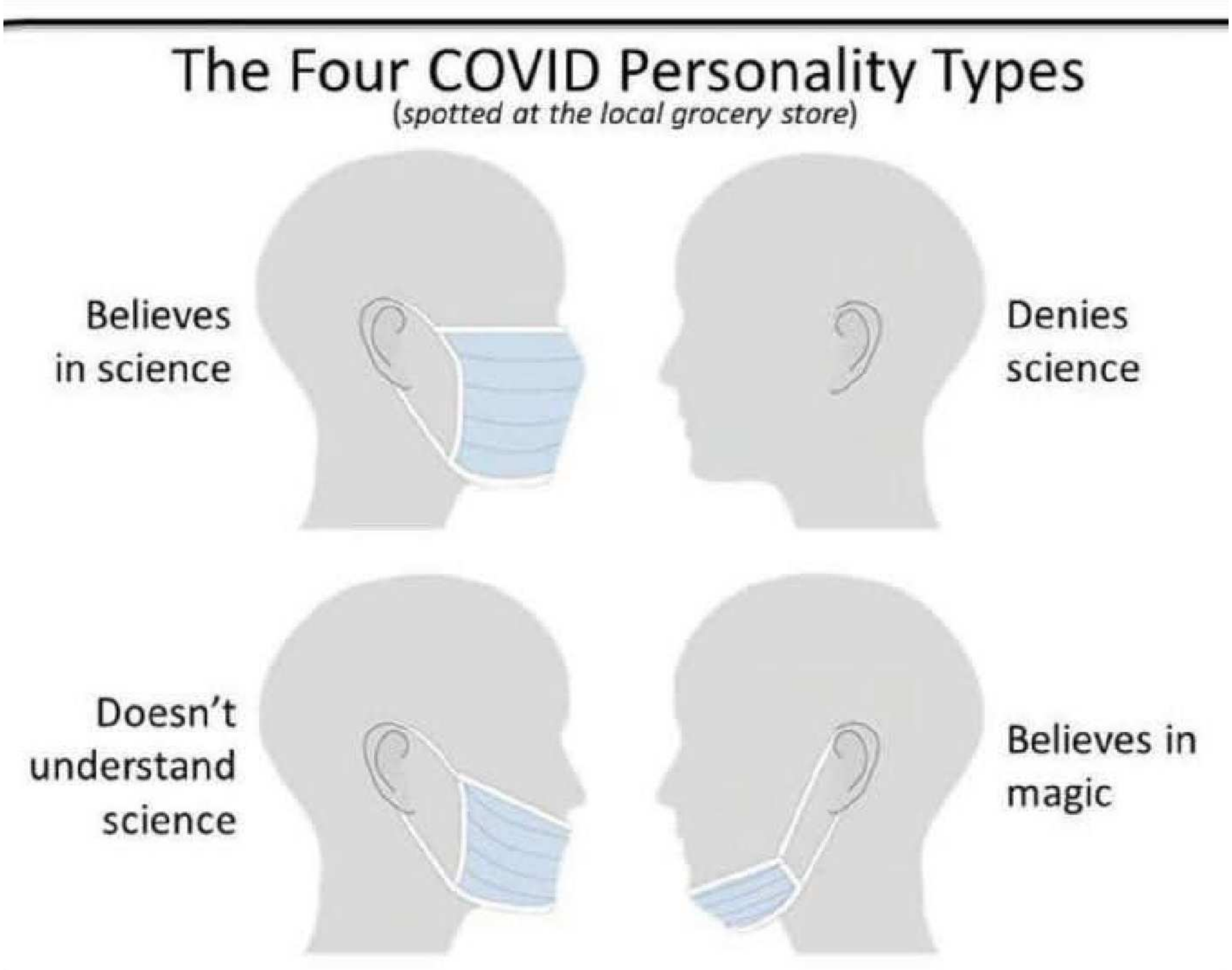

The Four COVID Personality Types
(spotted at the local grocery store)
Believes in science
Denies science
Doesn't understand science
Believes in magic

# The new "MUON G-2" Result and Supersymmetry

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

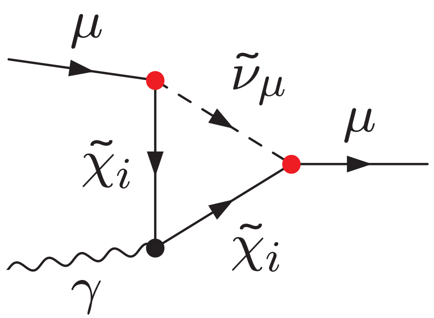
virtual, 05/2021

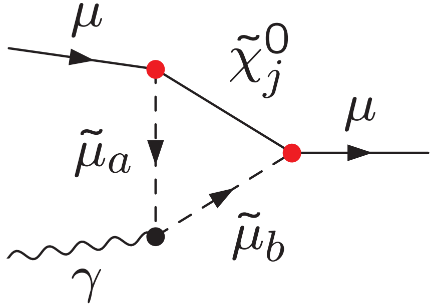
In collaboration with: *M. Chakraborti, I. Saha*

[*arXiv:2006.15157 (EPJC), 2103.13403, 2104.03287*]

## SUSY can easily explain the deviation in $a_\mu$:

Feynman diagrams for MSSM 1L corrections:




– Diagrams with chargino/sneutrino exchange

– Diagrams with neutralino/smuon exchange

Enhancement factor as compared to SM:

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

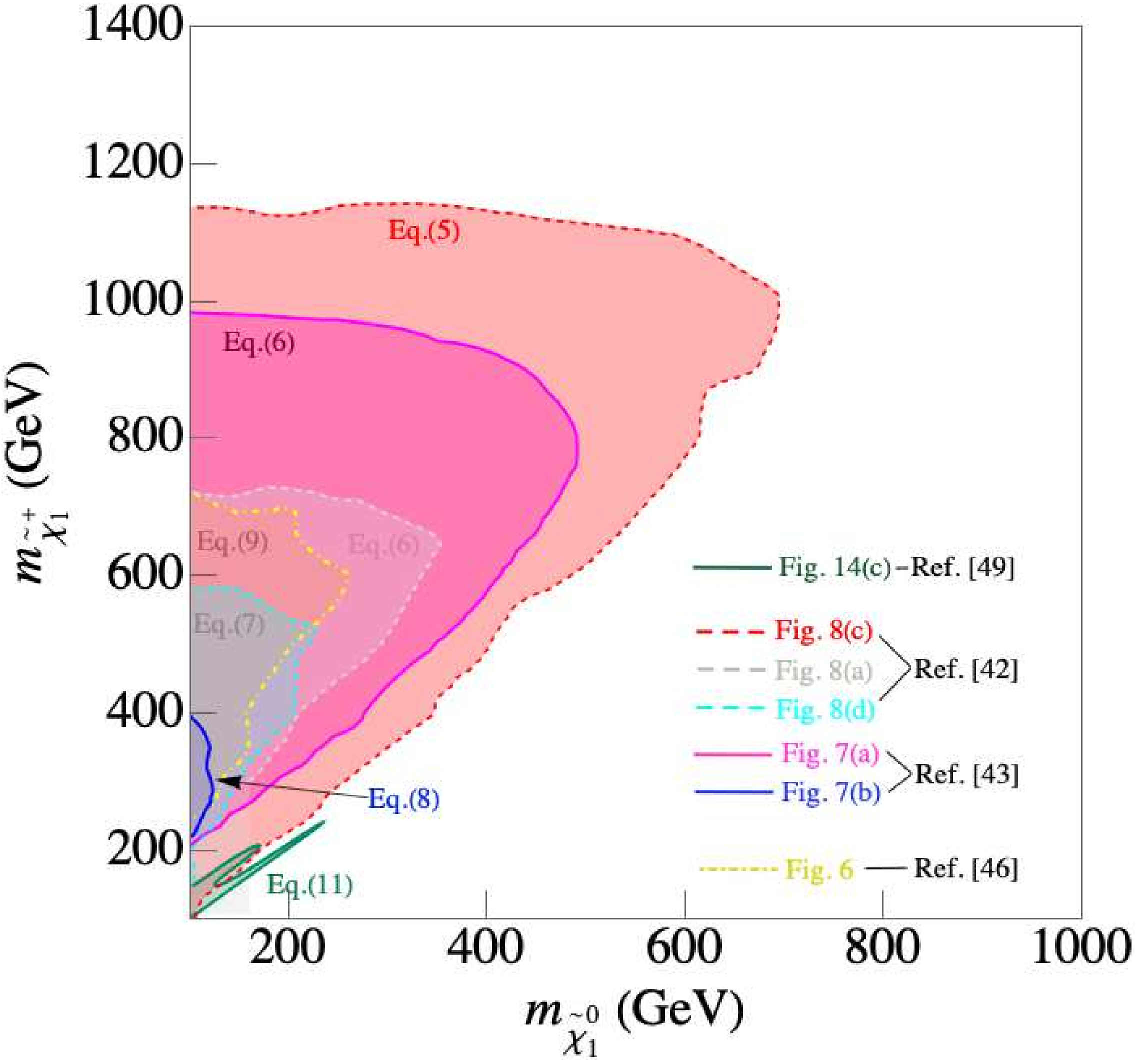
SM, EW 1L: $\frac{\alpha}{\pi}\,\frac{m_\mu^2}{M_W^2}$

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

## 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

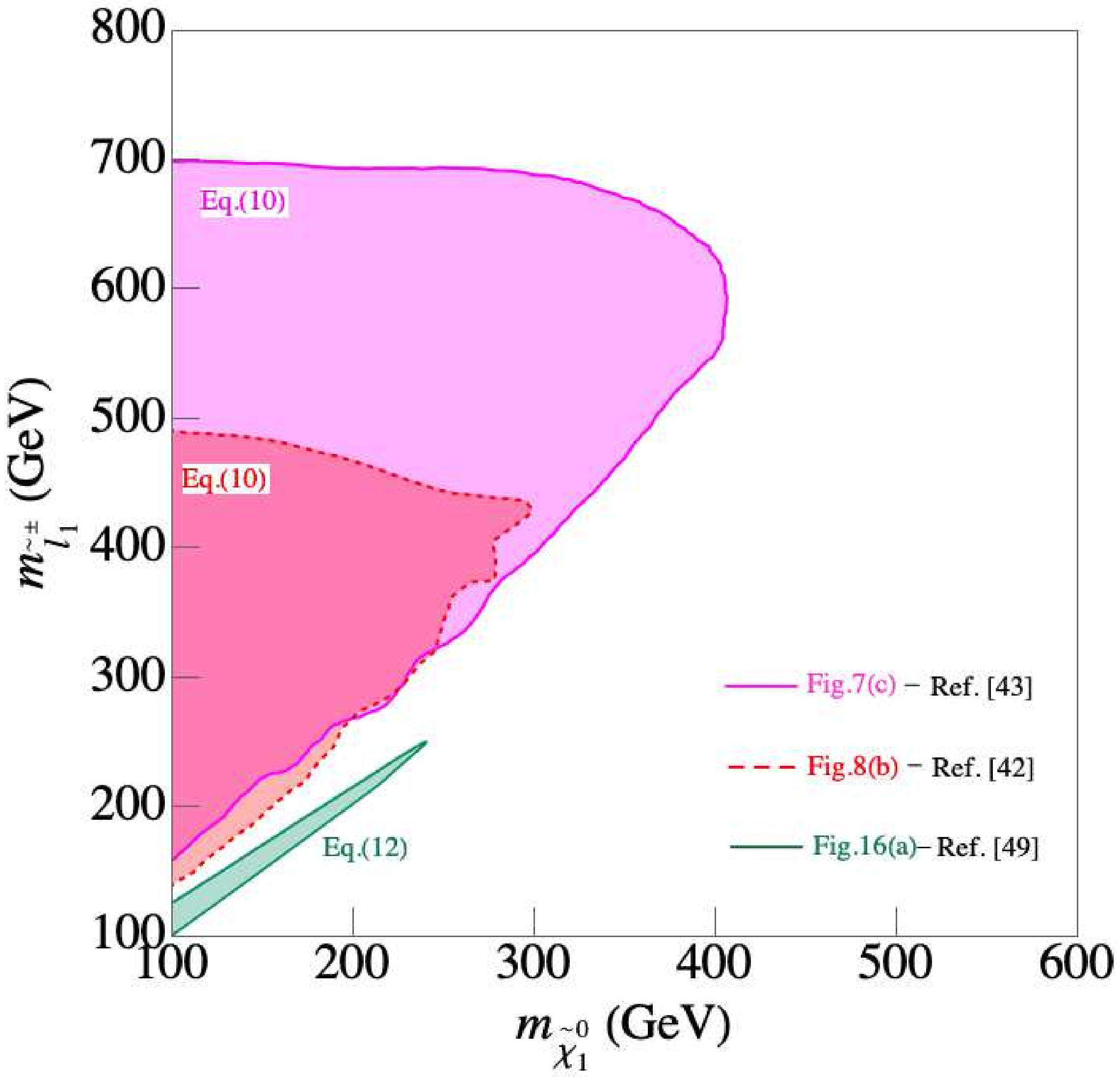
# LHC exclusion bounds (I) (as given for Simplified Model Spectra (SMS))




⇒ 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)

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

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

Note: $\Delta a_\mu^{\text{old}} - 2\,\sigma^{\text{old}} \approx \Delta a_\mu^{\text{new}} - 2\,\sigma^{\text{new}}$
⇒ upper limits on SUSY masses are not expected to change

## Dark Matter relic density: MicrOmegas

$$\Omega_{\text{CDM}} h^2 = 0.120 \pm 0.001$$
$$\text{or} \quad \Omega_{\text{CDM}} h^2 \leq 0.122$$

(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
   $\Rightarrow$ full relic DM constraint $\Rightarrow$ updated with $\Delta a_\mu^{\text{new}}$

2. bino DM with slepton co-annihilation case-L
   $\Rightarrow$ full relic DM constraint $\Rightarrow$ updated with $\Delta a_\mu^{\text{new}}$

3. bino DM with slepton co-annihilation case-R
   $\Rightarrow$ full relic DM constraint $\Rightarrow$ 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 $\Rightarrow m_{\tilde\chi_1^0} \sim 1$ TeV $\Rightarrow (g-2)_\mu$ not ok
   $\Rightarrow$ relic DM upper bound

5. wino DM: $m_{\tilde\chi_1^0} \approx m_{\tilde\chi_1^\pm}$
   full relic DM constraint $\Rightarrow m_{\tilde\chi_1^0} \sim 3$ TeV $\Rightarrow (g-2)_\mu$ not ok
   $\Rightarrow$ relic DM upper bound

## Mini summary of the results:

A) bino/wino DM with chargino co-annihilation

relic DM density 100% fulfilled

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

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

relic DM density 100% fulfilled

$\Rightarrow m_{\text{(N)LSP}} \lesssim$ 550(600) GeV 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 $m_{\tilde{\chi}_1^0} \sim 1$ TeV)

$\Rightarrow m_{\text{(N)LSP}} \lesssim$ 500 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 $m_{\tilde{\chi}_1^0} \sim 3$ TeV)

