
The Four COVID Personality Types

(spotted at the local grocery store)

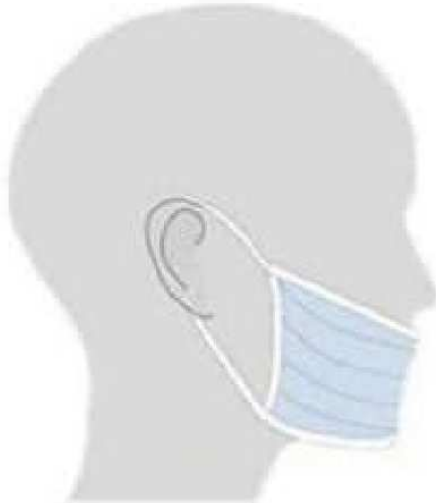
Believes
in science



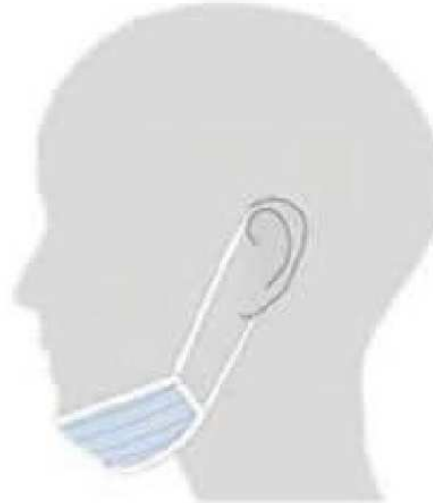
Denies
science



Doesn't
understand
science



Believes in
magic



The new MUON G-2 Result and Supersymmetry

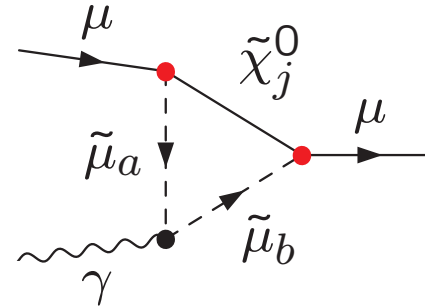
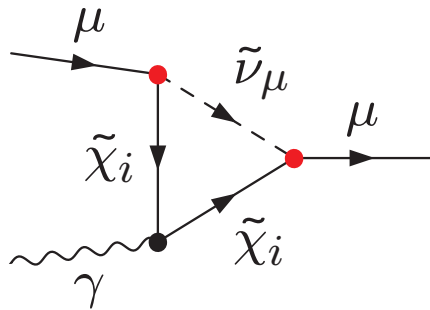
Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)

virtual, 05/2021

In collaboration with: *M. Chakraborti, I. Saha*
[*arXiv:2006.15157 (EPJC), 2103.13403, 2104.03287*]

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:

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

$$\mu - \tilde{\chi}_j^0 - \tilde{\mu}_a : \sim m_\mu \tan \beta$$

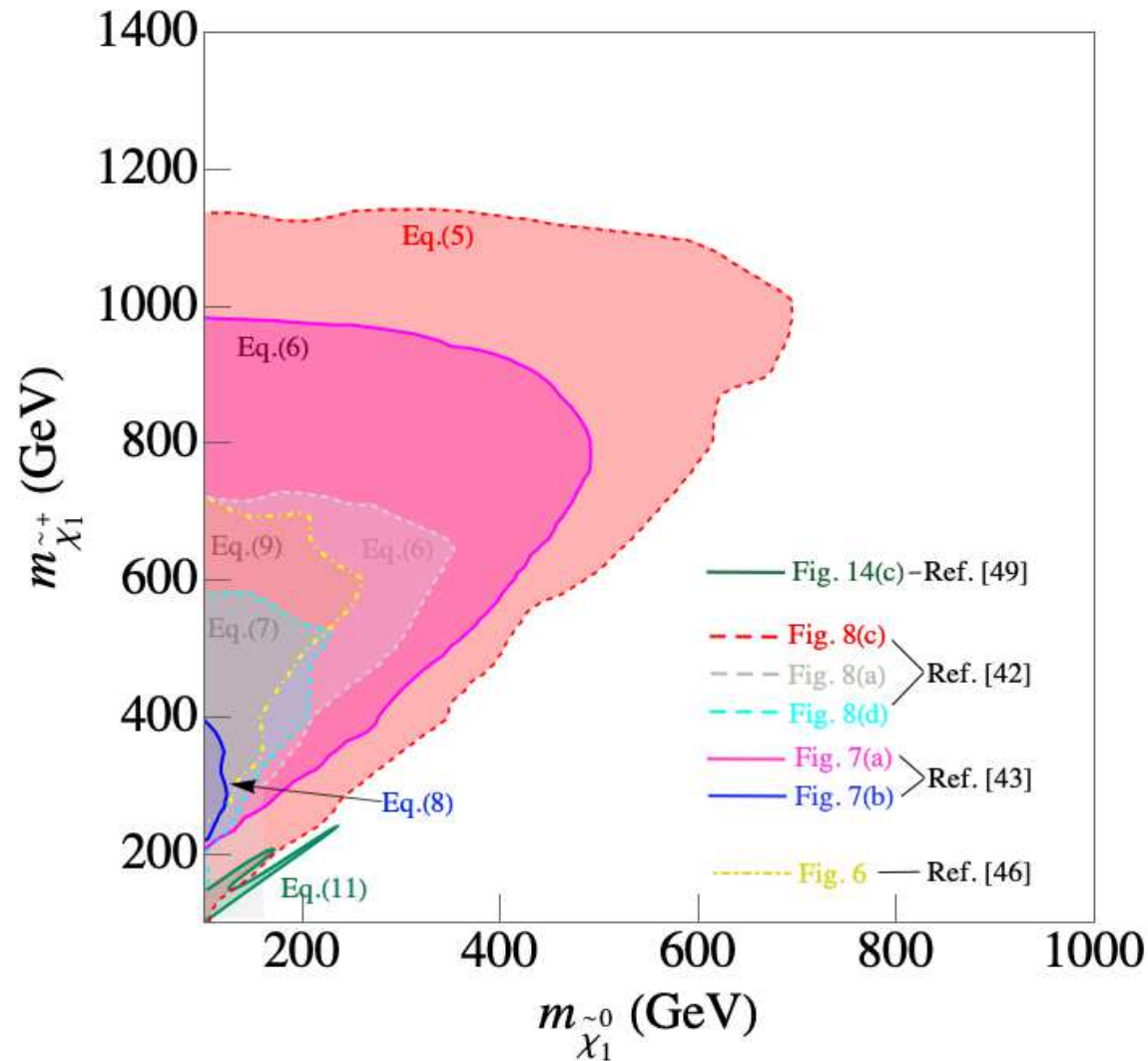
$$\text{SM, EW 1L: } \frac{\alpha}{\pi} \frac{m_\mu^2}{M_W^2}$$

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

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
 - bino/wino DM with chargino co-annihilation
 - bino/wino DM with slepton co-annihilation
 - higgsino DM
 - wino DM
- obtain lower and upper limits on the various EW particle masses
- evaluate the prospects for future searches

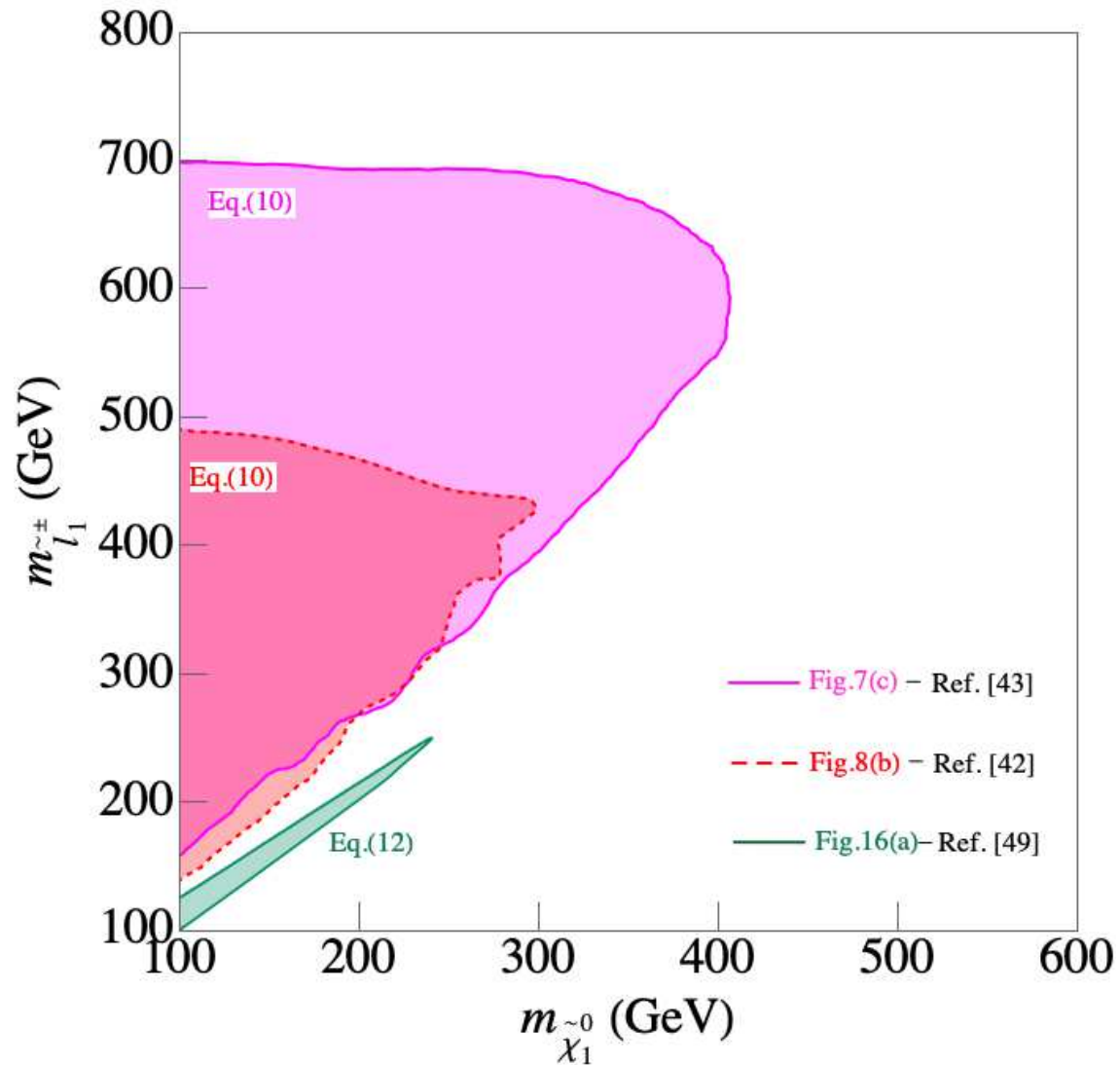
LHC exclusion bounds (I) (as given for Simplified Model Spectra (SMS))



⇒ all newly included into CheckMate [M.C & I.S.]

Exception: compressed spectra ⇒ direct application

LHC exclusion bounds (II) (as given for Simplified Model Spectra (SMS))



⇒ all newly included into CheckMate [M.C & I.S.]

Exception: compressed spectra ⇒ direct application

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

$$\begin{aligned} \text{old: } \Delta a_\mu^{\text{old}} &= (28.0 \pm 7.4) \times 10^{-10} \\ \text{new: } \Delta a_\mu^{\text{new}} &= (25.1 \pm 5.9) \times 10^{-10} \end{aligned}$$

\Rightarrow some results for $\Delta a_\mu^{\text{new}} (\equiv \Delta a_\mu)$
some results only available for $\Delta a_\mu^{\text{old}}$

Note: $\Delta a_\mu^{\text{old}} - 2\sigma^{\text{old}} \approx \Delta a_\mu^{\text{new}} - 2\sigma^{\text{new}}$

\Rightarrow upper limits on SUSY masses are not expected to change

Dark Matter relic density: MicrOmegas

$$\begin{aligned} \Omega_{\text{CDM}} h^2 &= 0.120 \pm 0.001 \\ \text{or } \Omega_{\text{CDM}} h^2 &\leq 0.122 \end{aligned}$$

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

Dark Matter direct detection: MicrOmegas

limit on spin independent scattering cross section (Xenon1T)

[*Xenon collab. '18*]

Possible scenarios:

1. bino/wino DM with chargino co-annihilation
⇒ full relic DM constraint ⇒ updated with $\Delta a_\mu^{\text{new}}$
2. bino DM with slepton co-annihilation case-L
⇒ full relic DM constraint ⇒ updated with $\Delta a_\mu^{\text{new}}$
3. bino DM with slepton co-annihilation case-R
⇒ full relic DM constraint ⇒ updated with $\Delta a_\mu^{\text{new}}$
4. higgsino DM: $m_{\tilde{\chi}_1^0} \approx m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^\pm}$
full relic DM constraint ⇒ $m_{\tilde{\chi}_1^0} \sim 1 \text{ TeV} \Rightarrow (g - 2)_\mu$ not ok
⇒ relic DM upper bound
5. wino DM: $m_{\tilde{\chi}_1^0} \approx m_{\tilde{\chi}_1^\pm}$
full relic DM constraint ⇒ $m_{\tilde{\chi}_1^0} \sim 3 \text{ TeV} \Rightarrow (g - 2)_\mu$ not ok
⇒ relic DM upper bound

Mini summary of the results:

A) bino/wino DM with chargino co-annihilation

relic DM density 100% fulfilled

$$\Rightarrow m_{(N)\text{LSP}} \lesssim 600(650) \text{ GeV} \text{ for new (and old) } (g-2)_\mu$$

B/C) bino/wino DM with slepton co-annihilation

relic DM density 100% fulfilled

$$\Rightarrow m_{(N)\text{LSP}} \lesssim 550(600) \text{ GeV} \text{ for new (and old) } (g-2)_\mu$$

D) higgsino DM: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim \mu$

relic DM density as upper limit (otherwise $m_{\tilde{\chi}_1^0} \sim 1 \text{ TeV}$)

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

E) wino DM: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^\pm} \sim M_2$

relic DM density as upper limit (otherwise $m_{\tilde{\chi}_1^0} \sim 3 \text{ TeV}$)

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

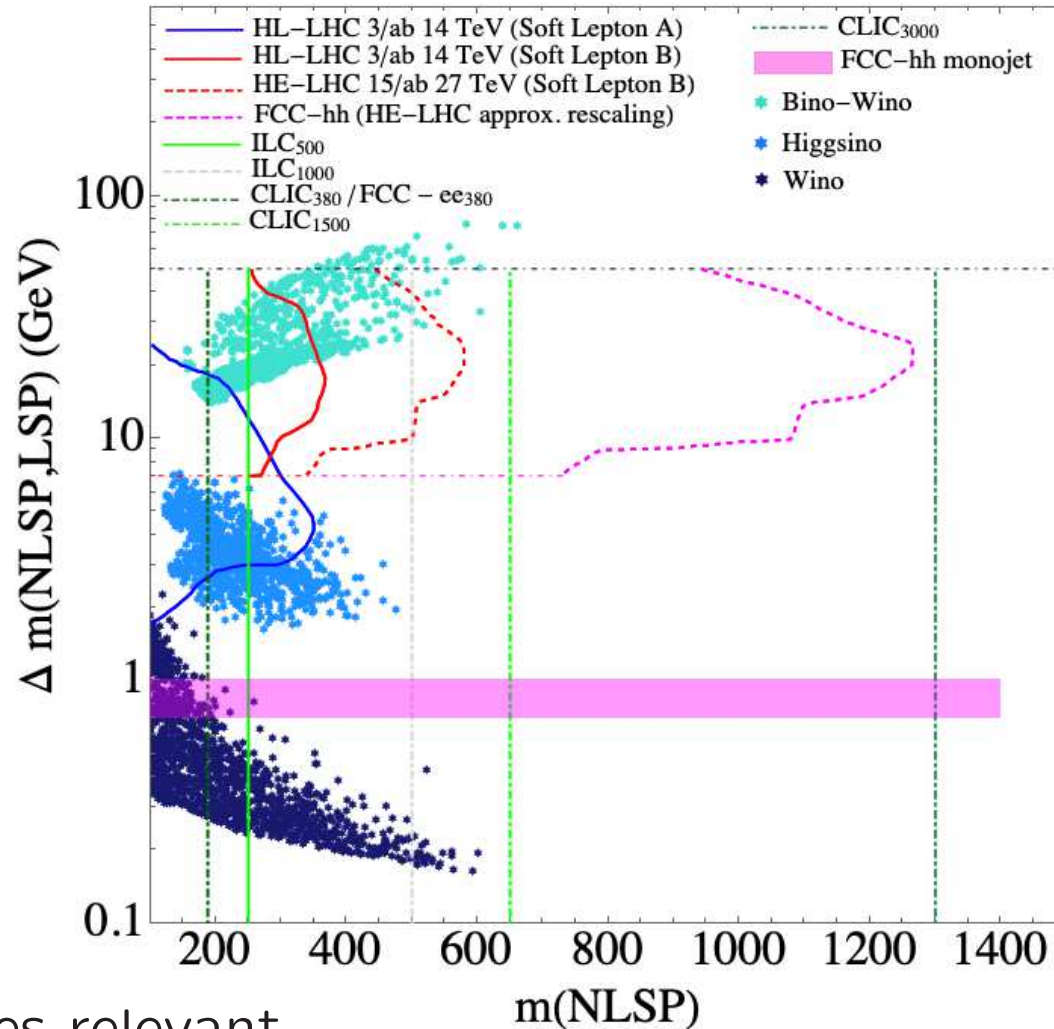
\Rightarrow predictions for future colliders?!

