
We still believe in supersymmetry
You must be joking

Compressed Electroweak SUSY Spectra from $(g-2)_\mu$ and Dark Matter

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In collaboration with: *M. Chakraborti, I. Saha* [*arXiv:2006.15157, EPJC*]

1. The general idea

2. Experimental constraints

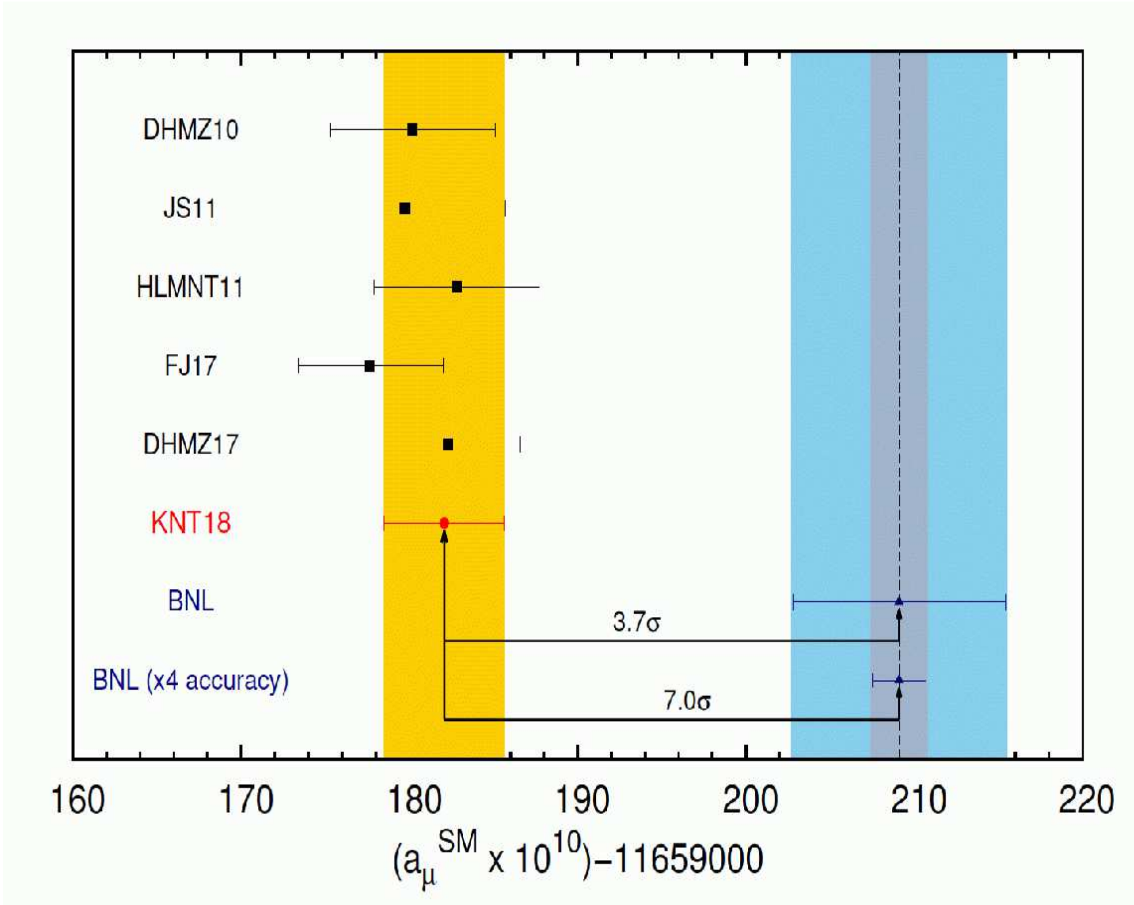
3. Results for chargino coannihilation

4. Conclusions

1. The general idea

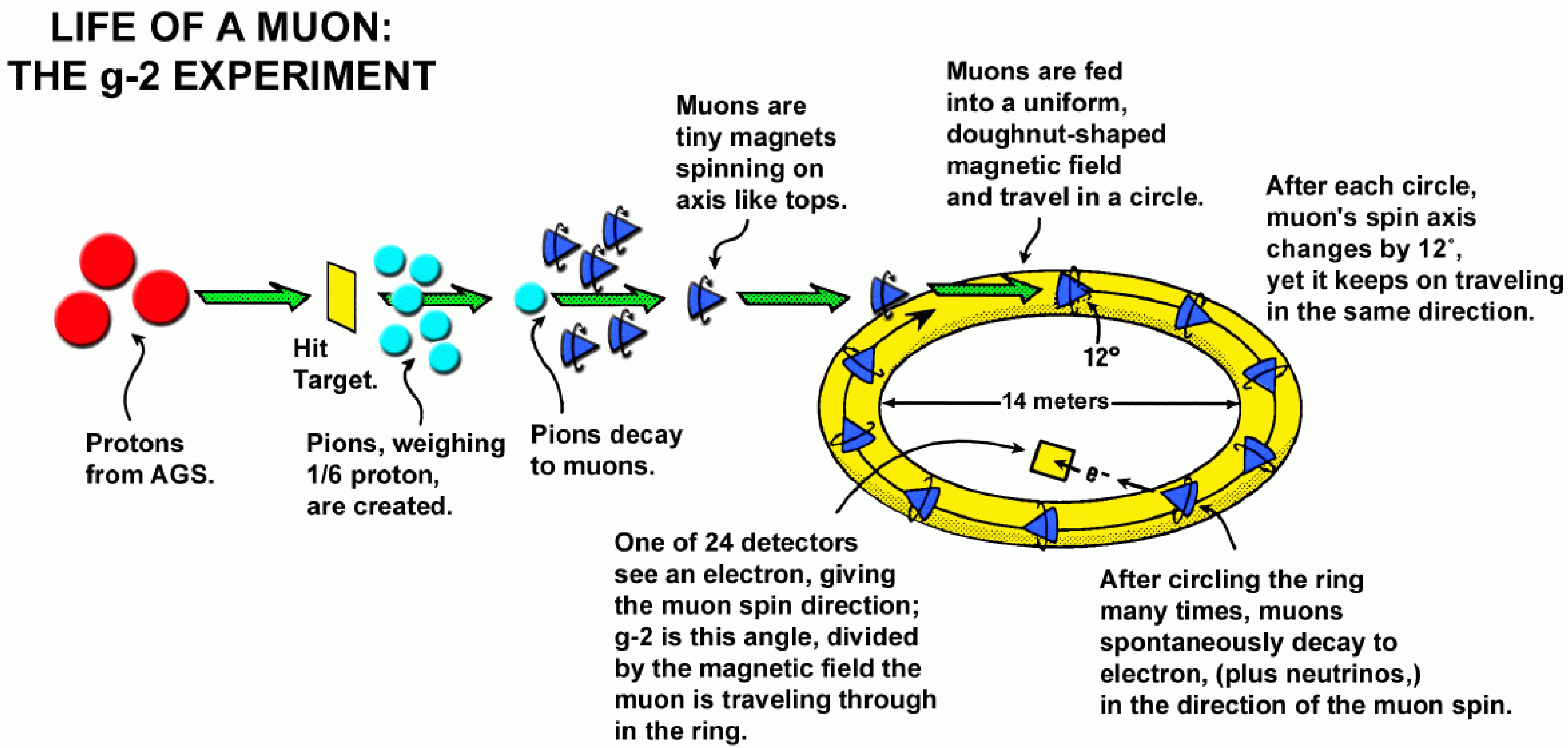
The anomalous magnetic moment of the muon: $a_\mu \equiv (g-2)_\mu/2$

Overview about the current experimental and SM (theory) result:
[A. Keshavarzia, D. Nomura, T. Teubner '18, '20]



$$a_\mu^{\text{exp}} - a_\mu^{\text{theo,SM}} \approx (28.02 \pm 7.37) \times 10^{-10} \quad : 3.8\,\sigma$$