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

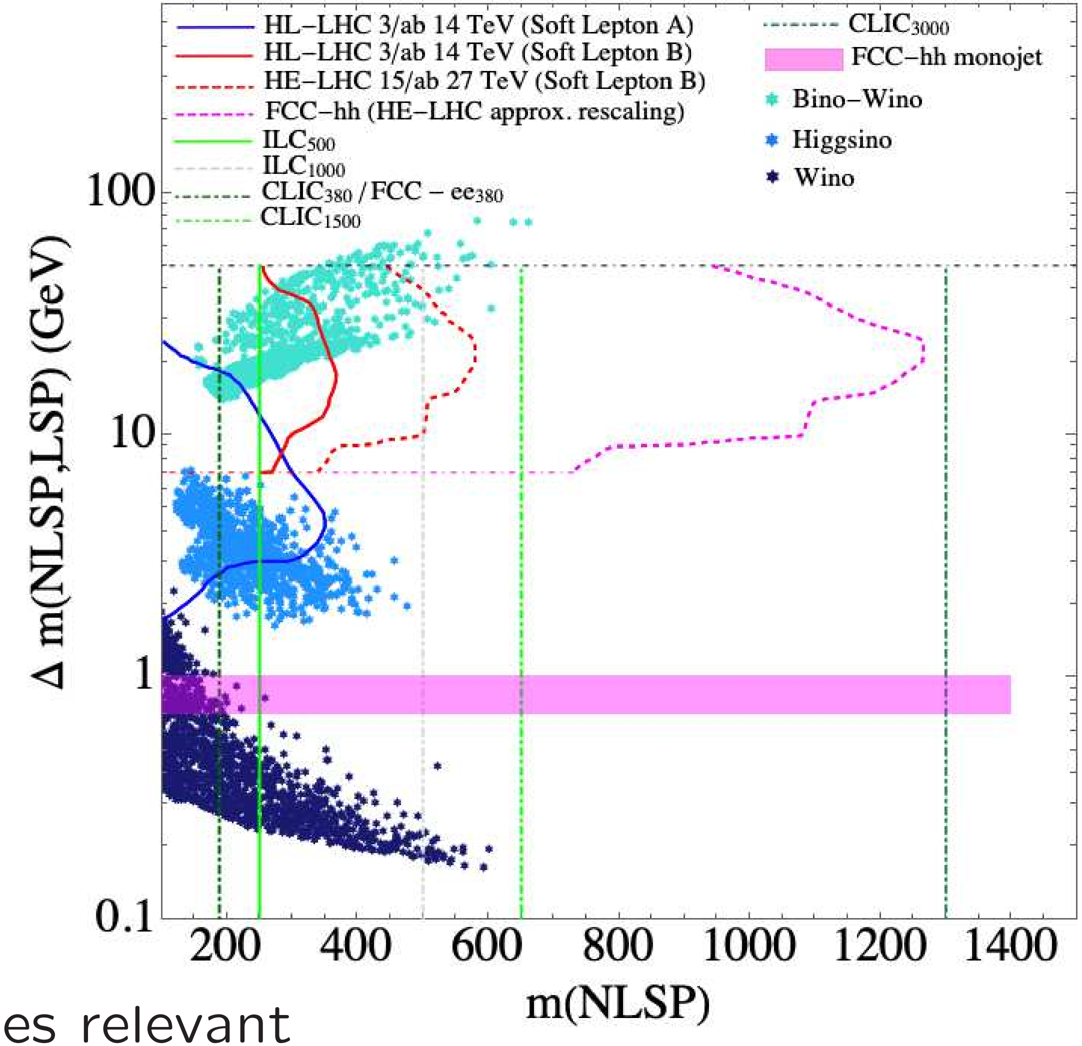
$\Rightarrow$ predictions for future $(e^+e^-)$ colliders?!

# Predictions for future colliders

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

# Compressed spectra at current and future colliders

## Higgsino, wino and bino/wino DM:



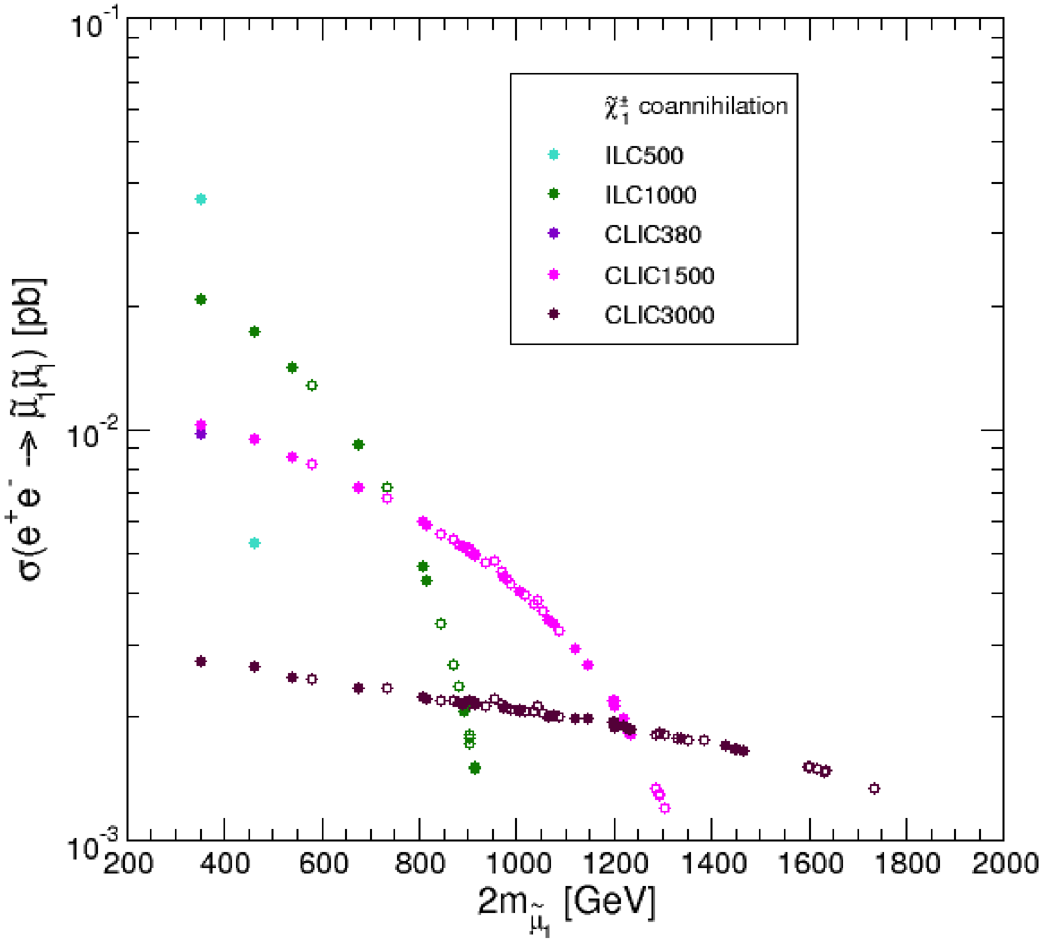

– current searches relevant

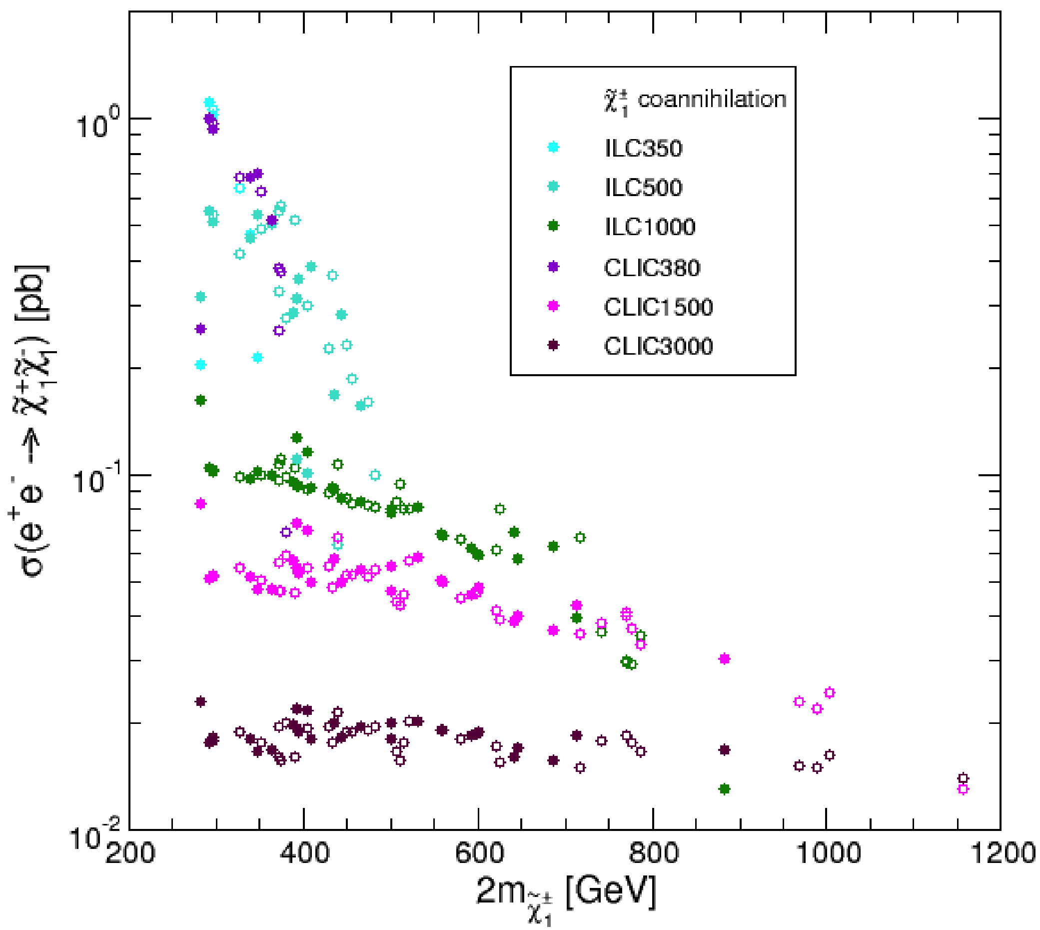
– HL-LHC searches can cover some part of the parameter space

– ILC/CLIC needed to cover these scenario

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

wino/bino DM with chargino co-ann. (open/full: "old" $(g-2)_\mu$)



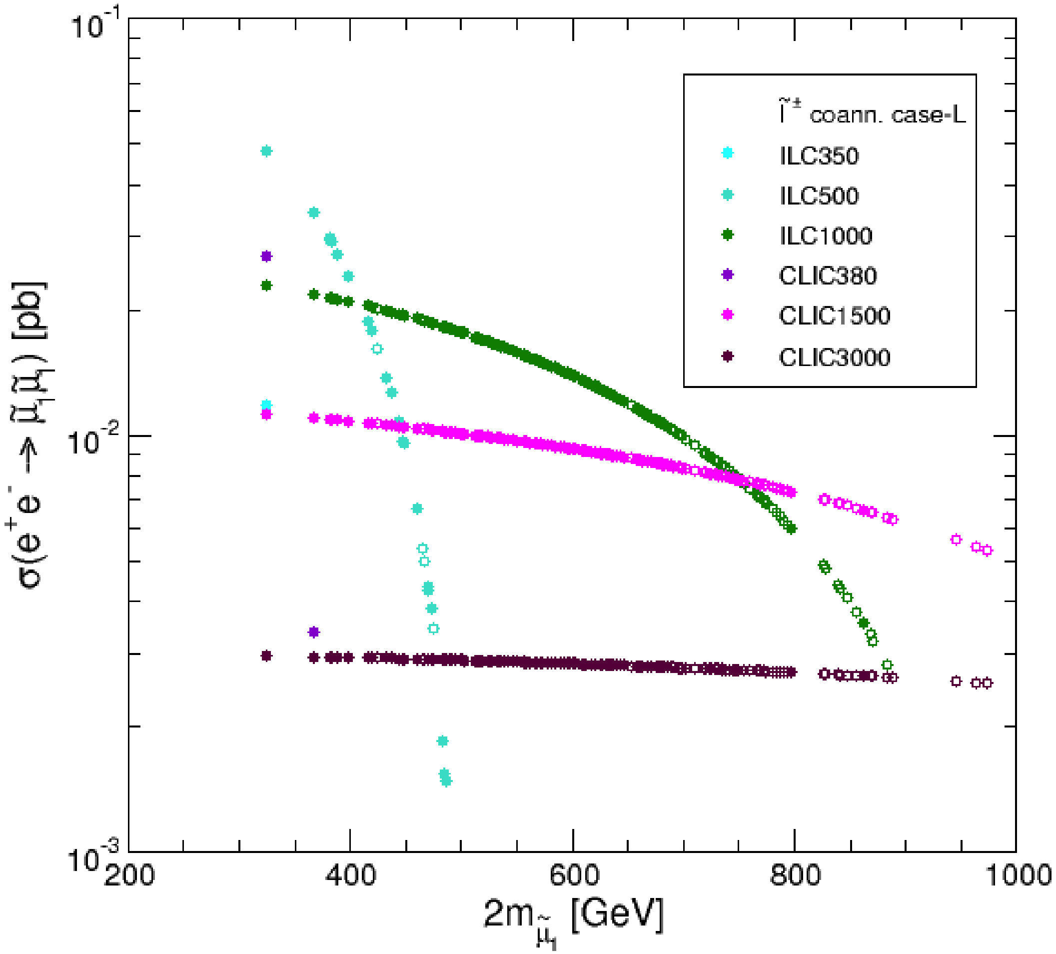



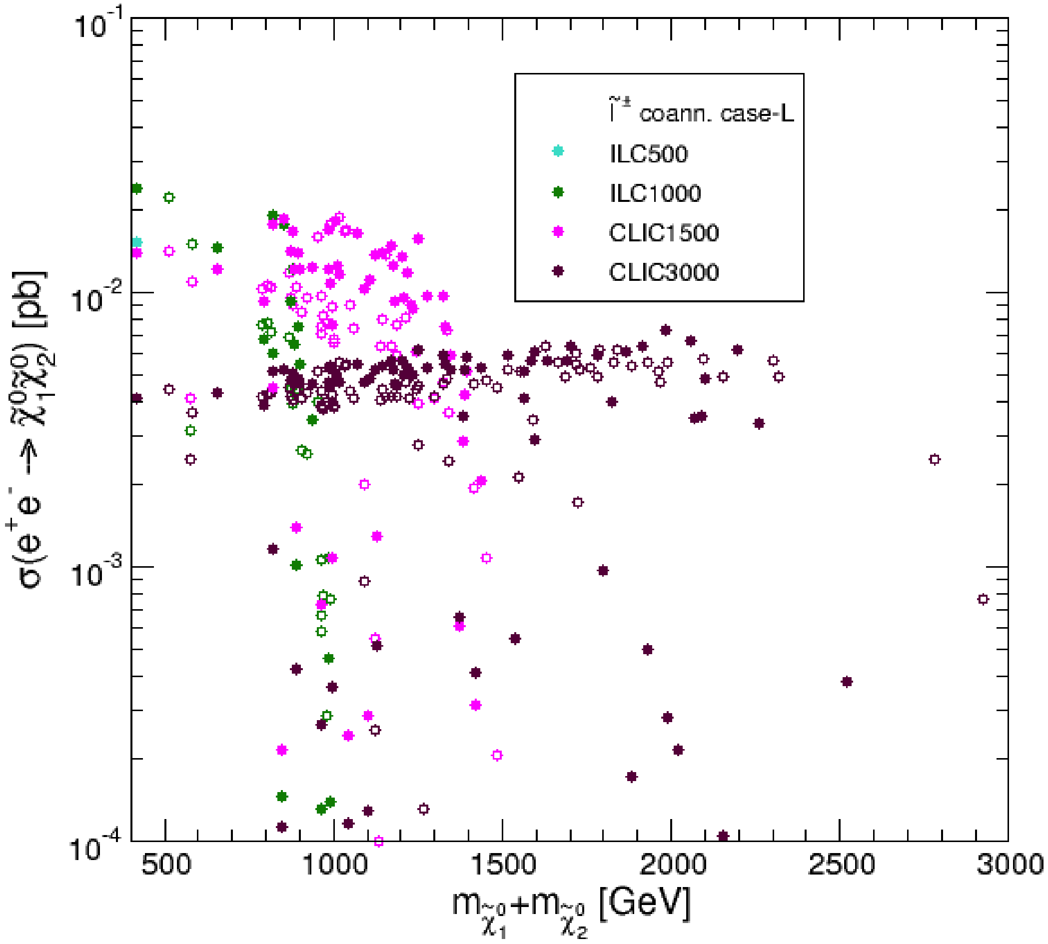

$\Rightarrow$ ILC has good prospects (particularly for $\tilde\chi_1^\pm\tilde\chi_1^\mp$)