Predictions for future colliders

- HL-LHC direct search projections
- HL-LHC searches for compressed spectra ⇐ focus
- future collider prospects for compressed spectra ⇐ focus
- direct production at e^+e^- colliders ⇐ focus
- ...

Compressed spectra at current and future colliders

Higgsino, wino and bino/wino DM:

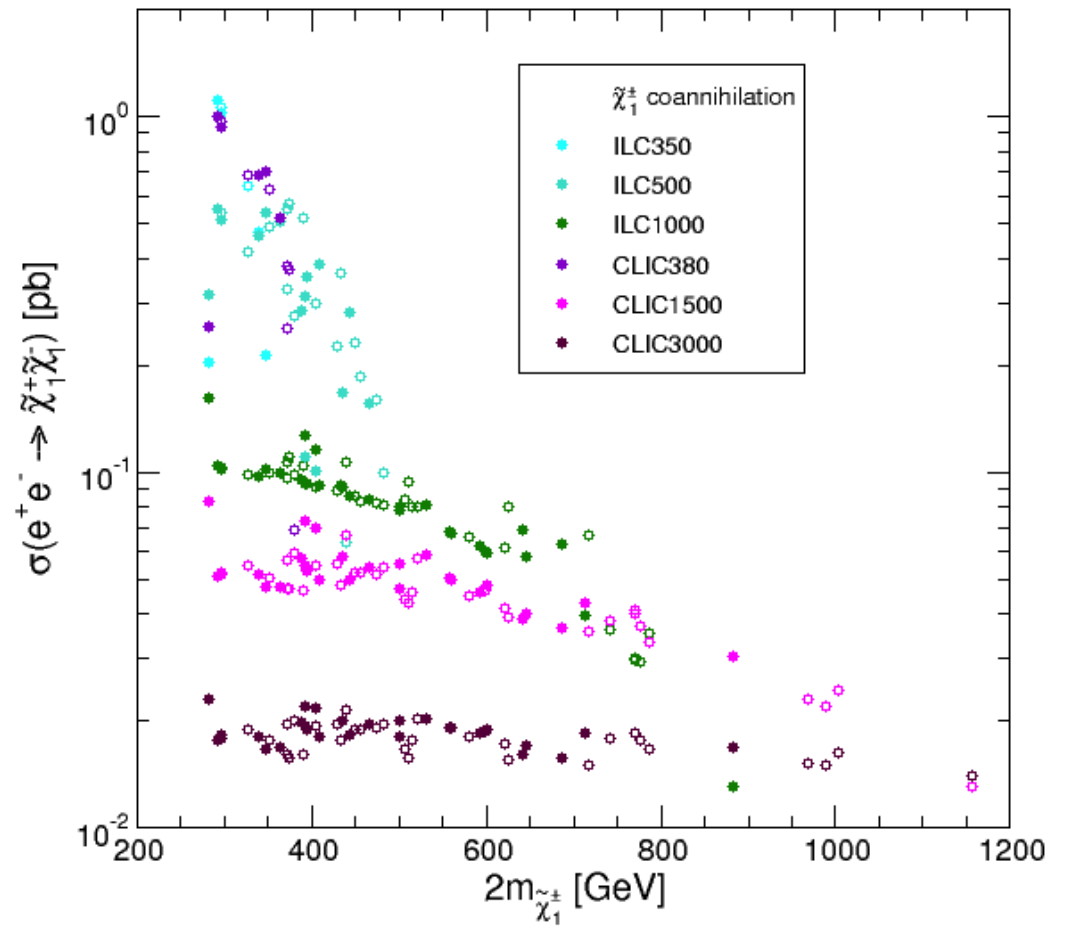
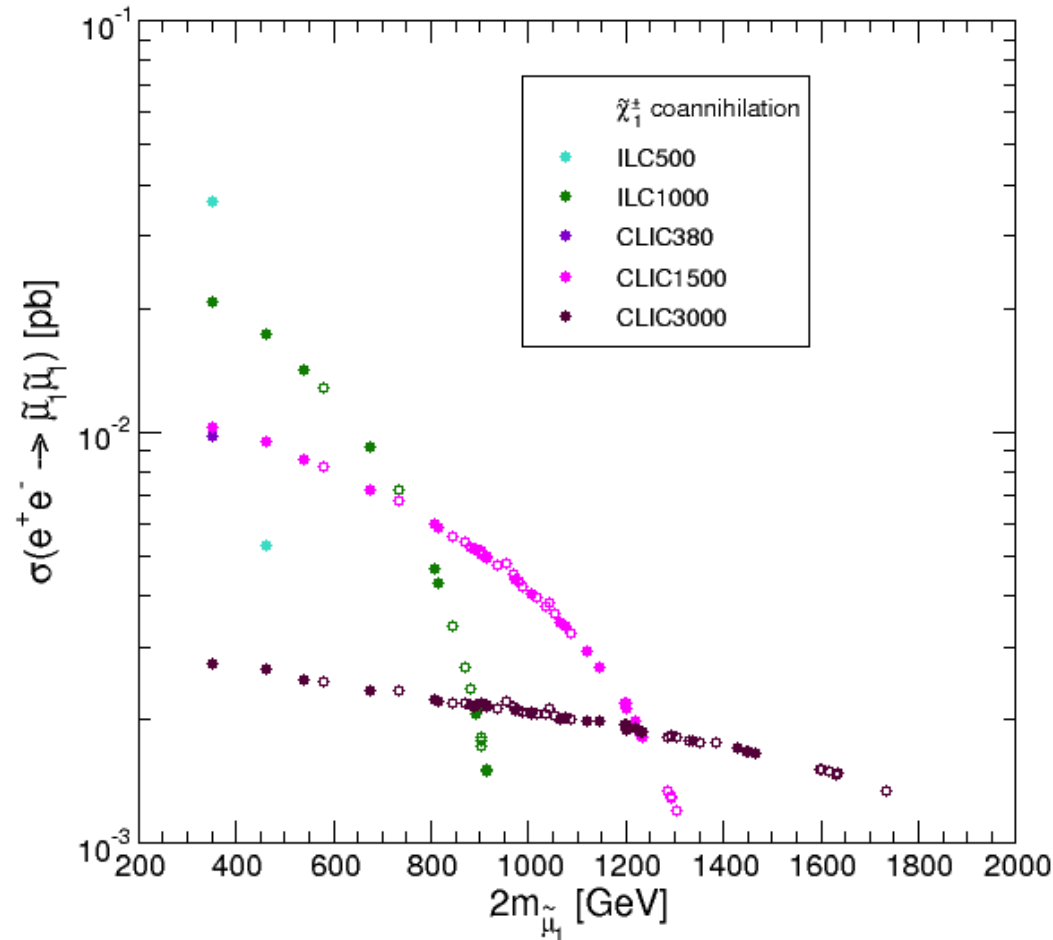


- current searches relevant
- HL-LHC searches very powerful (but ILC/CLIC needed to fully cover)
- ⇒ uncompressed spectra: not all channels available (and no CM yet)

Direct production at e^+e^- colliders (ILC/CLIC)

wino/bino DM with chargino co-ann.

(open/full: "old" $(g-2)_\mu$)



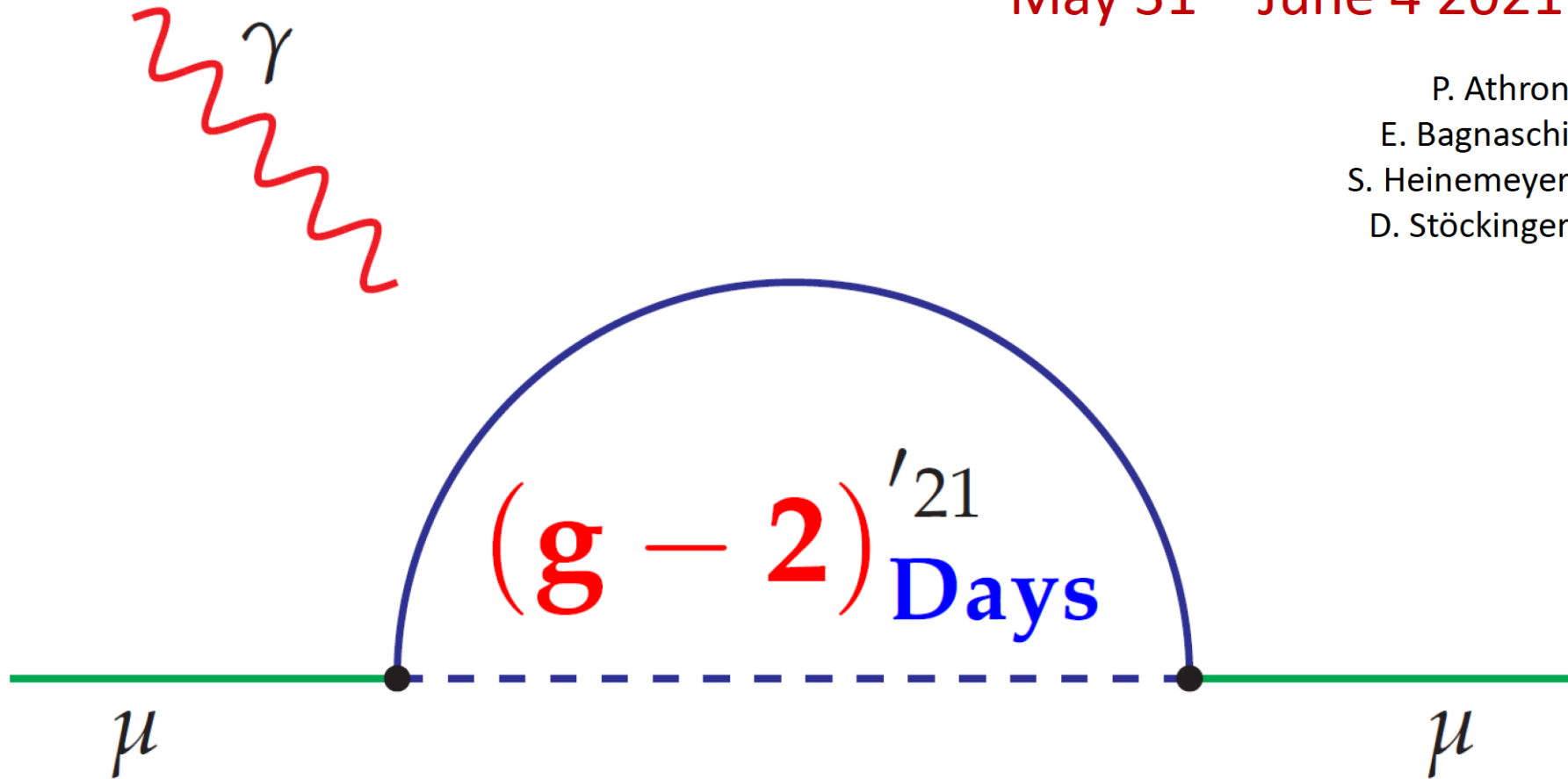
\Rightarrow ILC has good prospects (particularly for $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$)

\Rightarrow CLIC can cover everything

BSM physics in the light of $(g - 2)_\mu$

May 31 – June 4 2021

P. Athron
E. Bagnaschi
S. Heinemeyer
D. Stöckinger



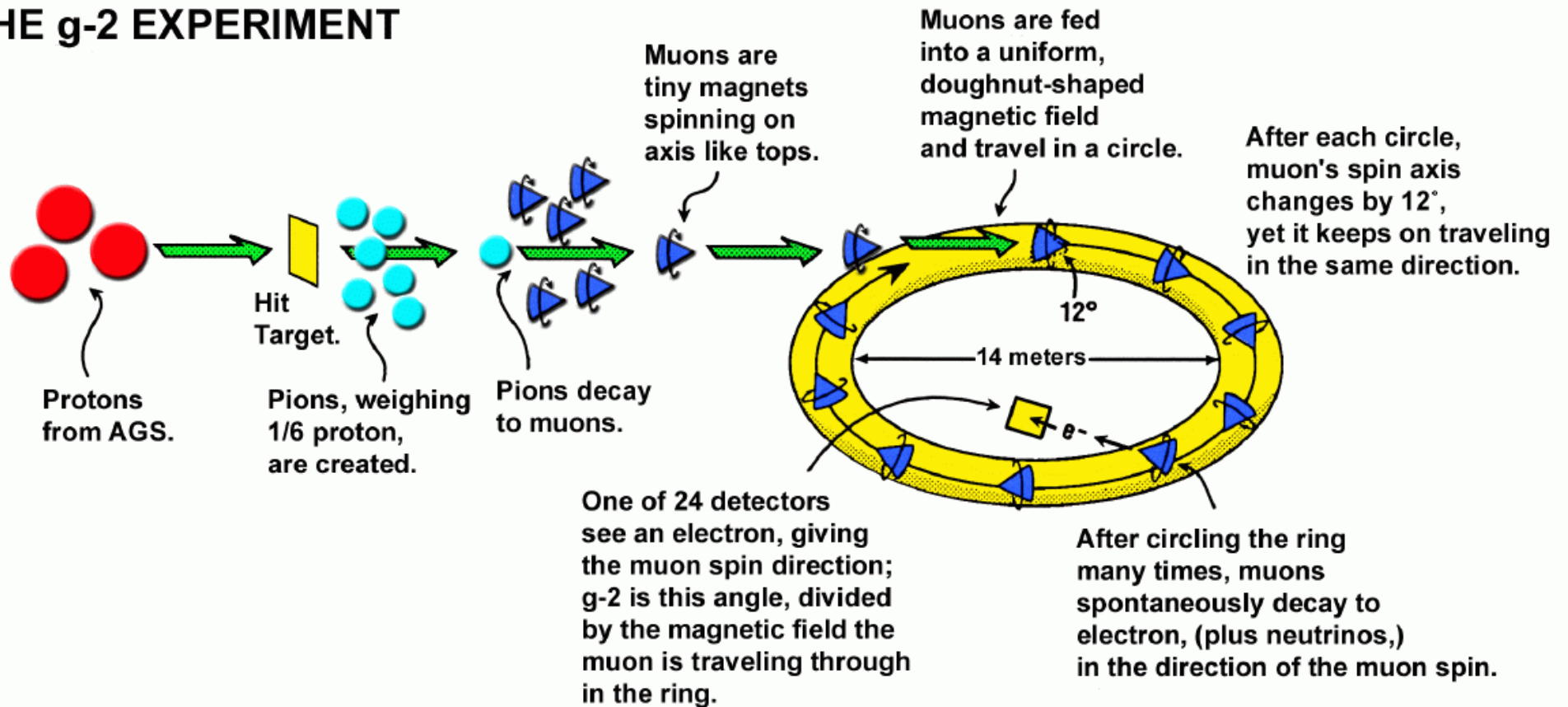
<http://pheno.csic.es/g-2Days21>



Further Questions?