The $(g-2)_\mu$ experiment:

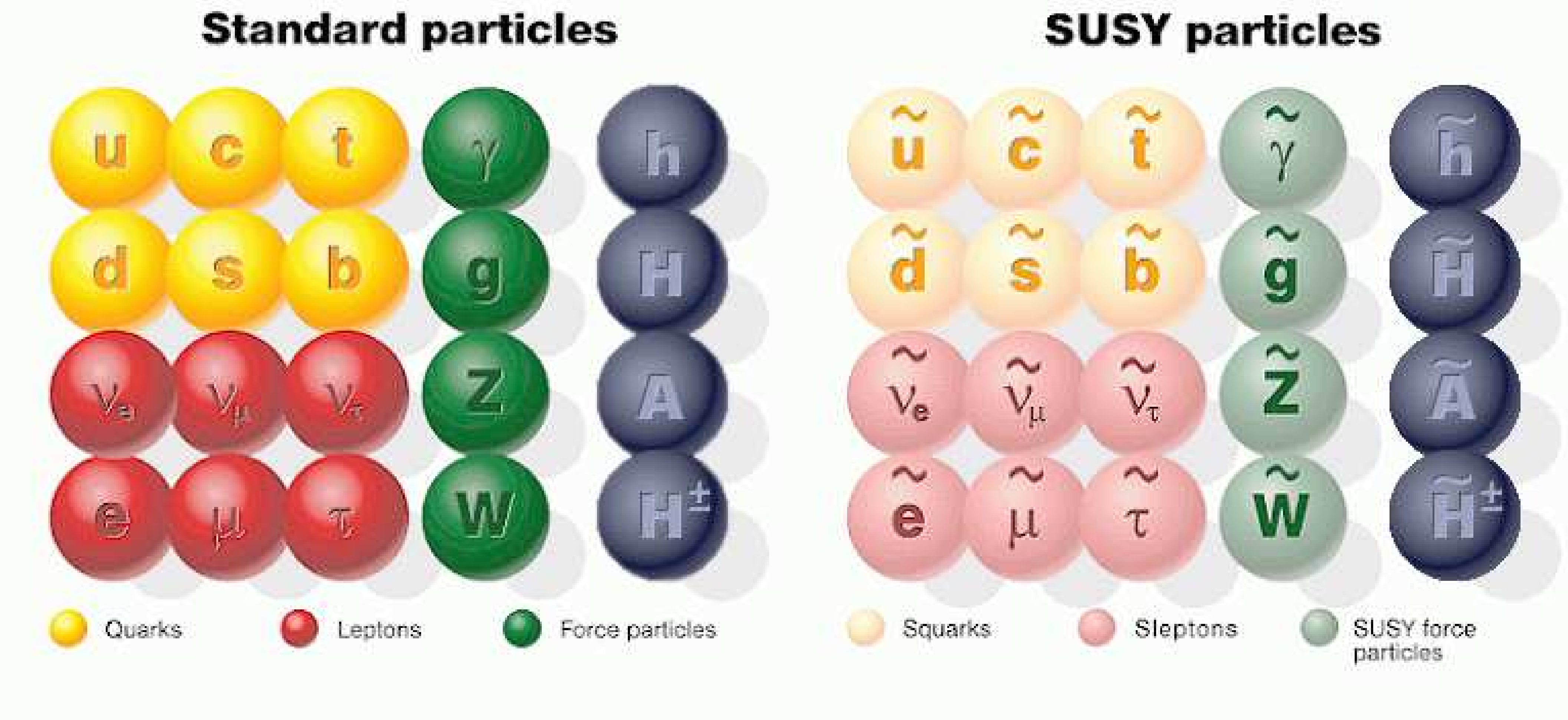


Coupling of muon to magnetic field : $\mu - \mu - \gamma$ coupling

$$\bar{u}(p') \left[\gamma^\mu F_1(q^2) + \frac{i}{2m_\mu} \sigma^{\mu\nu} q_\nu F_2(q^2) \right] u(p) A_\mu \qquad F_2(0) = a_\mu$$

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles



⇒ large uncolored / EW sector

Neutralinos and charginos:

Higgsinos and electroweak gauginos mix

charged:

$$\tilde{W}^+, \tilde{h}_u^+ \to \tilde{\chi}_1^+, \tilde{\chi}_2^+, \qquad \tilde{W}^-, \tilde{h}_d^- \to \tilde{\chi}_1^-, \tilde{\chi}_2^-$$

Diagonalization of the mass matrix:

$$\mathbf{X} = \begin{pmatrix} M_2 & \sqrt{2}\sin\beta\, M_W \\ \sqrt{2}\cos\beta\, M_W & \mu \end{pmatrix} ,$$

$$\mathbf{M}_{\tilde{\chi}^-} = \mathbf{V}^* \, \mathbf{X}^\top \, \mathbf{U}^\dagger = \begin{pmatrix} m_{\tilde{\chi}_1^\pm} & 0 \\ 0 & m_{\tilde{\chi}_2^\pm} \end{pmatrix}$$

$\Rightarrow$ charginos: mass eigenstates

mass matrix given in terms of M_2, μ, $\tan\beta$

neutral:

$$\underbrace{\tilde{\gamma}, \tilde{Z},}_{\tilde{W}^0,\, \tilde{B}^0} \tilde{h}_u^0, \tilde{h}_d^0 \to \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$$

Diagonalization of mass matrix:

$$\mathbf{Y} = \begin{pmatrix} M_1 & 0 & -M_Z\, s_W \cos\beta & M_Z\, s_W \sin\beta \\ 0 & M_2 & M_Z\, c_W \cos\beta & -M_Z\, c_W \sin\beta \\ -M_Z\, s_W \cos\beta & M_Z\, c_W \cos\beta & 0 & -\mu \\ M_Z\, s_W \sin\beta & -M_Z\, c_W \sin\beta & -\mu & 0 \end{pmatrix},$$

$$\mathbf{M}_{\tilde{\chi}^0} = \mathbf{N}^* \, \mathbf{Y} \, \mathbf{N}^\dagger = \mathbf{diag}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0})$$

$\Rightarrow$ neutralinos: mass eigenstates

mass matrix given in terms of M_1, M_2, μ, $\tan\beta$
$\Rightarrow$ only one additional parameter

$\Rightarrow$ MSSM predicts mass relations between neutralinos and charginos

SUSY can easily explain the deviation in a_μ:

Feynman diagrams for MSSM 1L corrections:

– Diagrams with chargino/sneutrino exchange

– Diagrams with neutralino/smuon exchange

Enhancement factor as compared to SM:

$$\mu - \tilde{\chi}_i^\pm - \tilde{\nu}_\mu \quad : \quad \sim m_\mu \tan\beta$$
$$\mu - \tilde{\chi}_j^0 - \tilde{\mu}_a \quad : \quad \sim m_\mu \tan\beta$$

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

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

SUSY corrections at 1L:

$$a_\mu^{\text{SUSY,1L}} \approx 13 \times 10^{-10} \left(\frac{100\ \text{GeV}}{M_{\text{SUSY}}}\right)^2 \tan\beta\ \text{sign}(\mu)$$

$M_{\text{SUSY}} (= m_{\tilde{\mu}} = m_{\tilde{\nu}} = m_{\tilde{\chi}})$: generic SUSY mass scale

$$\begin{aligned} a_\mu^{\text{SUSY,1L}} &= (-100 \ldots +100) \times 10^{-10} \\ a_\mu^{\text{exp}} - a_\mu^{\text{theo,SM}} &\approx (28 \pm 7.4) \times 10^{-10} \end{aligned}$$

$\Rightarrow$ SUSY could easily explain the "discrepancy"

$\Rightarrow$ a_μ can provide upper limits on the EW masses
(by requiering agreement at the 95% C.L.)

