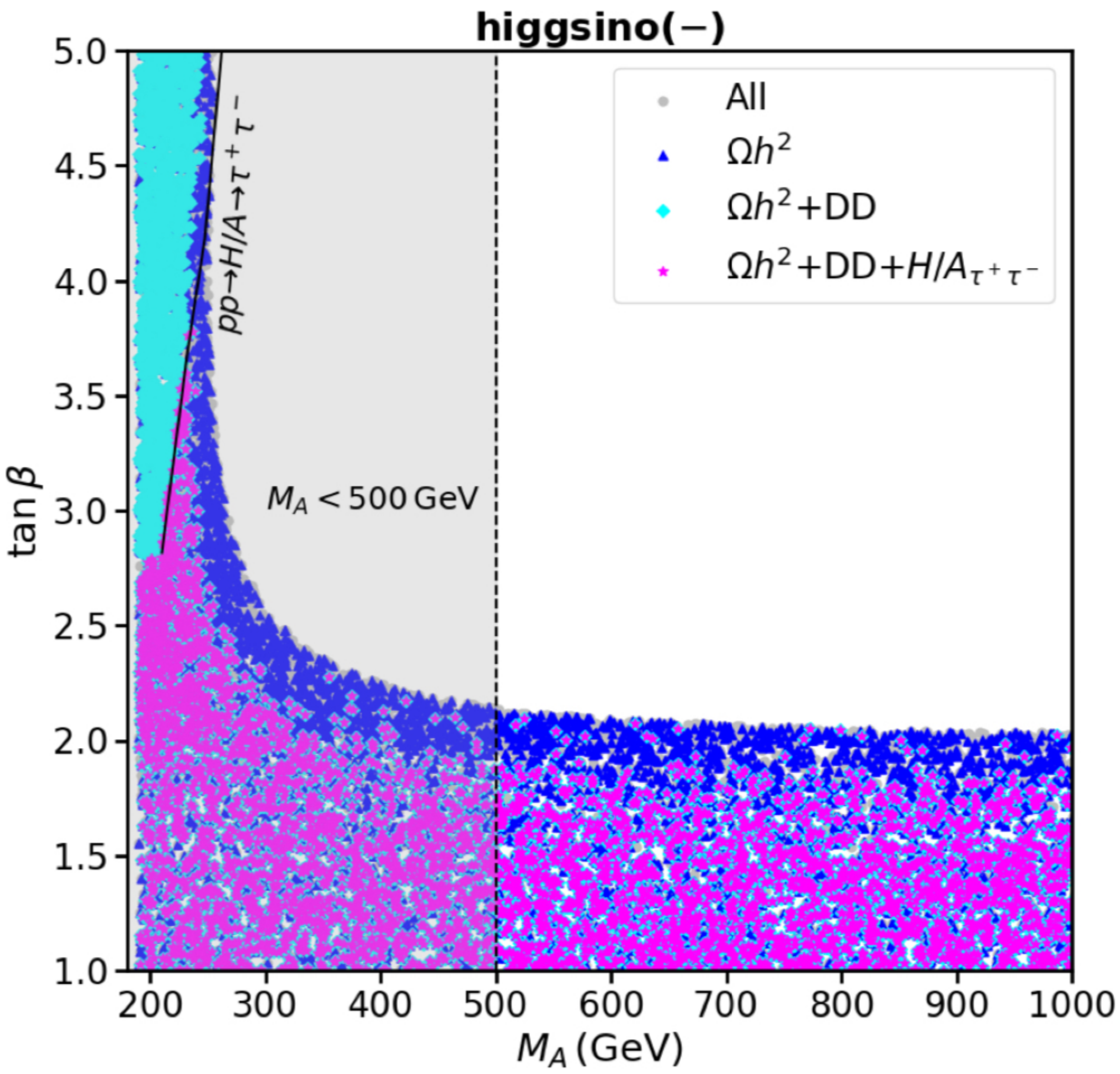
Original motivation : g-2

Additional Constraints

- Flavor physics
- Non-standard Higgs searches

Higgsino(-) DM

Higgsino(-) : $\mu \times M_1 < 0$

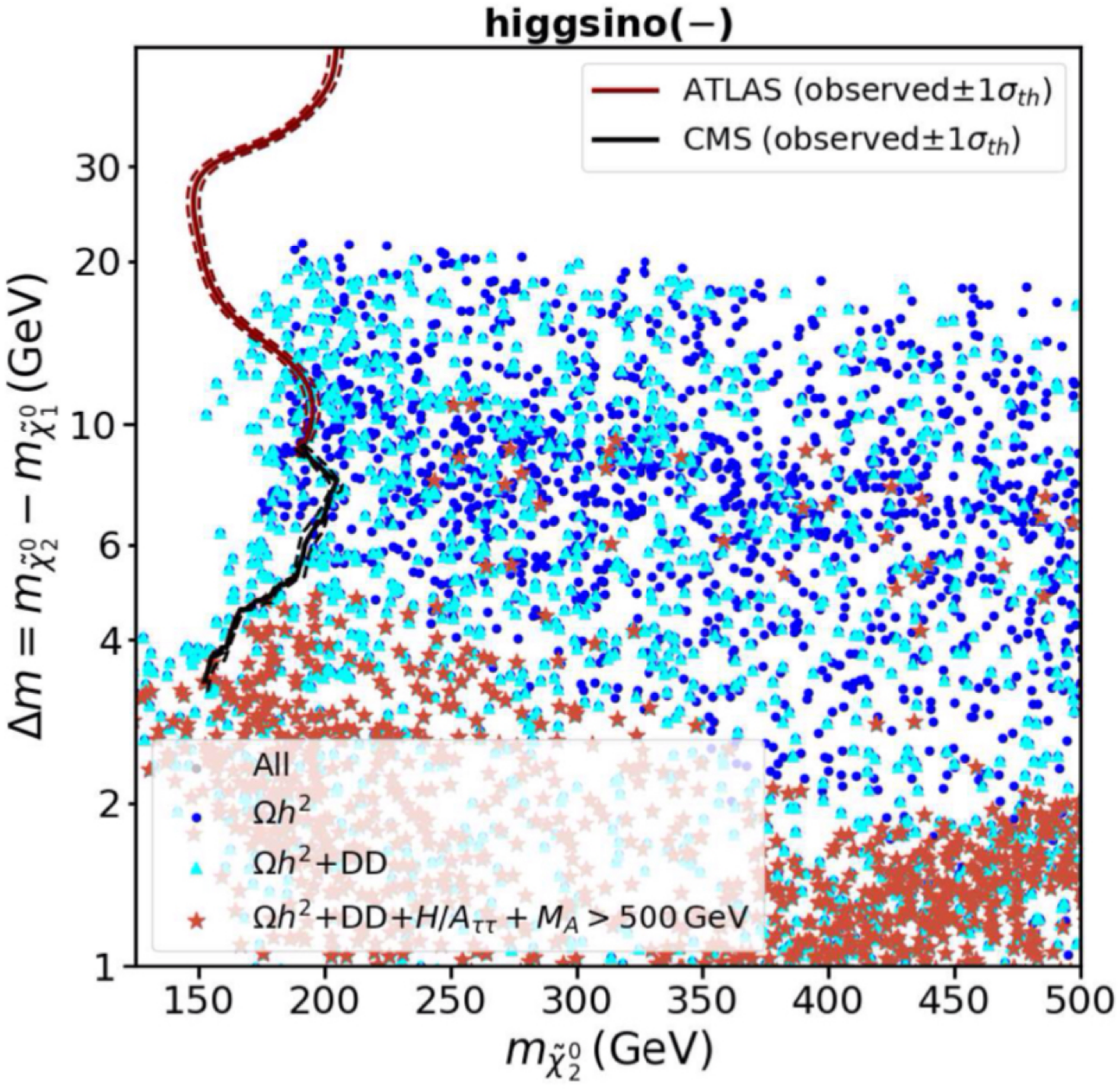


Additional Constraints

- ✦ Flavor physics
- ✦ Non-standard Higgs searches

$M_A \lesssim 500$ GeV, $\tan\beta \lesssim 2$

Higgsino(-) DM



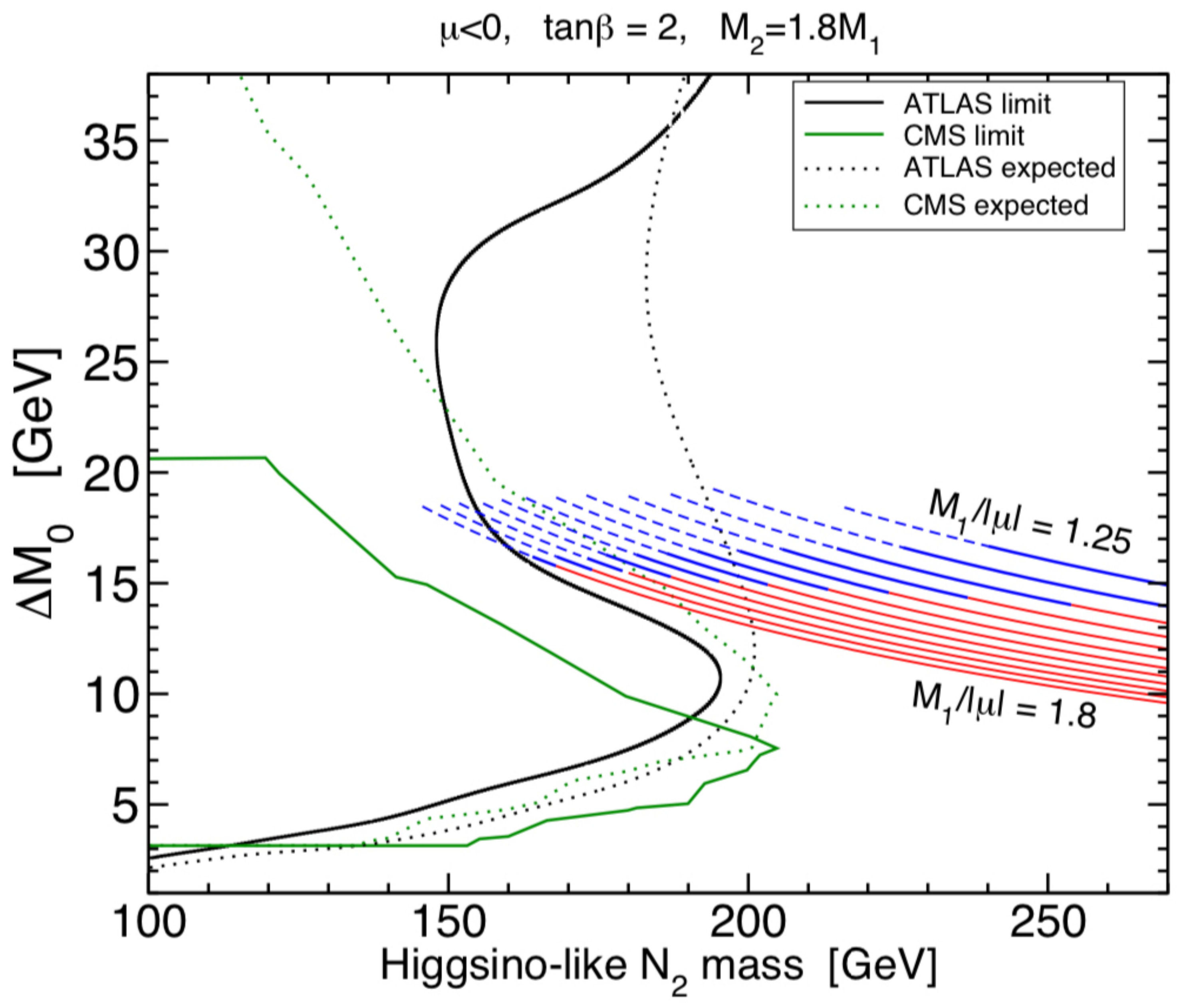
Δm still too low to explain "excesses"