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

LIFE OF A MUON: THE g-2 EXPERIMENT

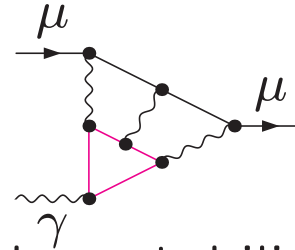


Coupling of muon to magnetic field : $\mu - \mu - \gamma$ coupling

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

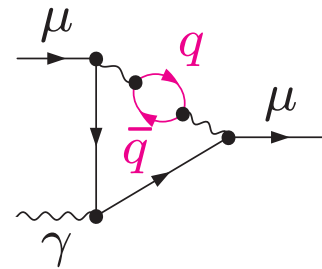
Theory of $(g - 2)_\mu$:

- the **light-by-light** contribution:



2002: sign error discovered; since then stabilized
2021: confirmed by LQCD

- the **hadronic vacuum** contribution:



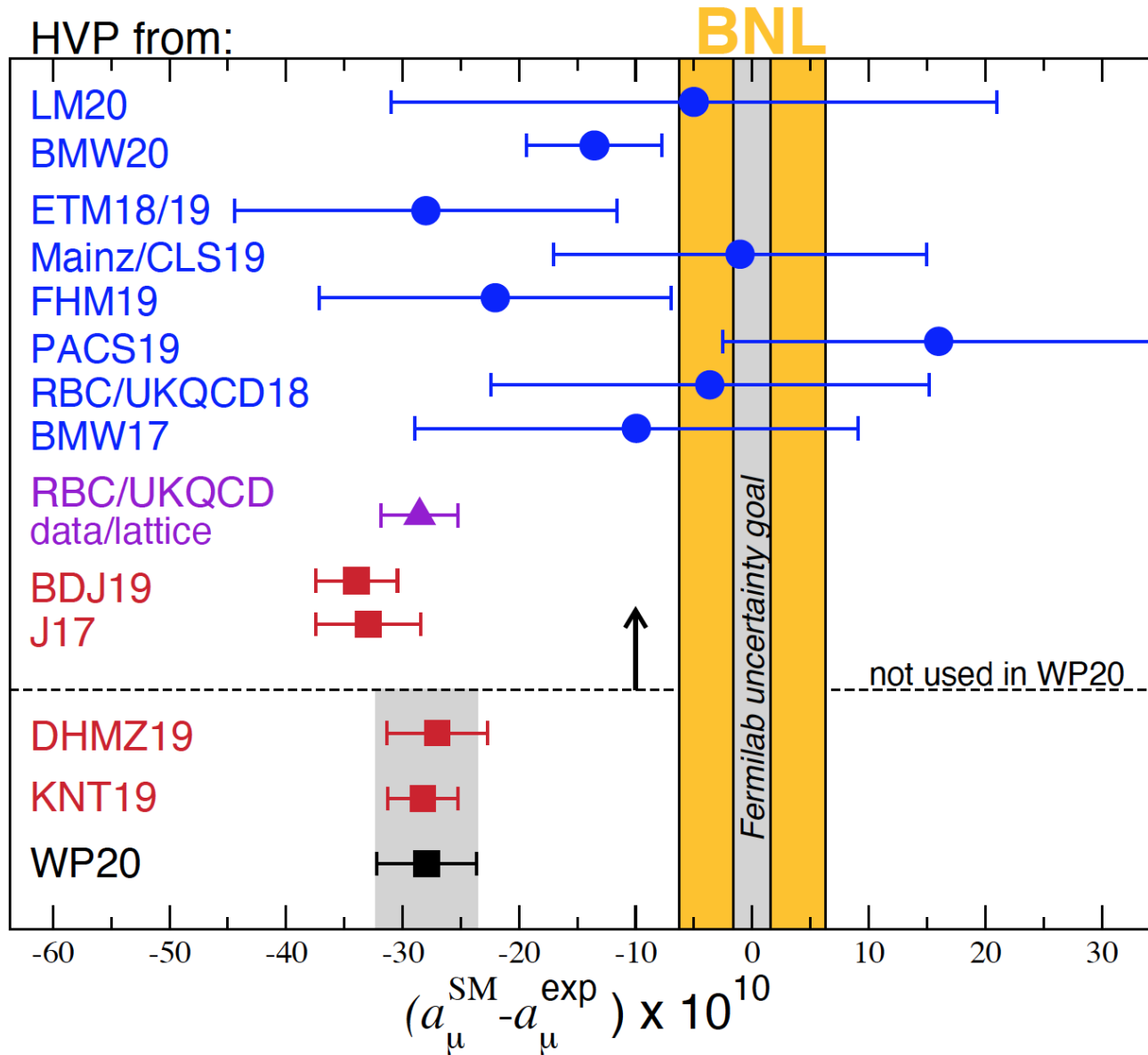
'direct' e^+e^- data:

from **CMD-II, SND, KLOE, BaBar** (radiative return)
 \Rightarrow agree relatively well (also with old e^+e^- data)
 \Rightarrow **tension with LQCD results**

τ data:

tended to be closer to experimental result
inclusion of γ - ρ mixing: agreement with e^+e^- [F. Jegerlehner, R. Szafron '10]
 \Rightarrow still under discussion ...

HVP summary:



⇒ BMW20: difference to experimental data $\sim 1.5\sigma$

LHC searches: (as given for Simplified Model Spectra (SMS))

Decay via sleptons (3I)

$$\begin{aligned}\tilde{\chi}_1^\pm \tilde{\chi}_2^0 &\rightarrow (\tilde{l}^\pm \nu)(\tilde{l}^+ l^-) \rightarrow 3l + \cancel{E}_T , \\ \tilde{\chi}_1^\pm \tilde{\chi}_2^0 &\rightarrow (l^\pm \tilde{\nu})(\tilde{l}^+ l^-) \rightarrow 3l + \cancel{E}_T\end{aligned}\quad (5)$$

Decay via sleptons (2I)

$$\begin{aligned}\tilde{\chi}_1^+ \tilde{\chi}_1^- &\rightarrow (\tilde{l}^+ \nu)(\tilde{l}^- \nu) \rightarrow 2l + \cancel{E}_T , \\ \tilde{\chi}_1^+ \tilde{\chi}_1^- &\rightarrow (l^+ \tilde{\nu})(l^- \tilde{\nu}) \rightarrow 2l + \cancel{E}_T\end{aligned}\quad (6)$$

Decay via gauge bosons

$$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow (W \tilde{\chi}_1^0)(Z \tilde{\chi}_1^0) \rightarrow 3l + \cancel{E}_T , \quad (7a)$$

$$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow (W \tilde{\chi}_1^0)(Z \tilde{\chi}_1^0) \rightarrow 2l + \text{jets} + \cancel{E}_T , \quad (7b)$$

$$\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow (W^+ \tilde{\chi}_1^0)(W^- \tilde{\chi}_1^0) \rightarrow 2l + \cancel{E}_T \quad (8)$$

Decay via Higgs bosons

$$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow (W \tilde{\chi}_1^0)(h \tilde{\chi}_1^0) \rightarrow l + b\bar{b} + \cancel{E}_T \quad (9)$$

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

$$\tilde{l}^+ \tilde{l}^- \rightarrow (l^+ \tilde{\chi}_1^0)(l^- \tilde{\chi}_1^0) \rightarrow 2l + \cancel{E}_T \quad (10)$$

Compressed spectra

$$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow (W^* \tilde{\chi}_1^0)(Z^* \tilde{\chi}_1^0) \rightarrow 2l + \cancel{E}_T + \text{ISR} , \quad (11)$$

$$\tilde{l}^+ \tilde{l}^- \rightarrow (l^+ \tilde{\chi}_1^0)(l^- \tilde{\chi}_1^0) \rightarrow 2l + \cancel{E}_T + \text{ISR} \quad (12)$$

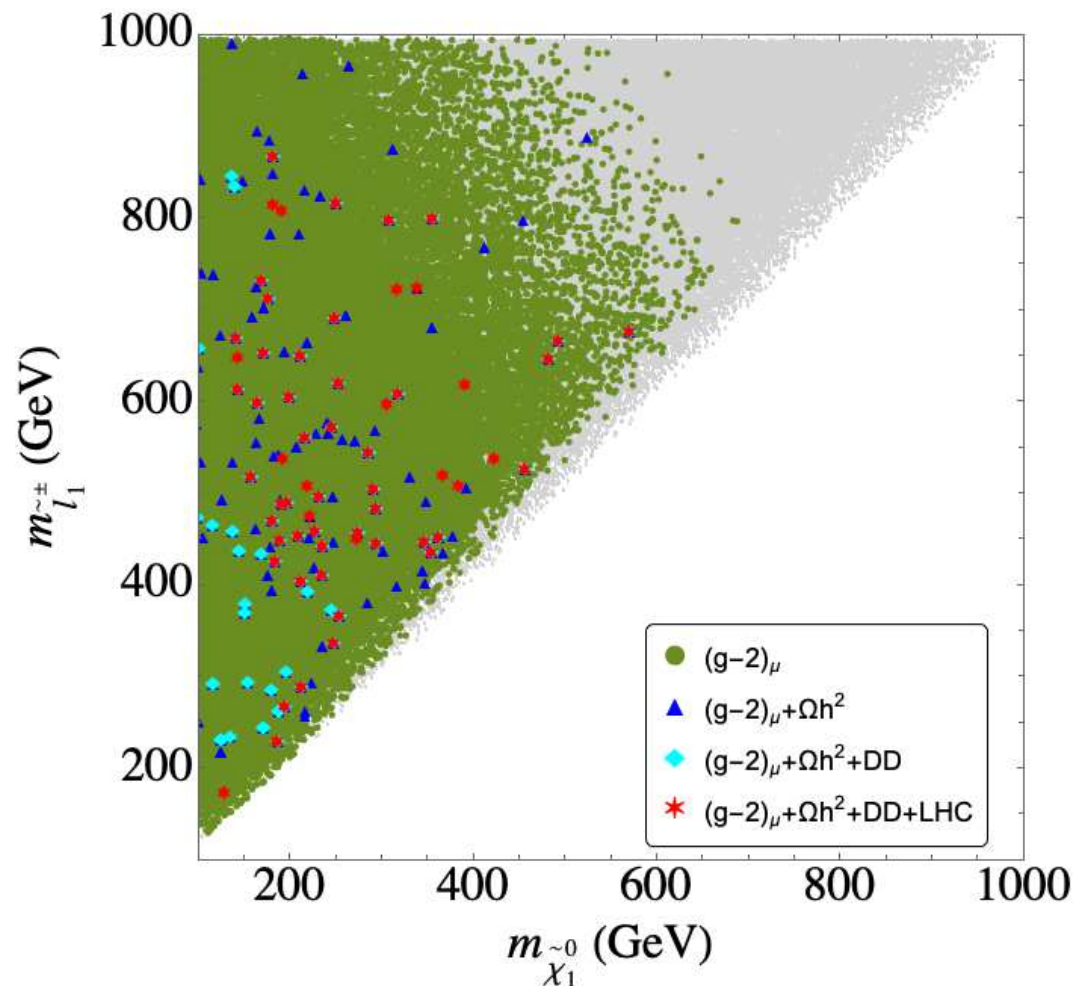
Searches involving Staus

\Rightarrow all newly included into CheckMate [M.C & I.S.]

Exception: compressed spectra \Rightarrow direct application

Example I: $\tilde{\chi}_1^\pm$ -coannihilation: $m_{\tilde{\chi}_1^0} - m_{\tilde{l}_1}$ plane:

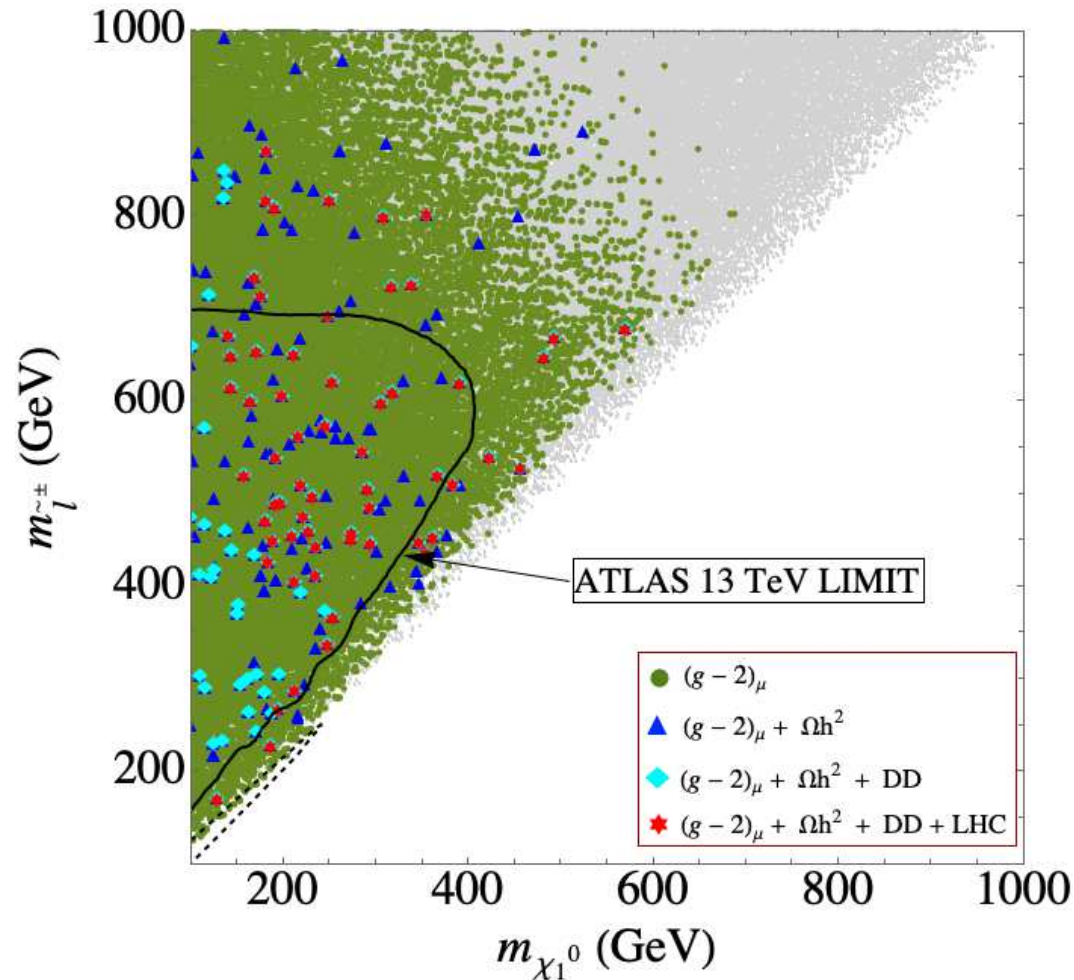
new $(g-2)_\mu$



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

Example I: $\tilde{\chi}_1^\pm$ -coannihilation: $m_{\tilde{\chi}_1^0} - m_{\tilde{l}_1}$ plane:

old $(g - 2)_\mu$

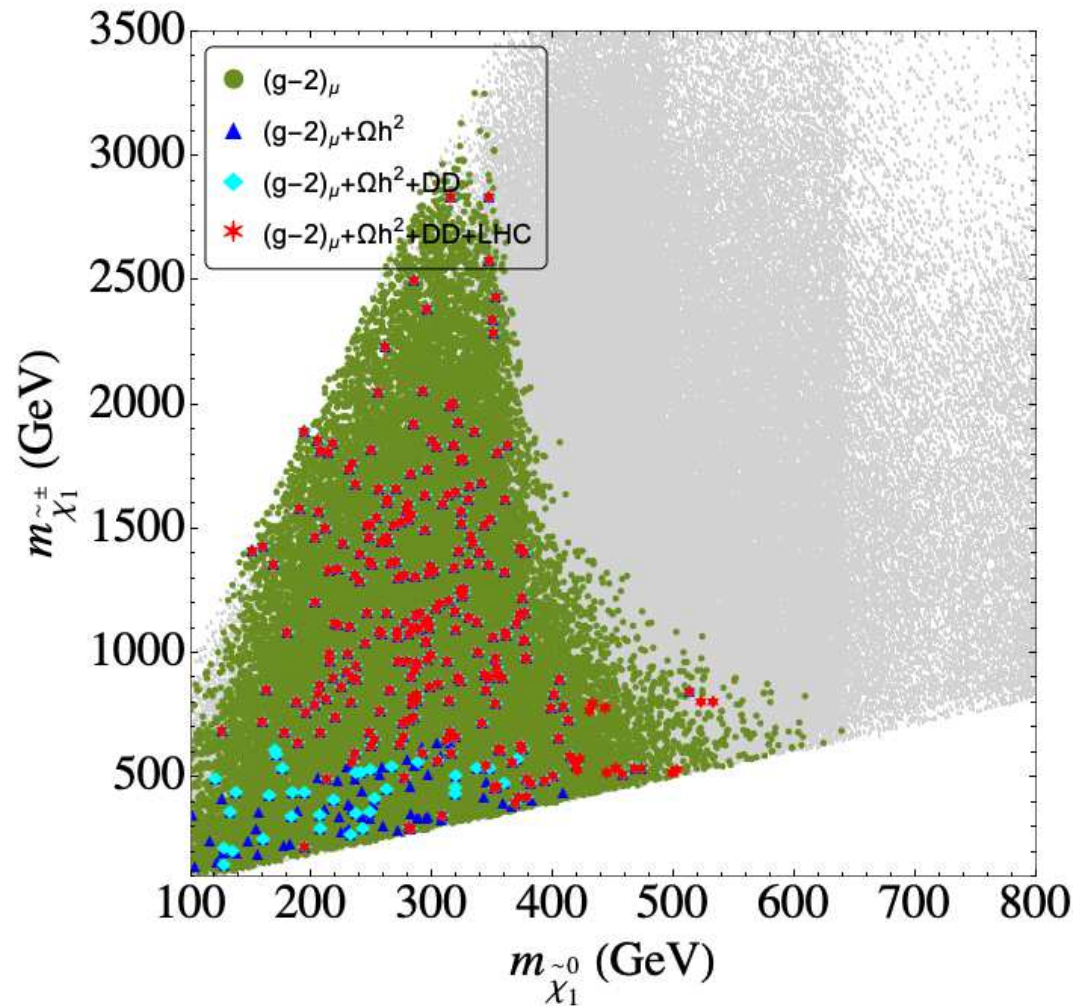


⇒ important: \tilde{l} -pair production searches (10)

⇒ naive application of LHC bounds fails

Example II: \tilde{l} -coannihilation: $m_{\tilde{\chi}_1^0} - m_{\tilde{\chi}_1^\pm}$ plane:

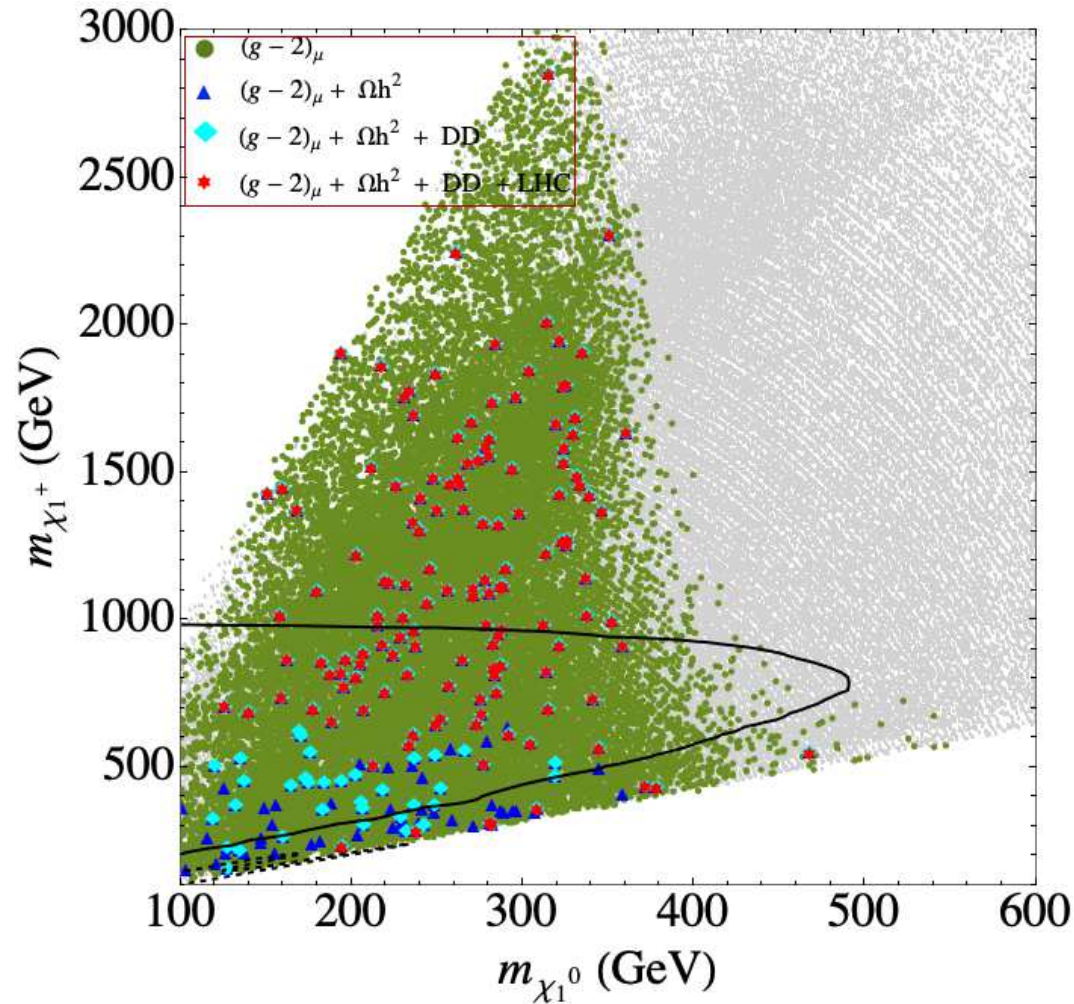
new $(g-2)_\mu$



⇒ important: $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production searches (5)

Example II: \tilde{l} -coannihilation: $m_{\tilde{\chi}_1^0} - m_{\tilde{\chi}_1^\pm}$ plane:

old $(g - 2)_\mu$

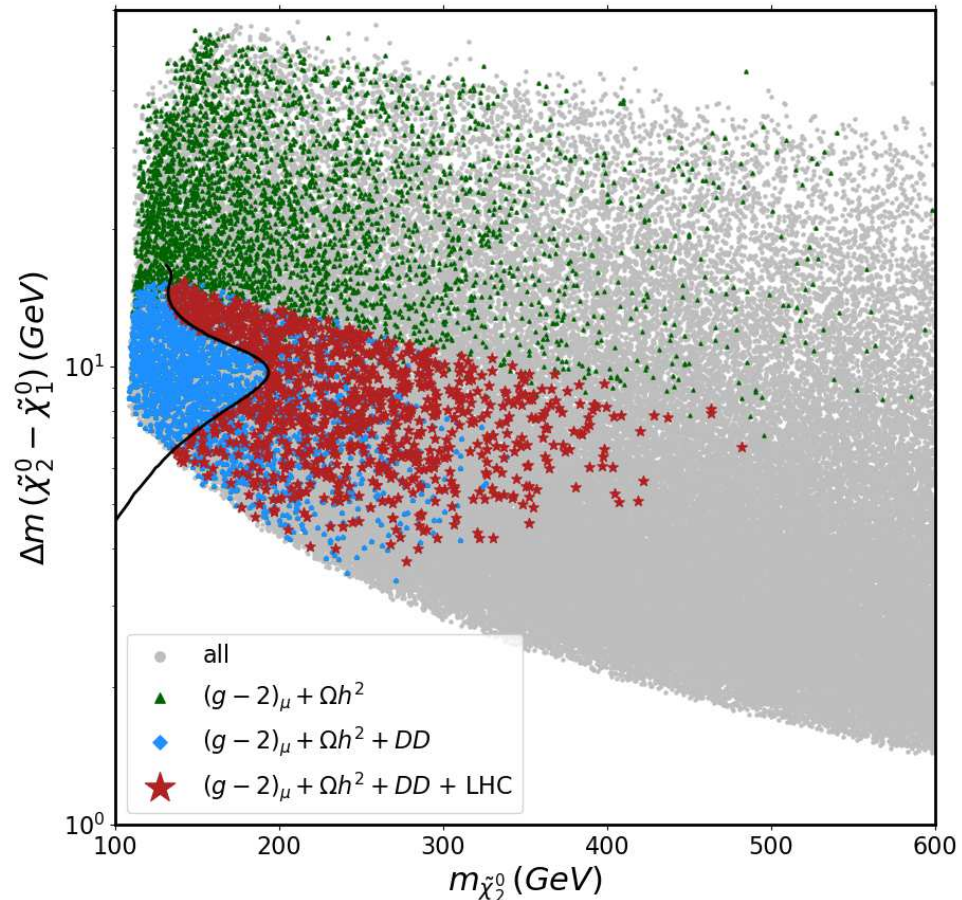


\Rightarrow important: $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production searches (5)

\Rightarrow naive application of LHC bounds fails

Example III: higgsino DM: $m_{\tilde{\chi}_2^0} - \Delta m$ plane:

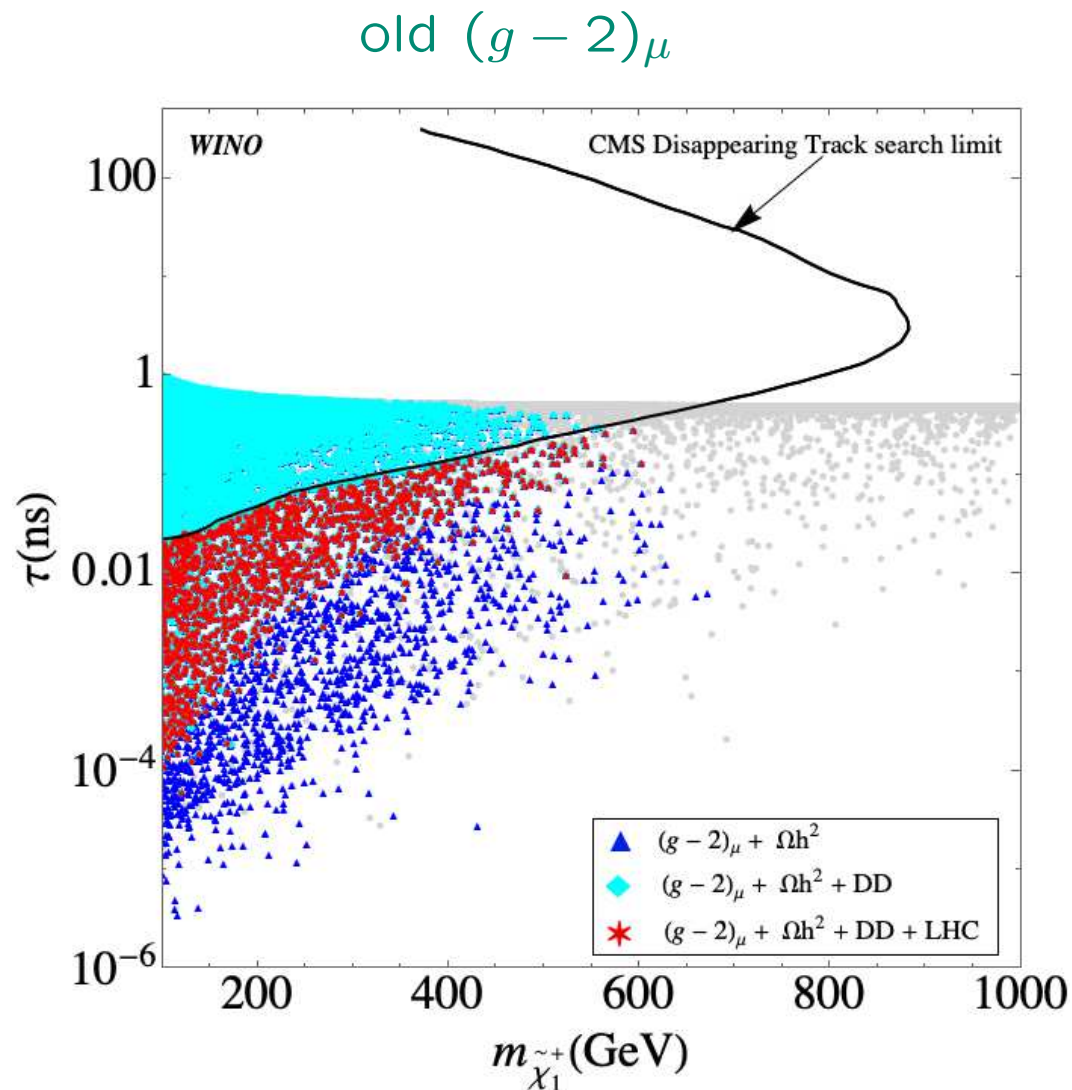
old $(g - 2)_\mu$



⇒ important: compressed spectra searches (11)

⇒ right where the model prediction sits ⇒ very powerful

Example IV: wino DM: $m_{\tilde{\chi}_1^\pm} - \tau_{\tilde{\chi}_1^\pm}$ plane:



⇒ important: disappearing track limit ⇒ $m_{(N)LSP} \lesssim 600$ GeV

⇒ allowed parameter space squeezed by DD limits and disapp. tracks

A) Bino/wino DM with chargino co-annihilation

[M. Chakraborti, S.H., I. Saha '20, '21]

Parameter scan:

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

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

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

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

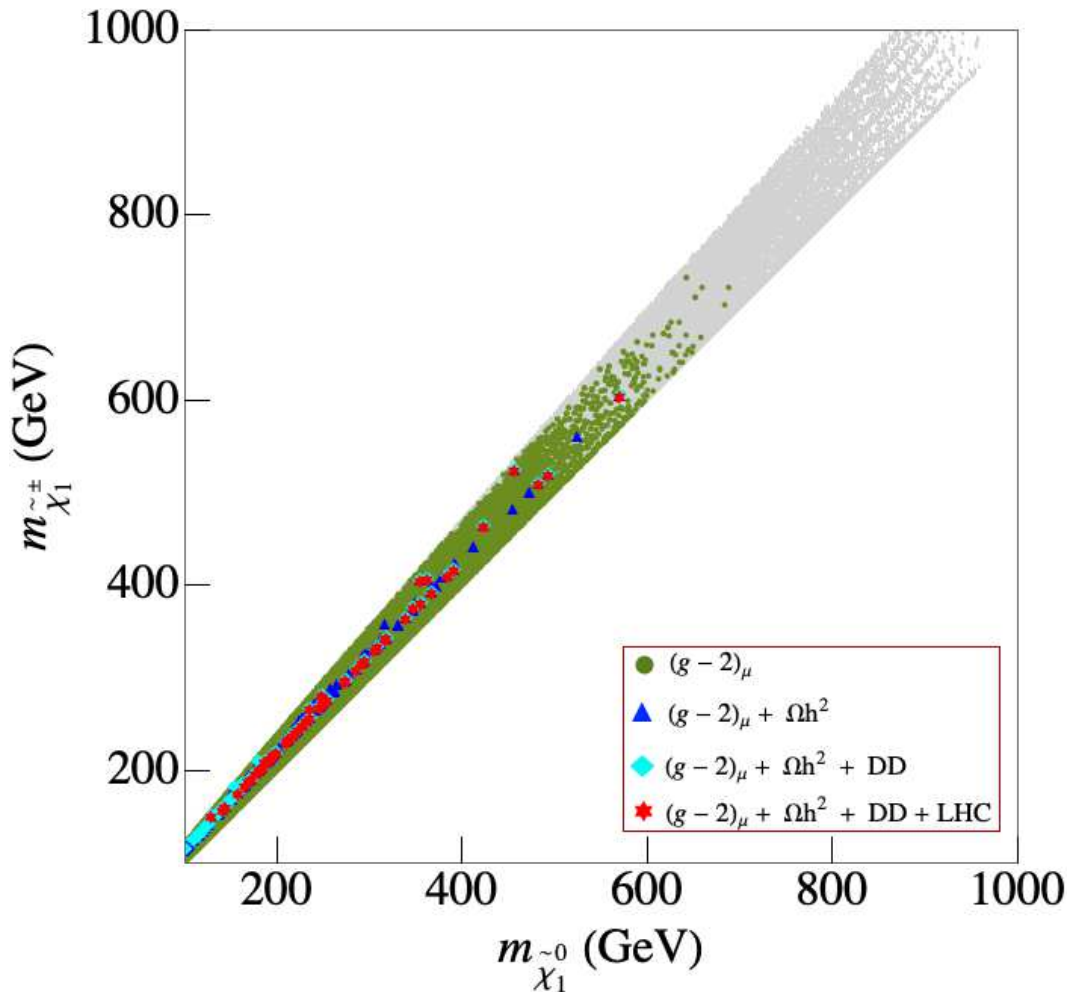
$$100 \text{ GeV} \leq m_{\tilde{L}} \leq 1 \text{ TeV} ,$$

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

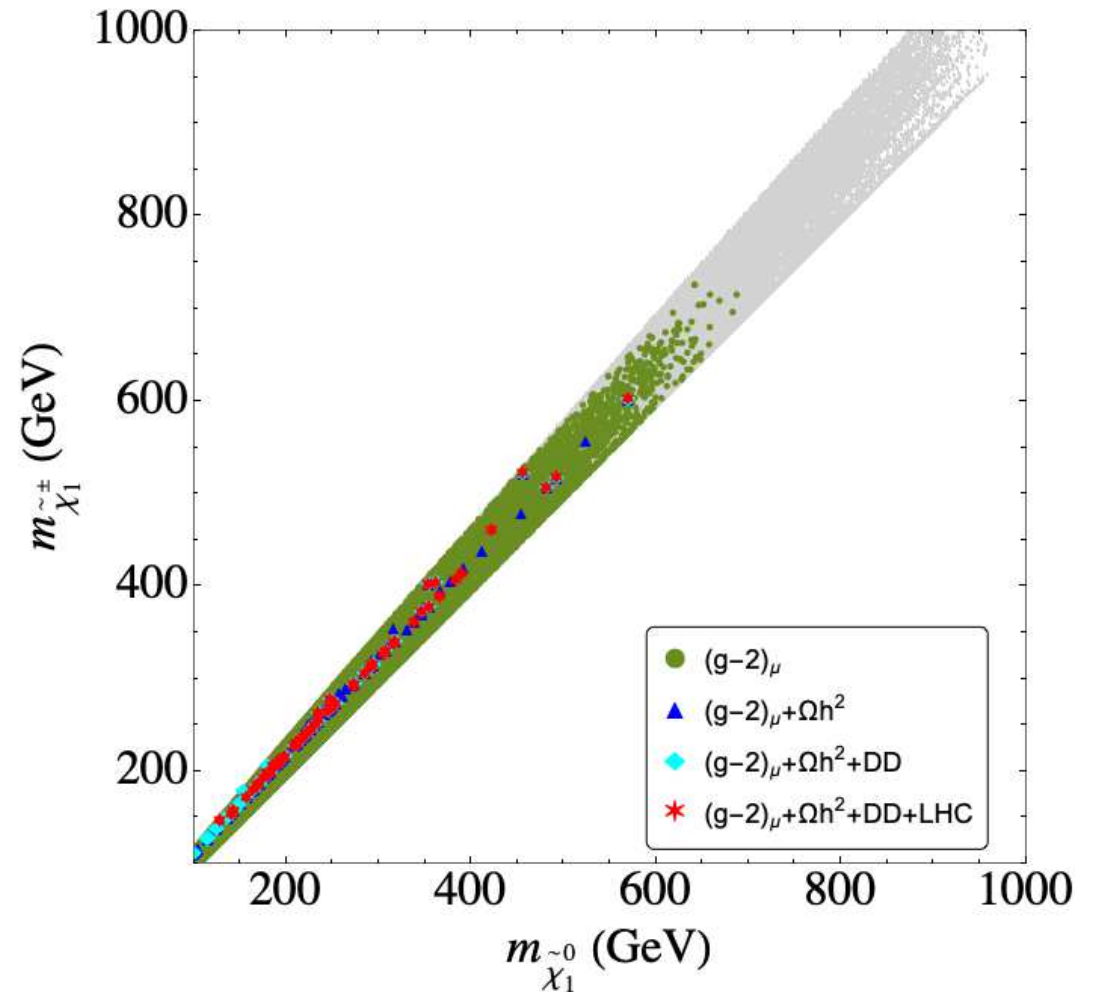
(latter condition only to make the analysis simpler, no relevant effect)

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

old $(g - 2)_\mu$



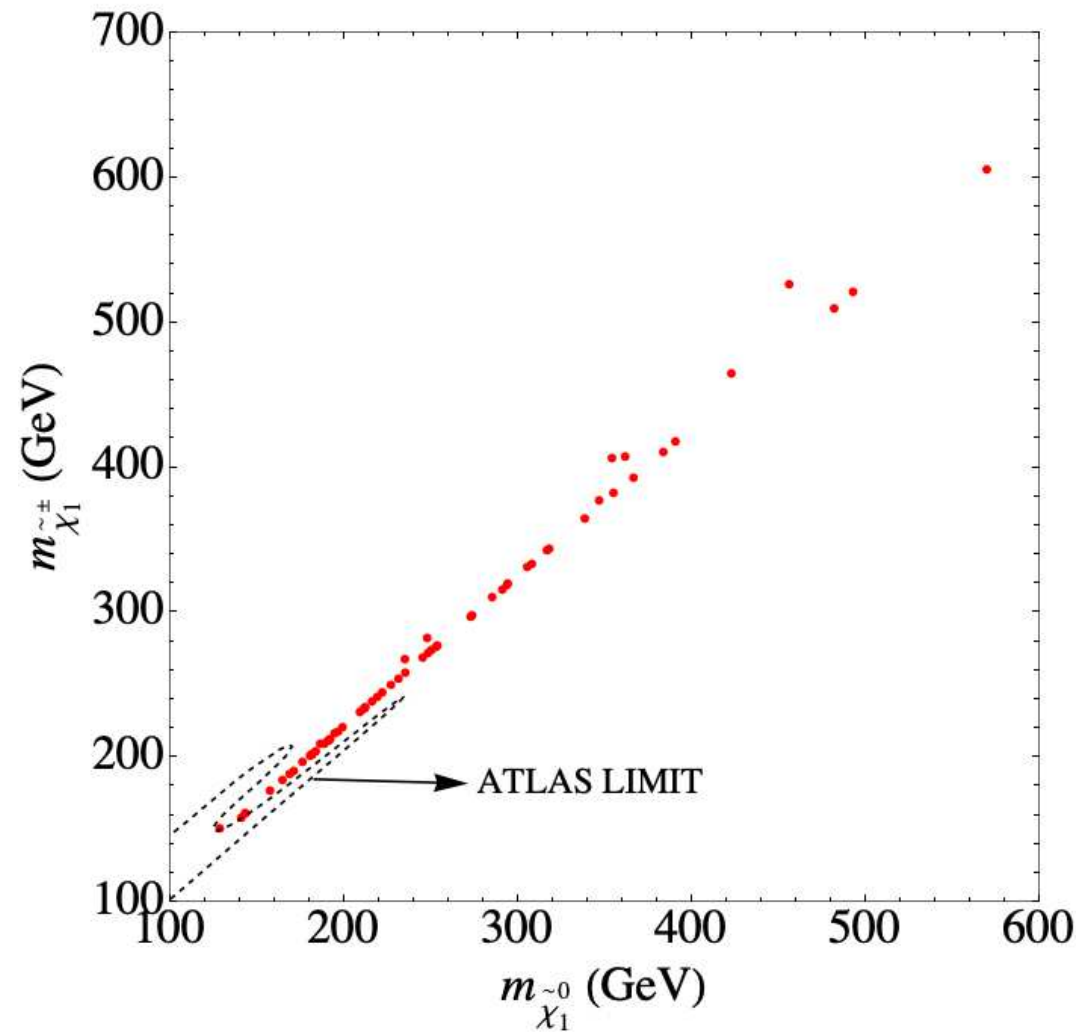
new $(g - 2)_\mu$



⇒ compressed spectrum as expected

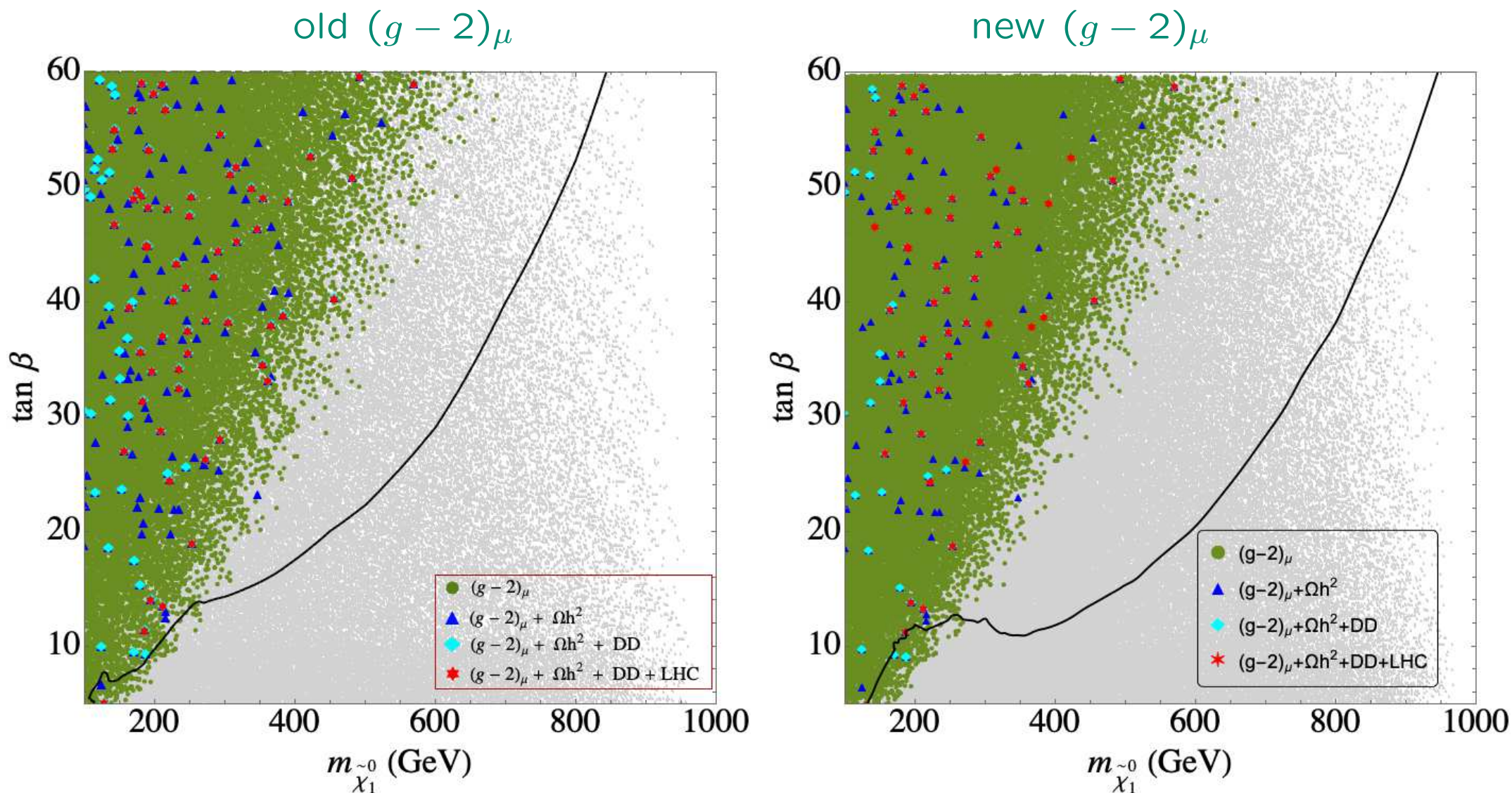
⇒ clear upper limits, $m_{(N)LSP} \lesssim 600(650)$ GeV confirmed

$\tilde{\chi}_1^\pm$ co-ann.: comparison with the compressed spectra searches:



⇒ compressed spectrum avoids current bounds!