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If SUSY exists, it should fix $(g-2)_\mu$!
$\Rightarrow$ there must be light EW SUSY particles!

The general idea:

- scan the relevant EW SUSY parameter space
- impose all relevant experimental constraints:
  - $(g-2)_\mu$
  - Dark Matter relic density
  - Dark Matter direct detection
  - LHC searches for EW particles
- Dark Matter relic density requires a mechanism to reduce the density in the early universe
  $\Rightarrow$ focus here: bino/wino DM with chargino coannihilation: $m_{\tilde{\chi}_1^0} \lesssim m_{\tilde{\chi}_1^\pm}$
  (Other scenarios investigated in the article.)
- obtain lower and upper limits on the various EW particle masses
- evaluate the prospects for future searches

2. Experimental constraints

LHC searches:

Decay via sleptons (3l)

$$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to (\tilde{l}^\pm \nu)(\tilde{l}^+ l^-) \to 3l + \not{E}_T \ ,$$
$$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to (l^\pm \tilde{\nu})(\tilde{l}^+ l^-) \to 3l + \not{E}_T \qquad (5)$$

Decay via sleptons (2l)

$$\tilde{\chi}_1^+ \tilde{\chi}_1^- \to (\tilde{l}^+ \nu)(\tilde{l}^- \nu) \to 2l + \not{E}_T \ ,$$
$$\tilde{\chi}_1^+ \tilde{\chi}_1^- \to (l^+ \tilde{\nu})(l^- \tilde{\nu}) \to 2l + \not{E}_T \qquad (6)$$

Decay via gauge bosons

$$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to (W \tilde{\chi}_1^0)(Z \tilde{\chi}_1^0) \to 3l + \not{E}_T \ , \qquad (7a)$$
$$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to (W \tilde{\chi}_1^0)(Z \tilde{\chi}_1^0) \to 2l + \text{jets} + \not{E}_T \ , \qquad (7b)$$
$$\tilde{\chi}_1^+ \tilde{\chi}_1^- \to (W^+ \tilde{\chi}_1^0)(W^- \tilde{\chi}_1^0) \to 2l + \not{E}_T \qquad (8)$$

Decay via Higgs bosons

$$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to (W \tilde{\chi}_1^0)(h \tilde{\chi}_1^0) \to l + b\bar{b} + \not{E}_T \qquad (9)$$

$\tilde{l}$-pair production (2l)

$$\tilde{l}^+ \tilde{l}^- \to (l^+ \tilde{\chi}_1^0)(l^- \tilde{\chi}_1^0) \to 2l + \not{E}_T \qquad (10)$$

Compressed spectra

$$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to (W^* \tilde{\chi}_1^0)(Z^* \tilde{\chi}_1^0) \to 2l + \not{E}_T \; + \text{ISR} \;, \qquad (11)$$

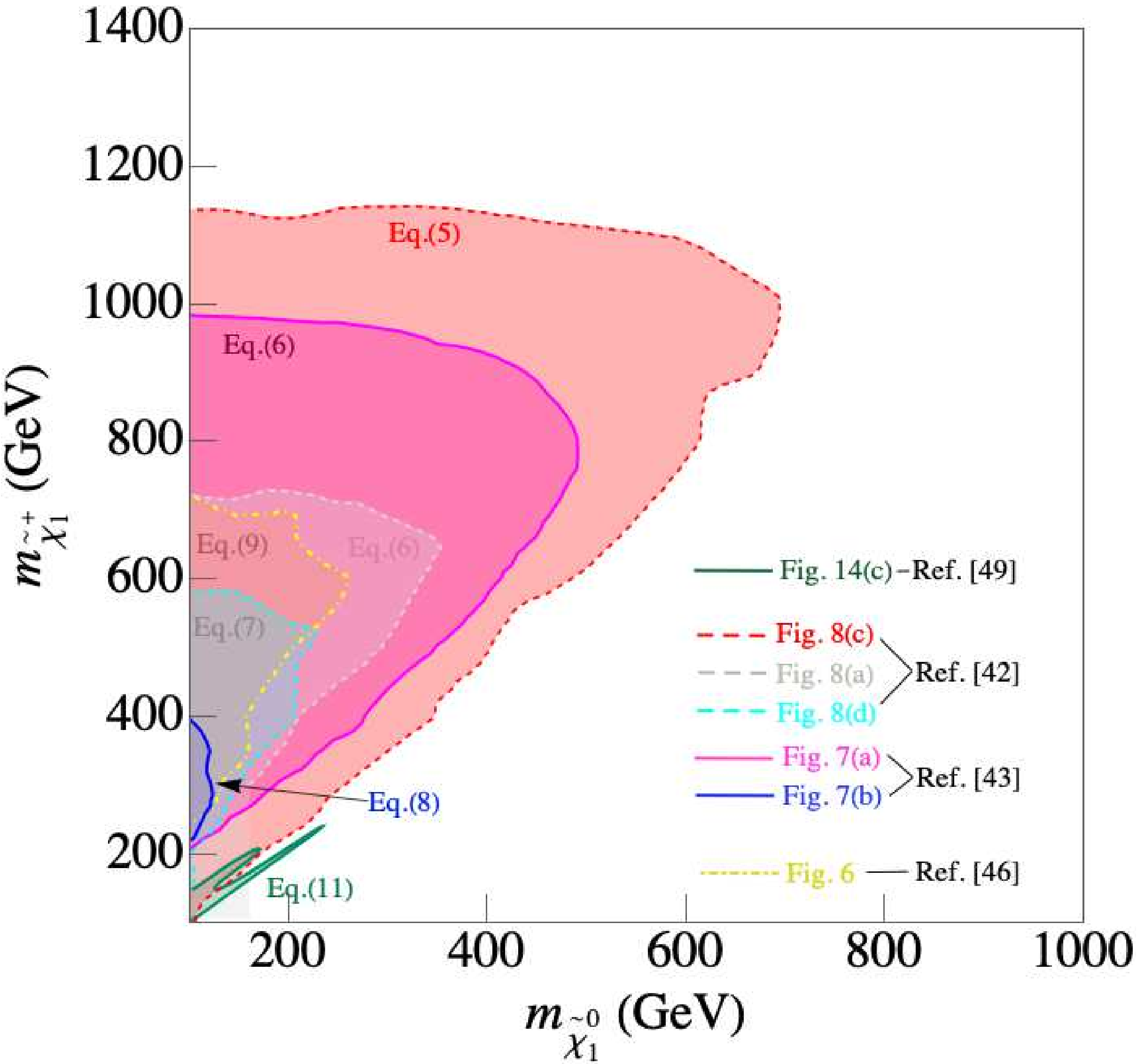
$$\tilde{l}^+ \tilde{l}^- \to (l^+ \tilde{\chi}_1^0)(l^- \tilde{\chi}_1^0) \to 2l + \not{E}_T \; + \text{ISR} \qquad (12)$$