$\Rightarrow$ CLIC can cover evertything

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

bino DM with slepton co-ann. (open/full: "old" $(g-2)_\mu$)



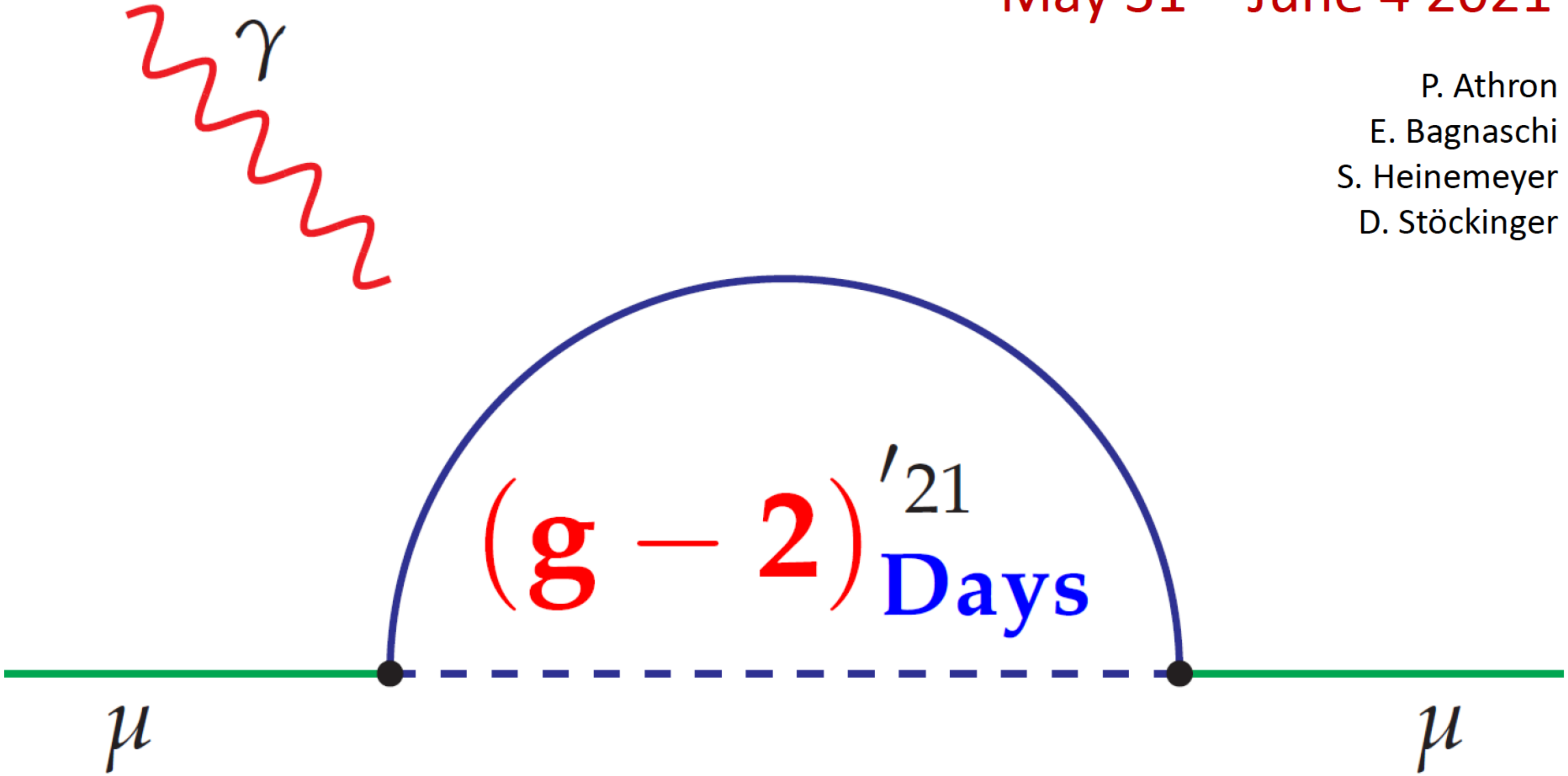

$\Rightarrow$ ILC can nearly covers full smuon channel (but not $\tilde{\chi}^0_1\tilde{\chi}^0_2$)

$\Rightarrow$ CLIC can cover evertything

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

May 31 – June 4 2021

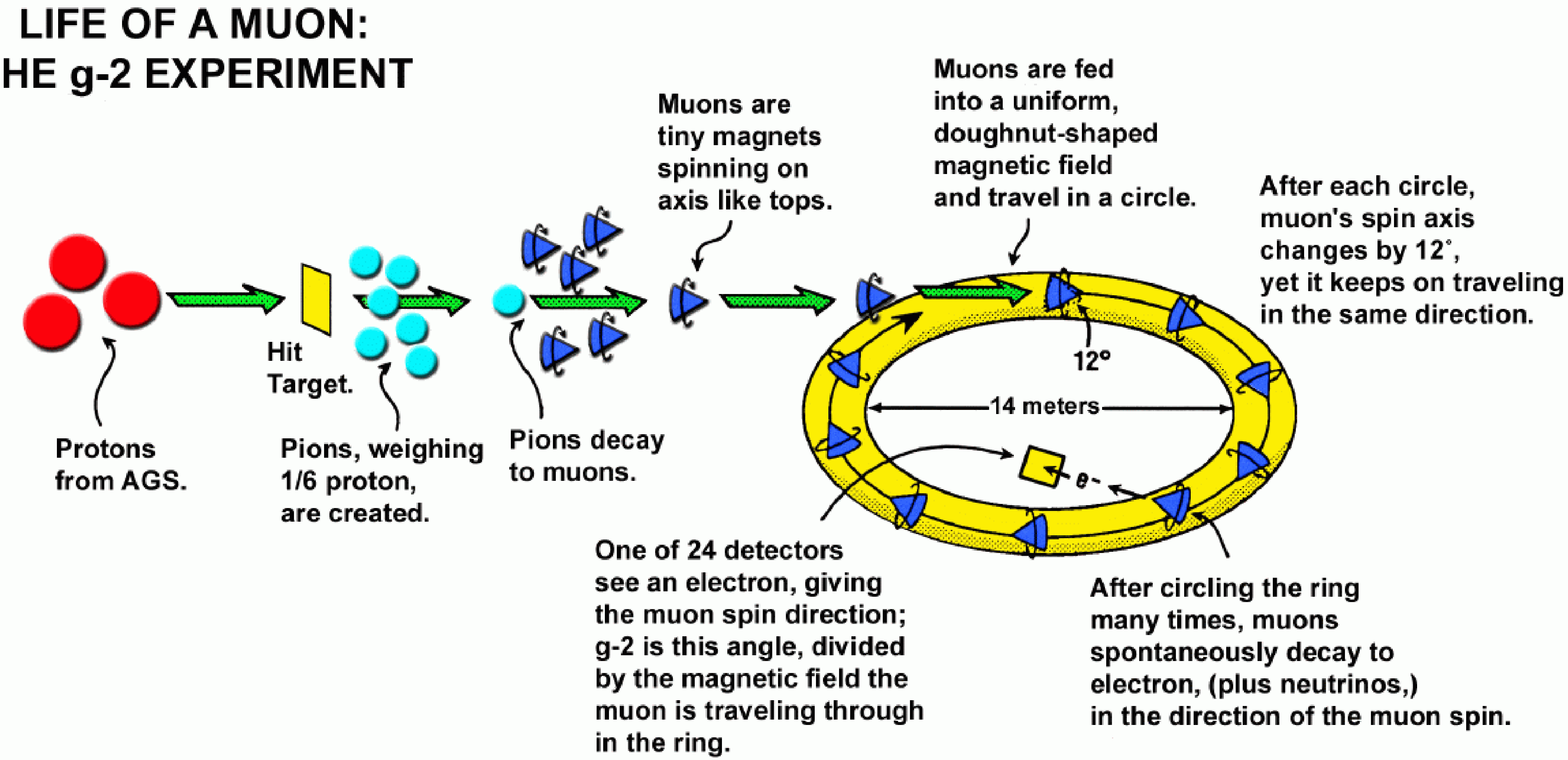
P. Athron
E. Bagnaschi
S. Heinemeyer
D. Stöckinger




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


Further Questions?

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

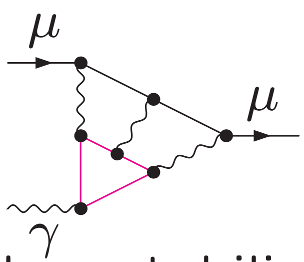



Coupling of muon to magnetic field : $\mu - \mu - \gamma$ coupling

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

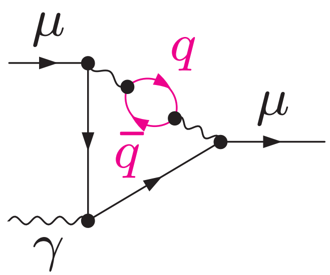
## Theory of $(g-2)_\mu$:

– the light-by-light contribution:




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

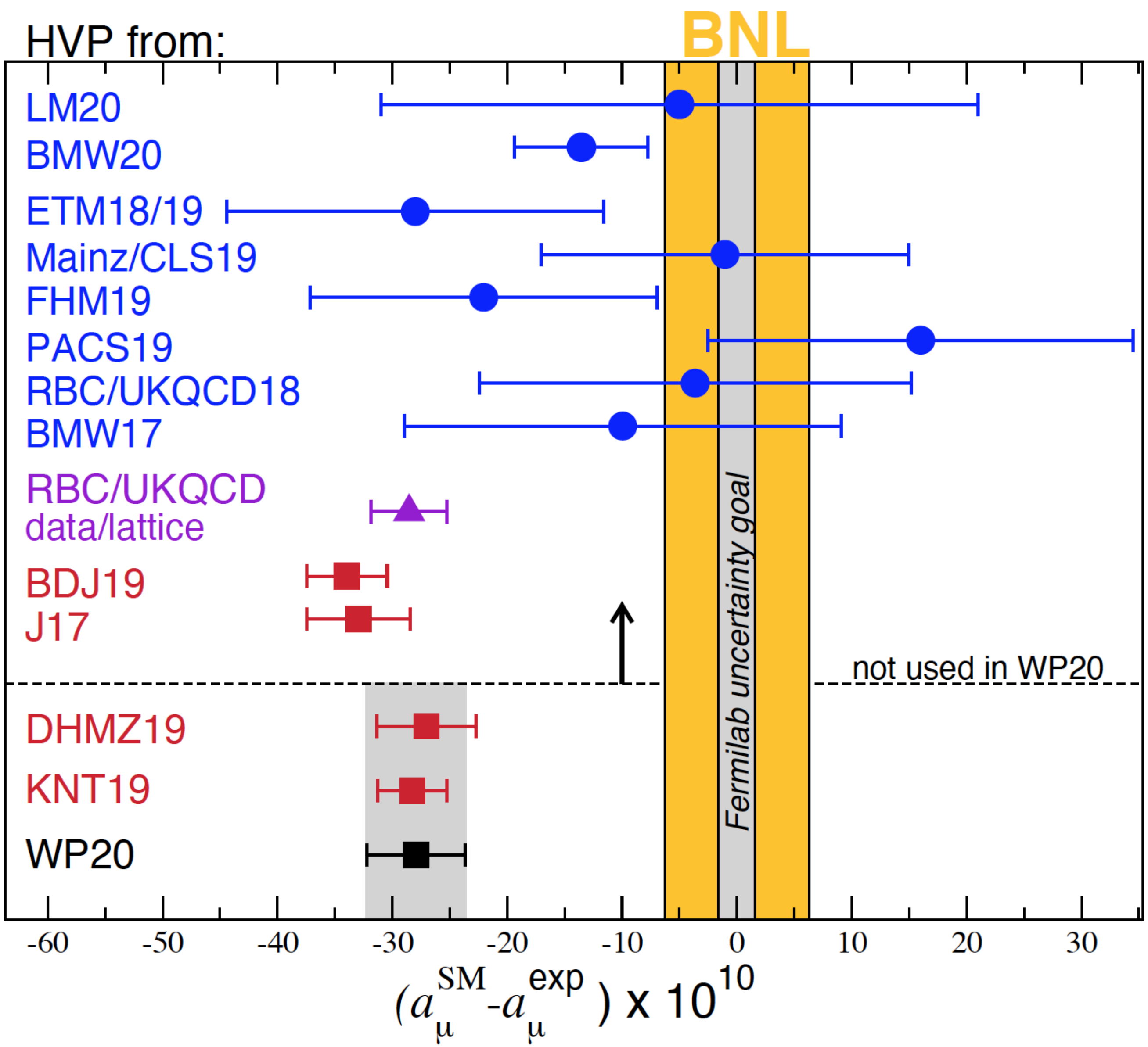
– the hadronic vacuum contribution:




'direct' $e^+e^-$ data:
from CMD-II, SND, KLOE, BaBar (radiative return)
$\Rightarrow$ agree relarively well (also with old $e^+e^-$ data)
$\Rightarrow$ tension with LQCD results

