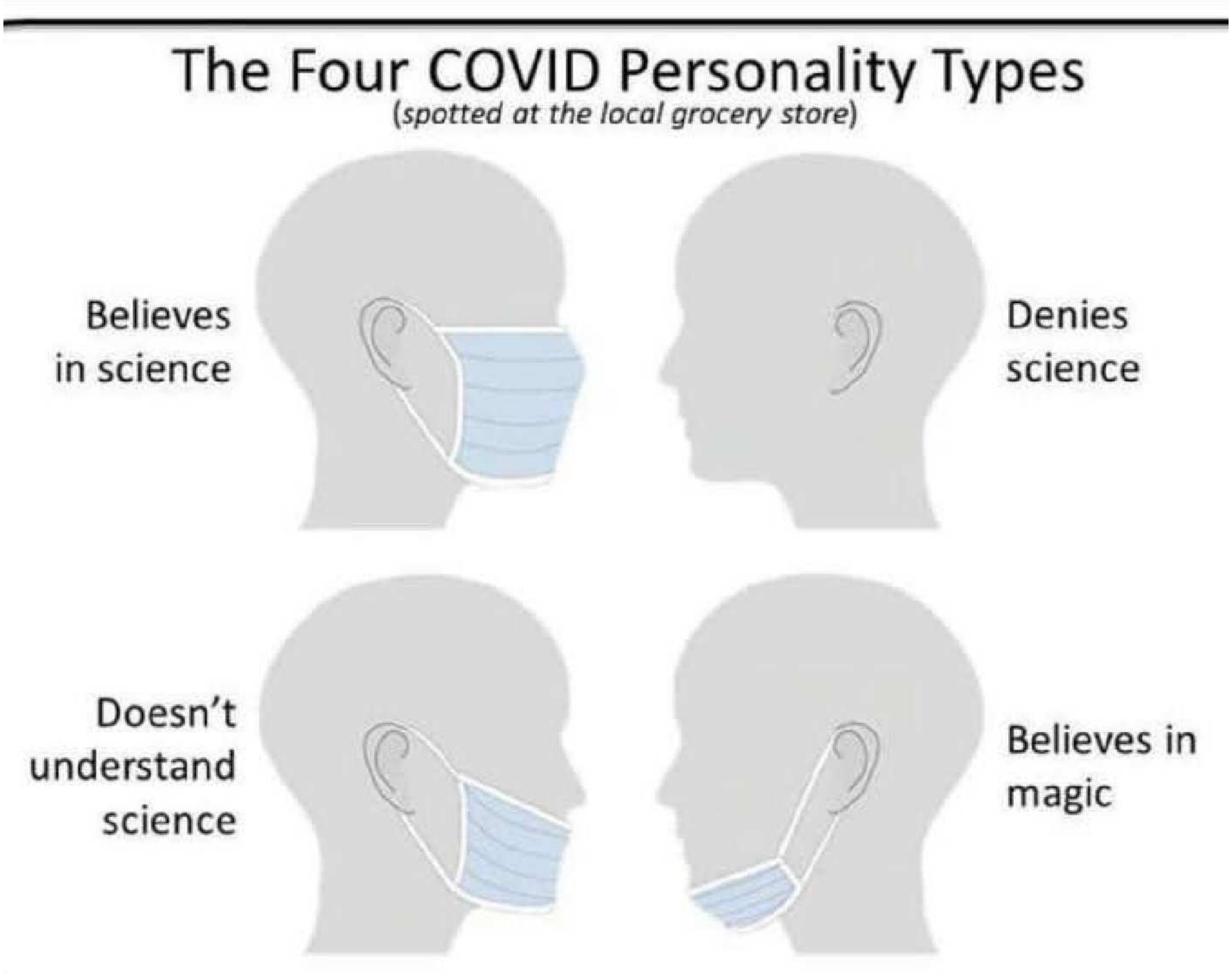


The Four COVID Personality Types
(spotted at the local grocery store)
Believes in science
Denies science
Doesn't understand science
Believes in magic

BSM Physics in the light of the new "MUON G-2" Result

Sven Heinemeyer, IFT (CSIC, Madrid)

virtual, 07/2021

1. Introduction

2. "Two Higgs Doublets are as natural as one"

3. "SUSY fits like a glove"

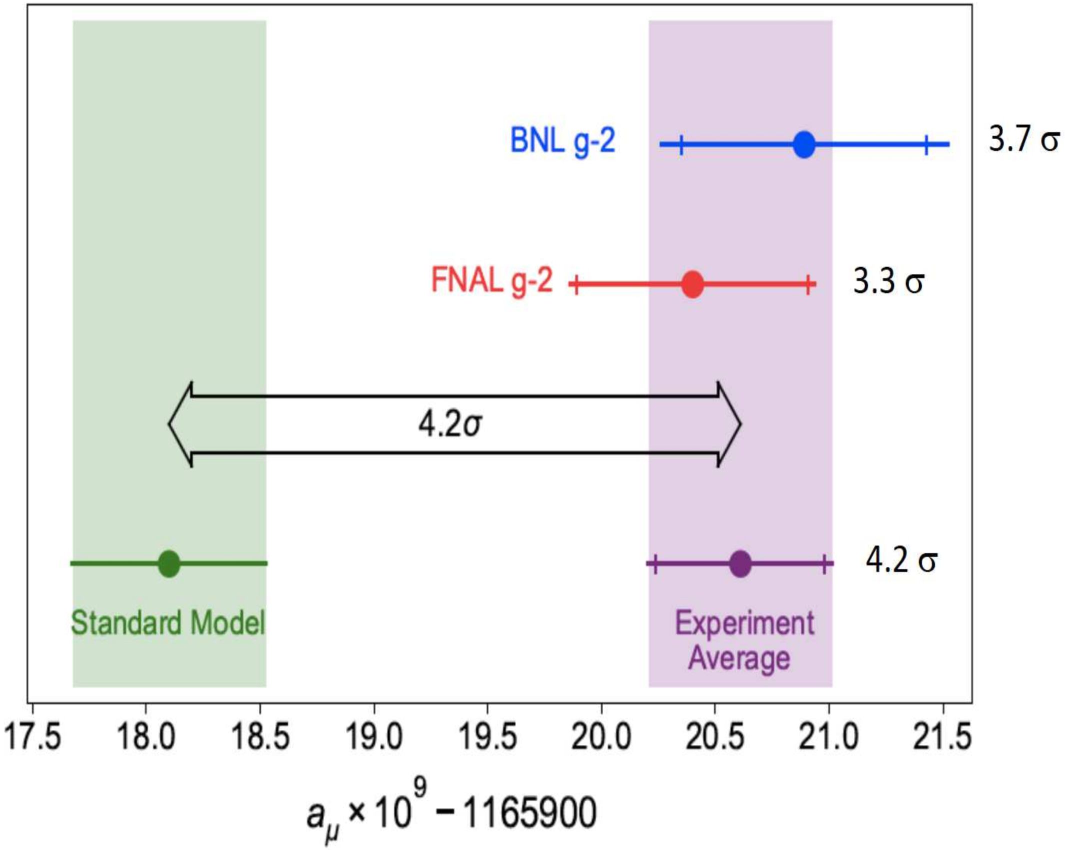
4. "There's always the axion"