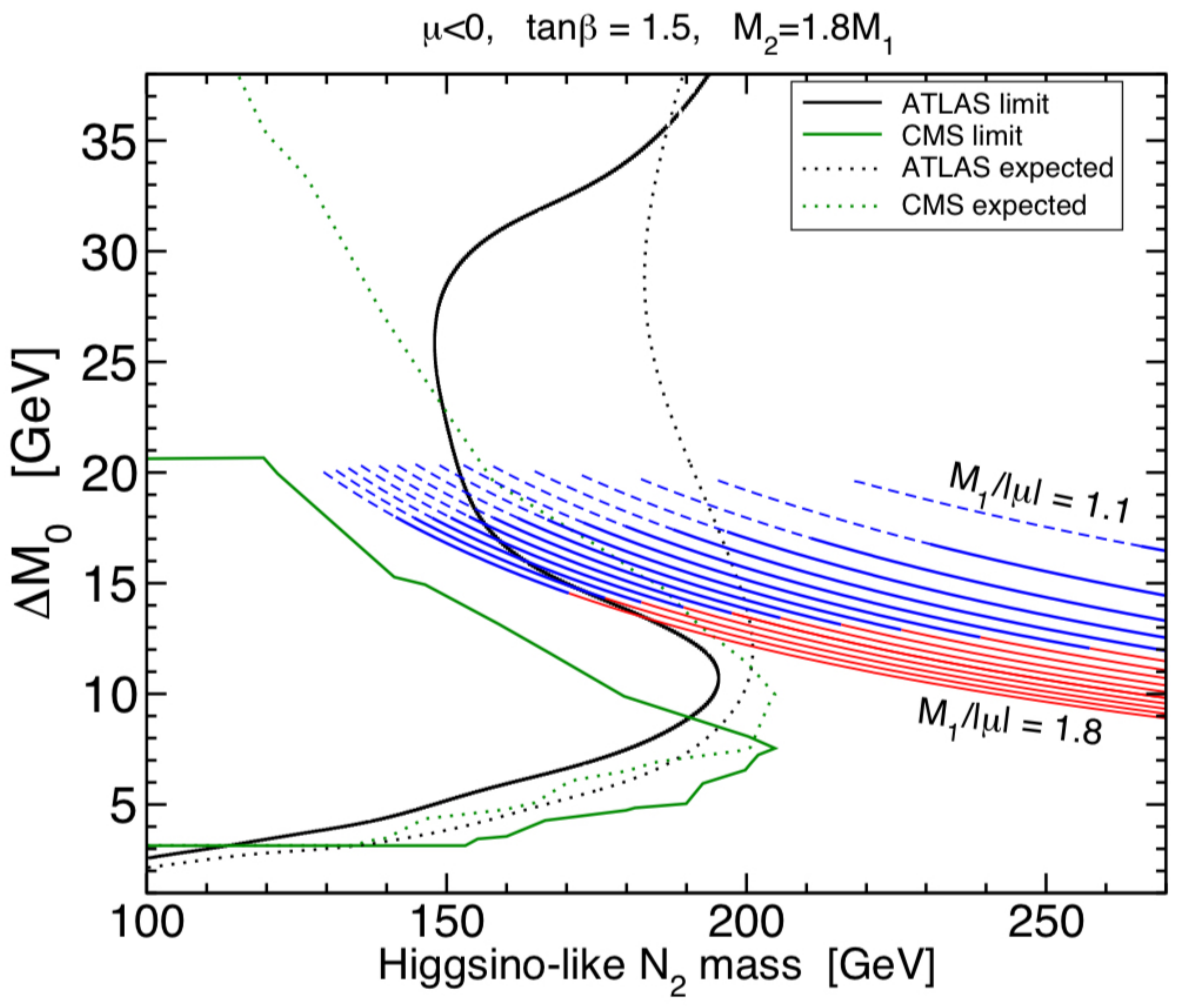
Higgsino(-) DM

Martin, 2403.19598

Higgsino(-) : $\mu \times M_1 < 0$

- $M_1 < 0$: motivation g-2
- Alternatively, $\mu < 0$

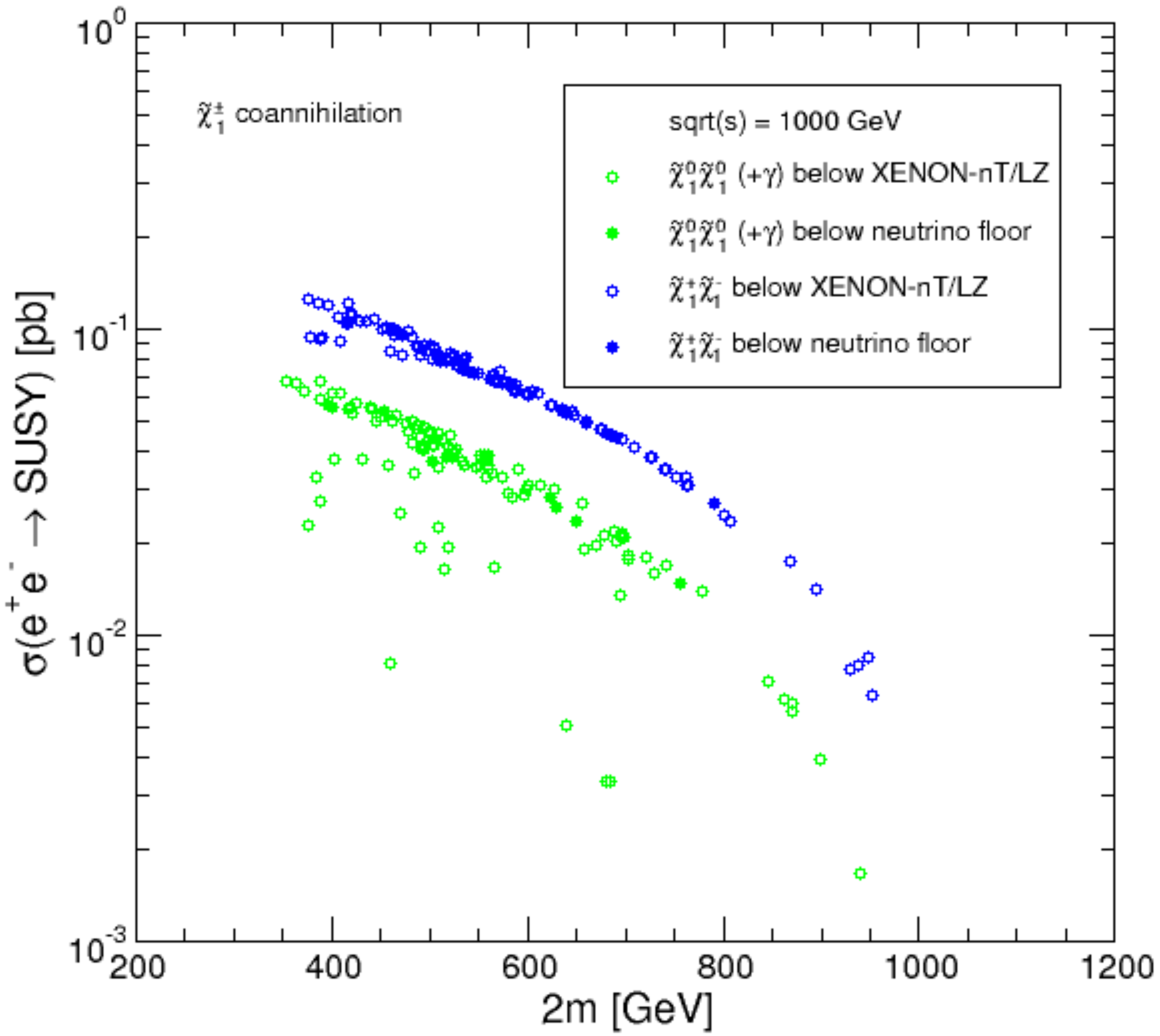




SD constraints restrict Δm

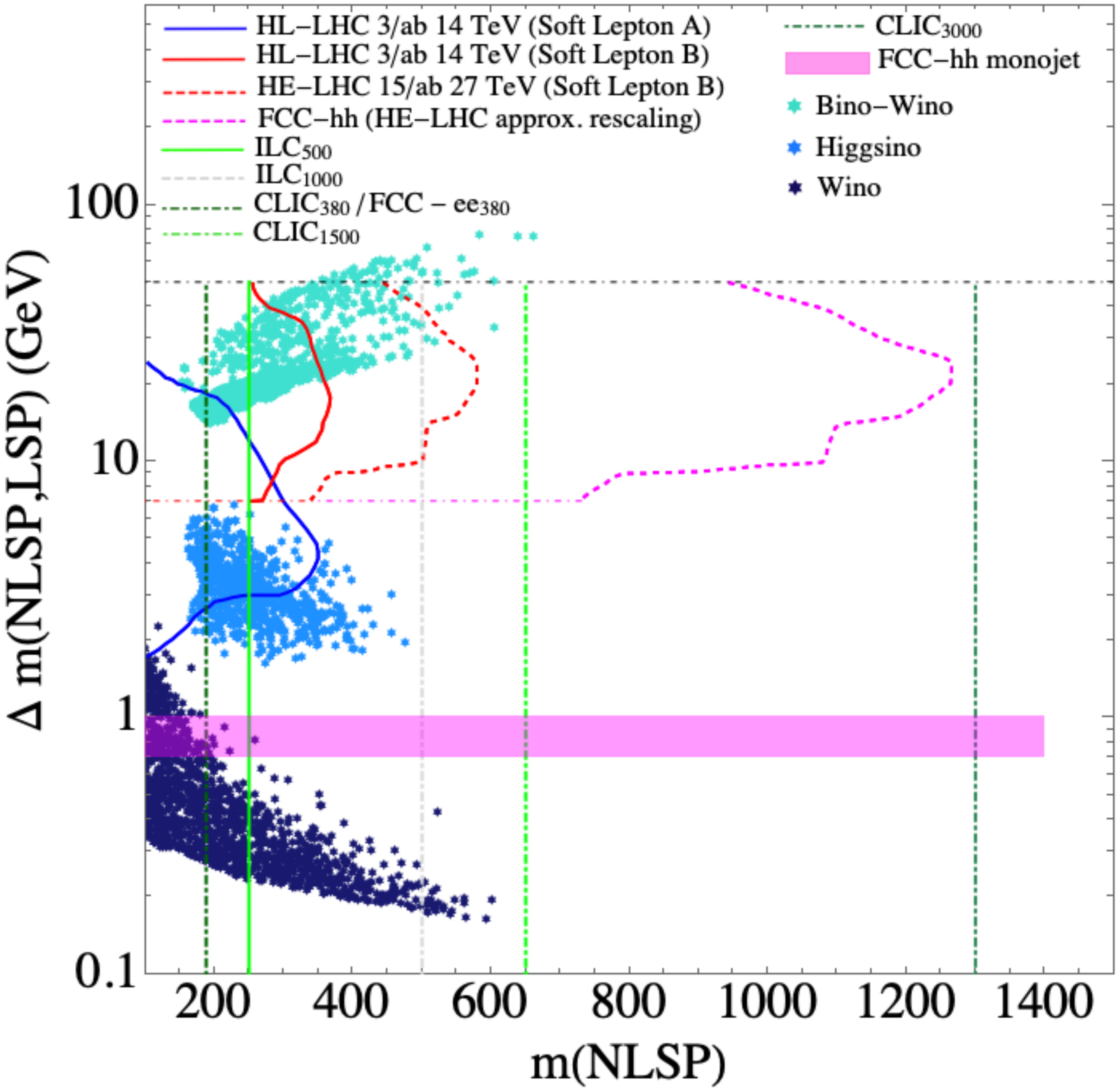
Future collider prospects

Wino/Bino (+) : $M_1 \times M_2 > 0$



MC, Heinemeyer, Saha, Schappacher' 20

Future collider prospects



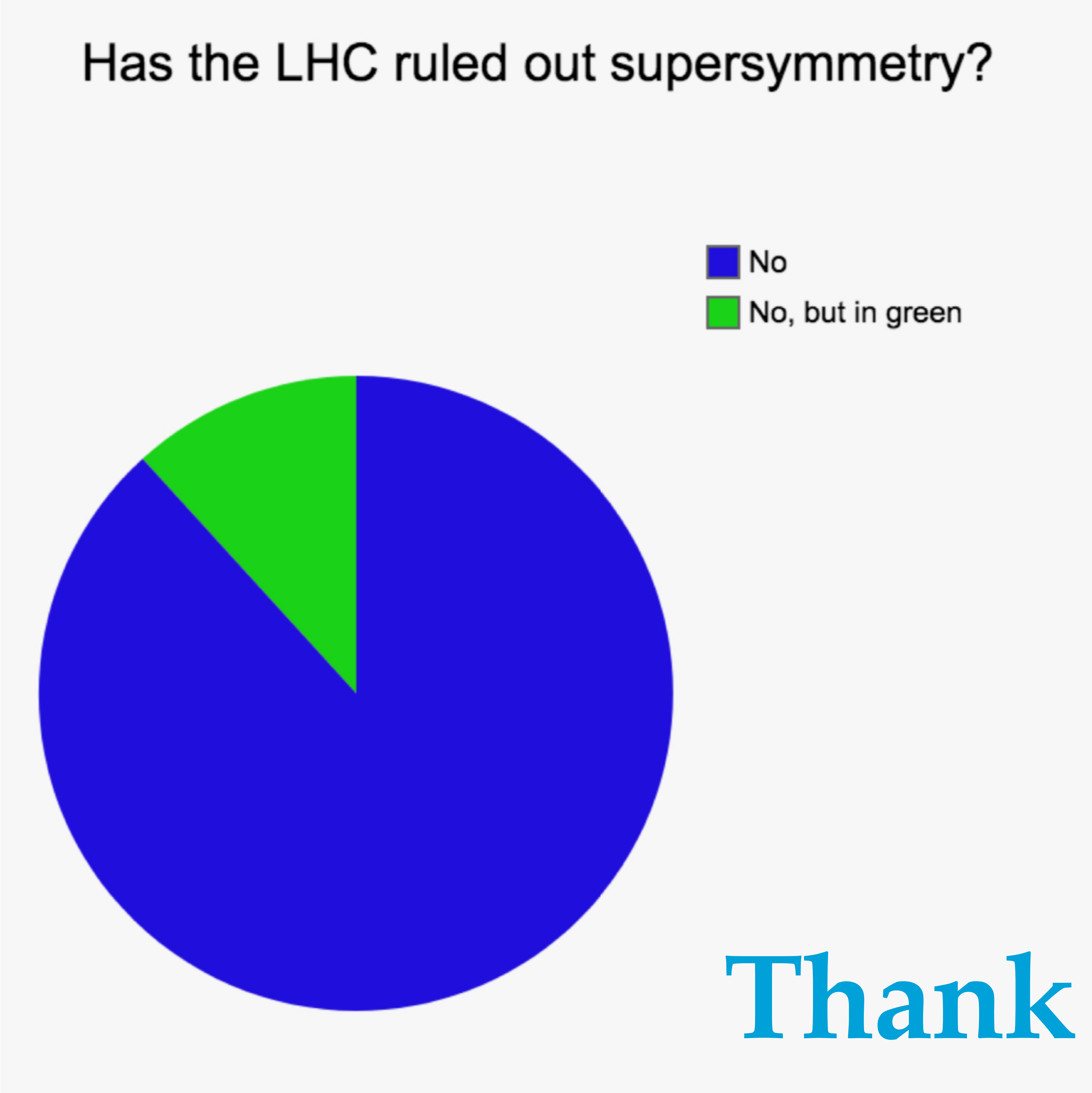
Berggren' 20

Summary