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

# HVP summary:




$\Rightarrow$ BMW20: difference to experimental data $\sim 1.5\,\sigma$

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

### 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

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

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

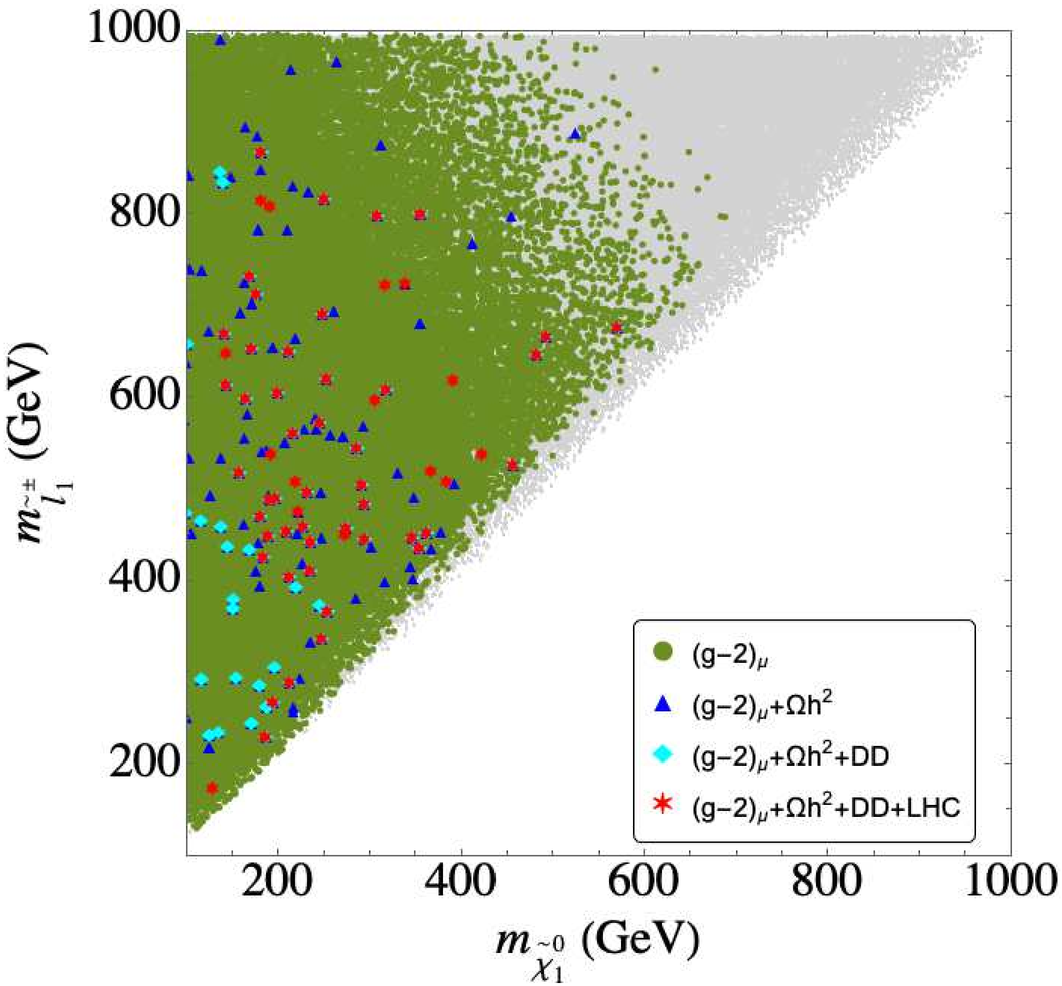
## Searches involving Staus

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

Exception: compressed spectra ⇒ direct application

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

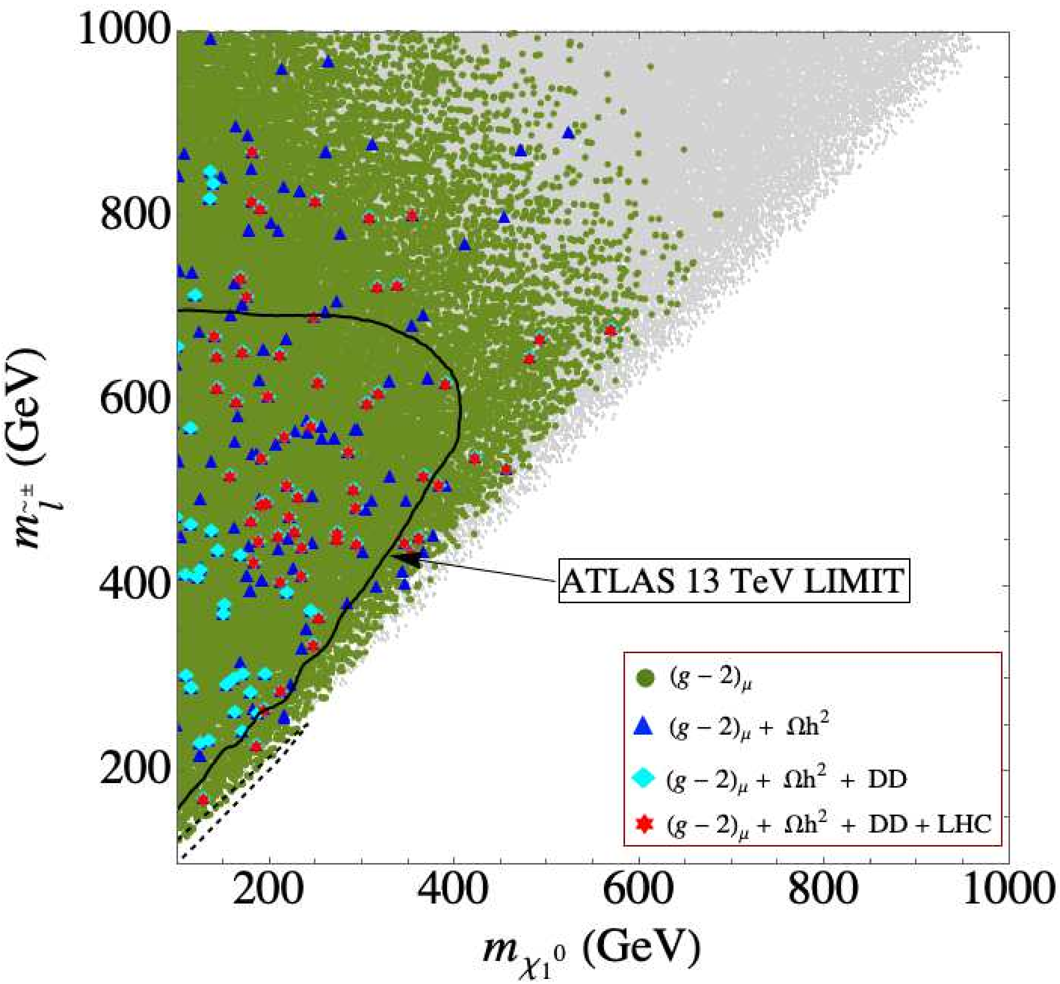
new $(g-2)_\mu$




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

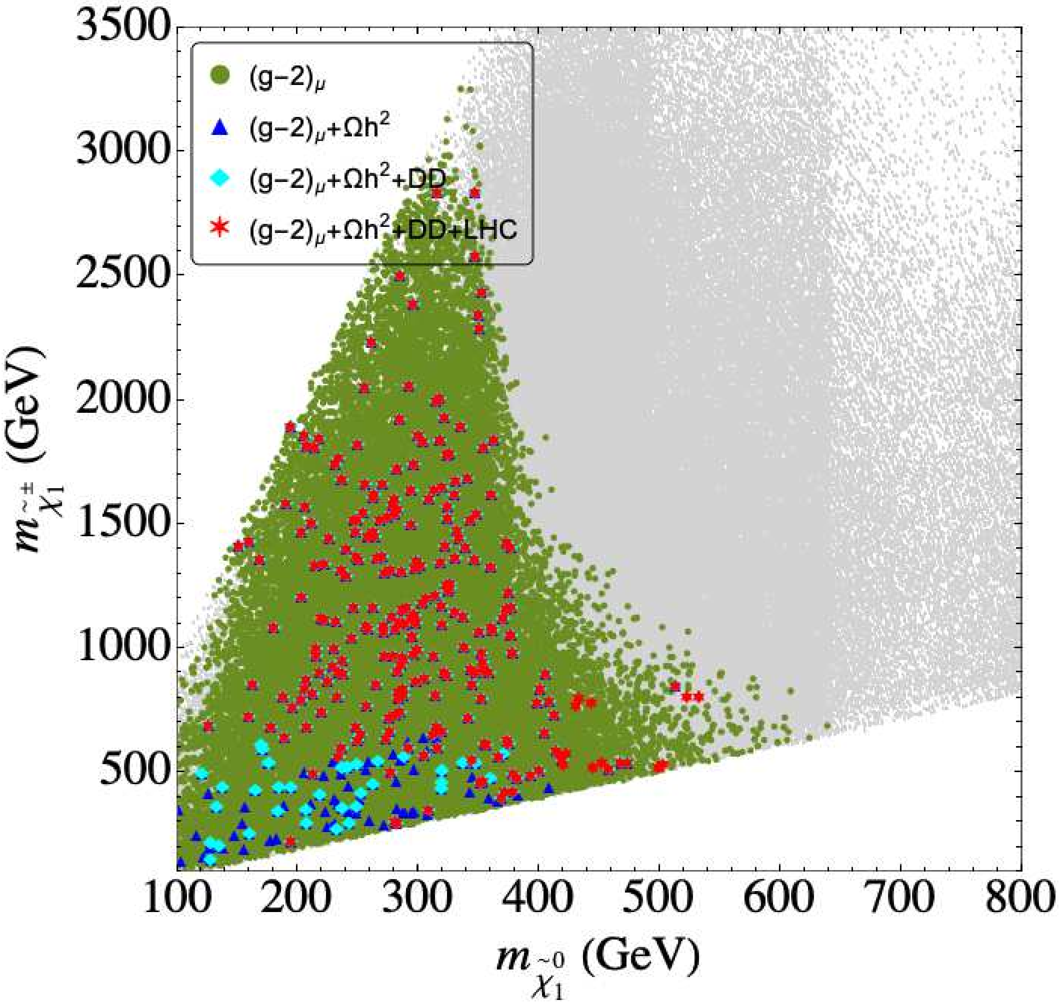



$\Rightarrow$ important: $\tilde{l}$-pair production searches (10)

$\Rightarrow$ naive application of LHC bounds fails

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

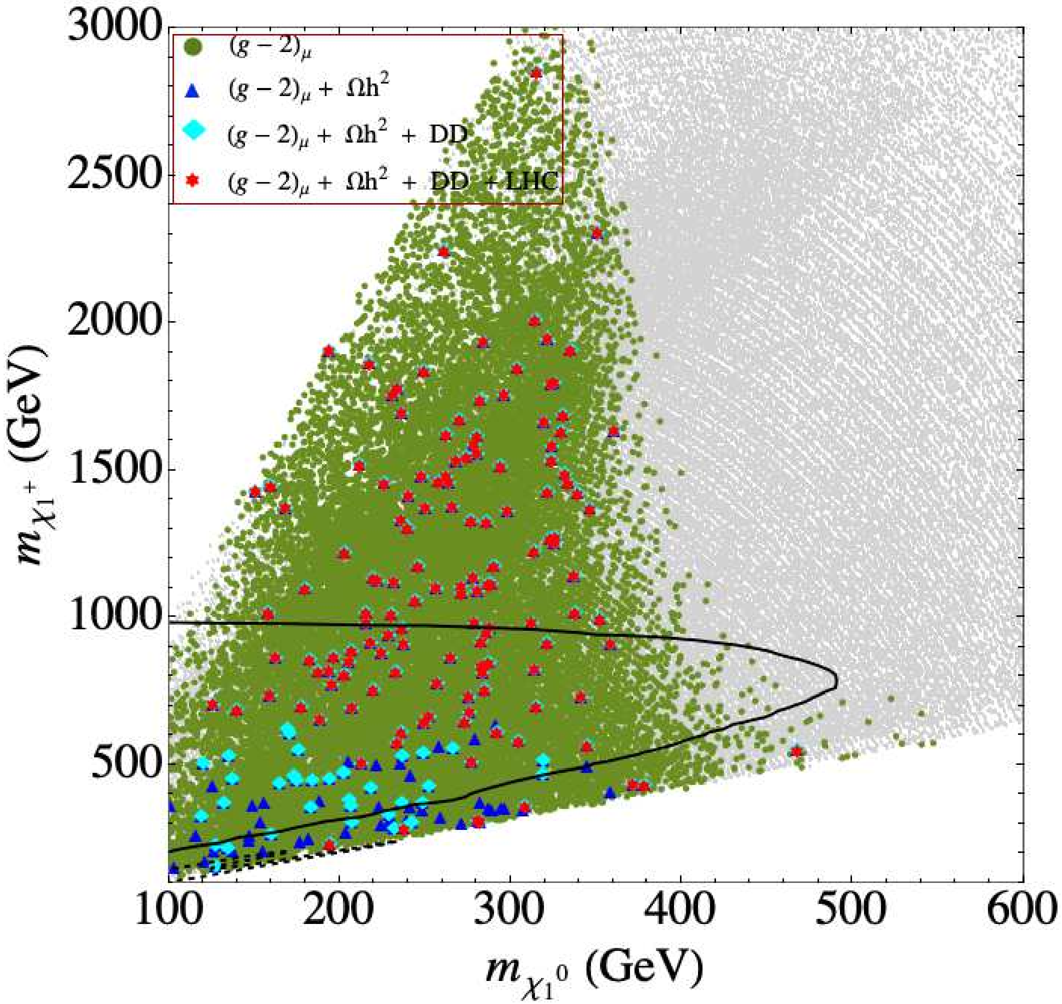
new $(g-2)_\mu$




⇒ 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 $(g-2)_\mu$

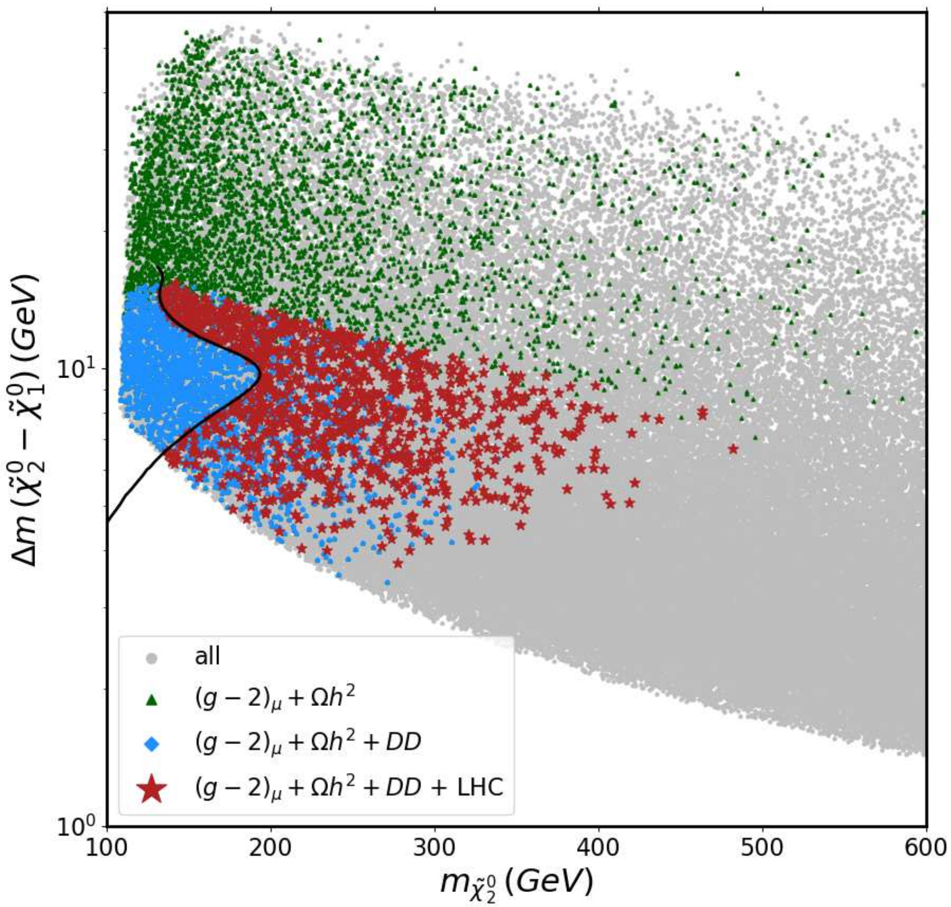



⇒ important: $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production searches (5)