5. Conclusions

1. Introduction

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

Overview about the current experimental and SM (theory) result:



$$a_\mu^{\text{exp}} - a_\mu^{\text{theo,SM}} \approx (25.1 \pm 5.9) \times 10^{-10} \quad : \; 4.2\,\sigma$$

$$a_\mu^{\rm exp} - a_\mu^{\rm theo,SM} \approx (25.1 \pm 5.9) \times 10^{-10} \quad : \; 4.2\,\sigma$$

discrepancy $\approx 2 \times a_\mu^{\rm SM,weak}$

but: expect $a_\mu^{\rm NP} \sim a_\mu^{\rm SM,weak} \times \left(\frac{M_W}{M_{\rm NP}}\right)^2 \times$ couplings

$$a_\mu \sim \frac{m_\mu \times (\text{some VEV}) \times (\mu_{L\leftrightarrow R}\text{-flipping parameter})}{M^2_{\rm typical}}$$

$$a_\mu^{\text{exp}} - a_\mu^{\text{theo,SM}} \approx (25.1 \pm 5.9) \times 10^{-10} \quad : \; 4.2\,\sigma$$

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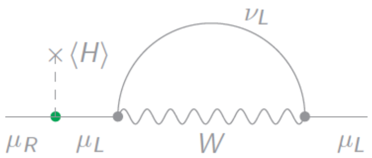
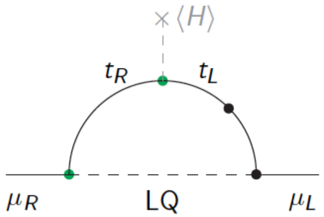
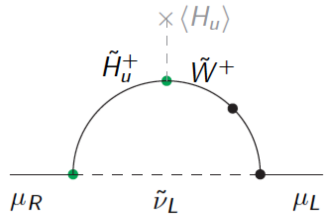
- EWSM: $\alpha \frac{m_\mu^2}{M_W^2}$



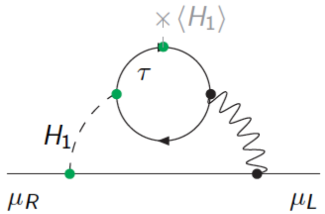
- LQ: $g_L g_R \frac{m_\mu m_t}{M^2_{\text{LQ}}}$



- SUSY: $\alpha \frac{m_\mu^2 \tan\beta}{M^2_{\text{SUSY}}} \frac{\mu}{M_{\text{SUSY}}}$



- 2HDM: $\alpha^2 \tan^2\beta \frac{m_\mu^2}{M_H^2}$



- rad. m_μ $\quad \sim \frac{m_\mu^2}{M^2_{\text{NP}}}$

2. “Two Higgs Doublets are as natural as one” (2HDM)

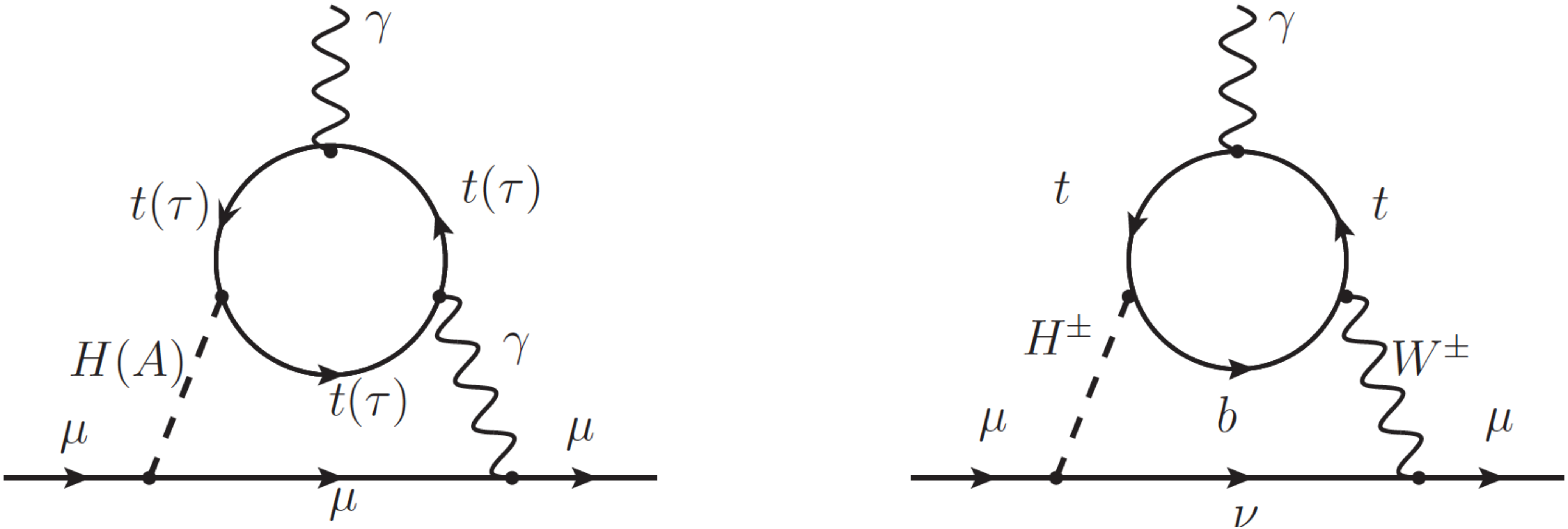
Extension of the Z_2 symmetry to fermions determines four types:

	u-type	d-type	leptons
type I	Φ_2	Φ_2	Φ_2
type II	Φ_2	Φ_1	Φ_1
type III (lepton-specific)	Φ_2	Φ_2	Φ_1
type IV (flipped)	Φ_2	Φ_1	Φ_2

Couplings to fermions:

	u-type (c_{Att})	d-type (c_{Abb})	leptons ($c_{A\tau\tau}$)
type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
type II	$\cot\beta$	$\tan\beta$	$\tan\beta$
type III/X (lepton-specific)	$\cot\beta$	$\cot\beta$	$\tan\beta$
type IV/Y (flipped)	$\cot\beta$	$\tan\beta$	$\cot\beta$

Barr-Zee diagrams:

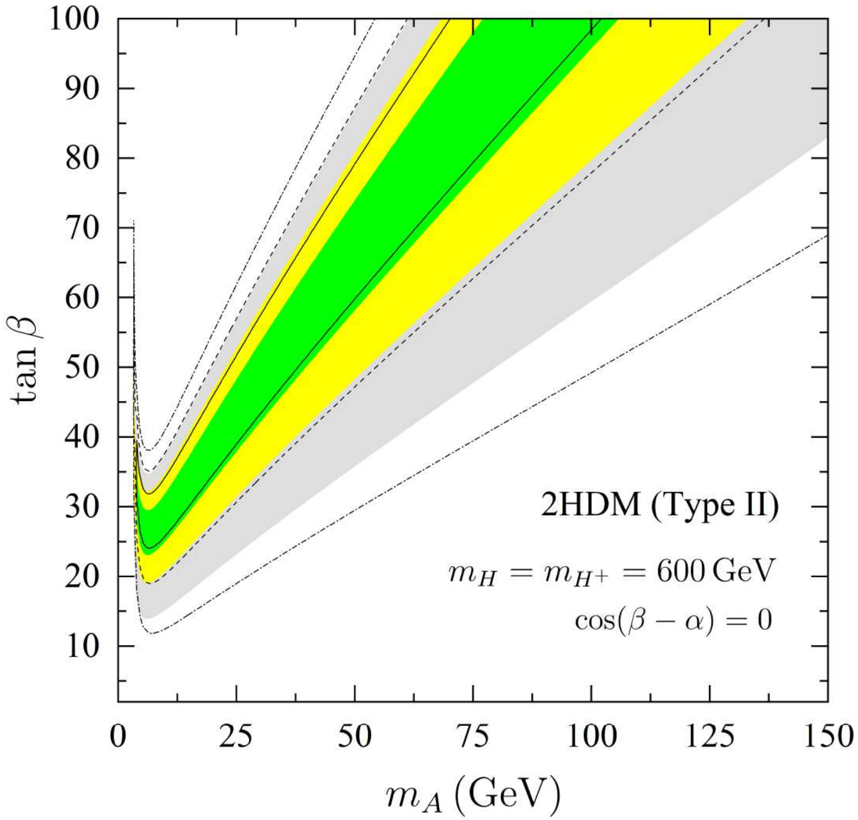


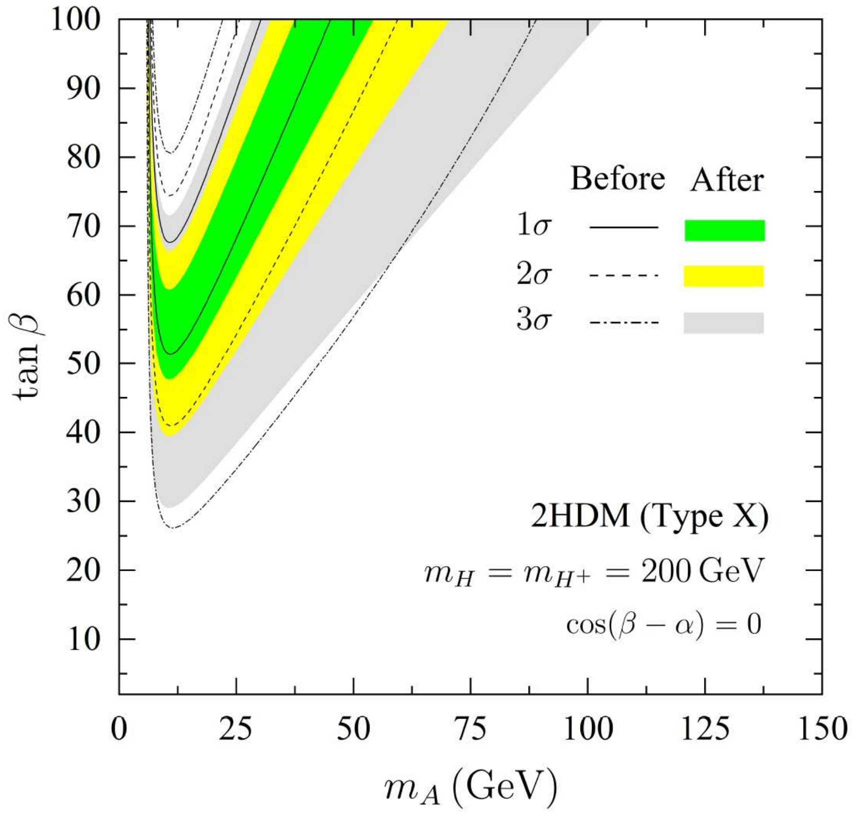
Known since long:

Light A at high $\tan\beta$ can explain the $(g-2)_\mu$ result

$\Rightarrow$ in type II and X: enhanced couplings to μ's

Updated 2HDM results: [P. Ferreira, B. Goncalvez, F. Joaquim, M. Sher '21]





Taking EWPO into account: $\Rightarrow M_{H^\pm} \lesssim 200$ GeV

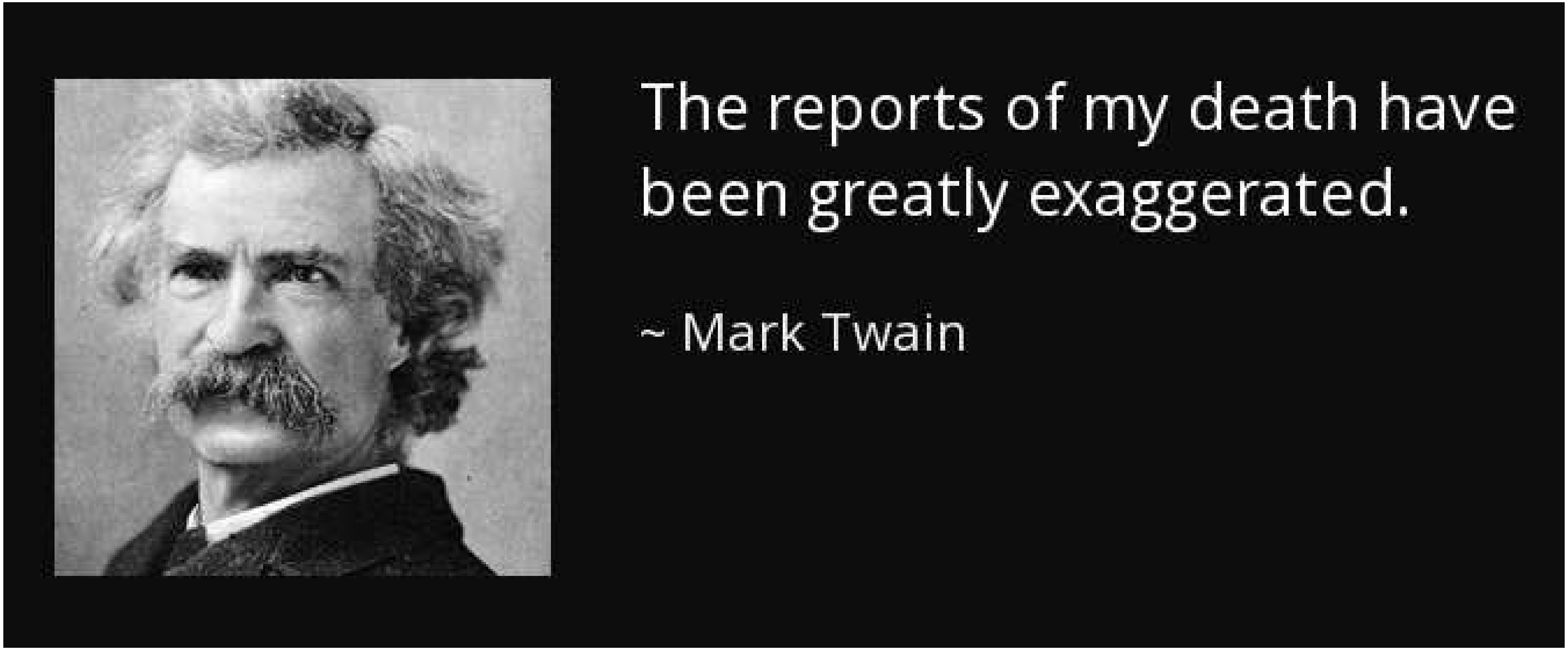
type II: problems with $b \to s\gamma$

$\Rightarrow$ only type X is in agreement with $(g-2)_\mu$, EWPO and flavor observables

$\Rightarrow$ Not taken into account here: $h_{125} \to AA$ . . .