- Much of MSSM parameter space still unexplored (even below ~ 1 TeV)
- "Simplified SUSY models" are not really SUSY. Proper recasting required.
- New muon g-2 result (Theory & experiment) upcoming. Independently at J-PARC, MuonE.
- Small excesses in ATLAS +CMS soft lepton searches : "Compressed" region needs better sensitivity.
  - VBF searches, ML-based triggers/cuts

LHC has not ruled out SUSY.

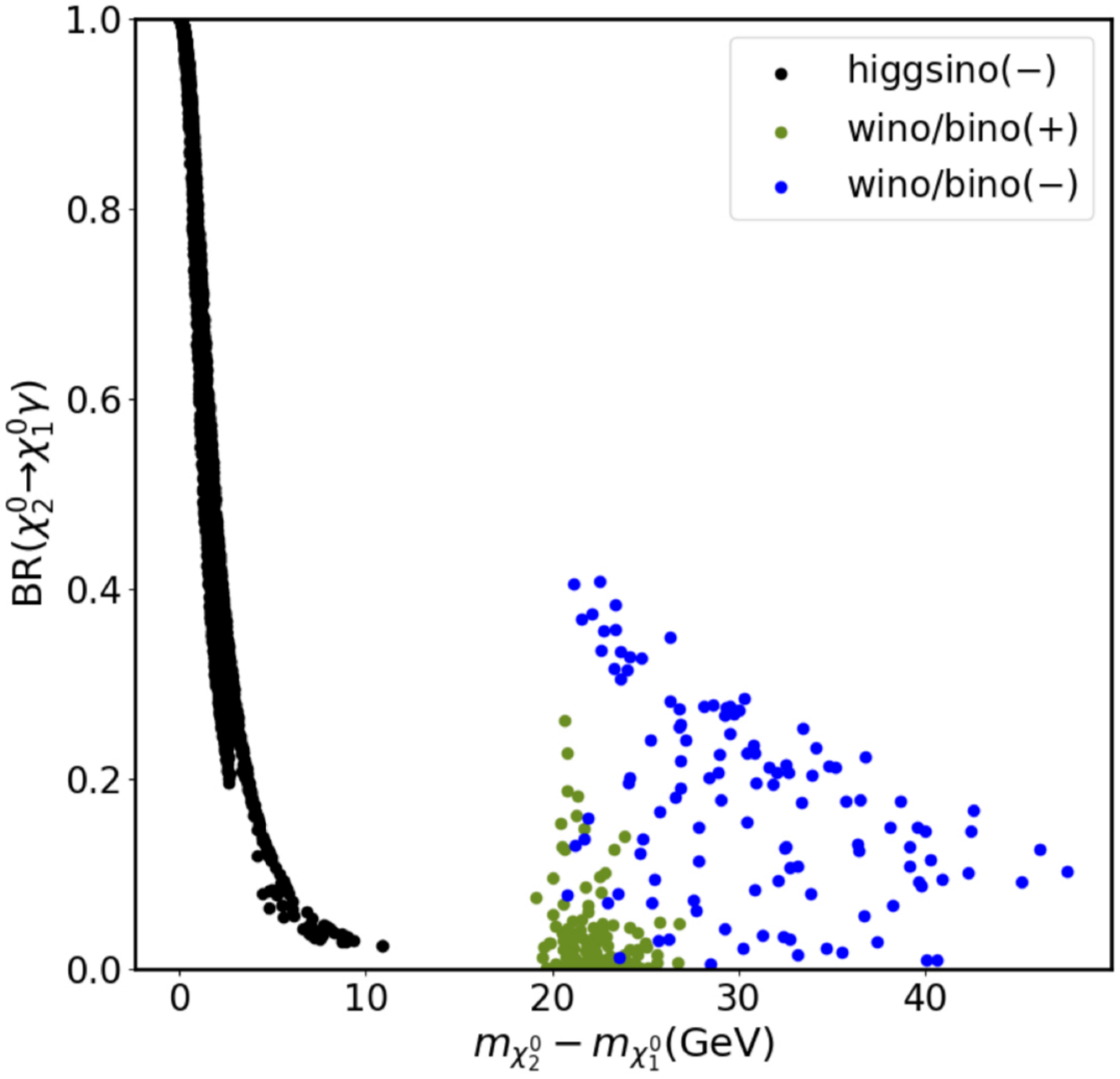
But when will it discover SUSY ? ⟶ Soon!