⇒ naive application of LHC bounds fails

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

old $(g-2)_\mu$

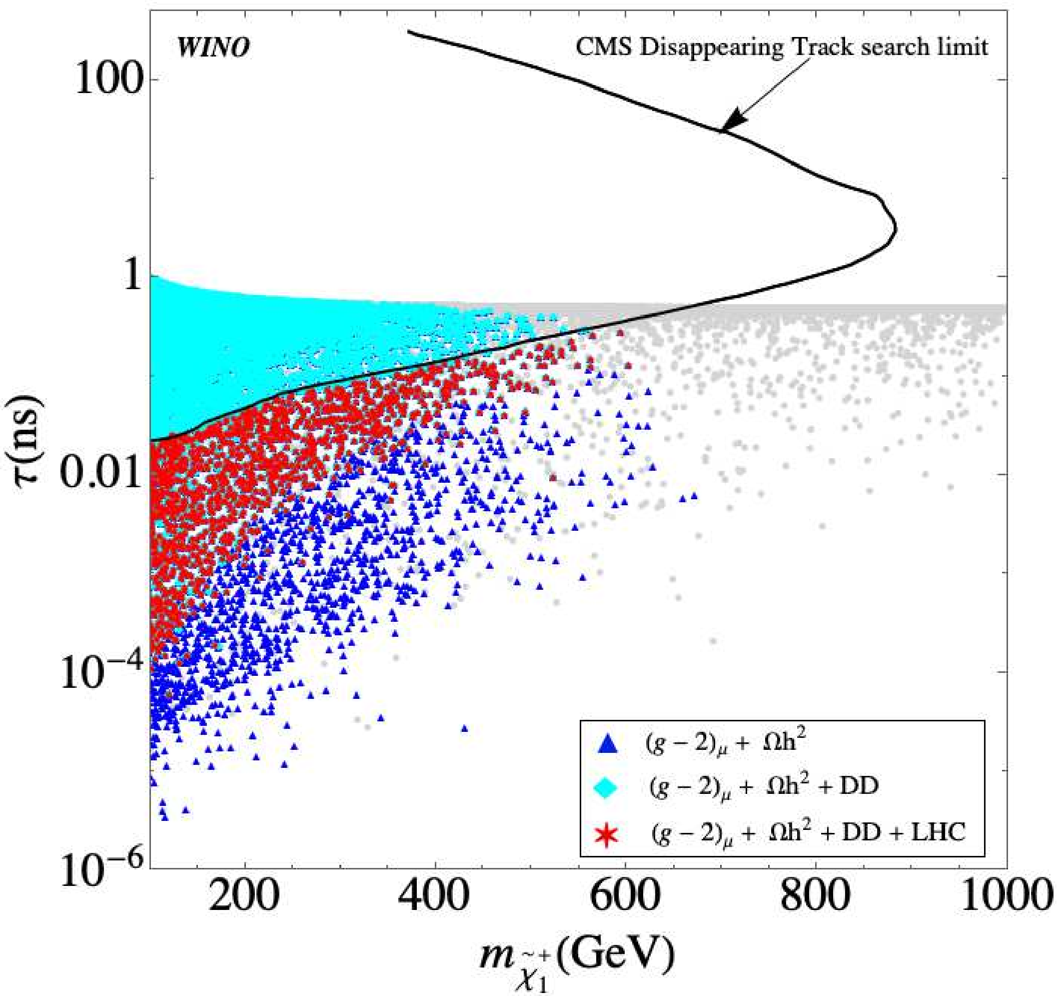



$\Rightarrow$ important: compressed spectra searches (11)

$\Rightarrow$ right where the model prediction sits $\quad\Rightarrow$ very powerful

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

old $(g-2)_\mu$




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

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

$$M_1 \le M_2 \le 1.1 M_1 \,,$$

$$1.1 M_1 \le \mu \le 10 M_1,$$

$$5 \le \tan\beta \le 60,$$

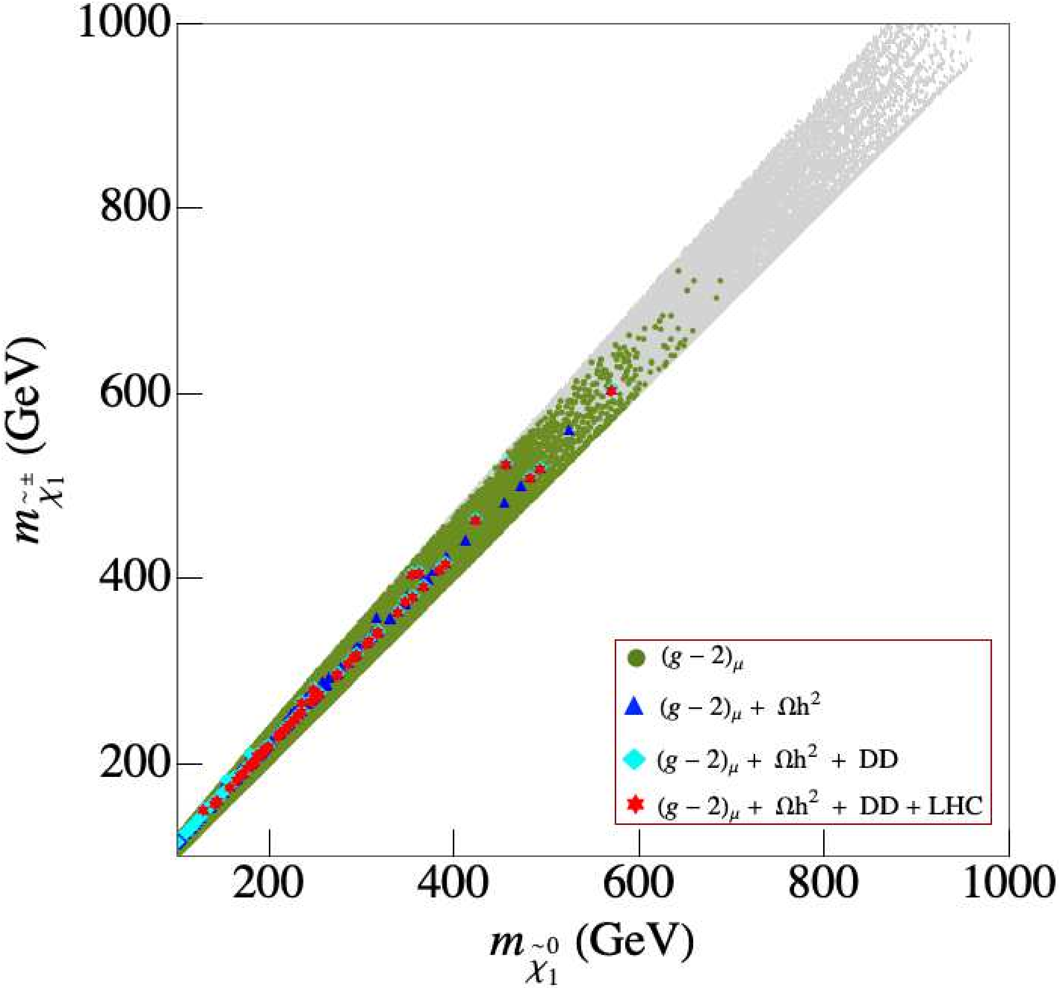
$$100\text{ GeV} \le m_{\tilde{L}} \le 1\text{ TeV},$$

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

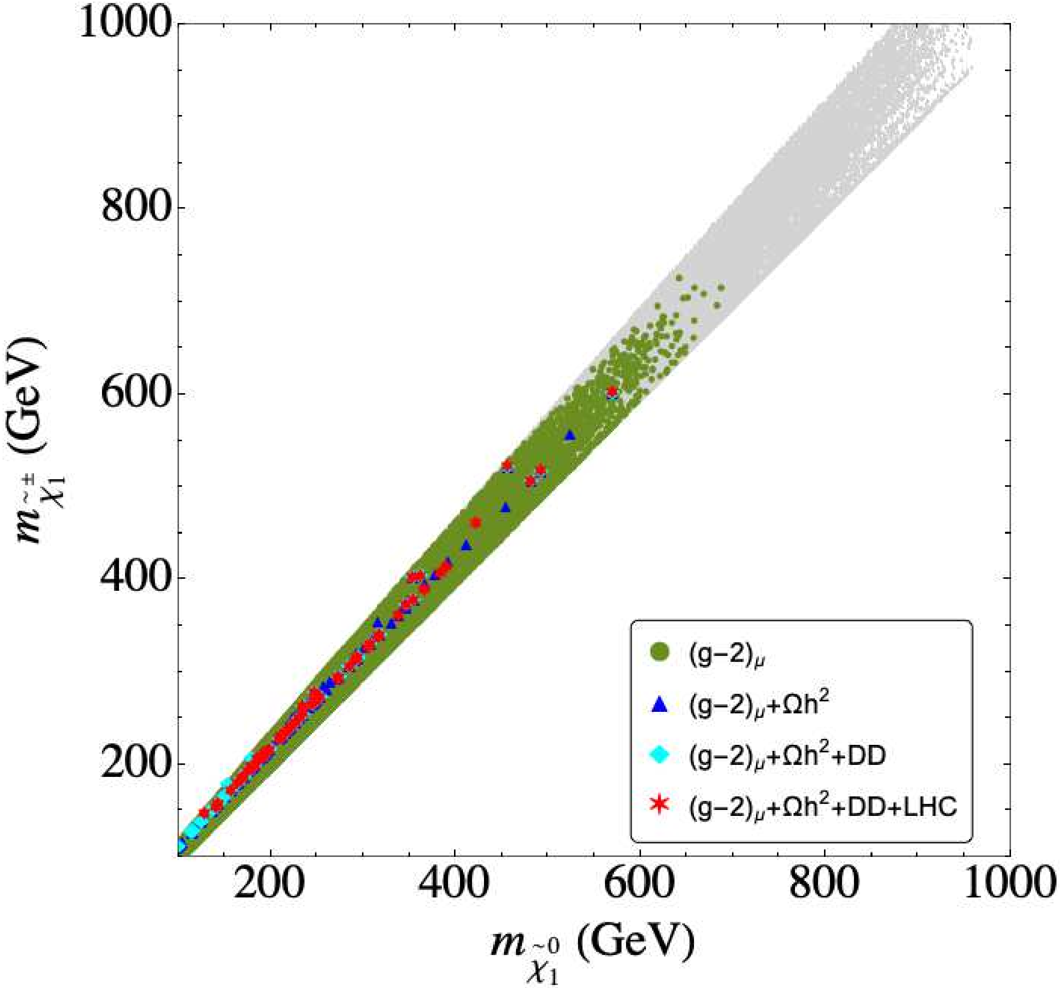
(latter condition only to make the analysis simpler, no relevant effect)

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

old $(g-2)_\mu$



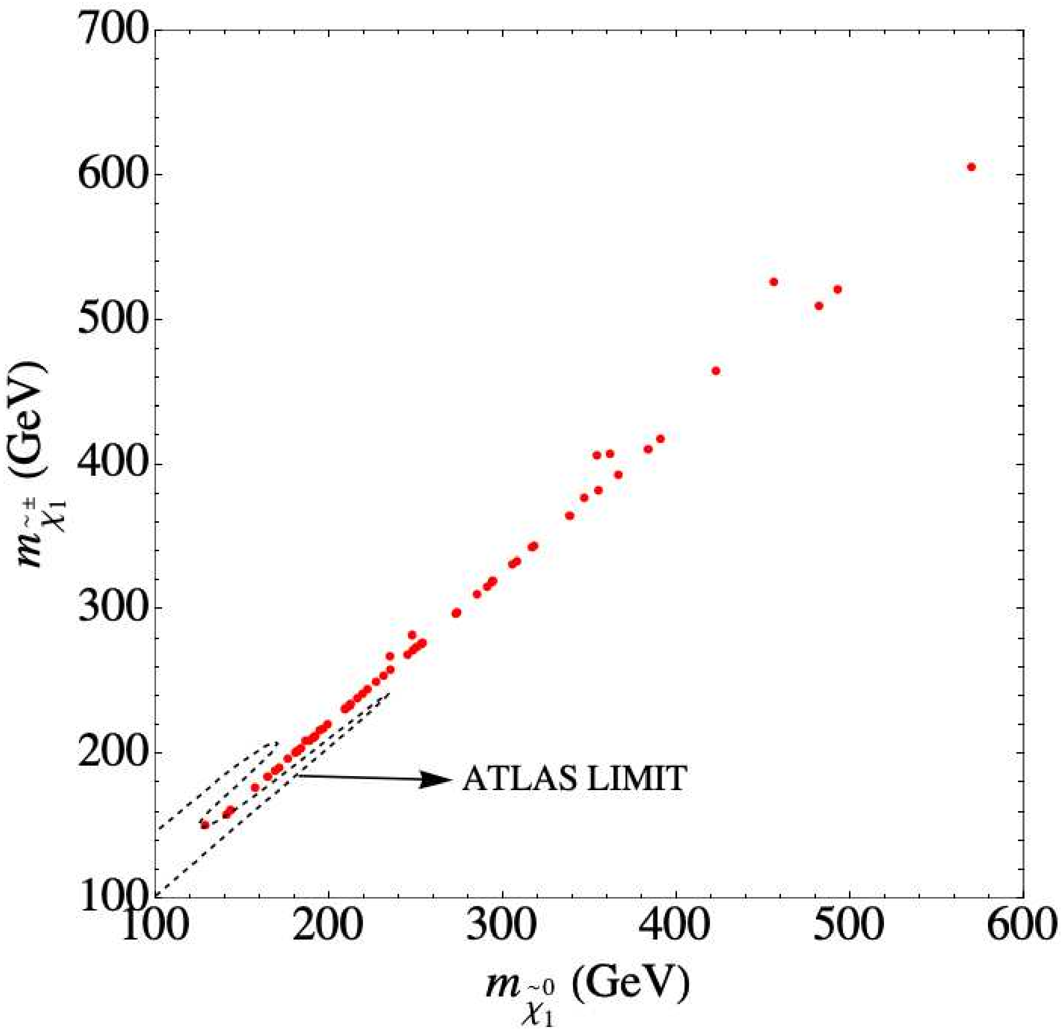

new $(g-2)_\mu$




⇒ compressed spectrum as expected

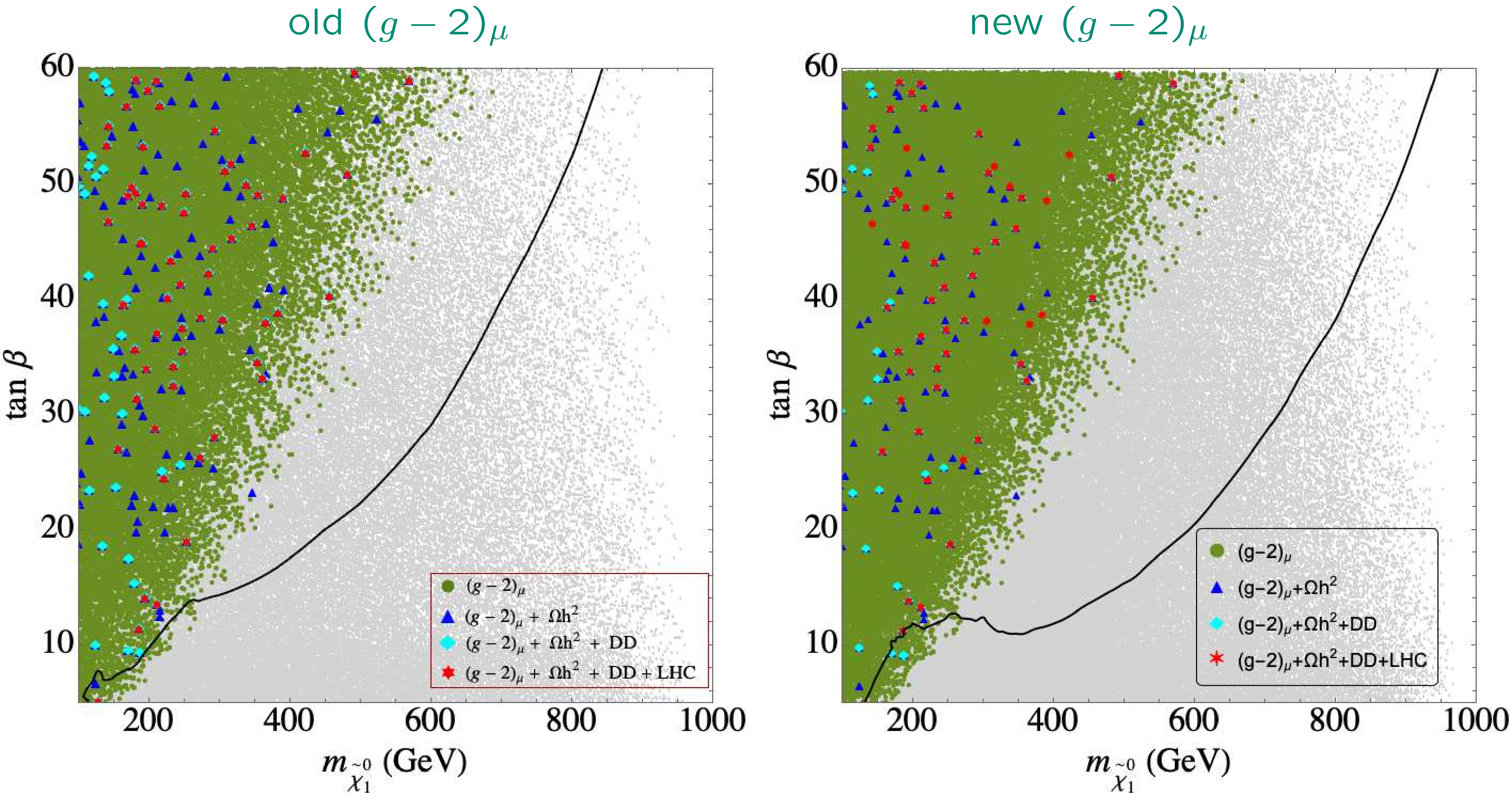
⇒ clear upper limits, $m_{\text{(N)LSP}} \lesssim 600(650)$ GeV confirmed

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




$\Rightarrow$ compressed spectrum avoids current bounds!