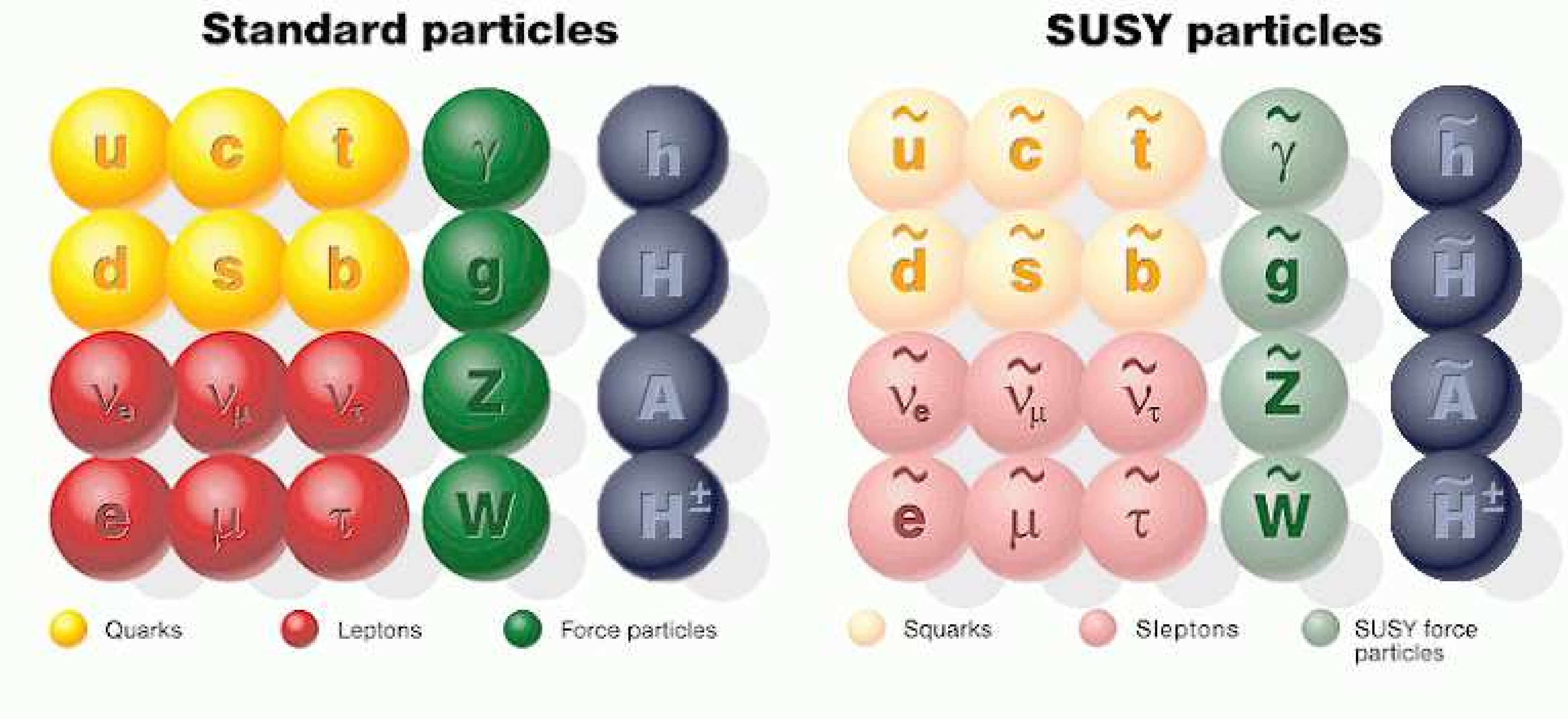
3. "SUSY fits like a glove"

→ quote by Bill Marciano after the BNL result came out in 2001



Simplest SUSY realization: the MSSM

Superpartners for Standard Model particles



$\Rightarrow$ 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:

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

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

Scalar lepton sector of the MSSM

Charged slepton mass matrices

$$\mathbf{M}^2_{\tilde{l}} = \begin{pmatrix} M^2_{\tilde{l}_L} + m_l^2 + DT_{l_1} & m_l X_l \\ m_l X_l & M^2_{\tilde{l}_R} + m_l^2 + DT_{l_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{l}}} \begin{pmatrix} m^2_{\tilde{l}_1} & 0 \\ 0 & m^2_{\tilde{l}_2} \end{pmatrix}$$

with

$$X_l = A_l - \mu \tan\beta$$

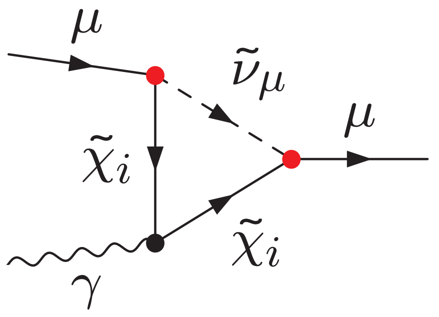
Sneutrino mass

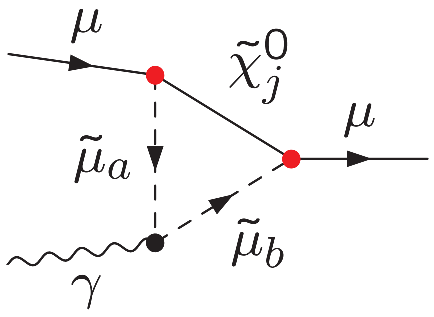
$$m^2_{\tilde{\nu}_l} = M^2_{\tilde{l}_L} + DT_\nu$$

Simplifying assumption: $M_{\tilde{l}_L}$ and $M_{\tilde{l}_R}$ identical for all three generations

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:

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

- 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

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

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

$\Rightarrow$ 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

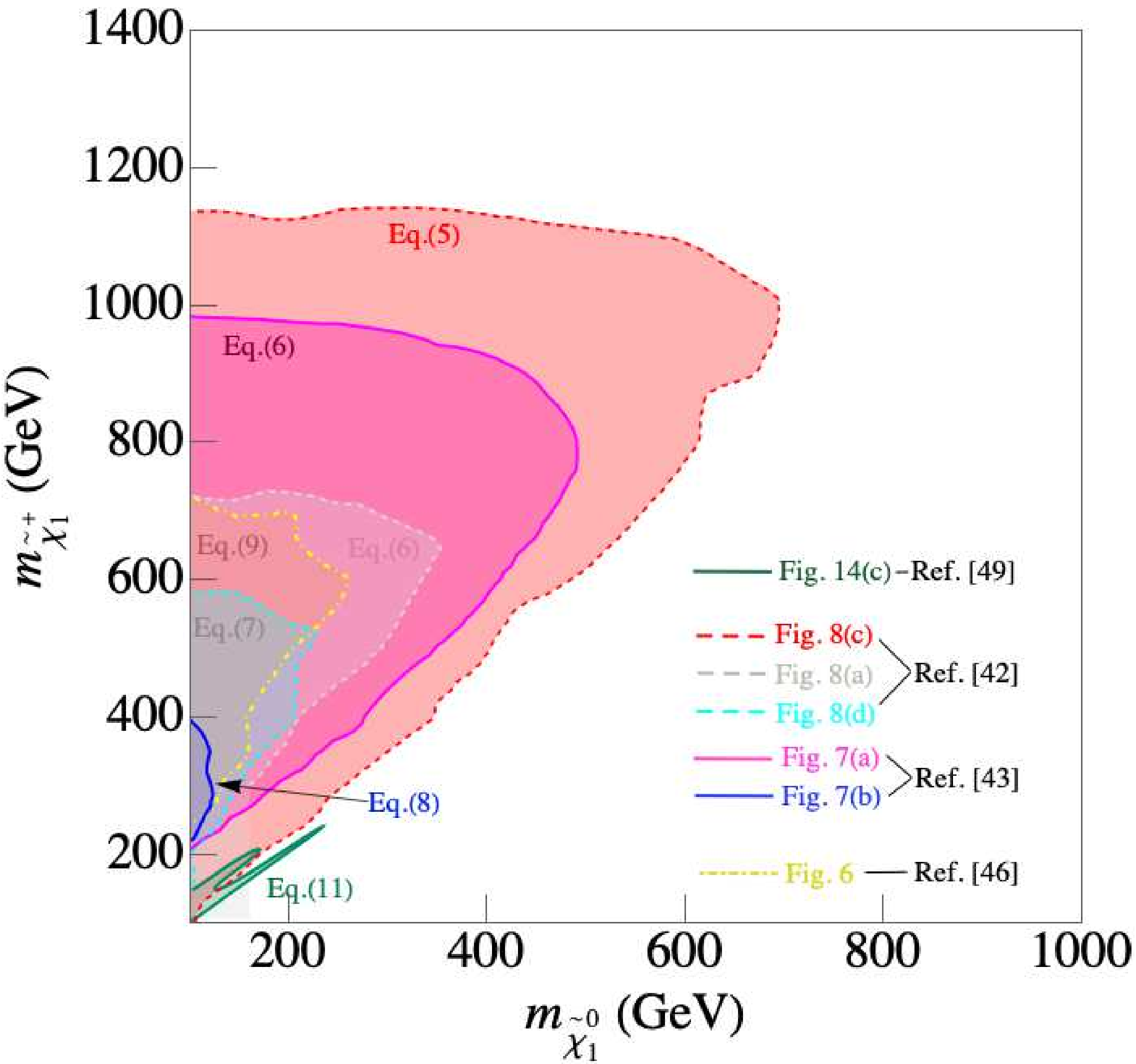
$$\Omega_{\text{CDM}} h^2 = 0.120 \pm 0.001$$
$$\text{or} \quad \Omega_{\text{CDM}} h^2 \leq 0.122$$