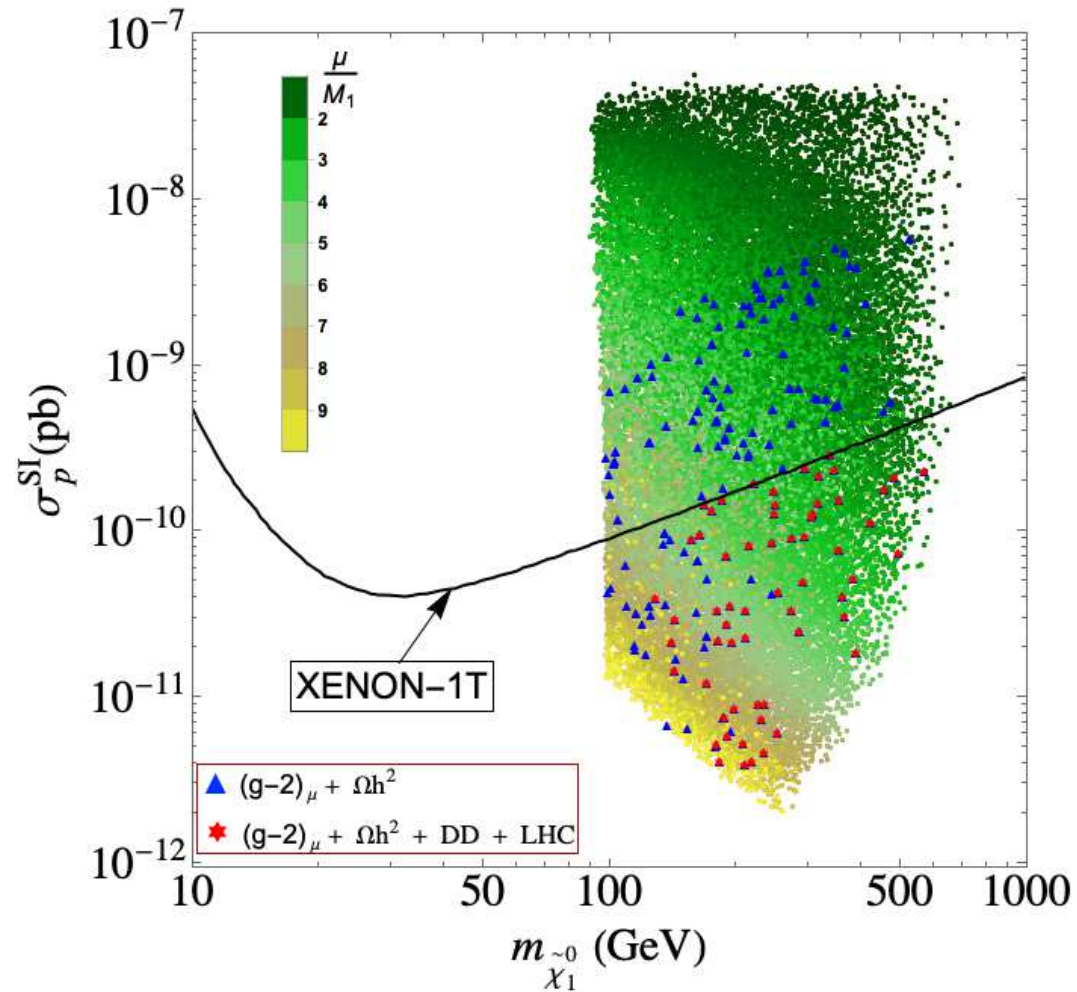
$\tilde{\chi}_1^\pm$ co-annihilation: results in the $m_{\tilde{\chi}_1^0}$ - $\tan\beta$ plane:



black contour: (simplified) application of $H/A \rightarrow \tau^+ \tau^-$
 \Rightarrow A -pole annihilation effectively excluded

$\tilde{\chi}_1^\pm$ co-annihilation: results in the $m_{\tilde{\chi}_1^0} - \sigma_p^{\text{SI}}$ plane:

old $(g-2)_\mu$



\Rightarrow larger μ values favored

B/C) Bino DM with slepton co-annihilation

[M. Chakraborti, S.H., I. Saha '20, '21]

Parameter scan:

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

$$M_1 \leq M_2 \leq 10M_1 ,$$

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

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

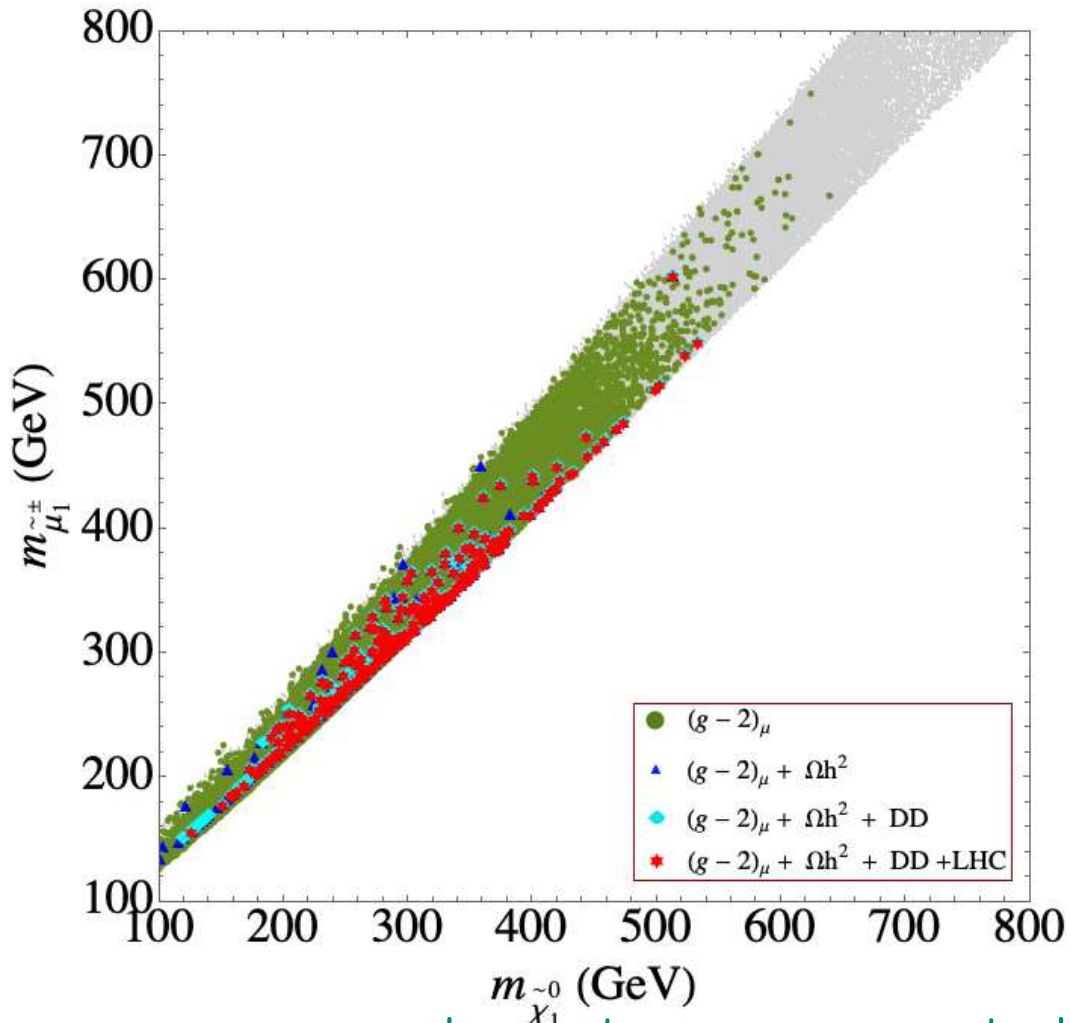
$$\text{Case-L: } M_1 \leq m_{\tilde{L}} \leq 1.2M_1, \quad M_1 \leq m_{\tilde{R}} \leq 10M_1 .$$

$$\text{Case-R: } M_1 \leq m_{\tilde{R}} \leq 1.2M_1, \quad M_1 \leq m_{\tilde{L}} \leq 10M_1 .$$

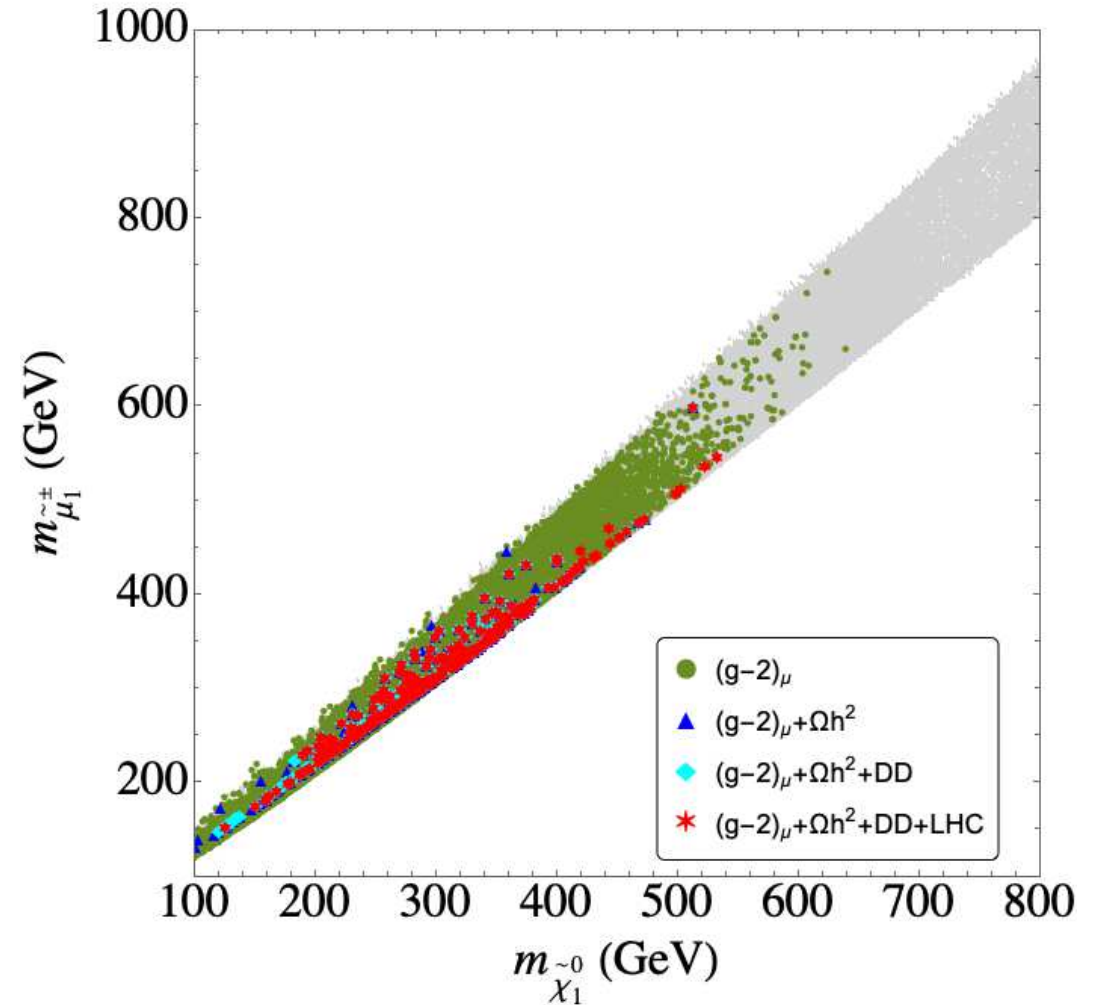
⇒ here focus on Case-L

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

old $(g-2)_\mu$



new $(g-2)_\mu$

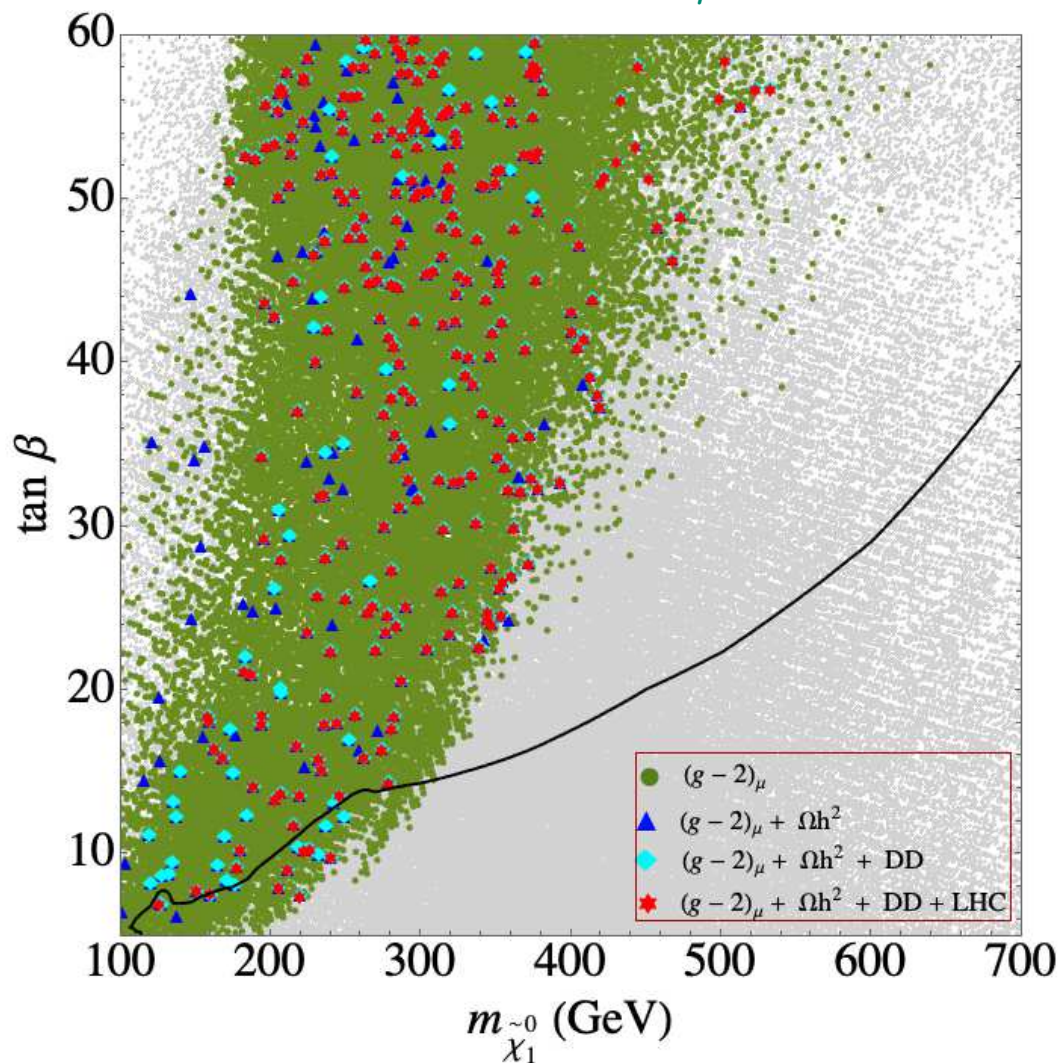


⇒ compressed spectrum as expected

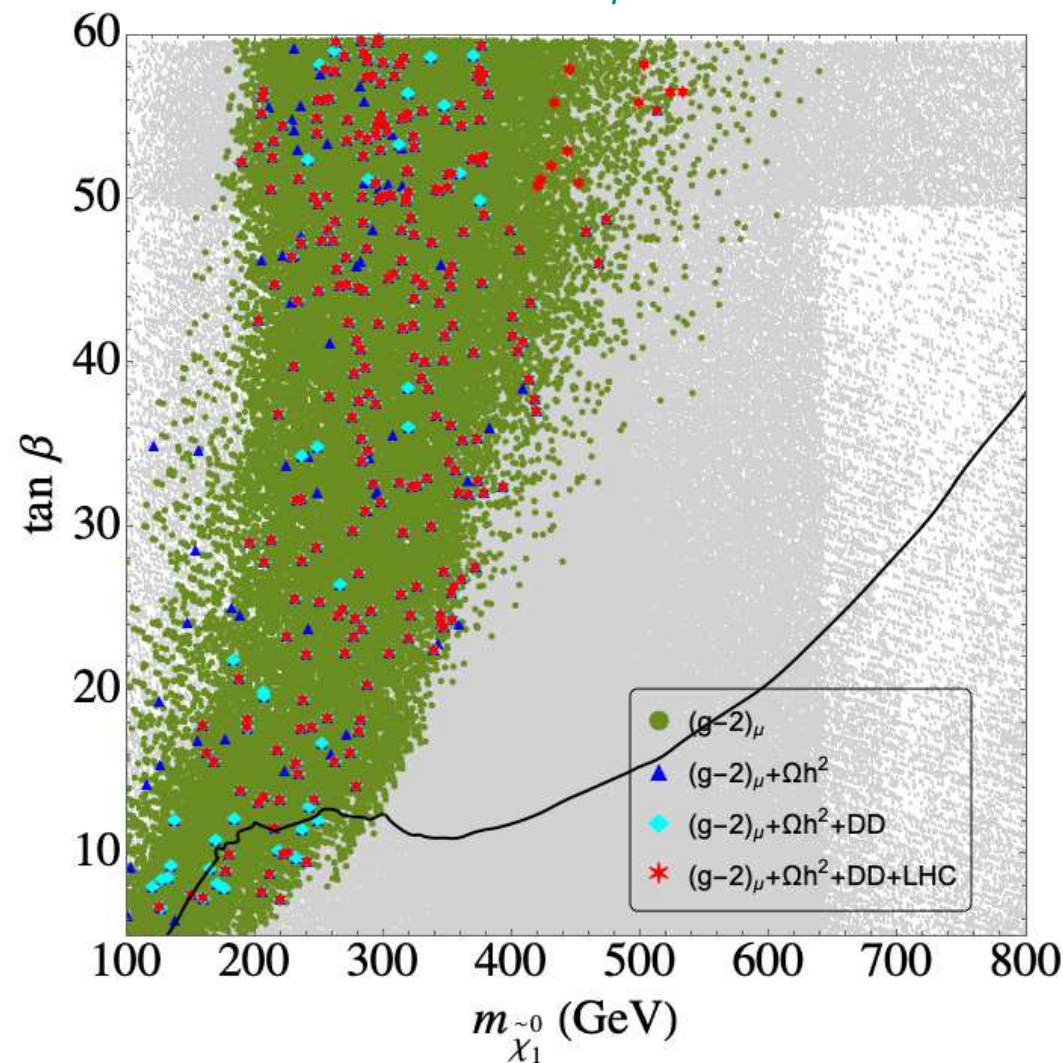
⇒ clear upper limits, $m_{(N)LSP} \lesssim 550(600)$ GeV confirmed