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

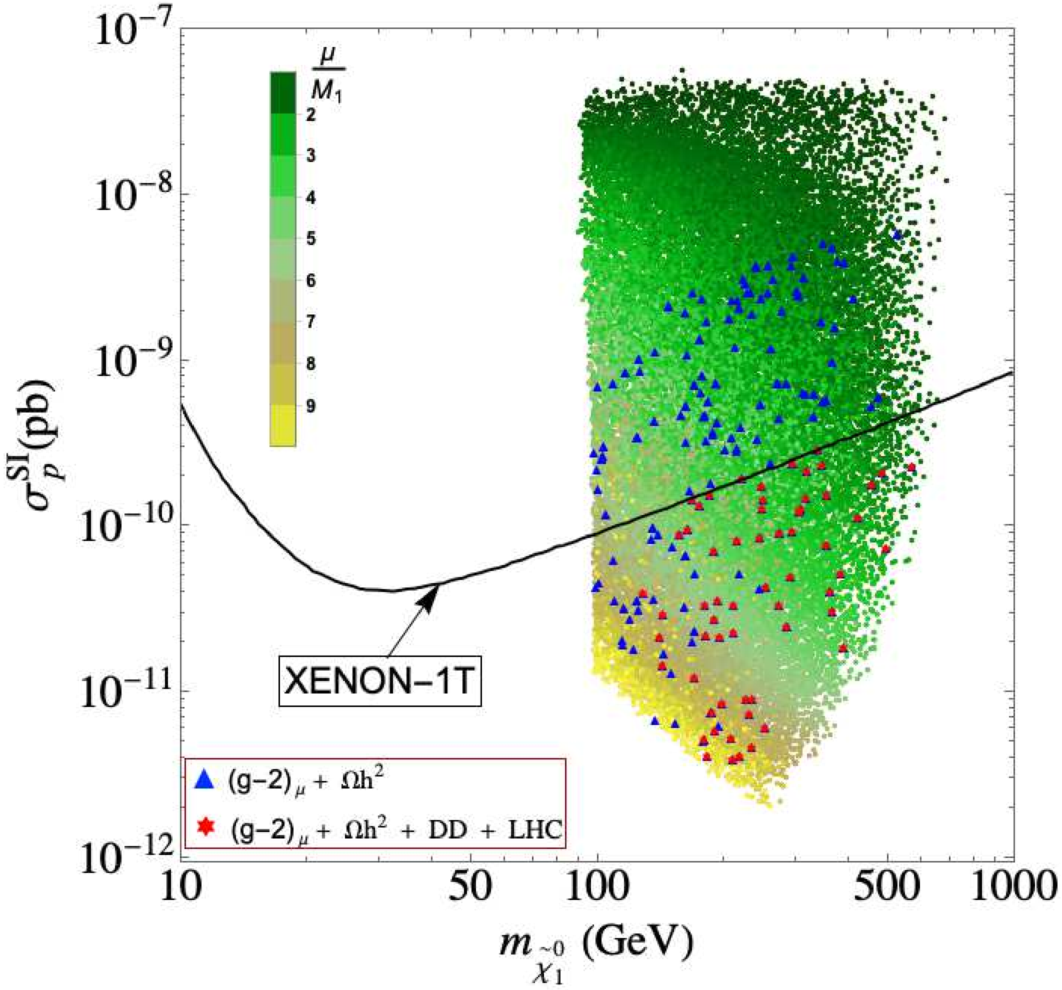



black contour: (simplified) application of $H/A \to \tau^+\tau^-$

$\Rightarrow$ $A$-pole annihilation effectively excluded

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

old $(g-2)_\mu$




$\Rightarrow$ larger $\mu$ values favored

## B/C) Bino DM with slepton co-annihilation

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

Parameter scan:

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

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

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

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

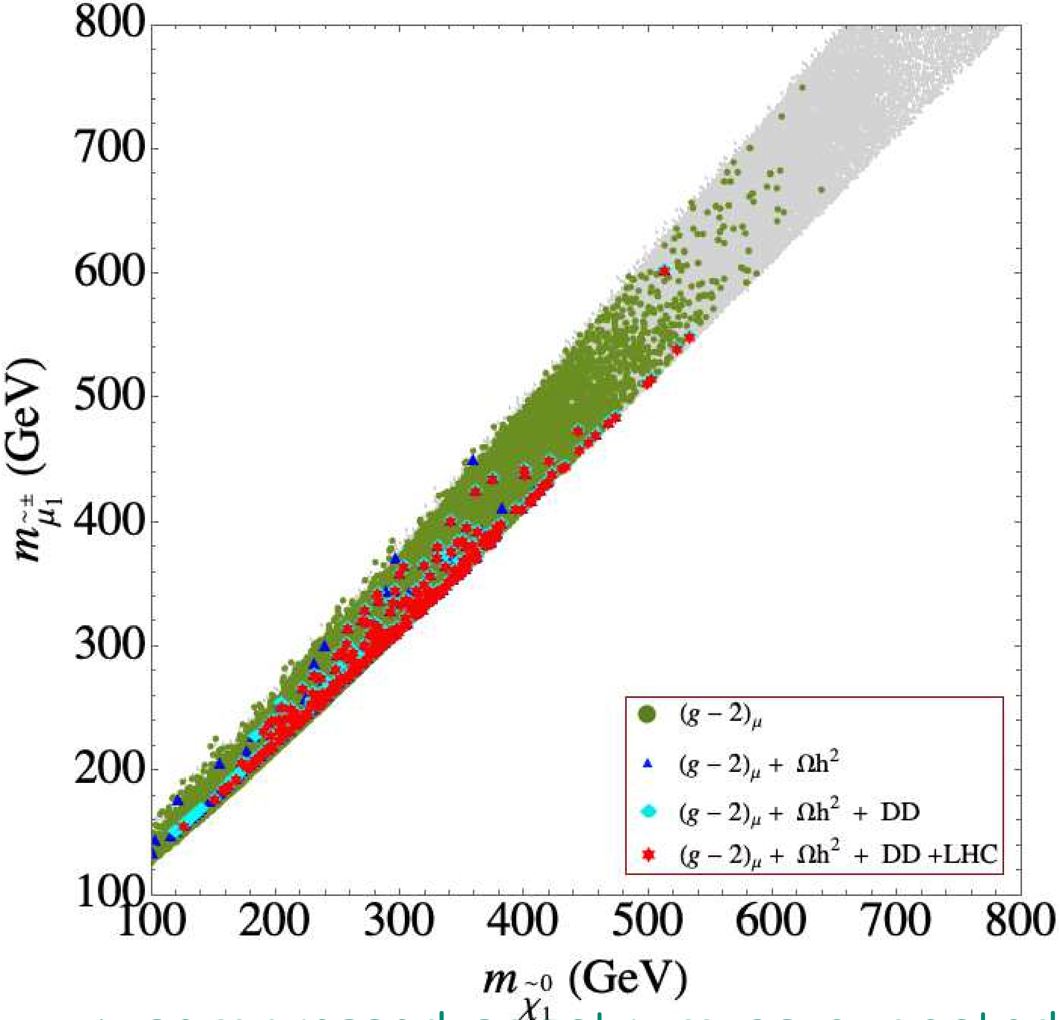
Case-L: $M_1 \leq m_{\tilde{L}} \leq 1.2 M_1,\quad M_1 \leq m_{\tilde{R}} \leq 10 M_1.$

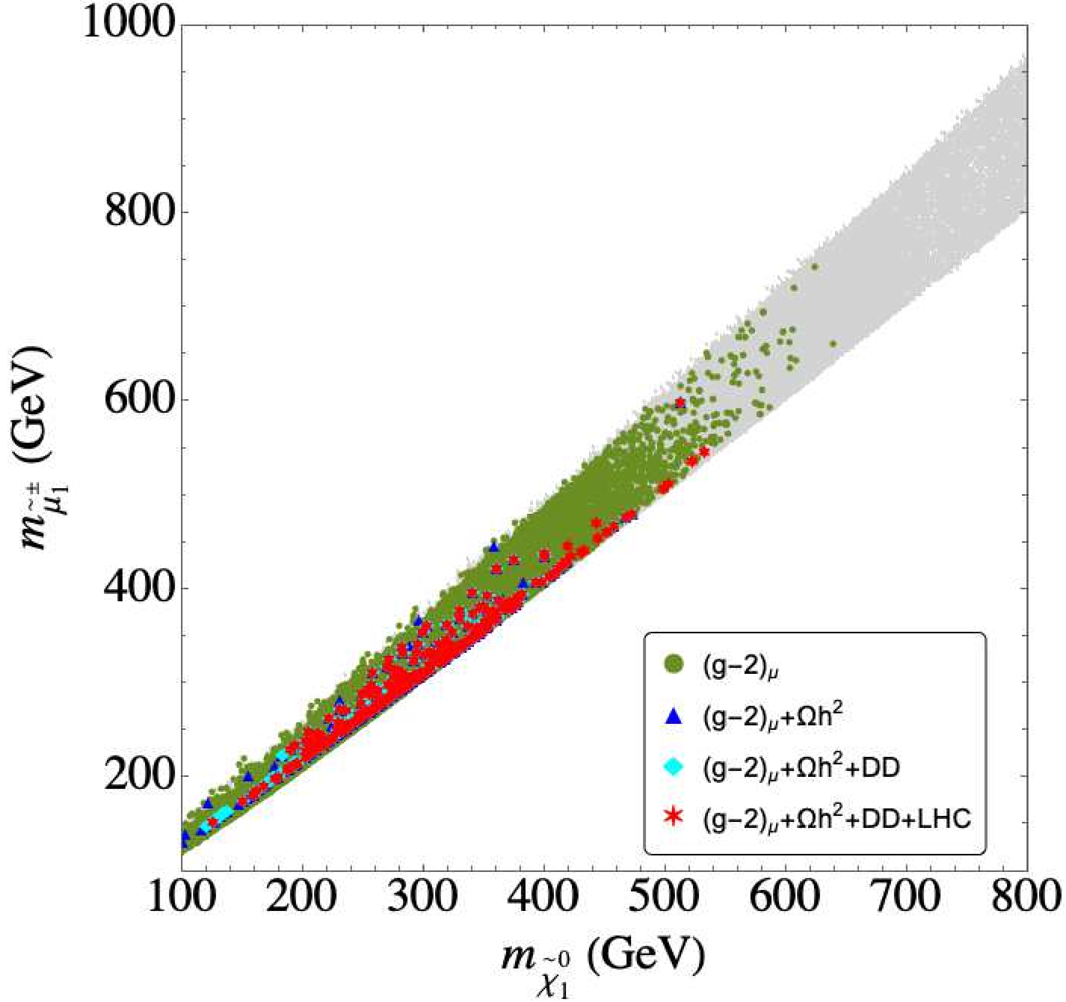
Case-R: $M_1 \leq m_{\tilde{R}} \leq 1.2 M_1,\quad M_1 \leq m_{\tilde{L}} \leq 10 M_1.$