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

Dark Matter direct detection: MicrOmegas

limit on spin independent scattering cross section (Xenon1T)
[*Xenon collab. '18*]

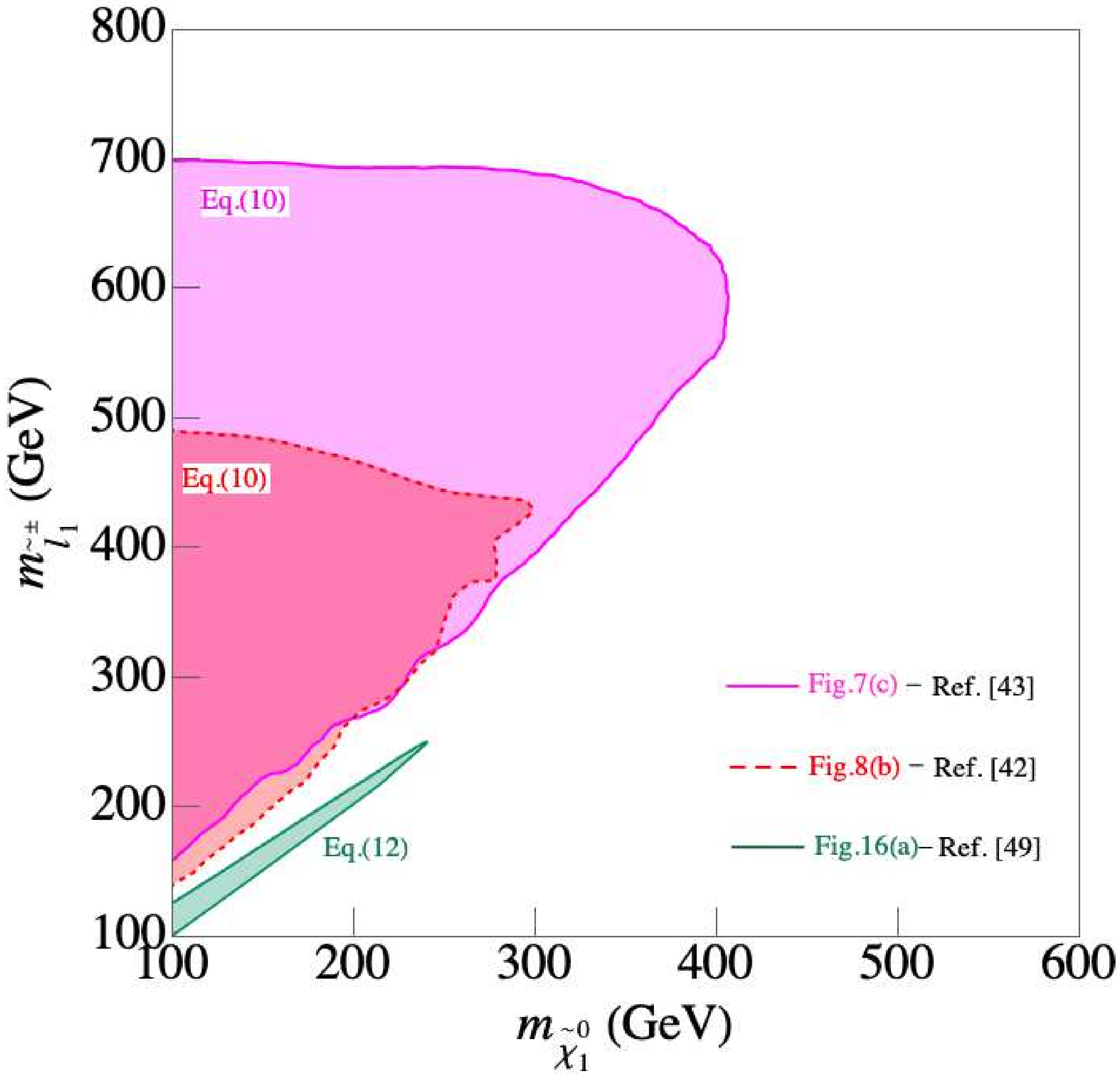
LHC exclusion bounds (I) (as given for Simplified Model Spectra (SMS))



⇒ 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

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 $\Delta a_\mu^{\text{new}}$