Thank You!

Extra

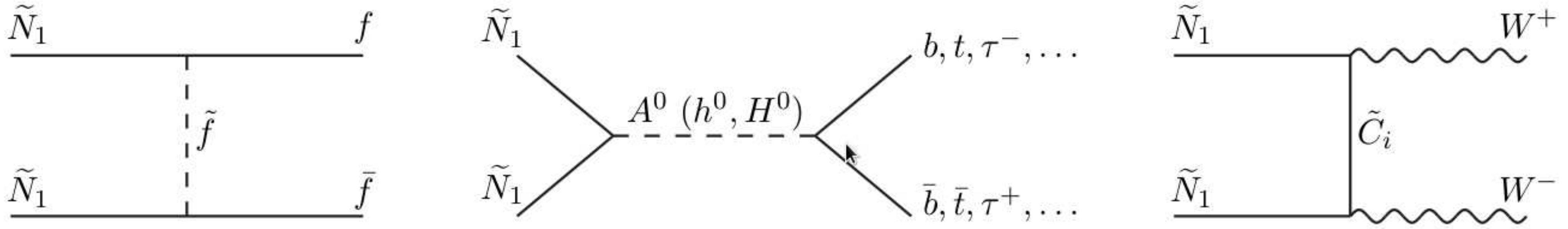
Chargino Co-annihilation



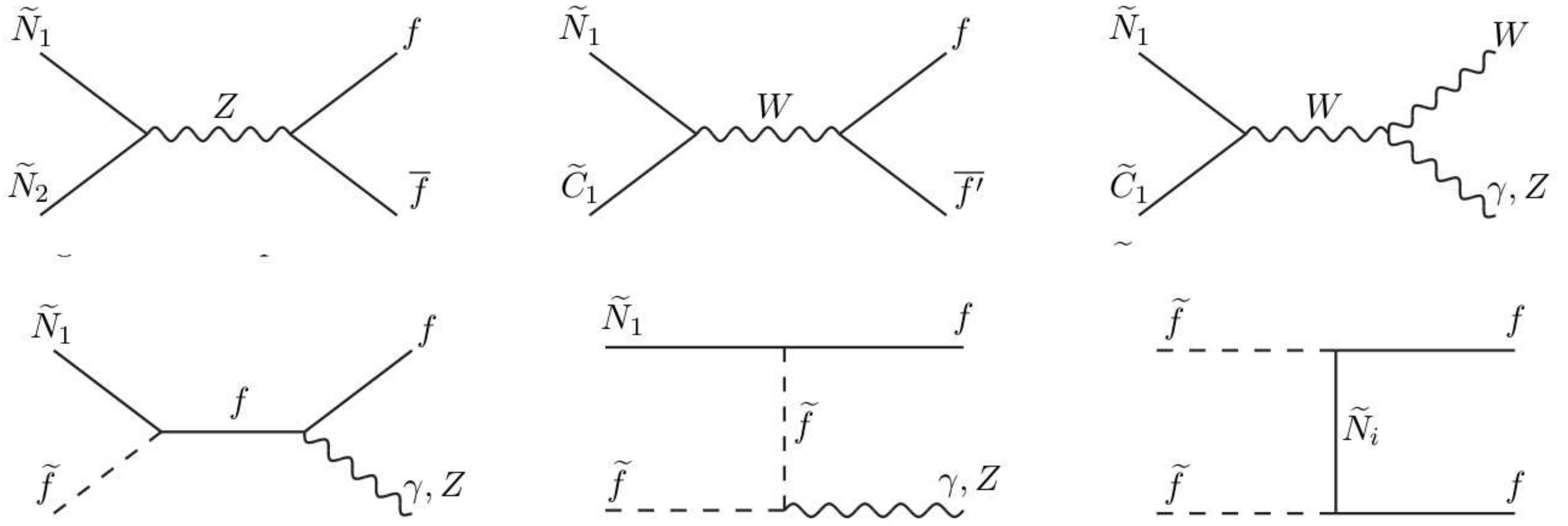
DM Constraints

Relic Density

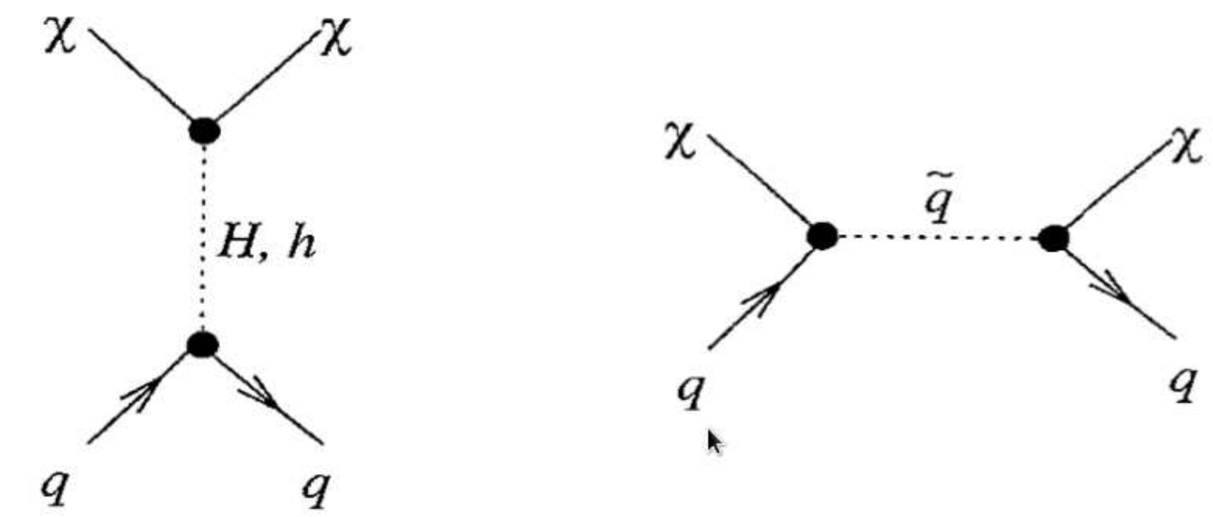
Some annihilation channels that could give right relic density :



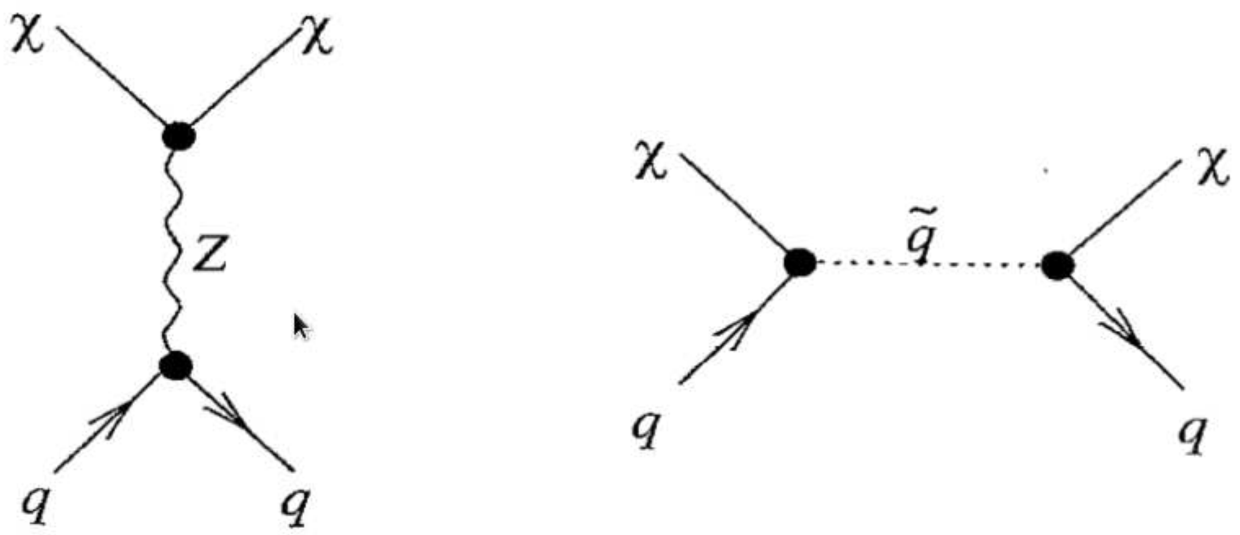
There can be coannihilations with sparticles of slightly heavier masses:



Direct Detection



Diagrams contributing to SI interactions



Diagrams contributing to SD interactions

A well-tempered bino-wino or bino-higgsino LSP → Chargino coannihilation

Bino - dominated LSP → Slepton coannihilation

LHC searches

$$c\tau \simeq 0.7 \text{ cm} \times \left[\left(\frac{\Delta m_+}{340\,\text{MeV}}\right)^3 \sqrt{1-\frac{m_\pi^2}{\Delta m_+^2}}\right]^{-1}$$