Slepton coann.: results in the $m_{\tilde{\chi}_1^0}$ - $\tan\beta$ plane:

old $(g-2)_\mu$



new $(g-2)_\mu$



black contour: (simplified) application of $H/A \rightarrow \tau^+ \tau^-$
 \Rightarrow A -pole annihilation largely excluded

D) Higgsino DM

[M. Chakraborti, S.H., I. Saha '21]

Parameter scan:

$$100 \text{ GeV} \leq \mu \leq 1.2 \text{ TeV} ,$$

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

$$1.1M_2 \leq \mu \leq 10\mu ,$$

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

$$100 \text{ GeV} \leq m_{\tilde{L}}, m_{\tilde{R}} \leq 2 \text{ TeV} ,$$

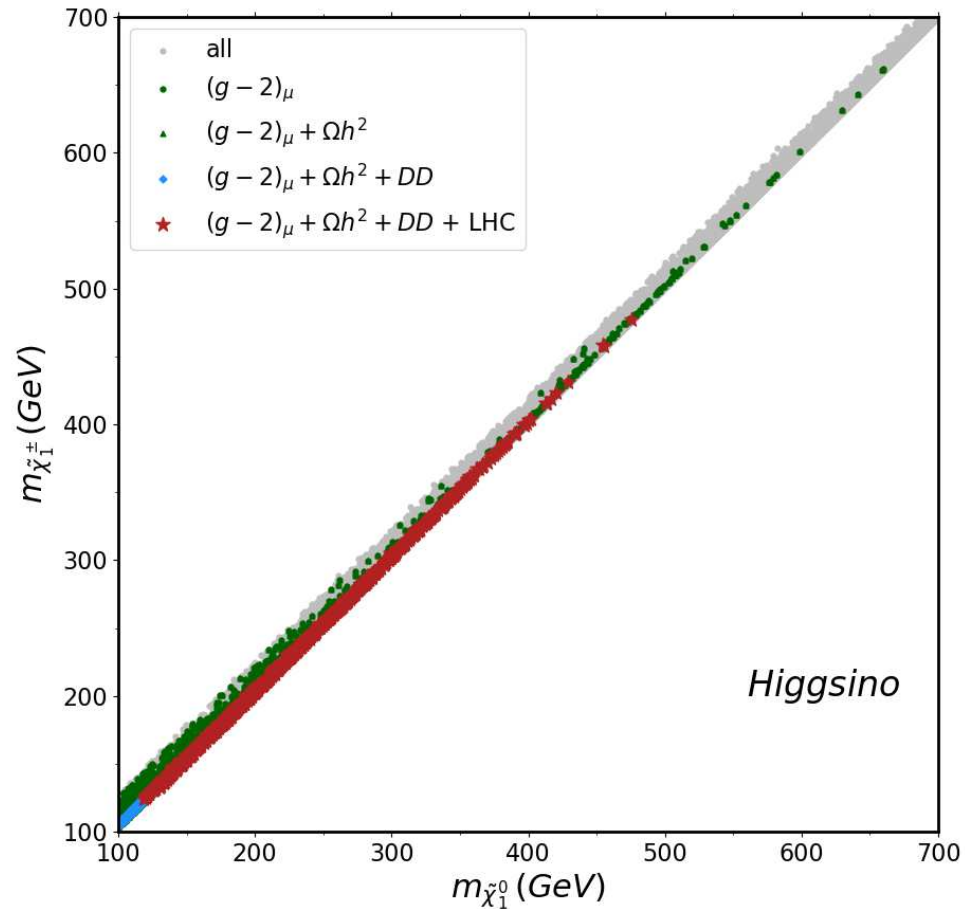
$$\Rightarrow m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim \mu$$

Full DM relic density reached only for $m_{\tilde{\chi}_1^0} \sim 1 \text{ TeV}$

\Rightarrow incompatible with $(g-2)_\mu$

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

old $(g - 2)_\mu$

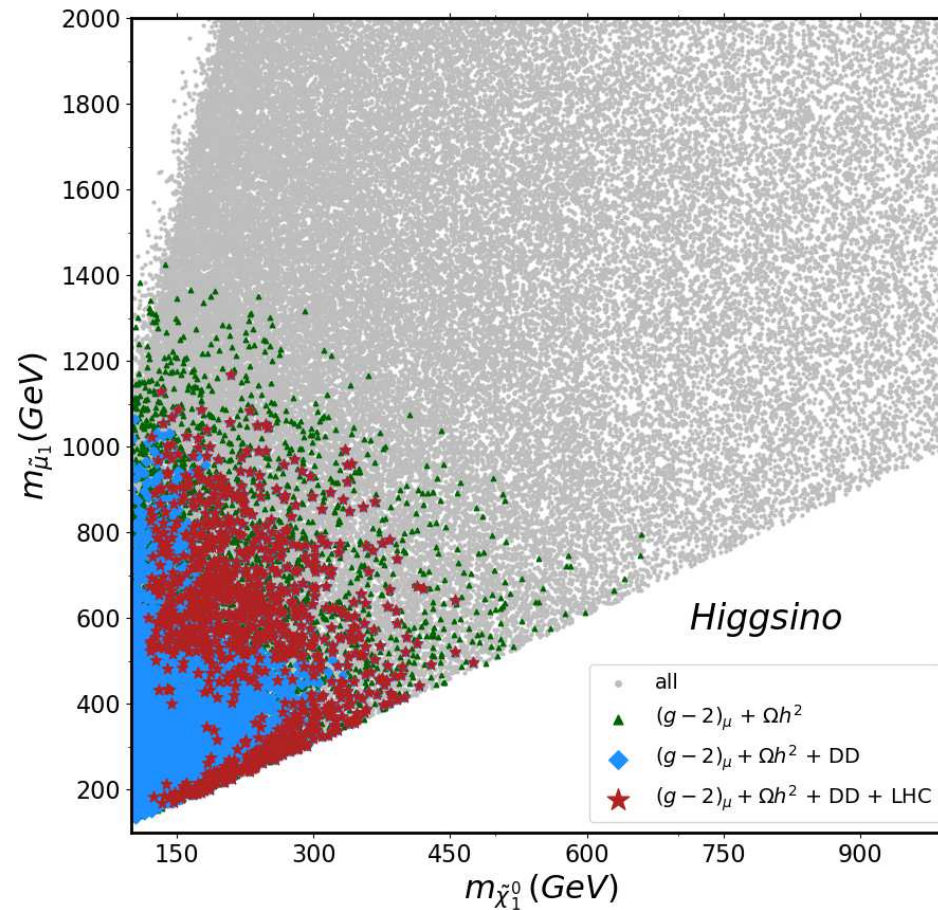


⇒ important: compressed spectra searches (11)

⇒ $\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow (W^* \tilde{\chi}_1^0)(Z^* \tilde{\chi}_1^0) \rightarrow 2l + \cancel{E}_T + \text{ISR} \Rightarrow m_{(N)\text{LSP}} \lesssim 500 \text{ GeV}$

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

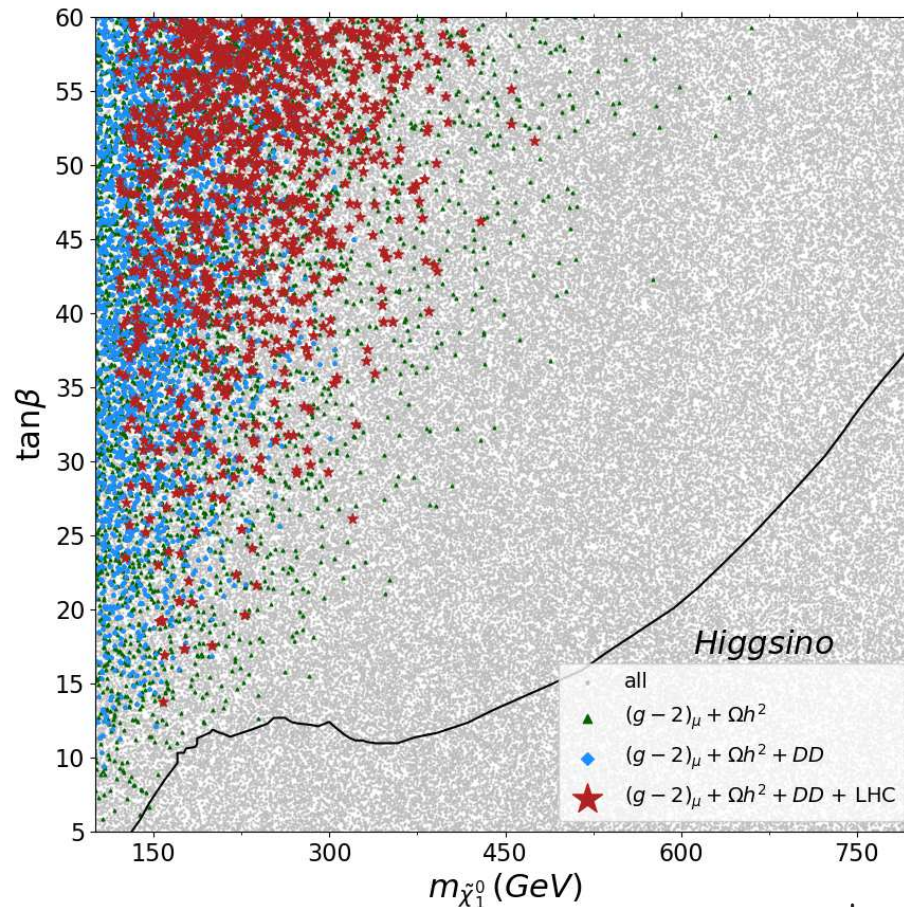
old $(g - 2)_\mu$



\Rightarrow upper limit on slepton masses: $m_{\tilde{l}_1} \lesssim 1.1$ TeV

Higgsino DM: results in the $m_{\tilde{\chi}_1^0}$ - $\tan\beta$ plane:

old $(g-2)_\mu$



black contour: (simplified) application of $H/A \rightarrow \tau^+ \tau^-$
 $\Rightarrow A$ -pole annihilation fully excluded

E) Wino DM

[M. Chakraborti, S.H., I. Saha '20, '21]

Parameter scan:

$$100 \text{ GeV} \leq M_2 \leq 1.5 \text{ TeV} ,$$

$$1.1M_2 \leq M_1 \leq 10M_2 ,$$

$$1.1M_2 \leq \mu \leq 10M_2 ,$$

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

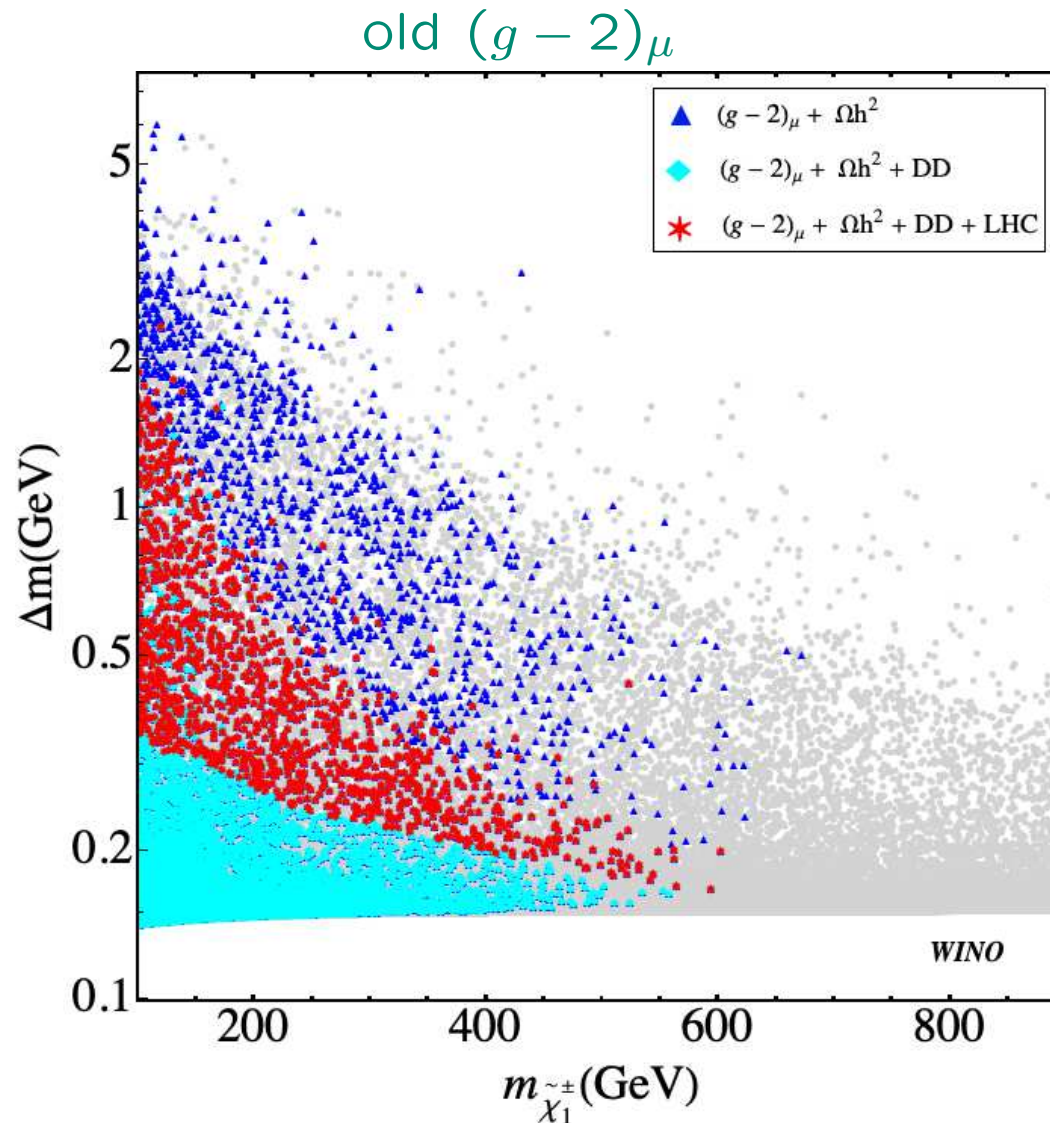
$$100 \text{ GeV} \leq m_{\tilde{L}}, m_{\tilde{R}} \leq 2 \text{ TeV} ,$$

$$\Rightarrow m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^\pm} \sim M_2$$