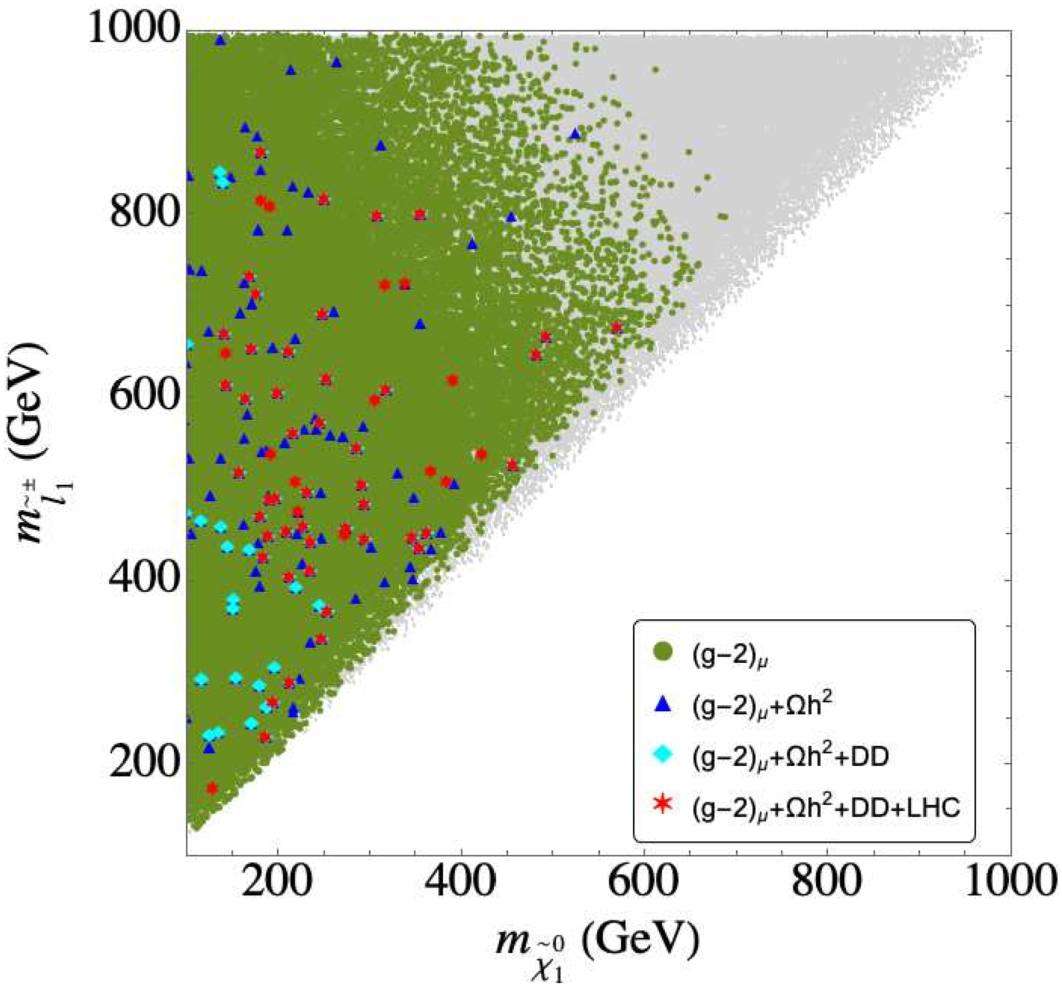
3. bino DM with slepton co-annihilation case-R
   $\Rightarrow$ full relic DM constraint $\Rightarrow$ updated with $\Delta a_\mu^{\text{new}}$