- Disappearing track searches

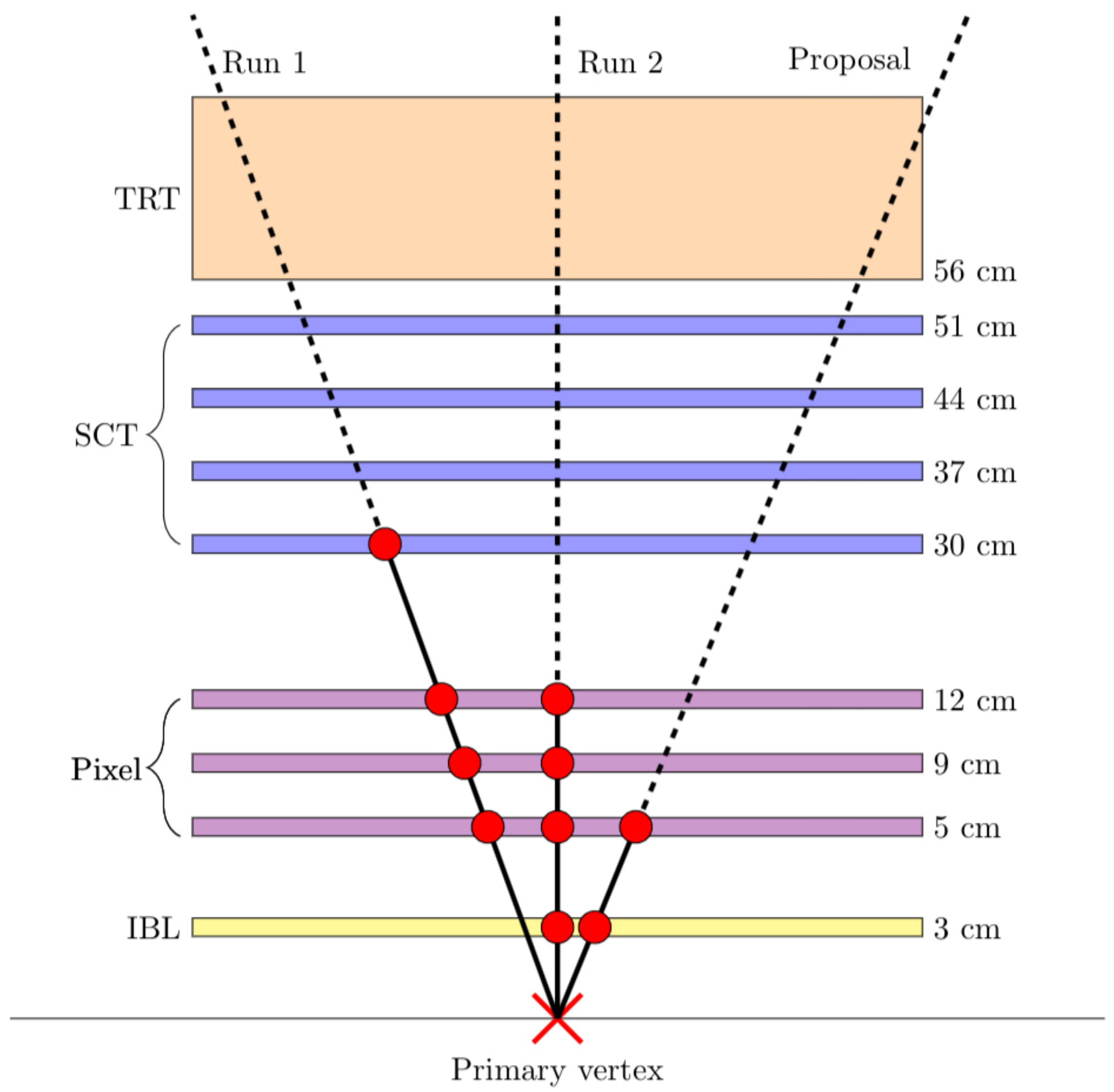


FIG. 1: Required number of hits in the ATLAS inner tracker for the analyses of Run-1&2 and ours.

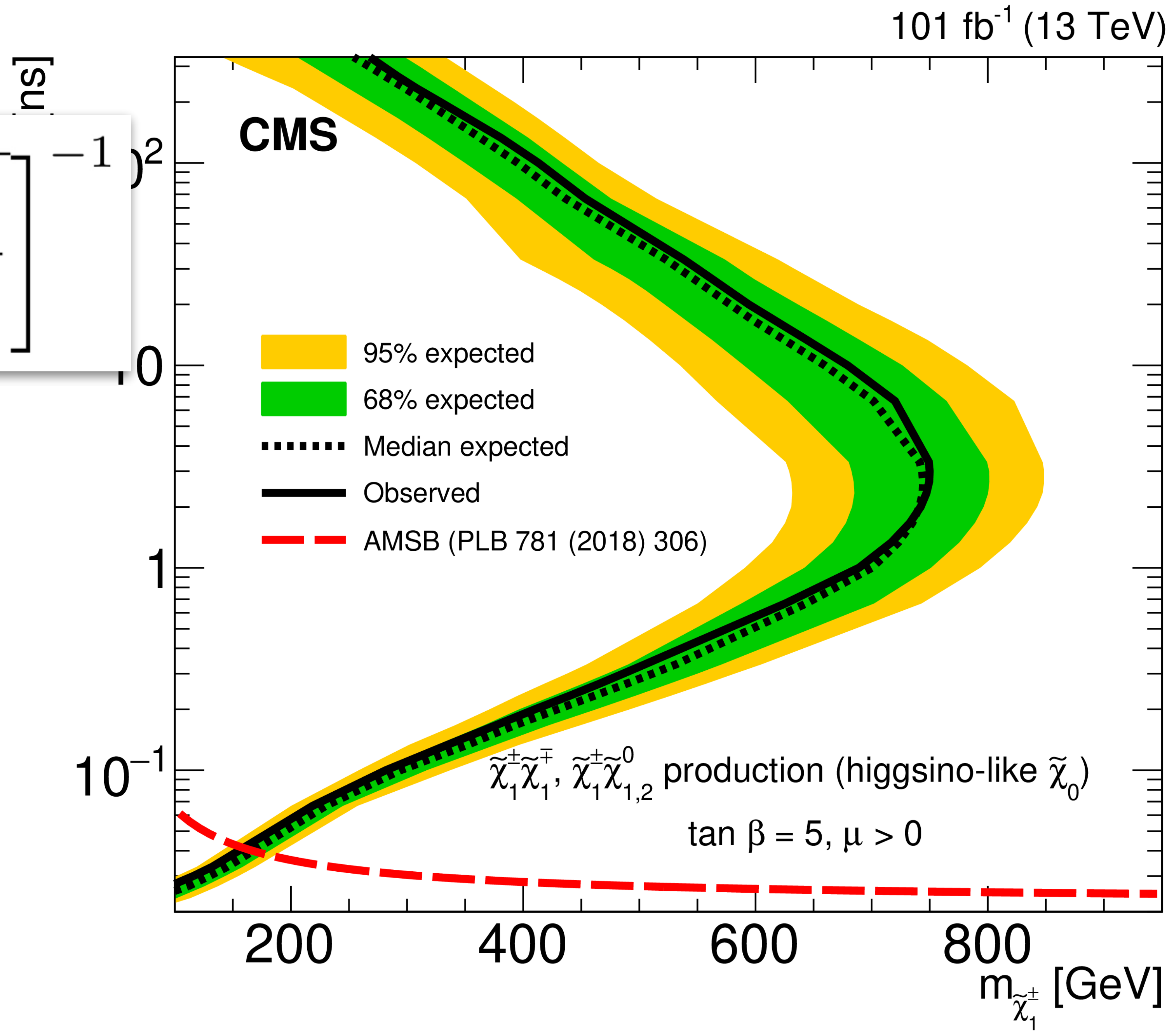
Fukuda, Nagata, Otono, Shirai '17

$\Delta m \sim 100$ MeV

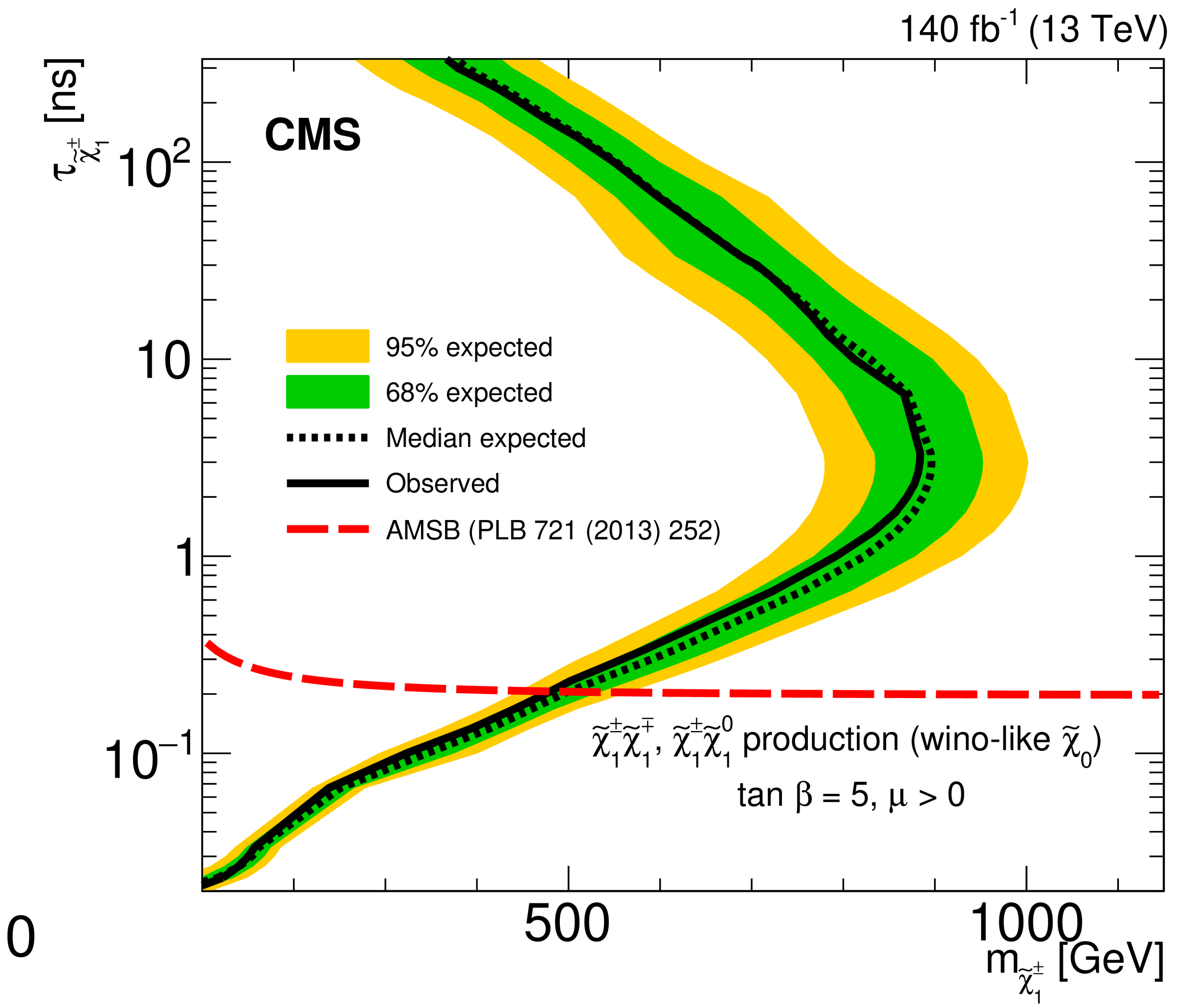
$\tilde{\chi}_1^\pm \to \pi^\pm \tilde{\chi}_1^0$