Searches involving Staus

$\Rightarrow$ all newly included into CheckMate

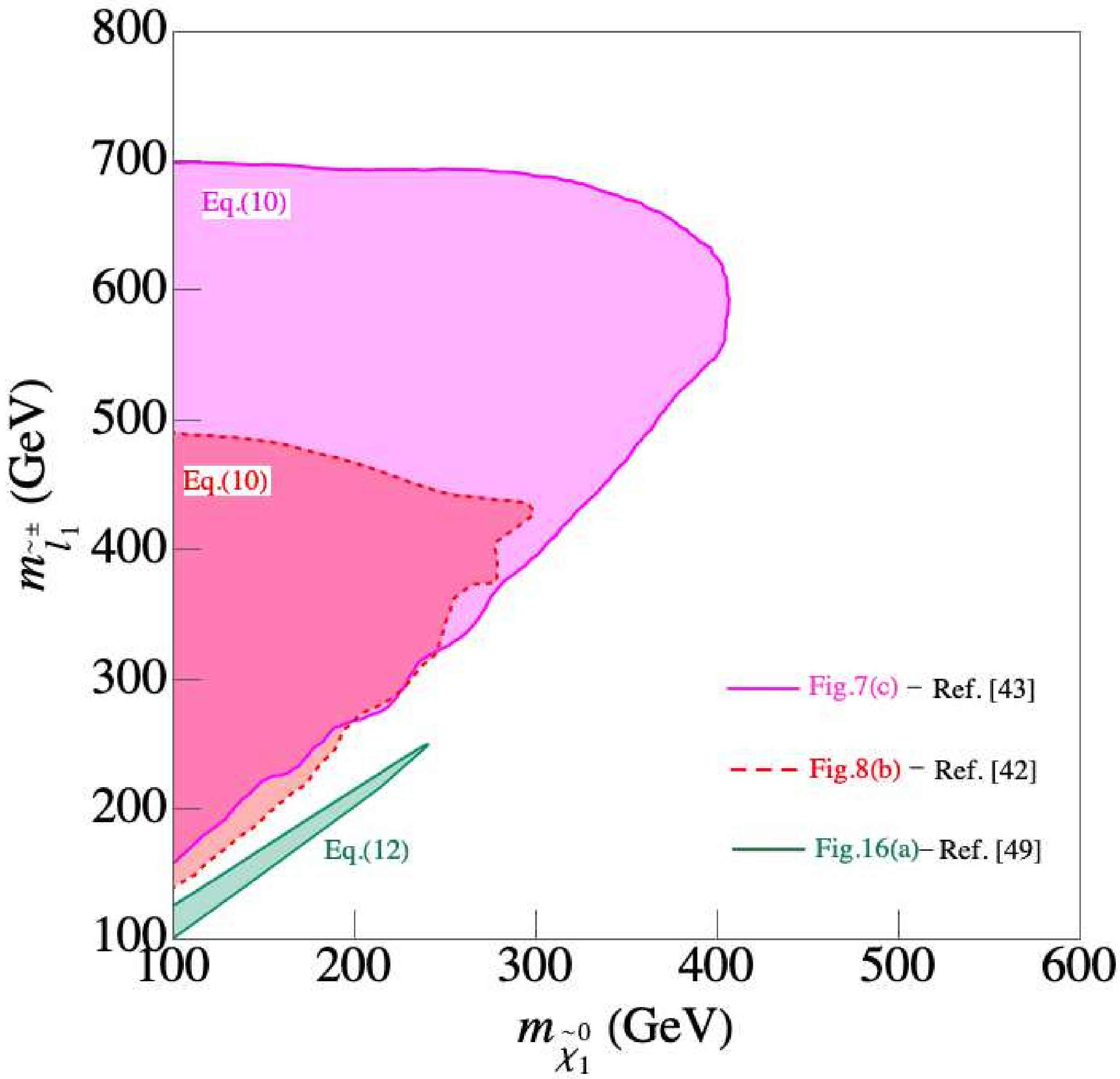
Exception: compressed spectra $\Rightarrow$ direct application

LHC exclusion bounds (I)



⇒ crucial to take latest bounds into account

LHC exclusion bounds (II)



⇒ crucial to take latest bounds into account

$(g-2)_\mu$ constraint: (GM2Calc)

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

Done, but not shown here:

Inclusion of anticipated MUON G-2 Run 1 data

$$\Delta a_\mu^{\text{fut}} = (28.02 \pm 5.2) \times 10^{-10}$$

Dark Matter relic density: MicrOmegas

$$\Omega_{\text{CDM}} h^2 \;=\; 0.120 \pm 0.001$$

(as taken from [*Planck '18*])

Dark Matter direct detection: MicrOmegas

limit on spin independent scattering cross section (Xenon1T)

[*Xenon collab. '18*]

3. Results for chargino coannihilation

Parameter scan:

$$100\ \text{GeV} \leq M_1 \leq 1\ \text{TeV}\ ,$$

$$M_1 \leq M_2 \leq 1.1 M_1\ ,$$

$$1.1 M_1 \leq \mu \leq 10 M_1,$$

$$5 \leq \tan\beta \leq 60,$$

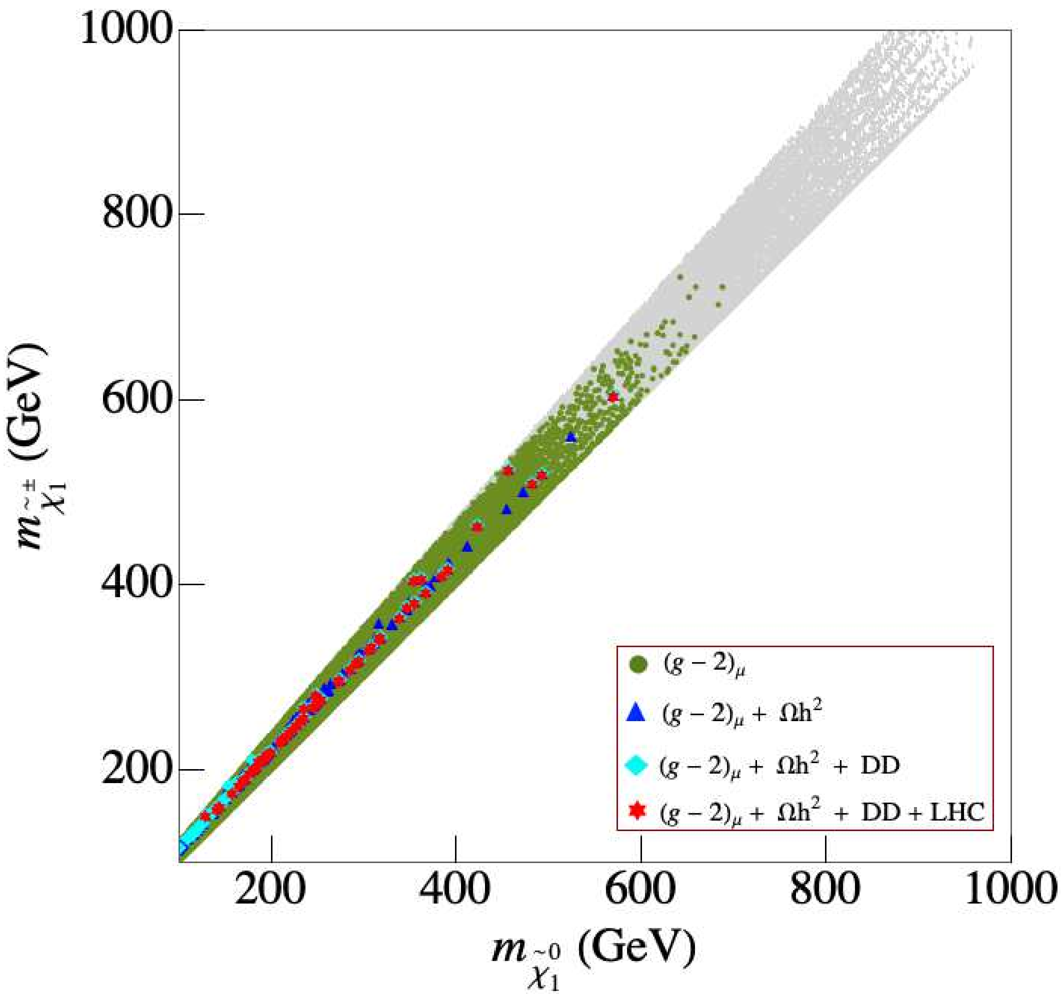
$$100\ \text{GeV} \leq m_{\tilde{L}} \leq 1\ \text{TeV},$$

$$m_{\tilde{R}} = m_{\tilde{L}}\ .$$

(latter condition only to make the analysis simpler, no relevant effect)

Done, but not shown here:
– $\tilde{l}$ coannihilation (Case-L: $SU(2)$ doublet)
– $\tilde{l}$ coannihilation (Case-R: $SU(2)$ singlet)