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

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

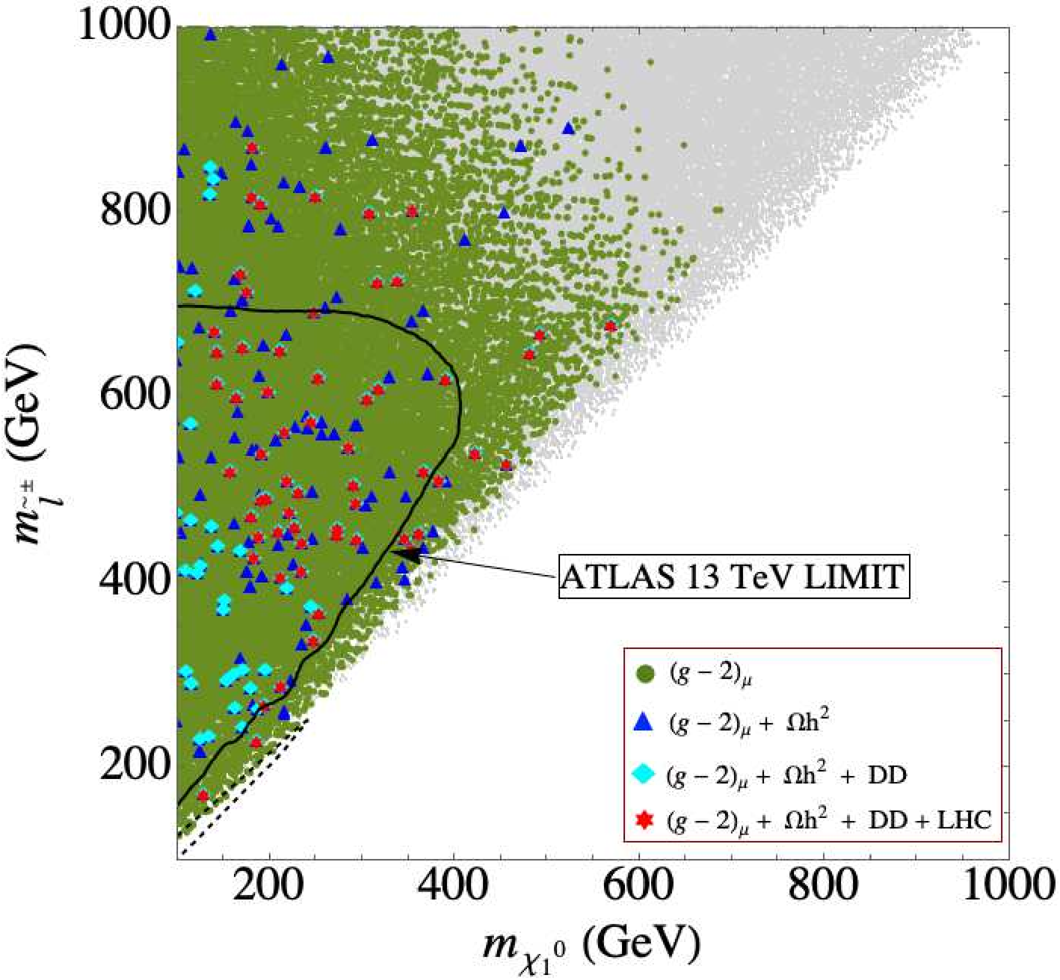
new $(g-2)_\mu$



⇒ 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 $(g-2)_\mu$

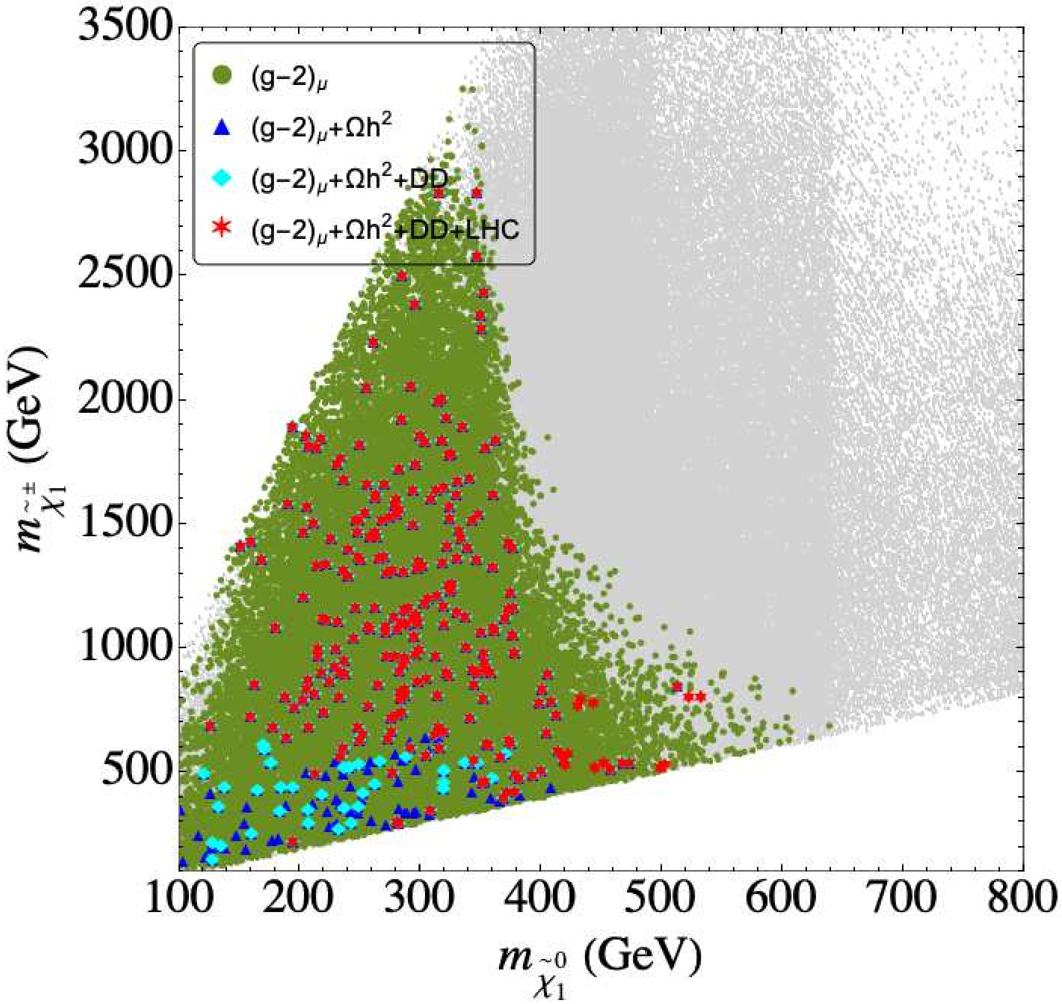


⇒ important: $\tilde{l}$-pair production searches (10)

⇒ naive application of LHC bounds fails

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

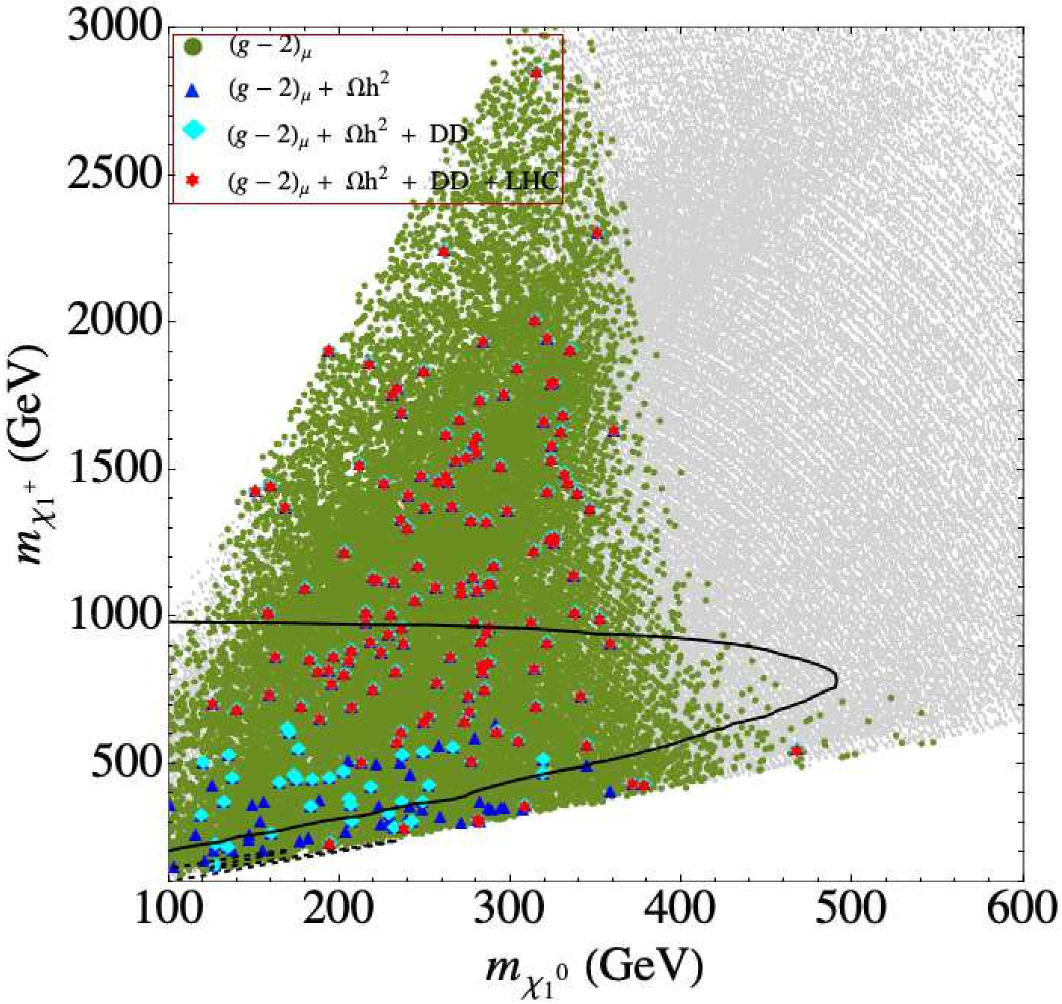
new $(g-2)_\mu$



⇒ 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 $(g-2)_\mu$

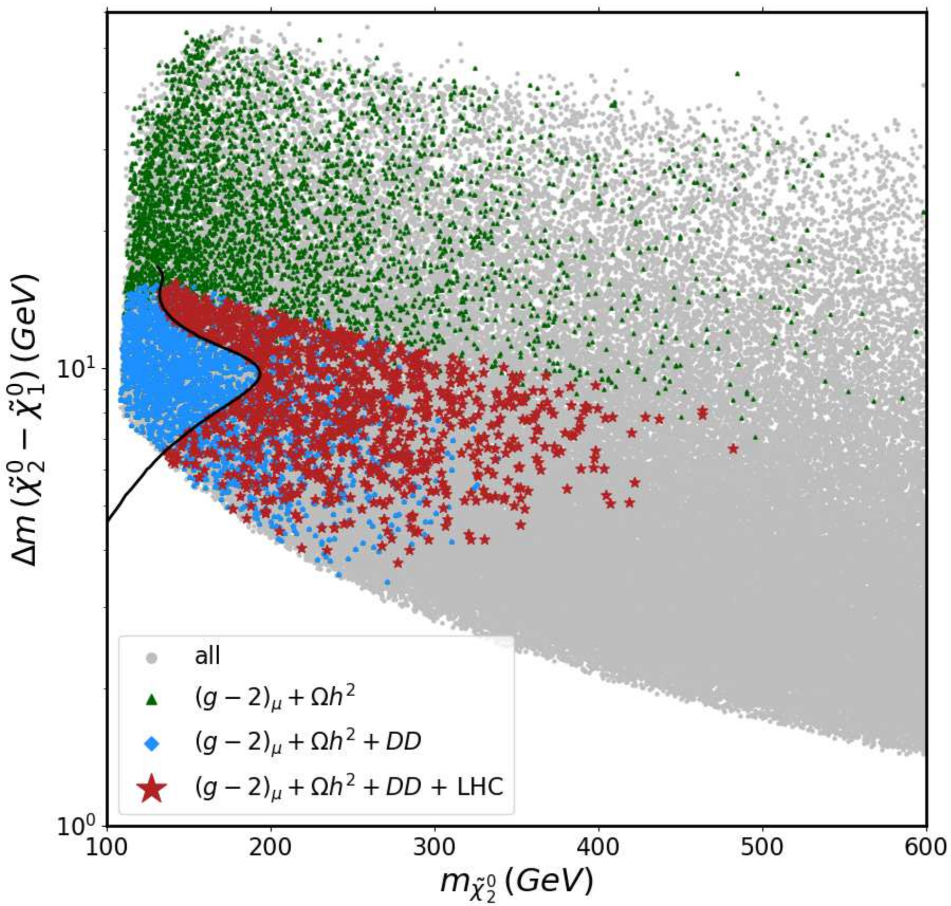


$\Rightarrow$ important: $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production searches (5)