Finite lifetime, decay within detector

Higgsino

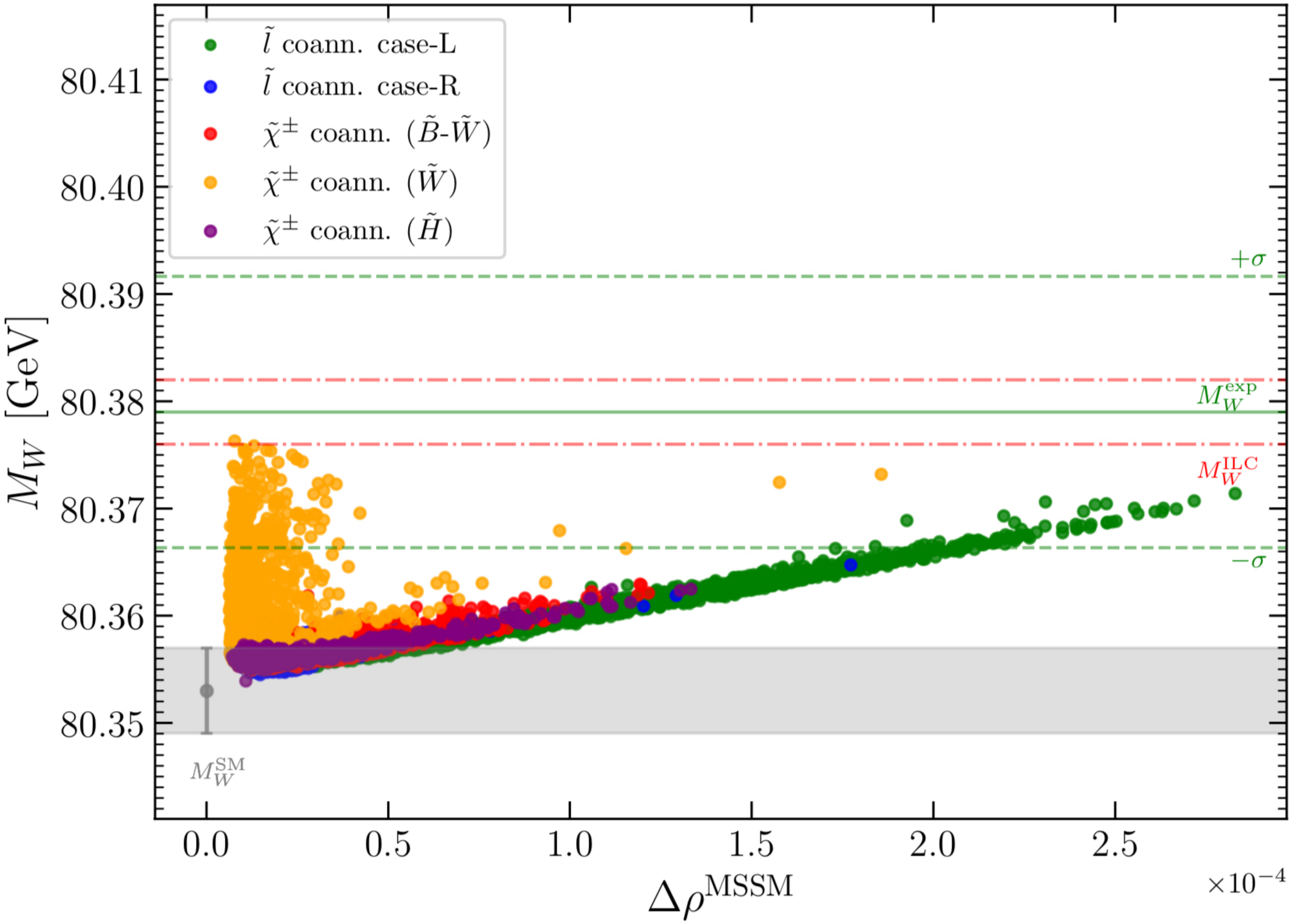


Wino



CMS-EXO-19-010

W-mass in MSSM



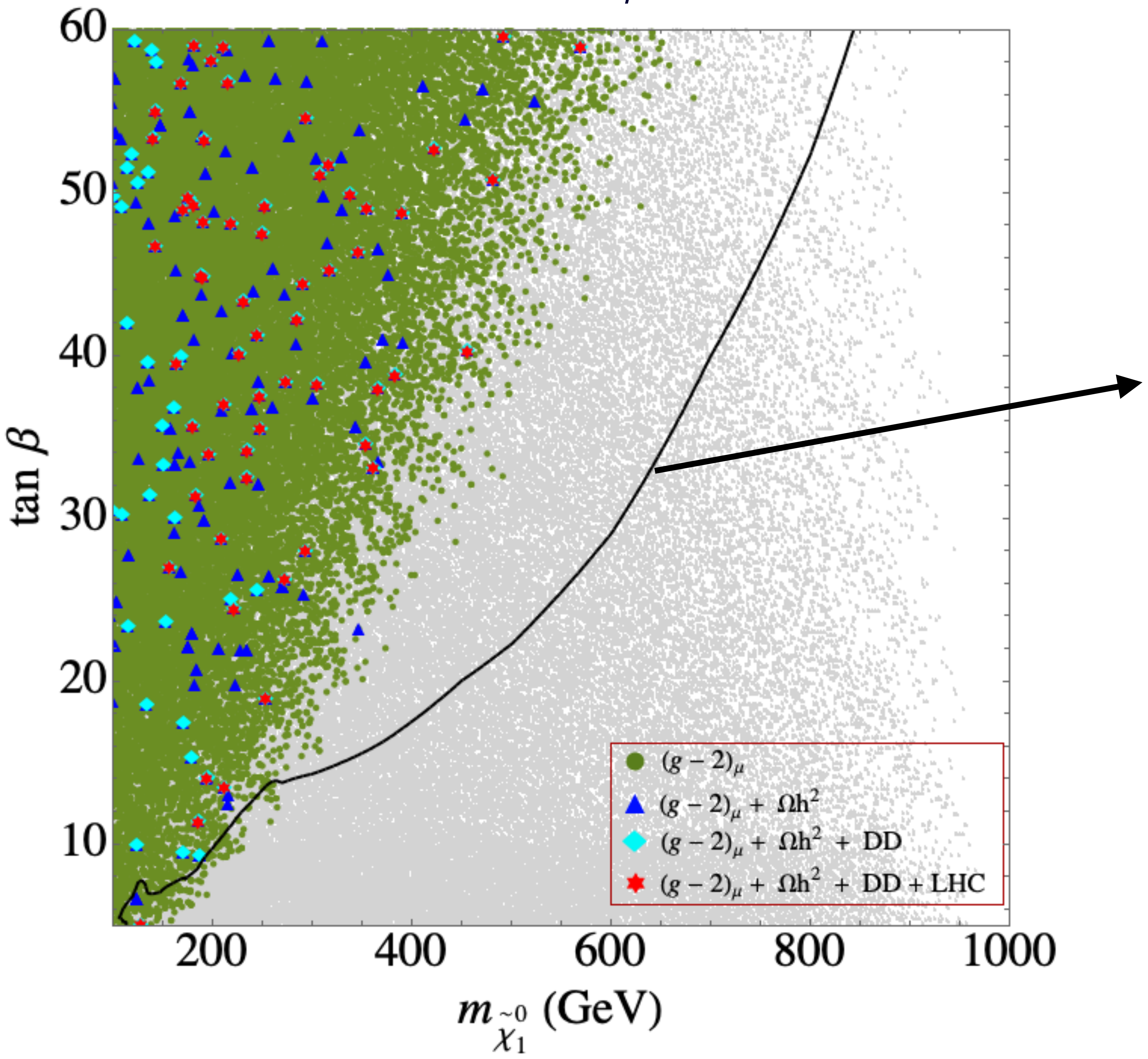
- Pure slepton loops contribute only via the self energies

- Mixed slepton/chargino/neutralino contributions enter via vertex and box diagrams

Possibility of A-pole annihilation

$$a_\mu \sim \frac{\tan\beta}{m_{EW}^2}$$

Current $(g-2)_\mu$ limit



$$m_{\tilde{\chi}_1^0} = \frac{M_A}{2}$$

$M_h^{125}(\tilde{\chi})$ Benchmark scenario

Bagnaschi et al. '18

Black contour : simplified application of $H/A \to \tau^+\tau^-$ → A-pole annihilation strongly constrained

$(g-2)_\mu$

- Large discrepancy from the SM (more than 3σ):

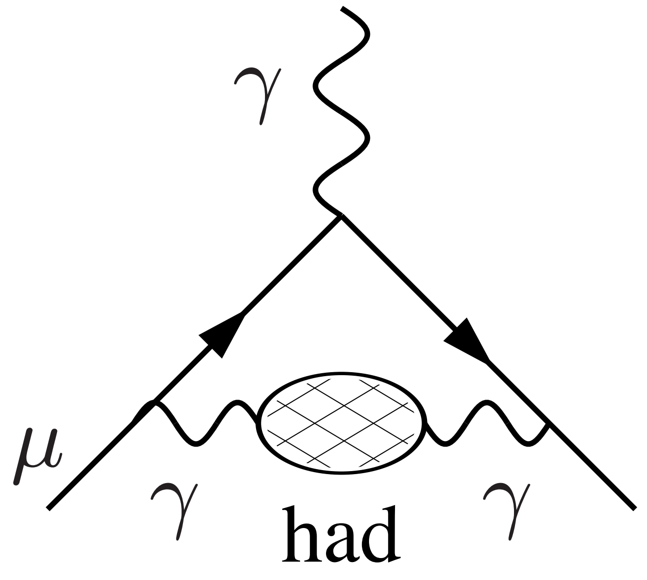
  $a_\mu^{exp} - a_\mu^{SM} = (28.02 \pm 7.37) \times 10^{-10}$.