$\Rightarrow$ here focus on Case-L

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

old $(g-2)_\mu$ | new $(g-2)_\mu$



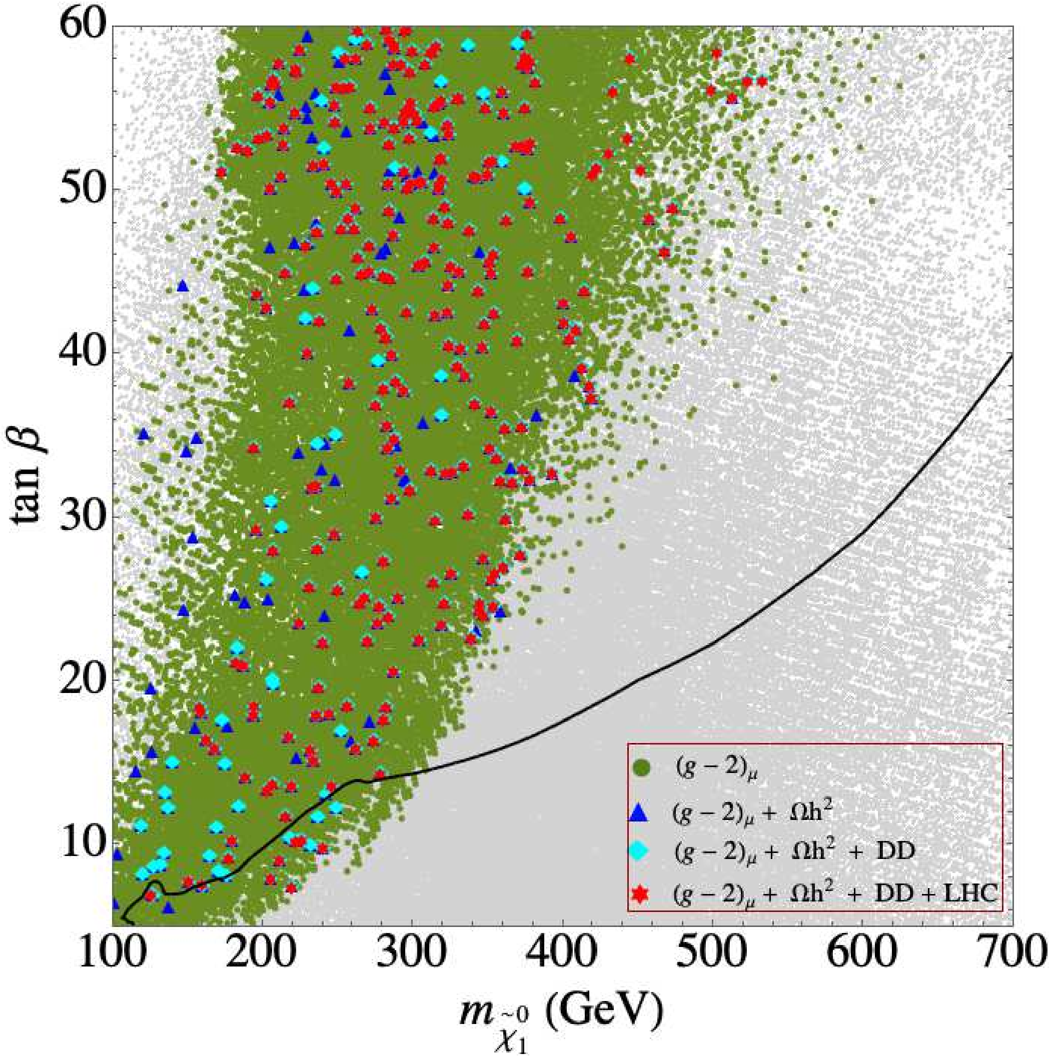



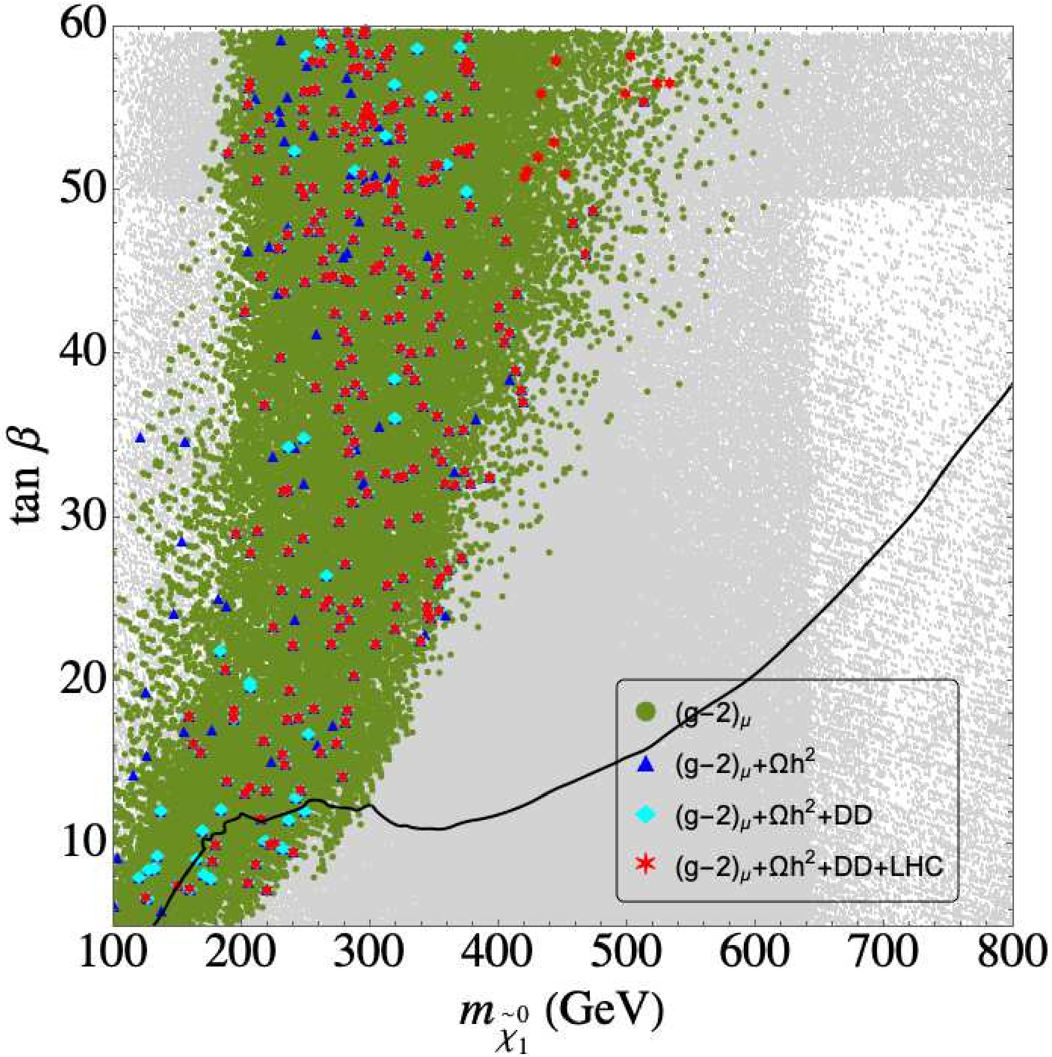

⇒ compressed spectrum as expected

⇒ clear upper limits, $m_{\text{(N)LSP}} \lesssim 550(600)$ 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 $H/A \to \tau^+\tau^-$

$\Rightarrow$ $A$-pole annihilation largely excluded

## D) Higgsino DM

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

Parameter scan:

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

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

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

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

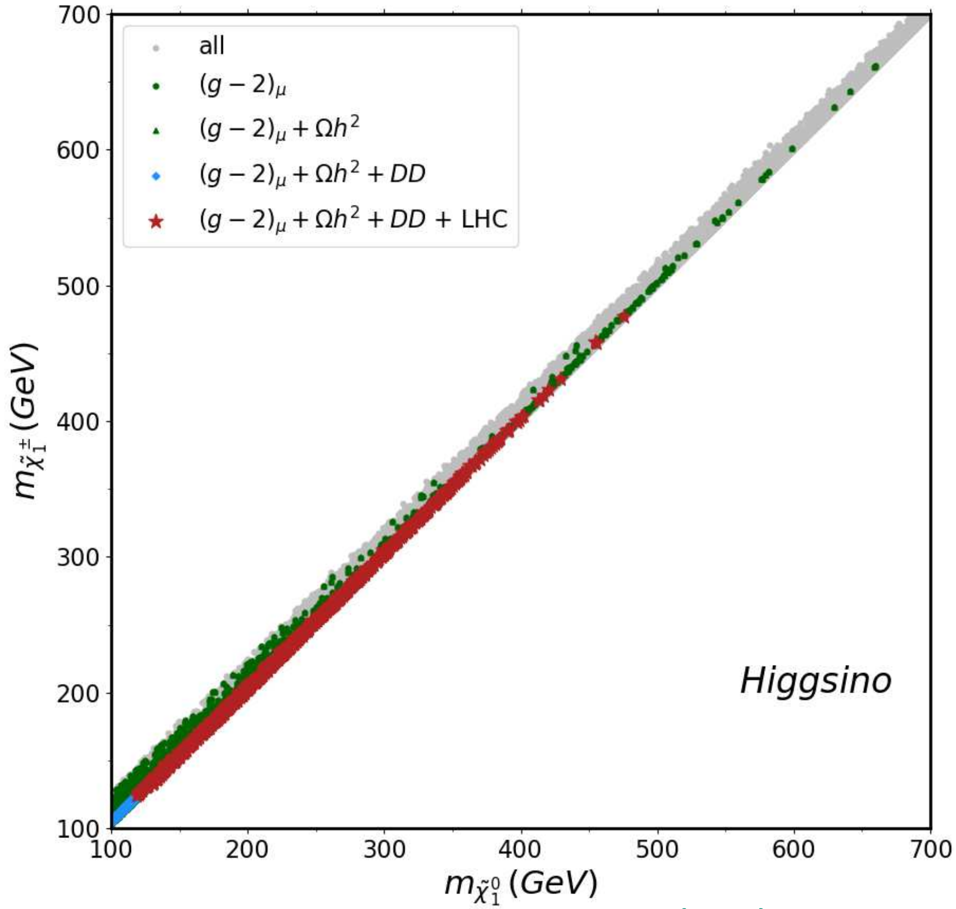
$$100 \text{ GeV} \leq m_{\tilde{L}}, m_{\tilde{R}} \leq 2 \text{ TeV},$$

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

Full DM relic density reached only for $m_{\tilde{\chi}_1^0} \sim 1$ TeV
$\Rightarrow$ incompatible with $(g-2)_\mu$

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

old $(g-2)_\mu$

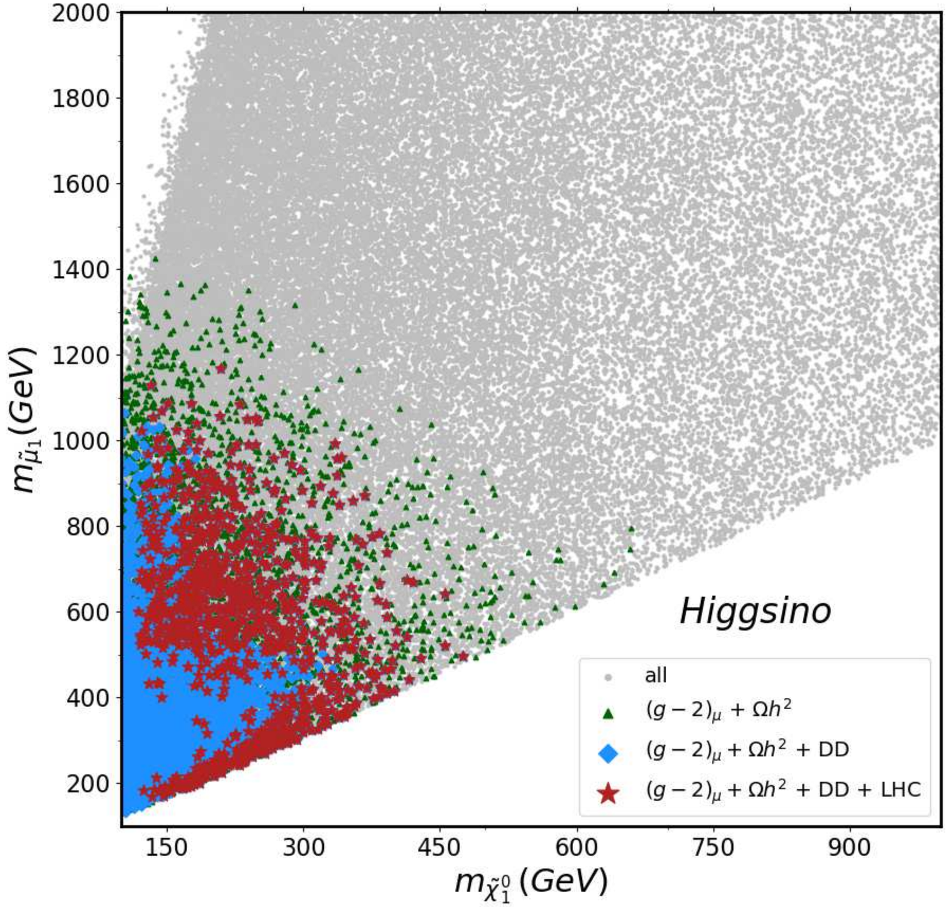



$\Rightarrow$ important: compressed spectra searches (11)

$\Rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to (W^* \tilde{\chi}_1^0)(Z^* \tilde{\chi}_1^0) \to 2l + \not{E}_T + \text{ISR}$ $\Rightarrow m_{\text{(N)LSP}} \lesssim 500$ GeV

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

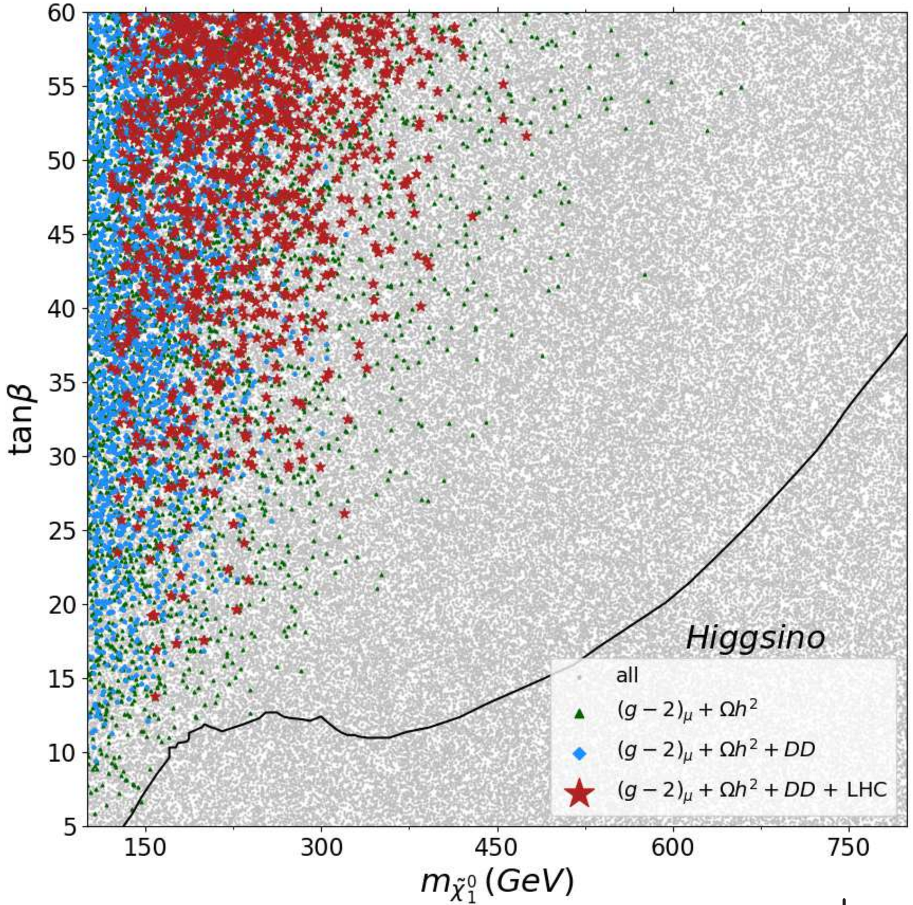
old $(g-2)_\mu$




$\Rightarrow$ 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 $H/A \to \tau^+\tau^-$

$\Rightarrow$ $A$-pole annihilation fully excluded

## E) Wino DM

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

Parameter scan:

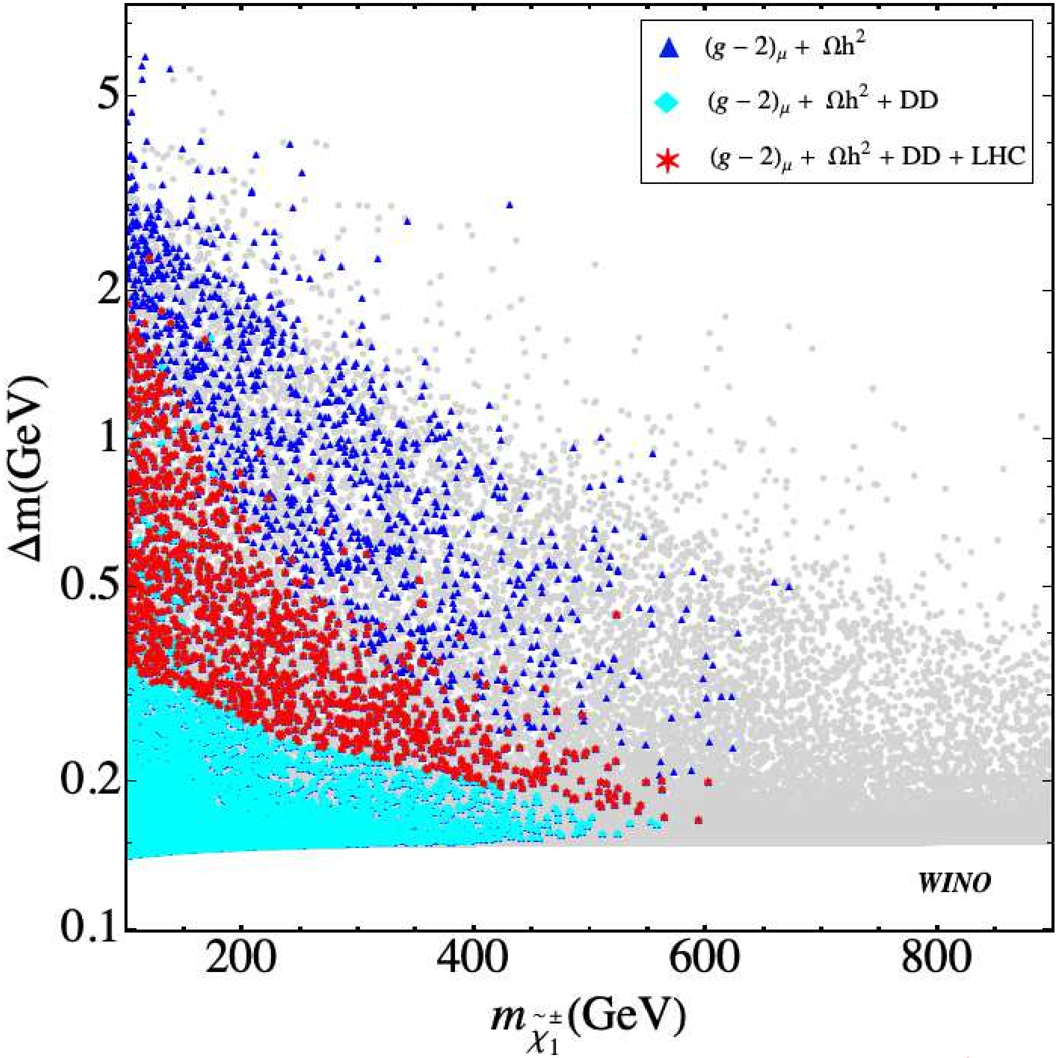
$$100\text{ GeV} \le M_2 \le 1.5\text{ TeV}\,,$$
$$1.1 M_2 \le M_1 \le 10 M_2\,,$$
$$1.1 M_2 \le \mu \le 10 M_2\,,$$
$$5 \le \tan\beta \le 60,$$
$$100\text{ GeV} \le m_{\tilde{L}}, m_{\tilde{R}} \le 2\text{ TeV},$$