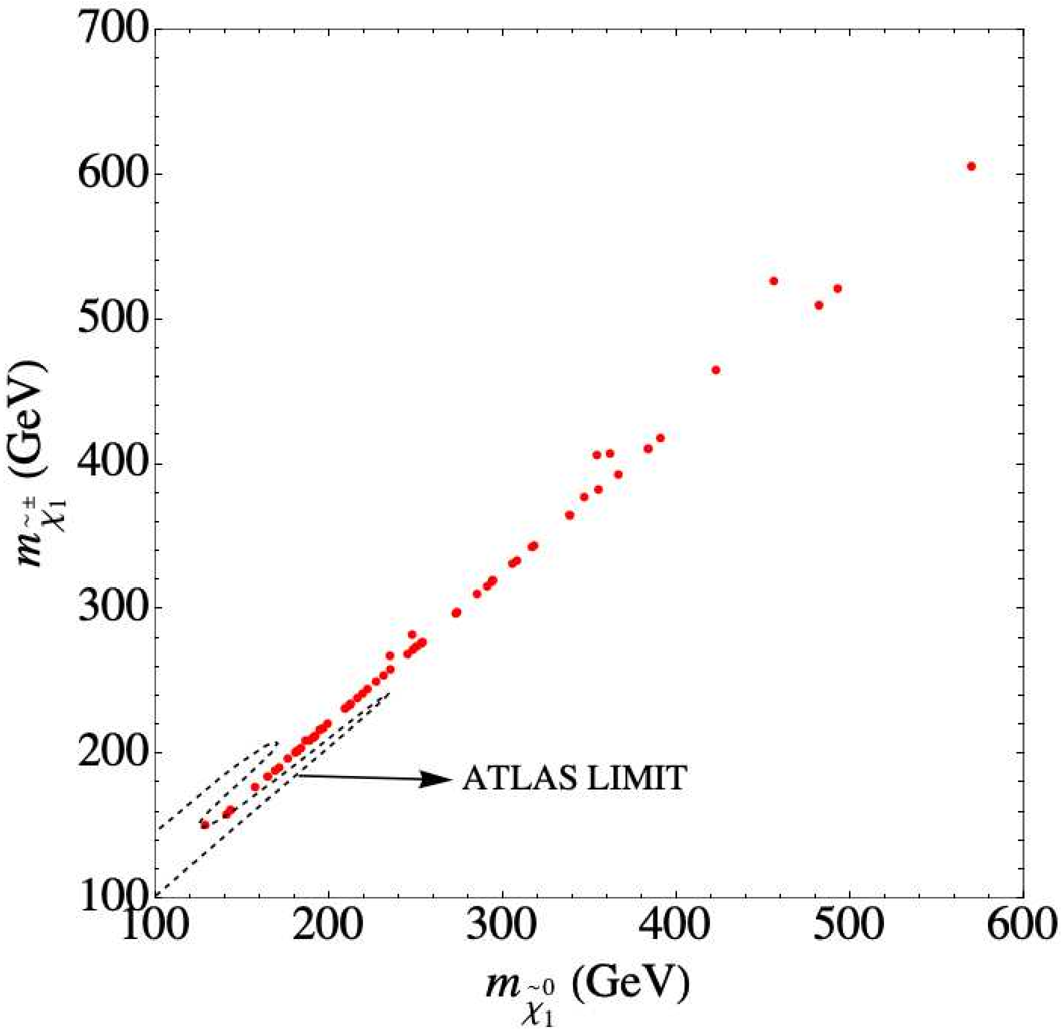
Results in the $m_{\tilde{\chi}_1^0}$-$m_{\tilde{\chi}_1^\pm}$ plane:



⇒ compressed spectrum as expected

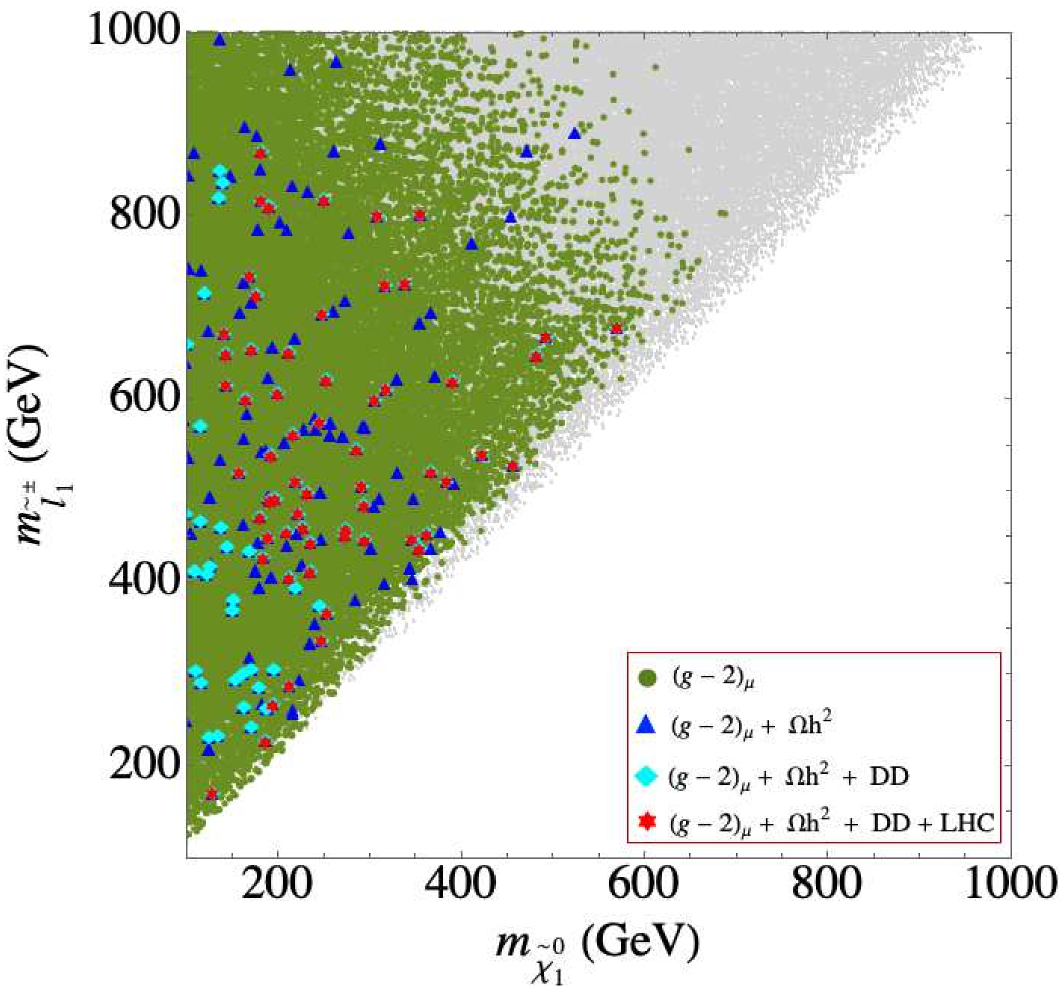
⇒ clear upper limits, $m_{\text{(N)LSP}} \lesssim 600$ GeV

Comparison with the compressed spectra searches:



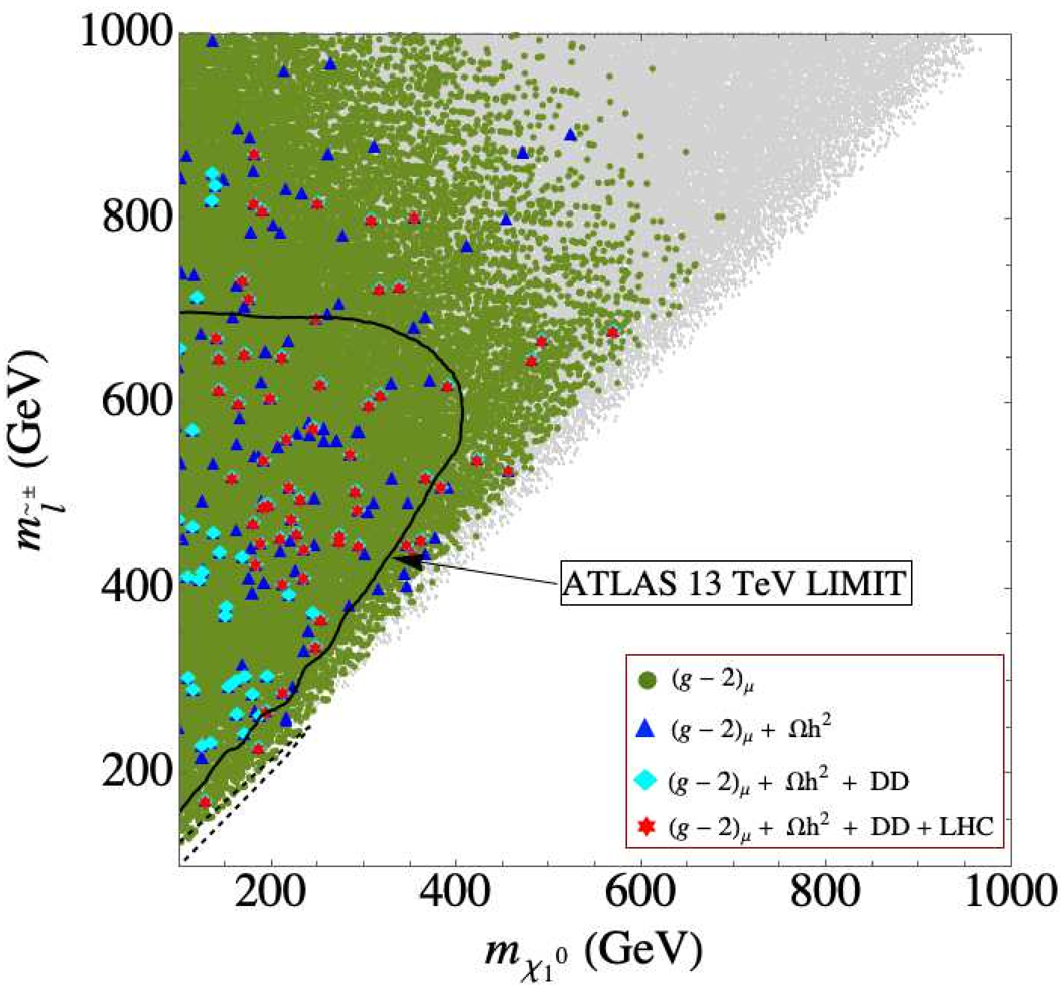
⇒ compressed spectrum avoids current bounds!

Results in the $m_{\tilde{\chi}_1^0}$-$m_{\tilde{l}_1}$ plane:



$\Rightarrow$ important: $\tilde{l}$-pair production searches (10)

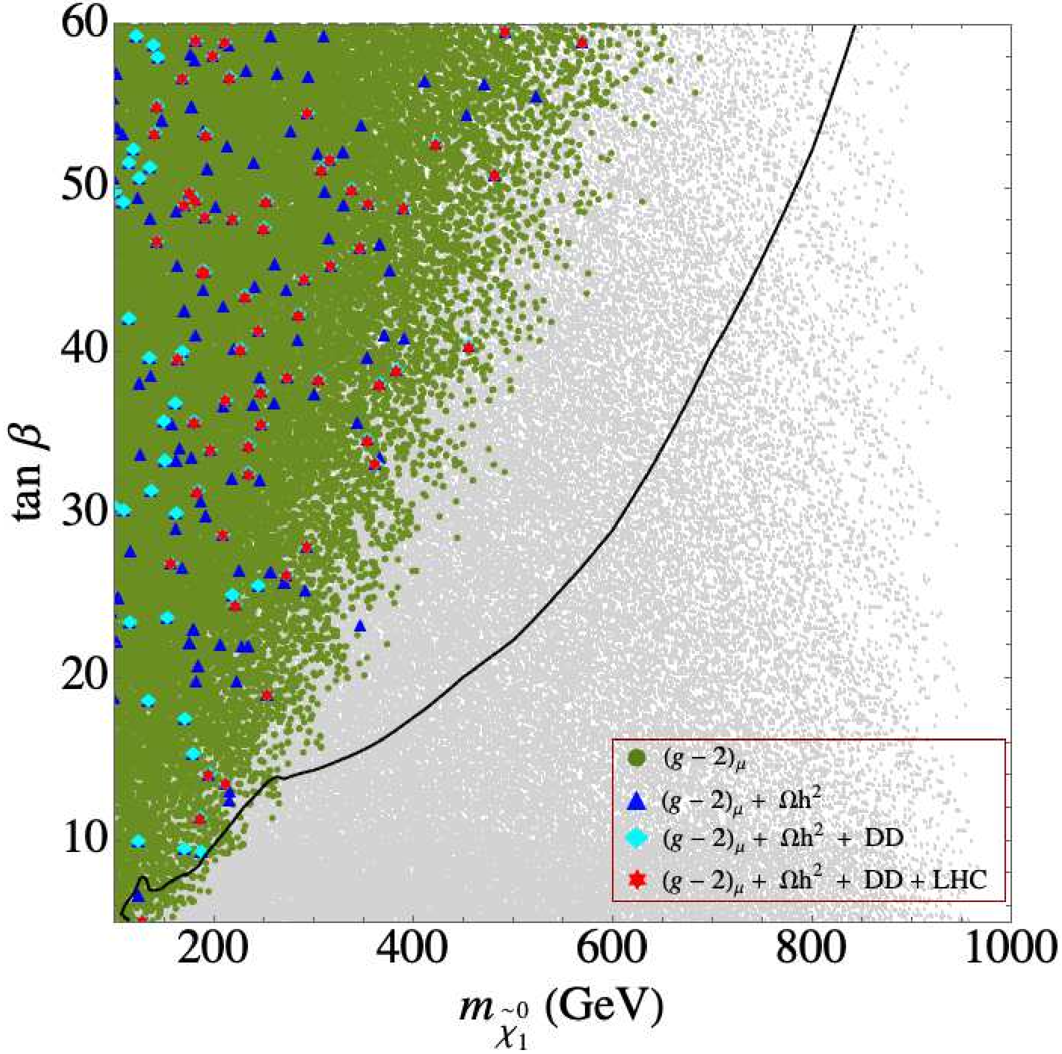
Results in the $m_{\tilde{\chi}_1^0}$-$m_{\tilde{l}_1}$ plane:



⇒ important: $\tilde{l}$-pair production searches (10)

⇒ naive application of LHC bounds fails

Results in the $m_{\tilde{\chi}_1^0}$-tan β plane:

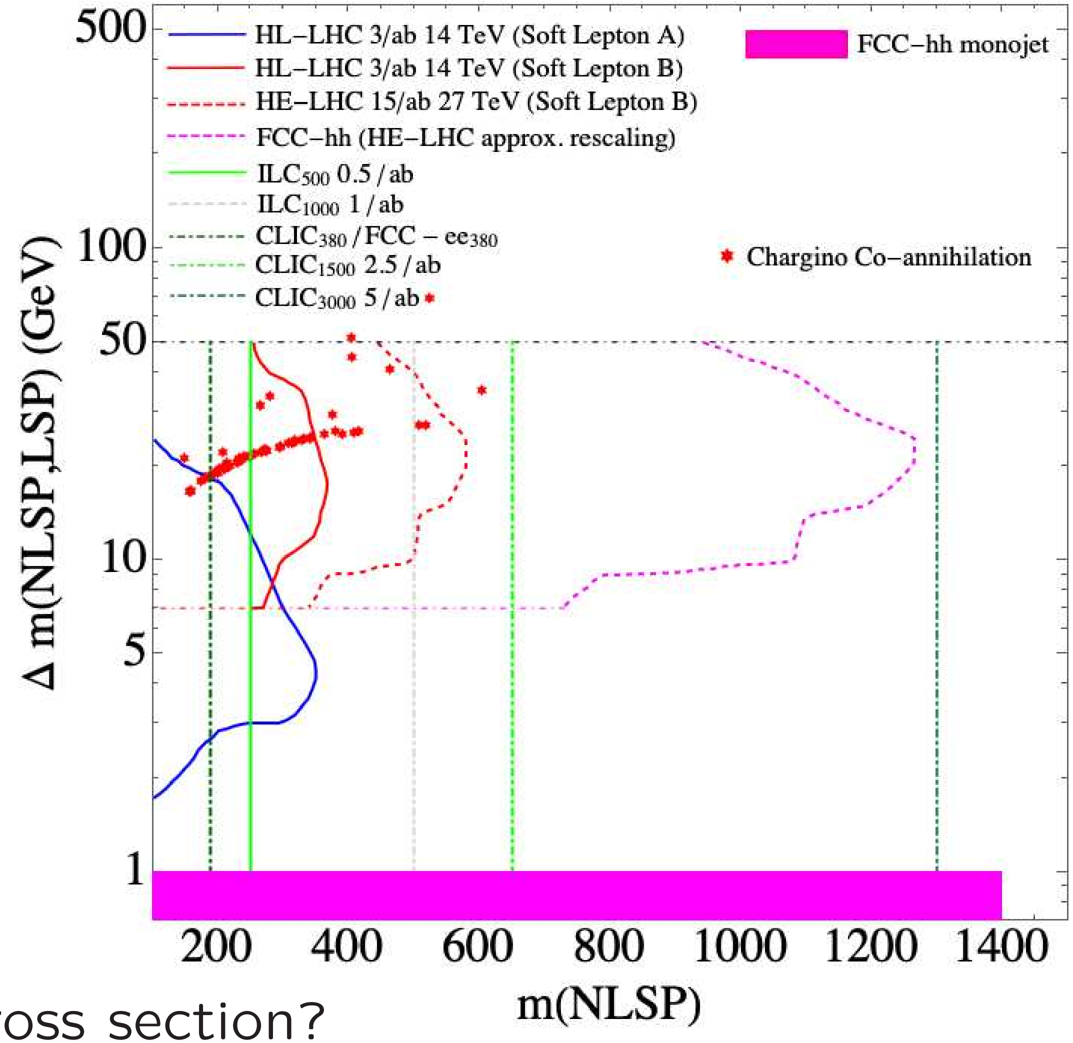


black contour: (simplified) application of $H/A \to \tau^+\tau^-$

$\Rightarrow$ A-pole annihilation effectively excluded

Future searches: available ONLY for higgsino LSP

⇒ naive inclusion of our points into the plot:



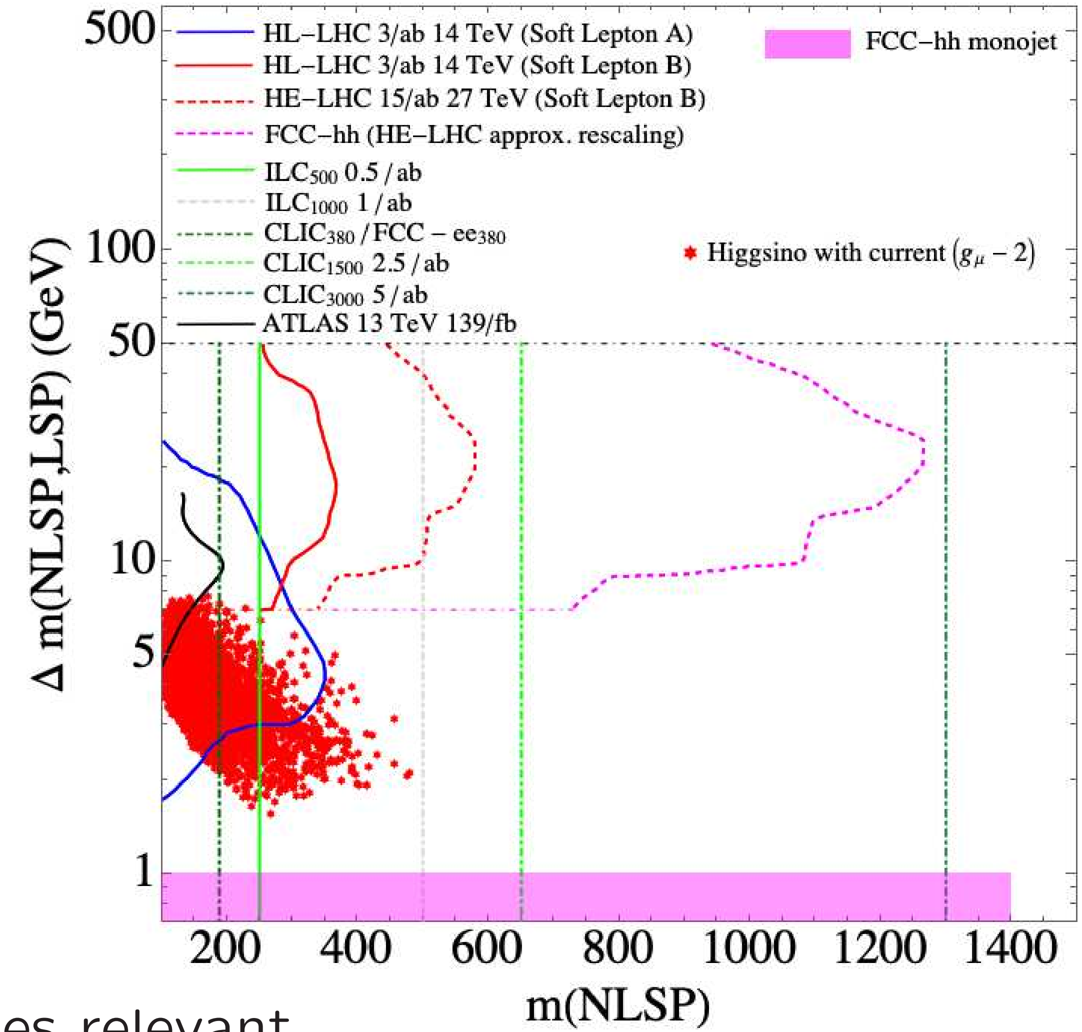
– scaling with cross section?

– possible problems?

– experimental projections for bino/wino/higgsino LSP?!

Outlook: same analysis for "Higgsino LSP" (but $\Omega_{CDM} \leq \Omega_{Planck}$)

[M. Chakraborti, S.H., I. Saha – PRELIMIMARY]



– current searches relevant
– HL-LHC searches very powerful
– ILC/CLIC needed to cover this scenario

4. Conclusinos

- General idea:
  - $(g-2)_\mu$ is real $\Rightarrow$ light EW particles
  - scan the EW sector of the MSSM
    with all constraints taken into account: $(g-2)_\mu$(today and future), DM relic density, DM direct detection, LHC EW searches
  - upper limits on EW masses
  - evaluate future prospects