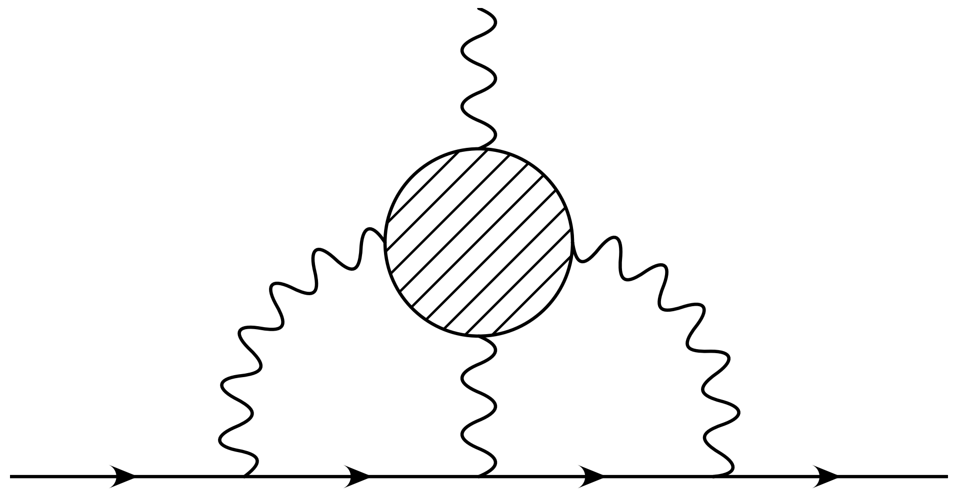
  Keshavarzi, Nomura, Teubner '19

- Important probe for new physics. $\frac{\delta a_l}{a_l} \sim \frac{m_l^2}{\Lambda^2}$.
- SM contributions : QED, weak, hadronic vacuum polarization, hadronic light by light scattering.
- QED : complete calculation upto 5 loops. EW : two loops.

  Aoyama, Hayakawa, Kinoshita, Nio '17, Ishikawa, Nakazawa, Yasu '18, Heinemeyer, Stökinger, Weiglein '04

- Uncertainty dominated by non-perturbative, hadronic sector.





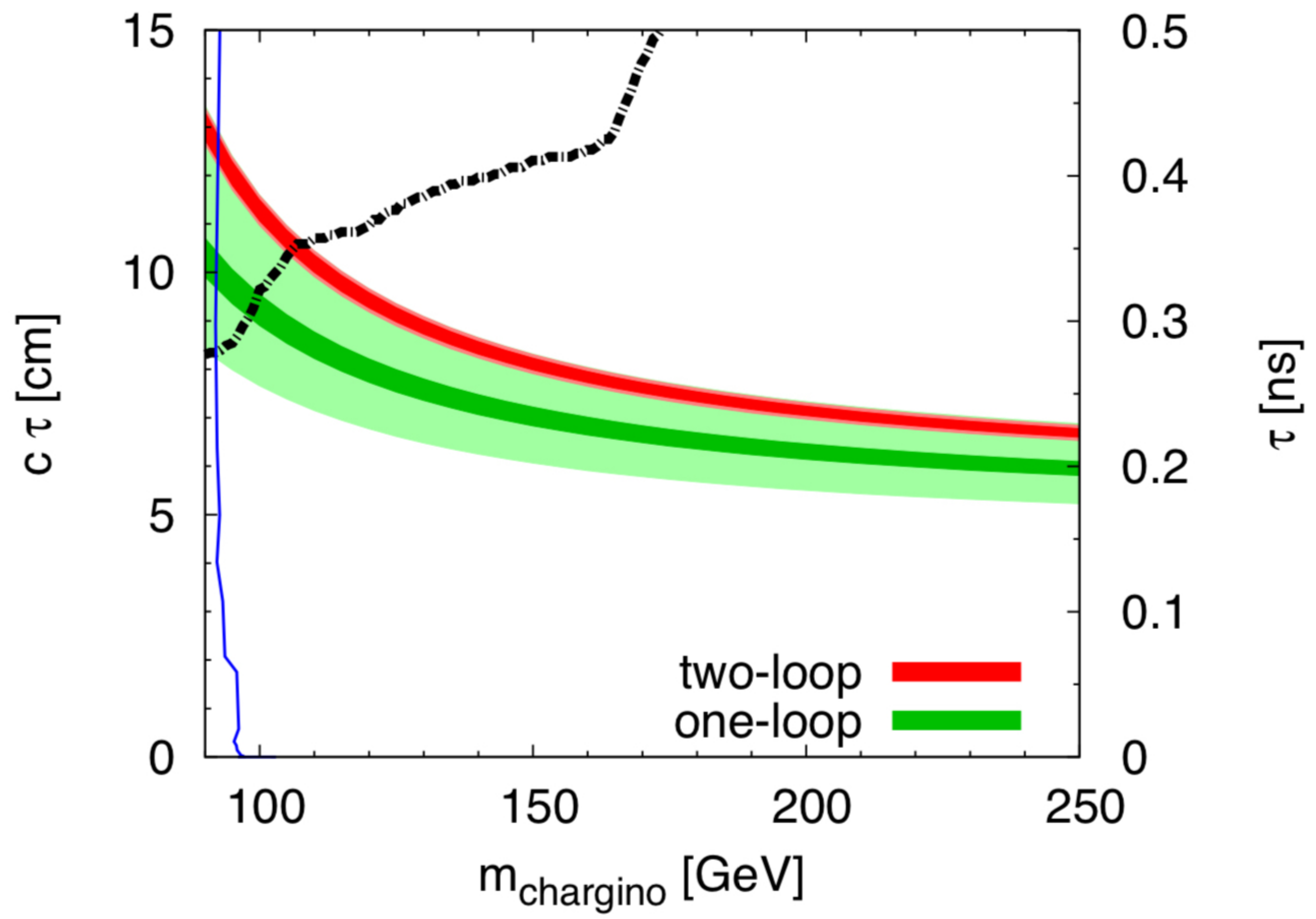


Figure 6: The lifetime of charged wino evaluated by using δm at the one-loop (green band) and two-loop (red band). We neglected the next-to-leading order corrections to the lifetime of the charged wino estimated in terms of the pion decay rate, which is expected to be a few percent correction. The black chain line is the upper limit on the lifetime for a given chargino mass by the ATLAS collaboration at 95 % CL ($\sqrt{s}$ = 7 TeV, $\mathcal{L}$ = 4.7 fb^{-1}) [28]. The blue line shows the constraints which are given by the LEP2 constraints [30]–[33].

Highest mass points

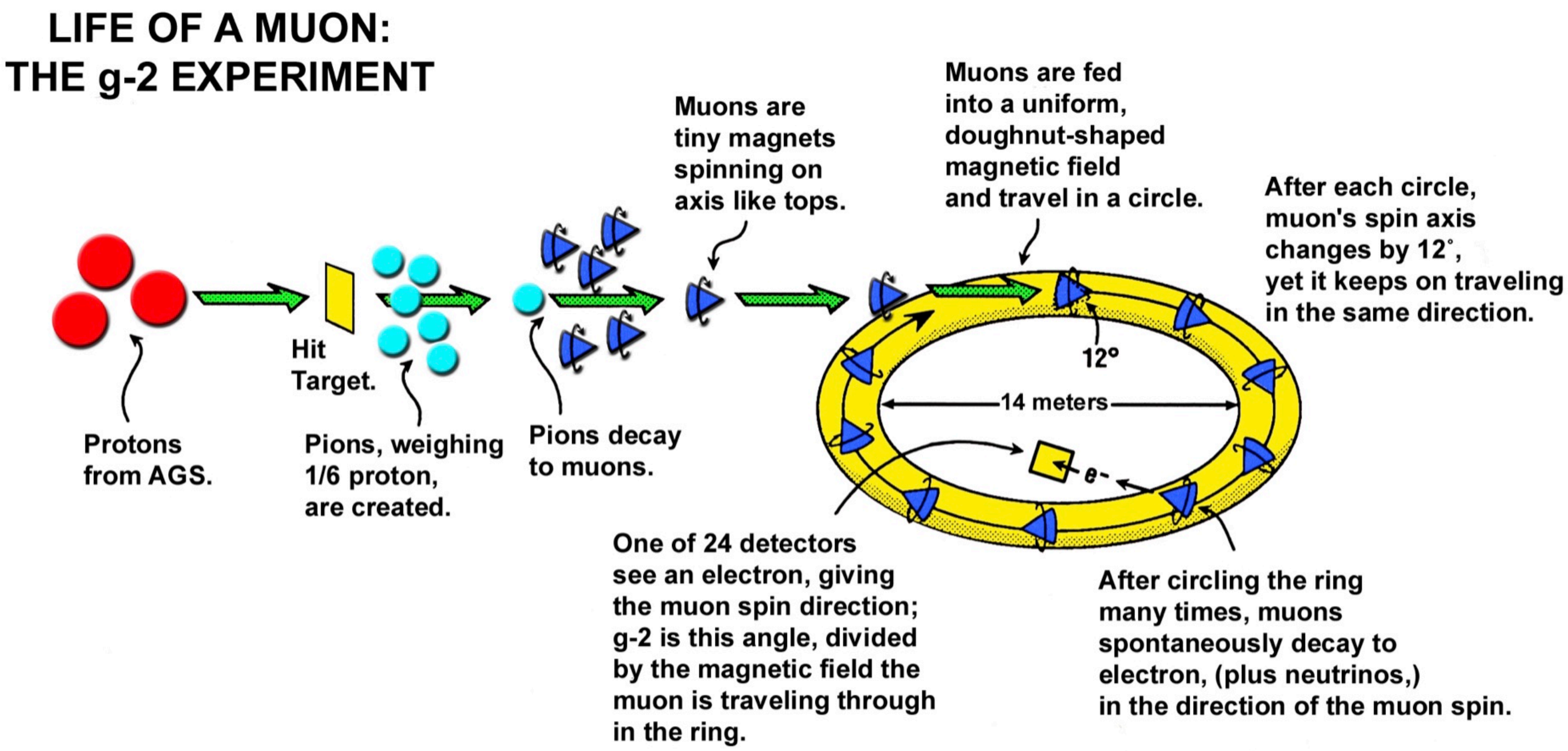
Current $(g-2)_\mu$ limit

Coannihilation	$\tilde{\chi}_1^\pm$	$\tilde{l}^\pm$ (Case-L)	$\tilde{l}^\pm$ (Case-R)
$m_{\tilde{\chi}_1^0}$	570	533	518
$m_{\tilde{\chi}_2^0}$	605	816	685
$m_{\tilde{\chi}_3^0}$	1087	1370	1098
$m_{\tilde{\chi}_1^\pm}$	605	816	685
$m_{\tilde{e}_1,\tilde{\mu}_1}$	680	549	696
$m_{\tilde{e}_2,\tilde{\mu}_2}$	680	1279	592
$m_{\tilde{\tau}_1}$	582	534	747
$m_{\tilde{\tau}_2}$	765	1286	526
$m_{\tilde{\nu}}$	675	544	692

Anticipated future $(g-2)_\mu$ limit

Coannihilation	$\tilde{\chi}_1^\pm$	$\tilde{l}^\pm$ (Case-L)	$\tilde{l}^\pm$ (Case-R)
$m_{\tilde{\chi}_1^0}$	423	499	402
$m_{\tilde{\chi}_2^0}$	464	535	448
$m_{\tilde{\chi}_3^0}$	1032	1019	830
$m_{\tilde{\chi}_1^\pm}$	464	535	448
$m_{\tilde{e}_1,\tilde{\mu}_1}$	542	511	795
$m_{\tilde{e}_2,\tilde{\mu}_2}$	541	2349	428
$m_{\tilde{\tau}_1}$	437	509	807
$m_{\tilde{\tau}_2}$	629	2350	406
$m_{\tilde{\nu}}$	536	505	792