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

Full DM relic density reached only for $m_{\tilde{\chi}_1^0} \sim 3$ TeV
$\Rightarrow$ incompatible with $(g-2)_\mu$

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

old $(g-2)_\mu$

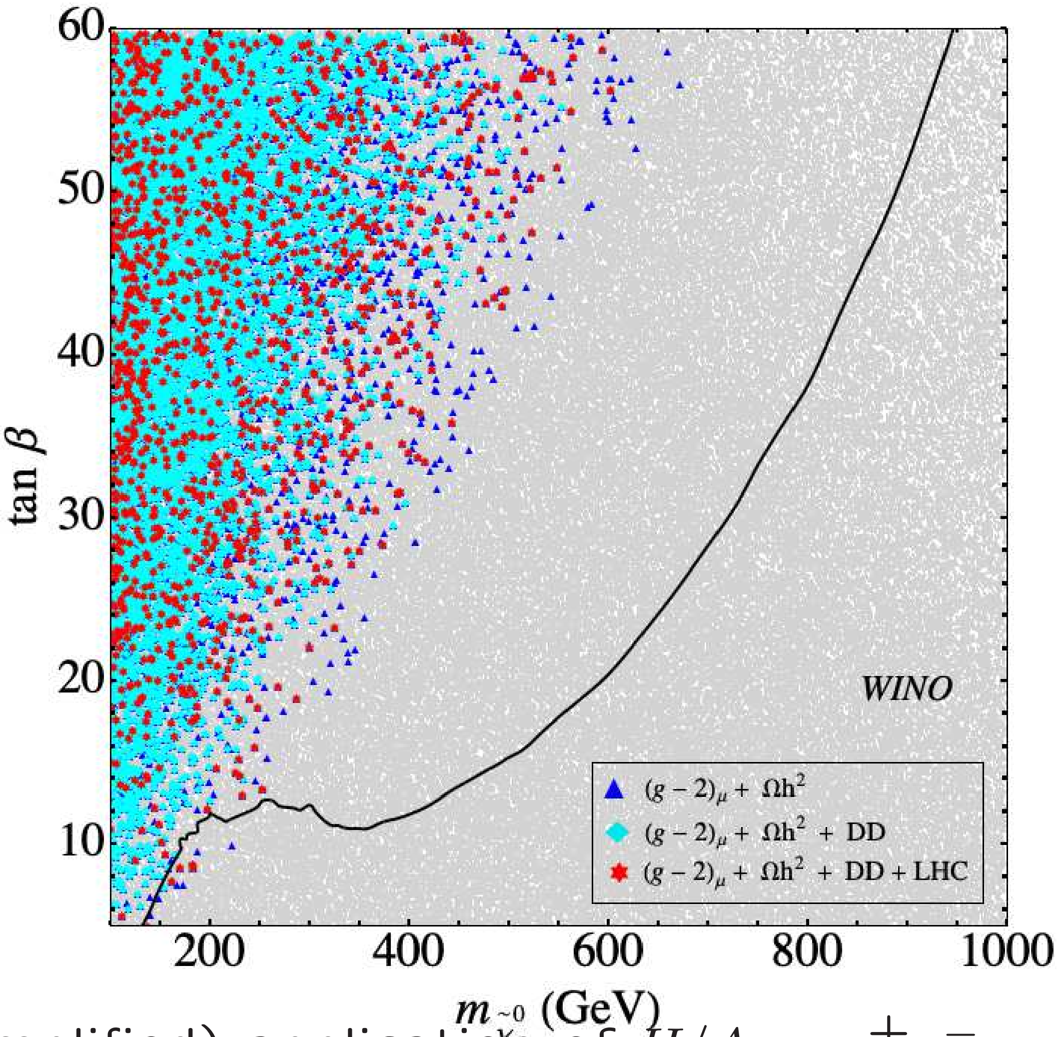



⇒ important: disappearing track limit ⇒ $m_{\text{(N)LSP}} \lesssim 600$ GeV

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

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

old $(g-2)_\mu$

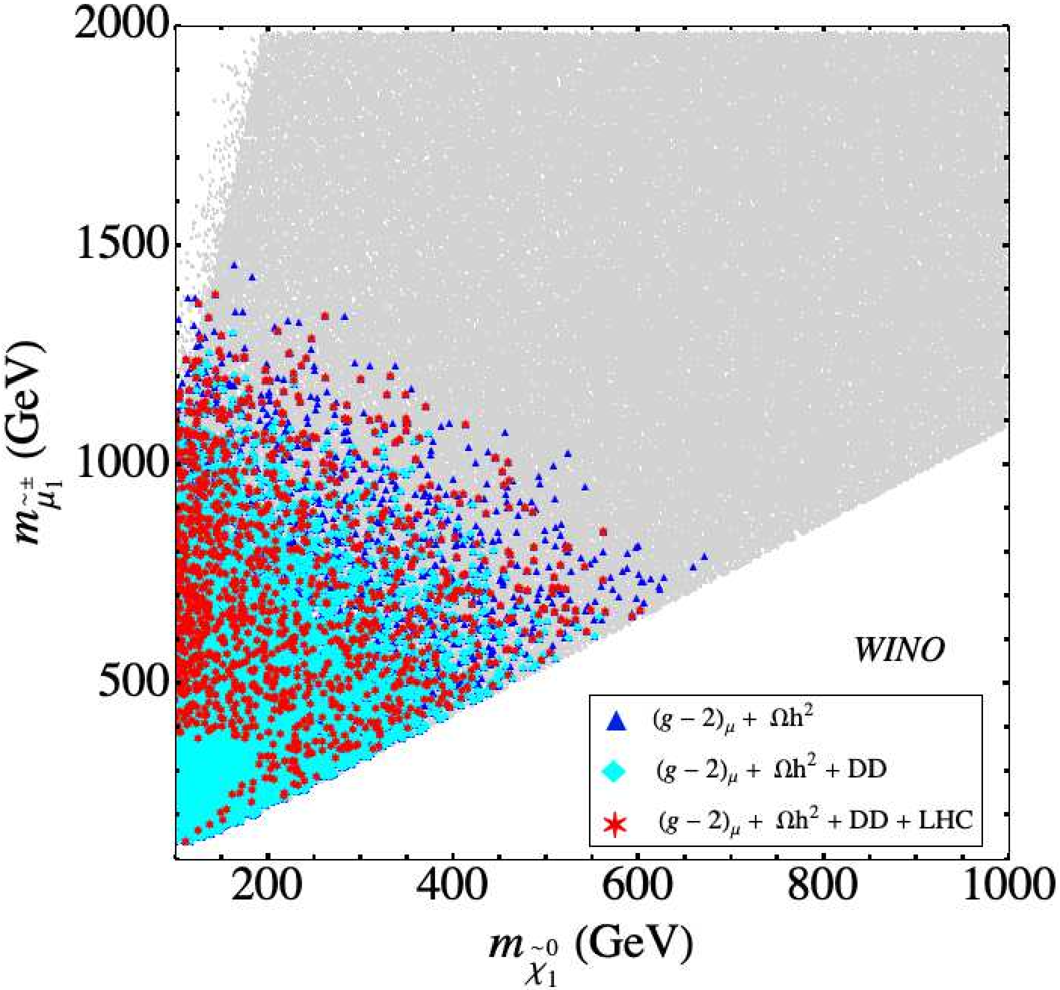



black contour: (simplified) application of $H/A \to \tau^+\tau^-$

$\Rightarrow$ $A$-pole annihilation largely excluded

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

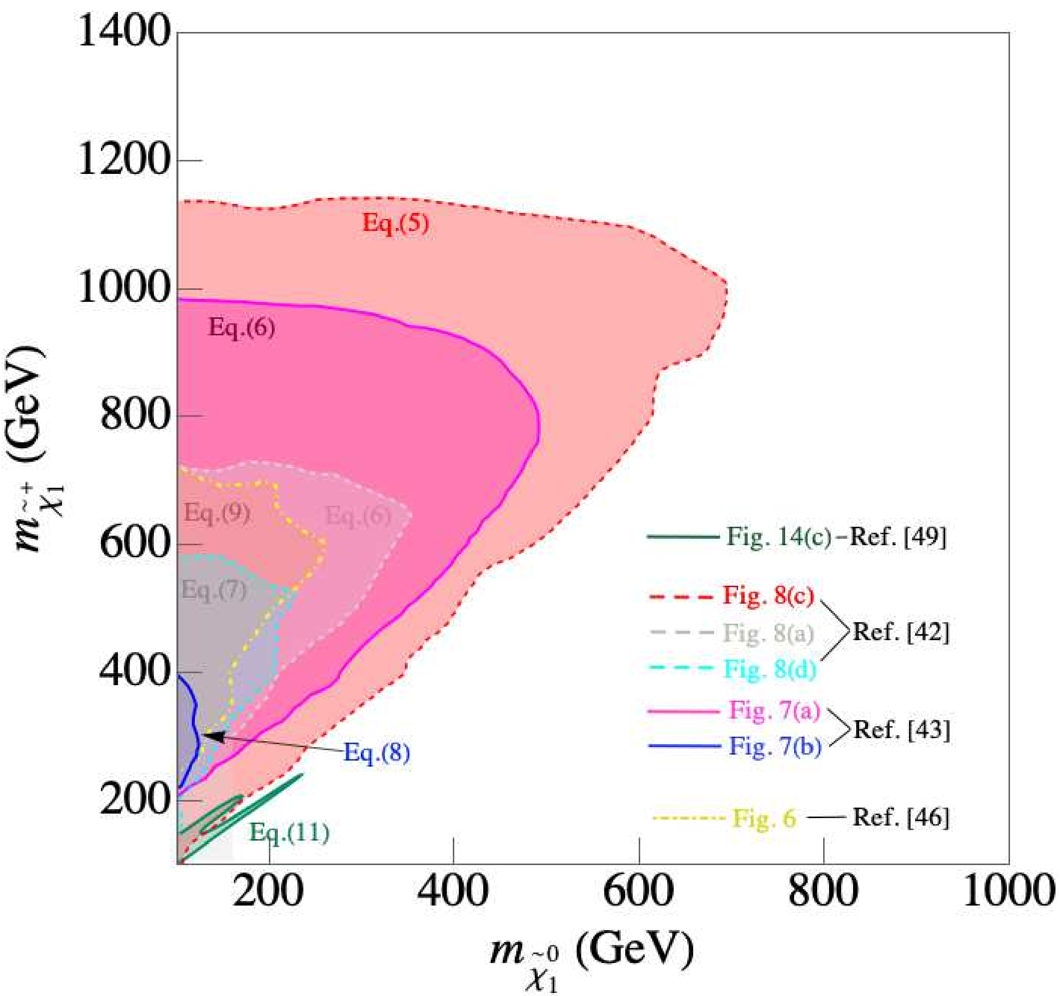
old $(g-2)_\mu$

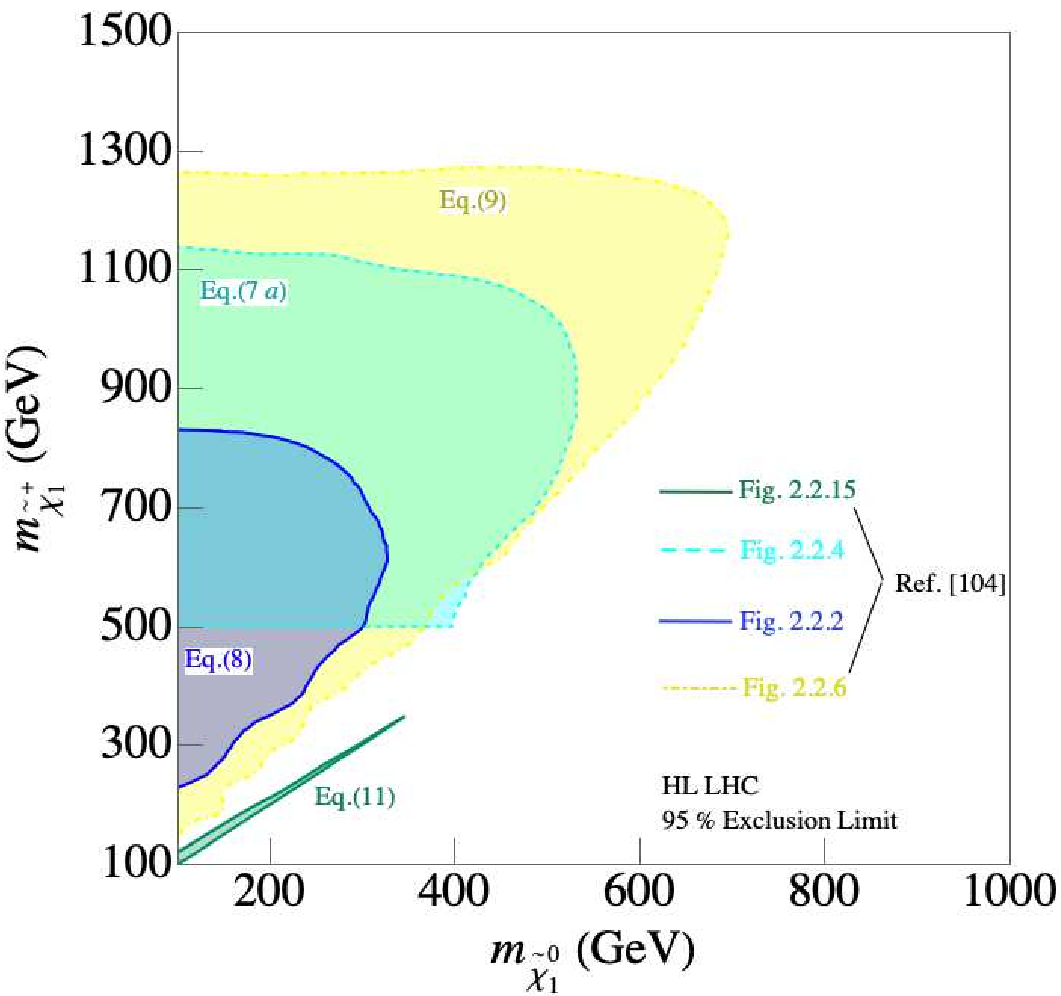



$\Rightarrow m_{\tilde{l}_1} \lesssim 1400(1200)$ GeV

# LHC exclusion bounds vs. HL-LHC exclusion bounds

not all channels available [*YR18*]




⇒ exclusion reach can be important

⇒ no CheckMate inclusion available . . .