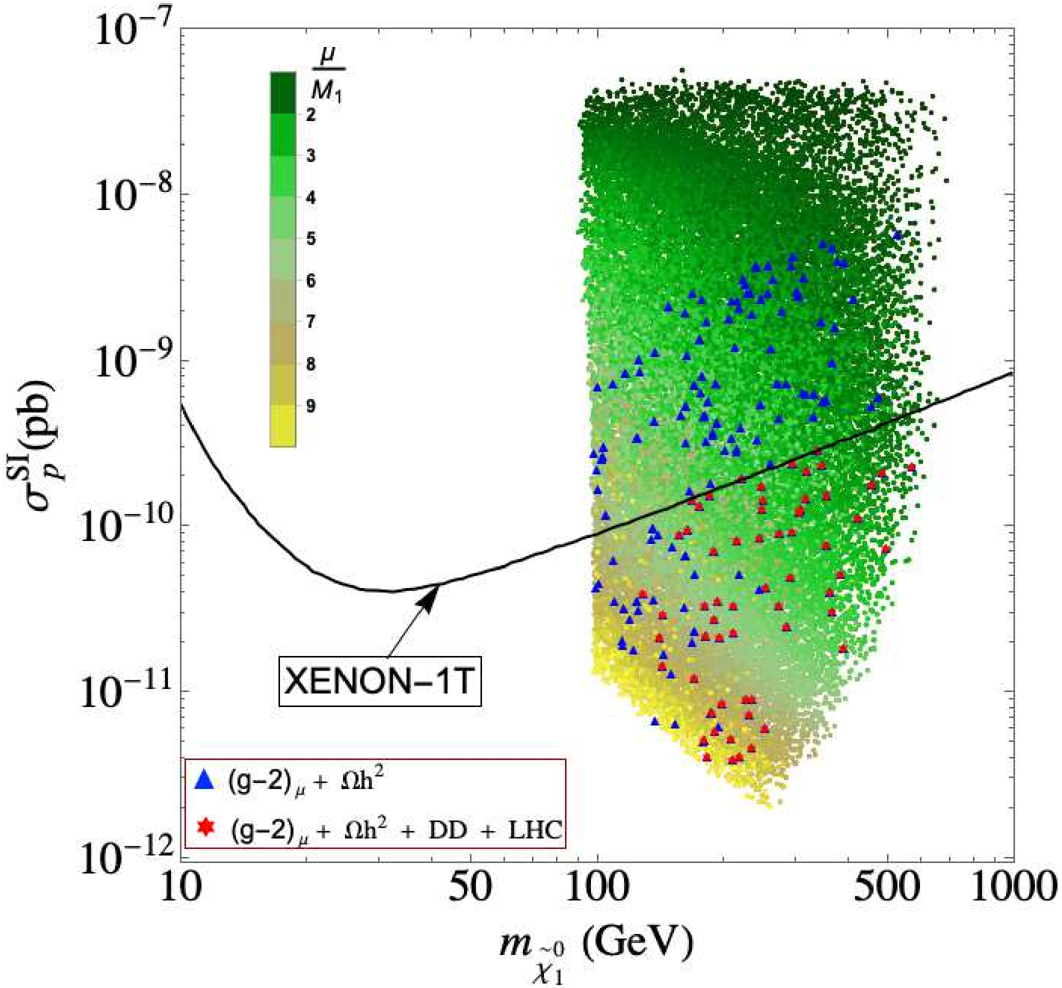
- LHC searches included via CheckMate
  $\Rightarrow$ many searches had to be included by M.C, I.S.
  $\Rightarrow$ crucial for correct application

- Chargino coannihilation:
  - compressed spectrum as expected
  - $\Rightarrow$ clear upper limits, $m_{\text{(N)LSP}} \lesssim 600$ GeV
  - future prospects only available for higgsino LSP
    Naive application? Cross section scaling? Potential problems?

- Outlook: higgsino LSP with $\Omega_{\text{CDM}} \leq \Omega_{\text{Planck}}$
  - HL-LHC searches very powerful
  - ILC/CLIC needed to cover this scenario


Further Questions?

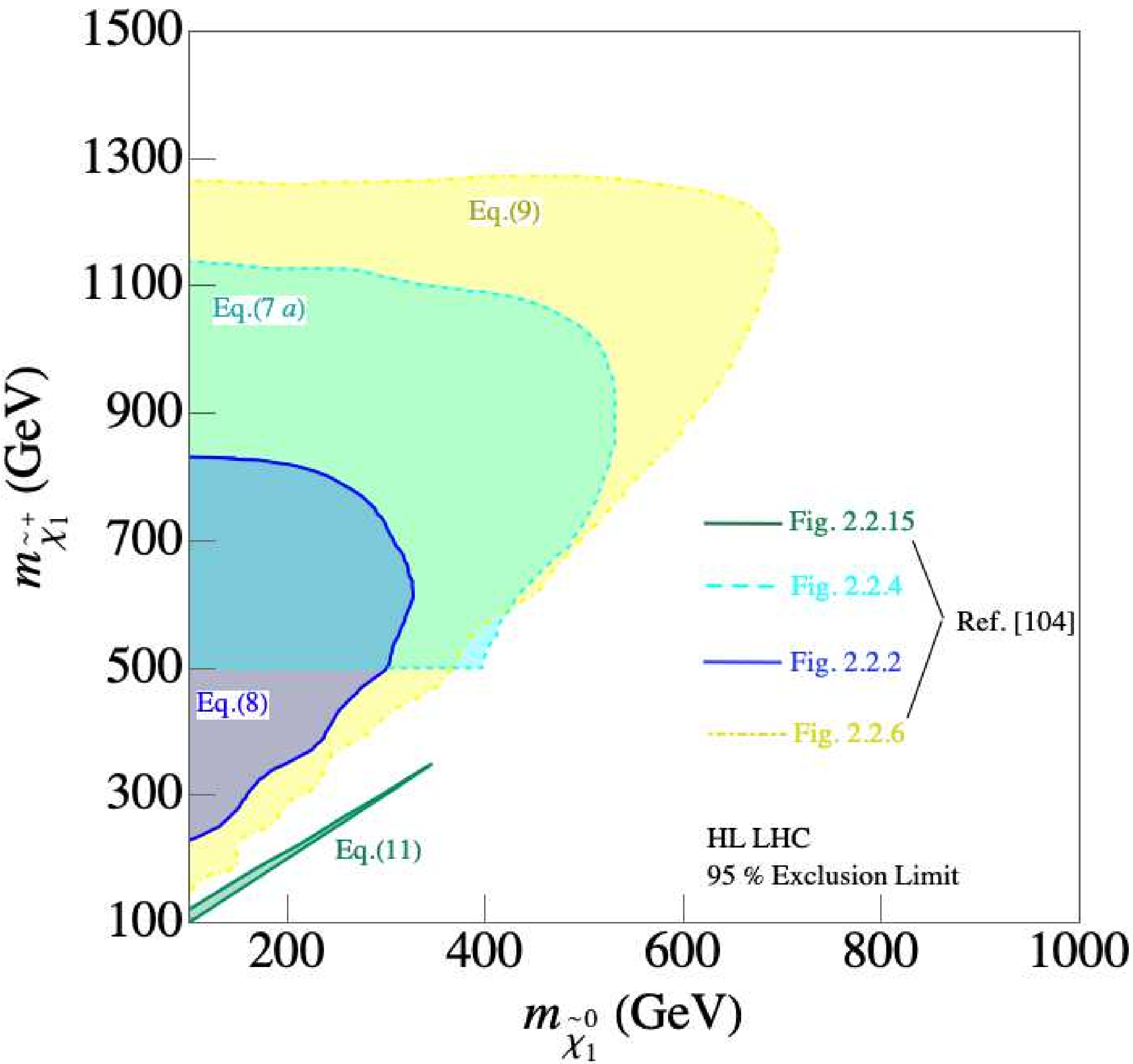
Results in the $m_{\tilde{\chi}_1^0}$-$\sigma_p^{\rm SI}$ plane:



⇒ larger μ values favored

HL-LHC prospects $m_{\tilde{\chi}_1^0}$-$m_{\tilde{\chi}_1^\pm}$ plane: exclusion

[*HL/HE-LHC YR '19*]



HL-LHC prospects $m_{\tilde{\chi}_1^0}$-$m_{\tilde{\chi}_1^\pm}$ plane: discovery

[*HL/HE-LHC YR '19*]