Full DM relic density reached only for $m_{\tilde{\chi}_1^0} \sim 3 \text{ TeV}$

\Rightarrow incompatible with $(g-2)_\mu$

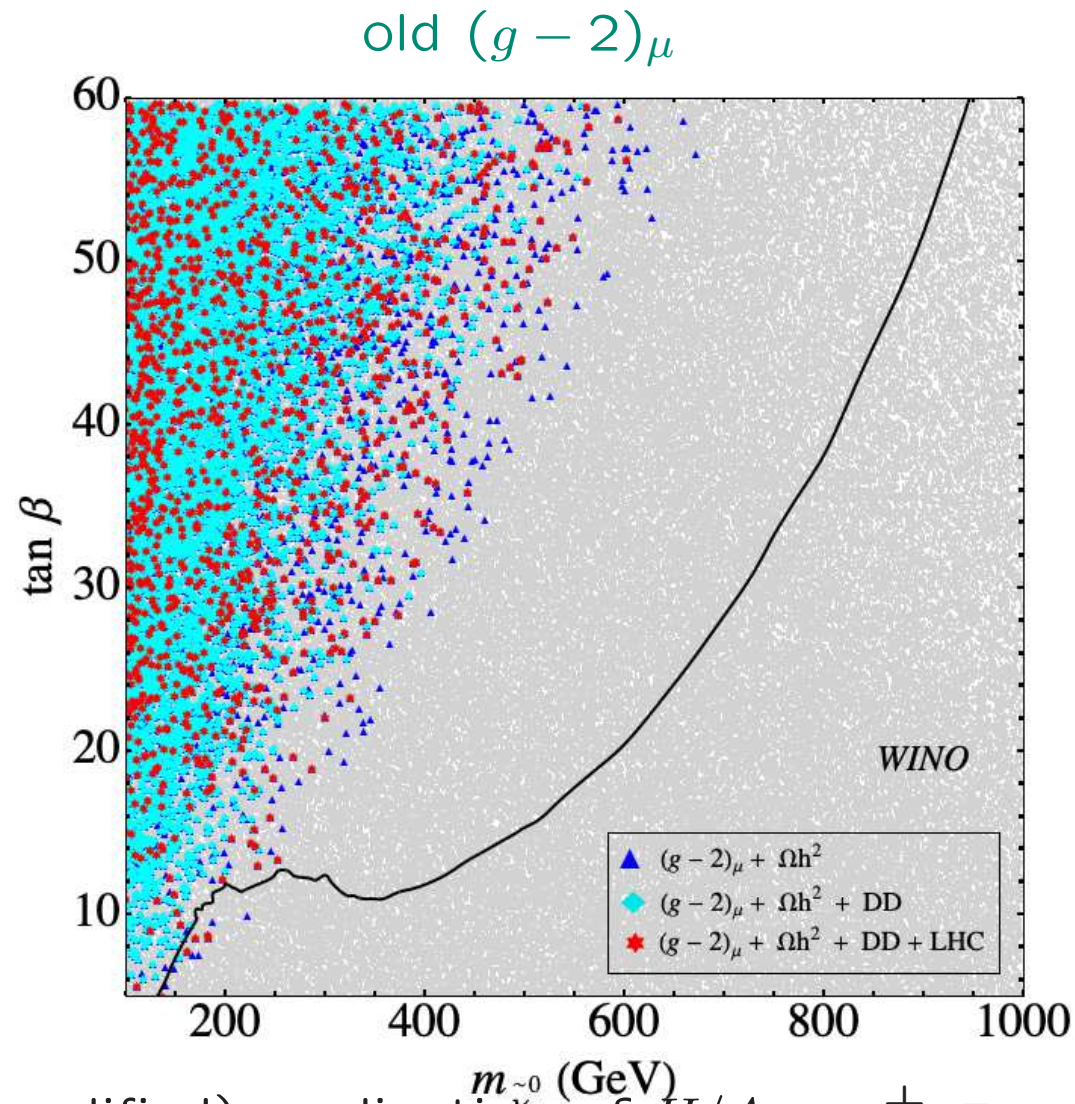
Results in the $m_{\tilde{\chi}_1^\pm} - \Delta m$ plane:



⇒ important: disappearing track limit ⇒ $m_{(N)\text{LSP}} \lesssim 600 \text{ GeV}$

⇒ allowed parameter space squeezed by DD limits and disapp. tracks

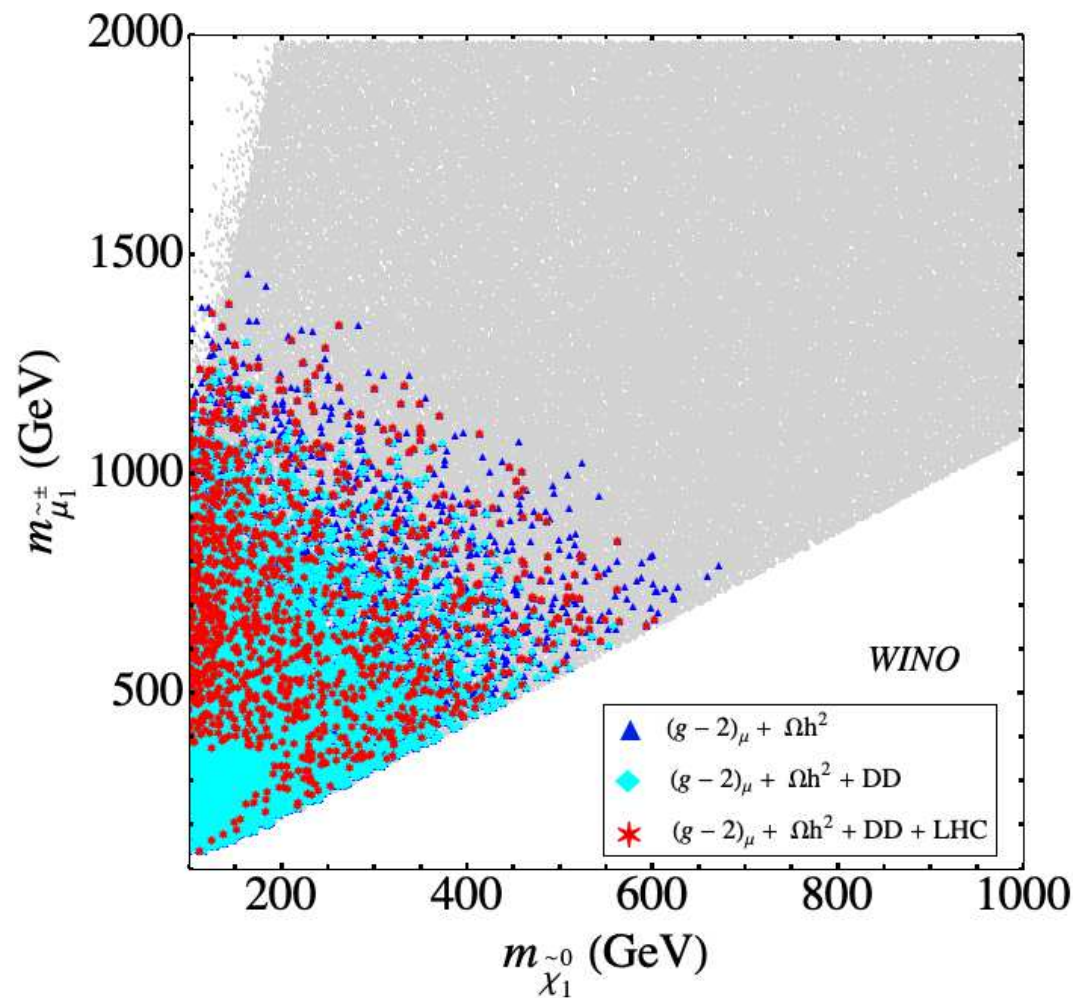
Wino DM: results in the $m_{\tilde{\chi}_1^0}$ - $\tan\beta$ plane:



black contour: (simplified) application of $H/A \rightarrow \tau^+\tau^-$
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Results in the $m_{\tilde{\chi}_1^0} - m_{\tilde{l}_1}$ plane:

old $(g - 2)_\mu$

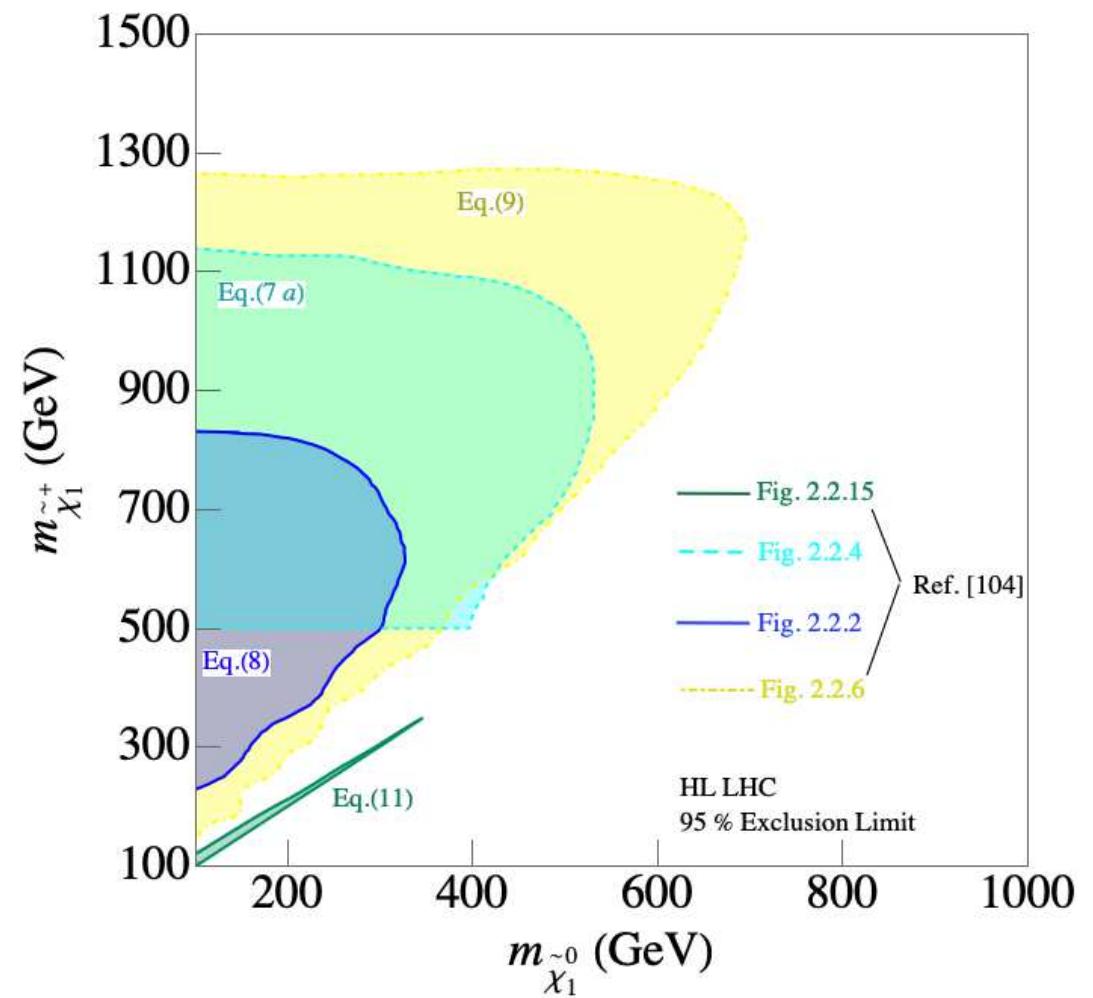
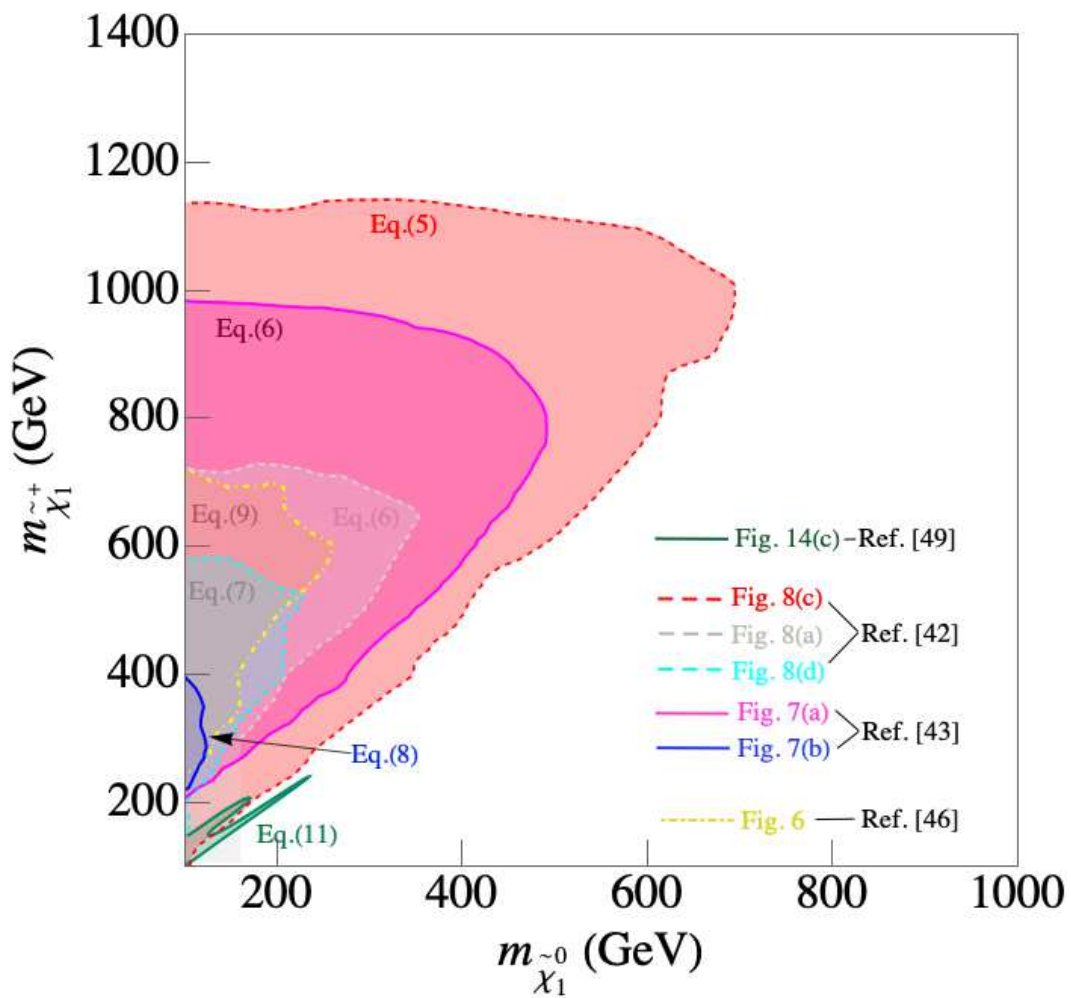


$\Rightarrow m_{\tilde{l}_1} \lesssim 1400(1200) \text{ GeV}$

LHC exclusion bounds vs. HL-LHC exclusion bounds

not all channels available

[YR18]



⇒ exclusion reach can be important

⇒ no CheckMate inclusion available . . .