Points satisfying $(g-2)_\mu$, DM and LHC constraints, masses in GeV.



$$\vec{\mu} = g_\mu \frac{e}{2m} \vec{s}$$

$$\bar{u}(p')[\gamma^\mu F_1(q^2) + \frac{i}{2m_\mu}\sigma^{\mu\nu} q_\nu F_2(q^2)] u(p) A_\mu$$

$$a_\mu = \frac{g_\mu - 2}{2}$$

$$F_2(0) = a_\mu$$

SUSY contributions to $(g-2)_\mu$

$$\Delta a_\mu(\tilde{W}, \tilde{H}, \tilde{\nu}_\mu) \simeq 15 \times 10^{-9} \left(\frac{\tan\beta}{10}\right) \left(\frac{(100\,\mathrm{GeV})^2}{M_2 \mu}\right) \left(\frac{f_C}{1/2}\right),$$

$$\Delta a_\mu(\tilde{W}, \tilde{H}, \tilde{\mu}_L) \simeq -2.5 \times 10^{-9} \left(\frac{\tan\beta}{10}\right) \left(\frac{(100\,\mathrm{GeV})^2}{M_2 \mu}\right) \left(\frac{f_N}{1/6}\right),$$

$$\Delta a_\mu(\tilde{B}, \tilde{H}, \tilde{\mu}_L) \simeq 0.76 \times 10^{-9} \left(\frac{\tan\beta}{10}\right) \left(\frac{(100\,\mathrm{GeV})^2}{M_1 \mu}\right) \left(\frac{f_N}{1/6}\right),$$

$$\Delta a_\mu(\tilde{B}, \tilde{H}, \tilde{\mu}_R) \simeq -1.5 \times 10^{-9} \left(\frac{\tan\beta}{10}\right) \left(\frac{(100\,\mathrm{GeV})^2}{M_1 \mu}\right) \left(\frac{f_N}{1/6}\right),$$

$$\Delta a_\mu(\tilde{\mu}_L, \tilde{\mu}_R, \tilde{B}) \simeq 1.5 \times 10^{-9} \left(\frac{\tan\beta}{10}\right) \left(\frac{(100\,\mathrm{GeV})^2}{m_{\tilde{\mu}_L}^2 m_{\tilde{\mu}_R}^2 / M_1 \mu}\right) \left(\frac{f_N}{1/6}\right).$$

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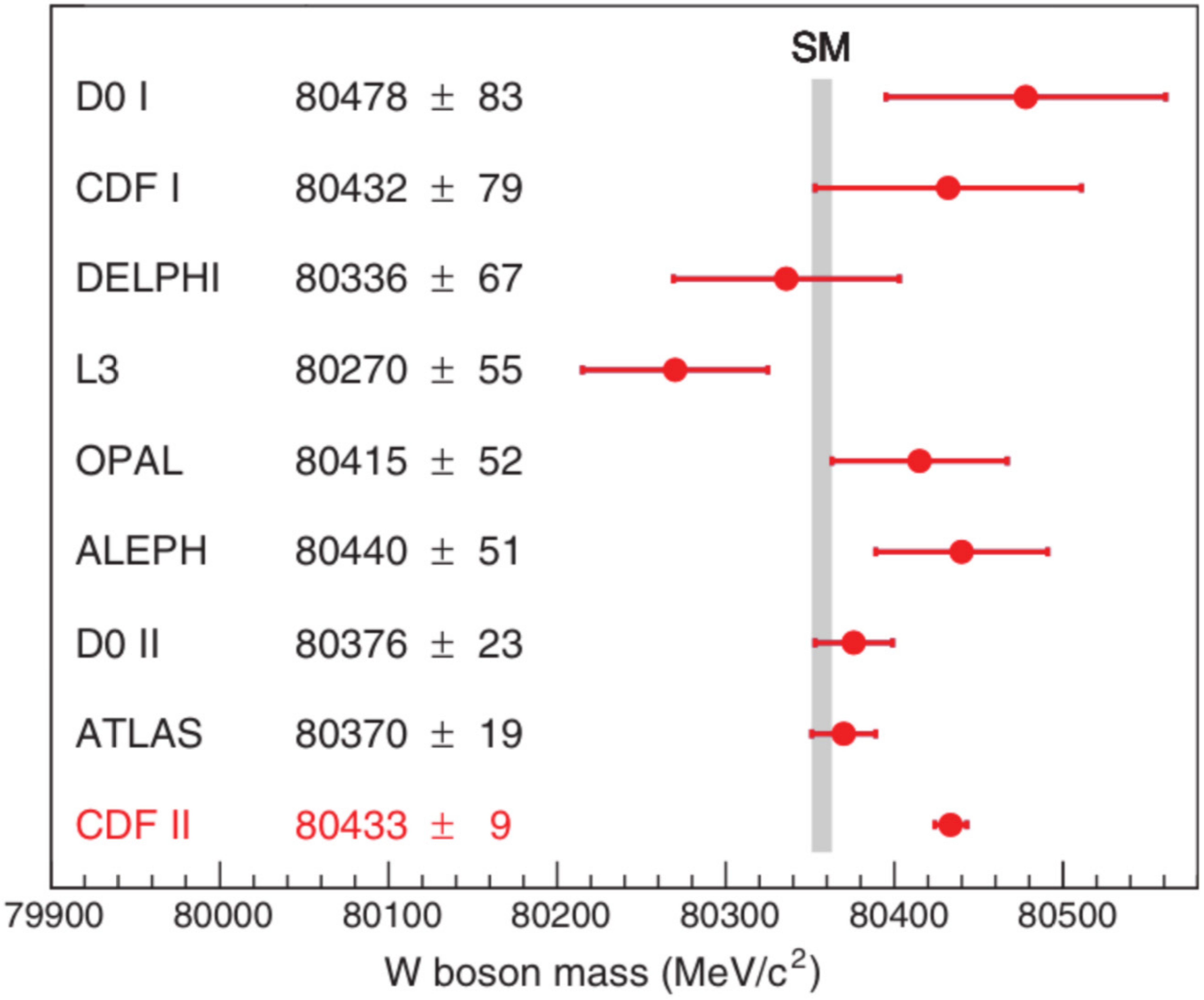


SM
D0 I 80478 ± 83
CDF I 80432 ± 79
DELPHI 80336 ± 67
L3 80270 ± 55
OPAL 80415 ± 52
ALEPH 80440 ± 51
D0 II 80376 ± 23
ATLAS 80370 ± 19
CDF II 80433 ± 9
79900 80000 80100 80200 80300 80400 80500
W boson mass (MeV/c^2)

tanβ enhancement in SUSY

$$\mathscr{L}_{\text{eff}} \ni i\tilde{a}_\mu \cdot \bar{\psi}_L \sigma^{\mu\nu} \psi_R F_{\mu\nu}$$

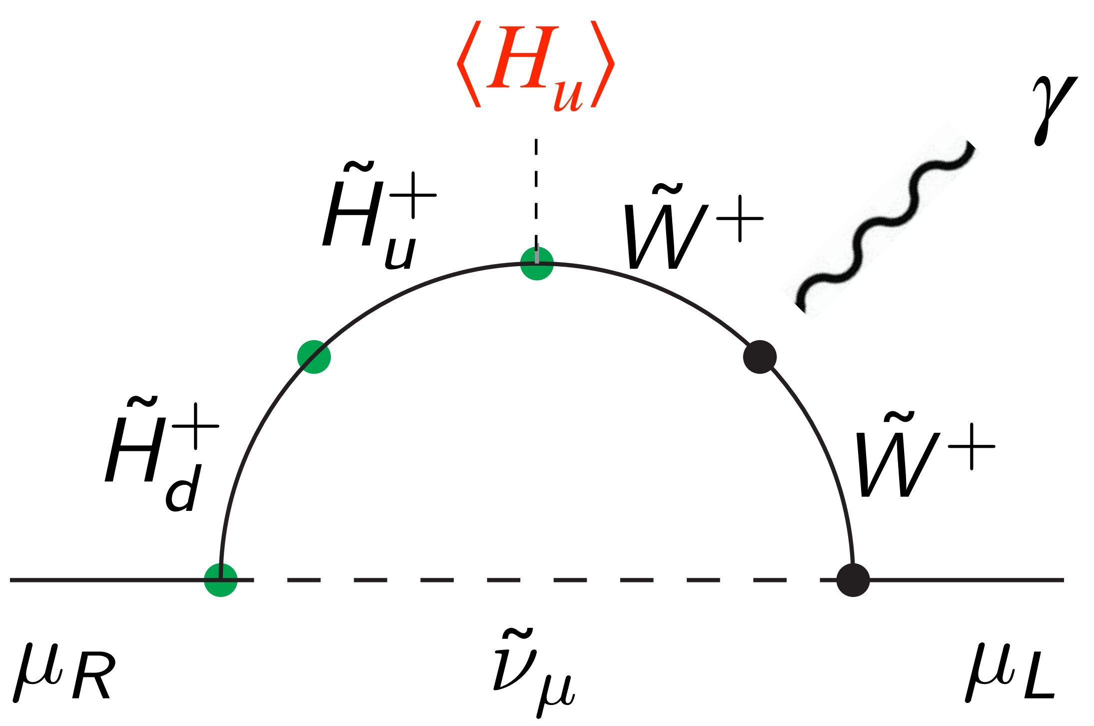
$$\vec{\mu} = g\left(\frac{e}{2m}\right)\vec{s}$$

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

SM: $\tilde{a}_\mu^{\text{SM}} \propto Y_\mu \langle H \rangle = m_\mu$

SUSY: $\Delta\tilde{a}_\mu^{\text{SUSY}} \propto Y_\mu \langle H_u \rangle = m_\mu \cdot \tan\beta$

$$m_\mu = Y_\mu \langle H_d \rangle \quad \tan\beta \equiv \frac{\langle H_u \rangle}{\langle H_d \rangle}$$



$$\Delta a_\mu^{\text{BSM}} \sim \Delta a^{\text{SM,EW}} \cdot \left(\frac{m_W^2}{m_{\text{SUSY}}^2}\right) \cdot \tan\beta$$

$\tan\beta \in [5-60]$ → $m_{\text{SUSY}} \in [200-600]$ GeV