$\Rightarrow$ naive application of LHC bounds fails

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

old $(g-2)_\mu$

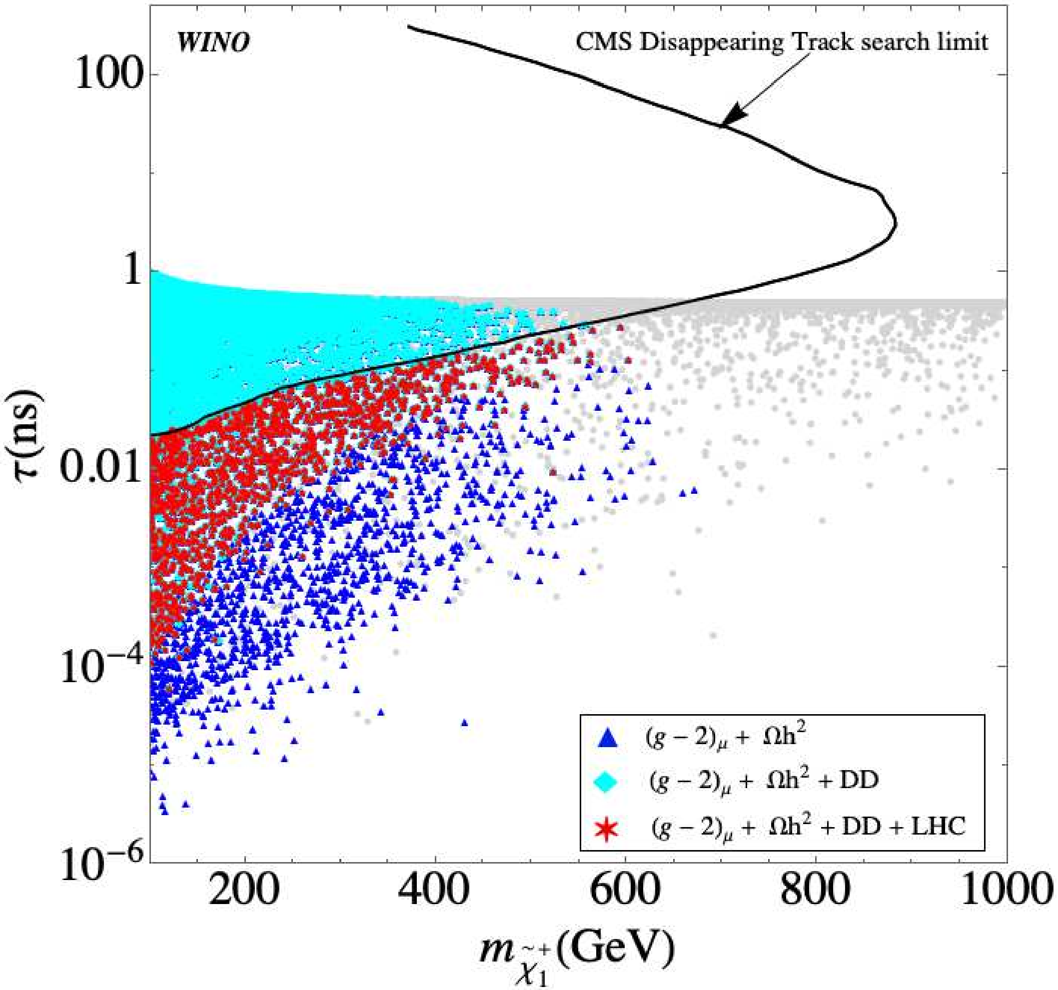


$\Rightarrow$ important: compressed spectra searches (11)

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

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

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

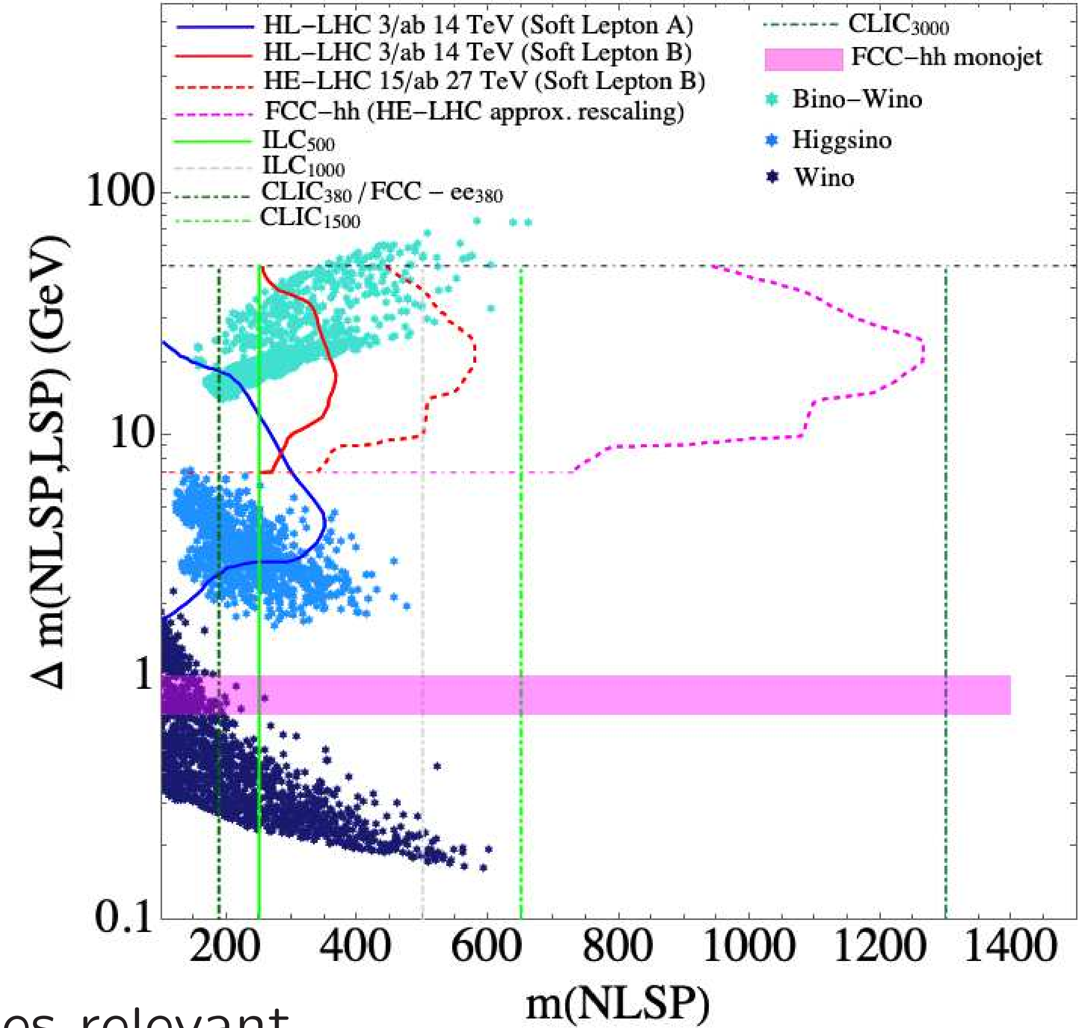
relic DM density as upper limit (otherwise $m_{\tilde{\chi}_1^0} \sim 3$ TeV)

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

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

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

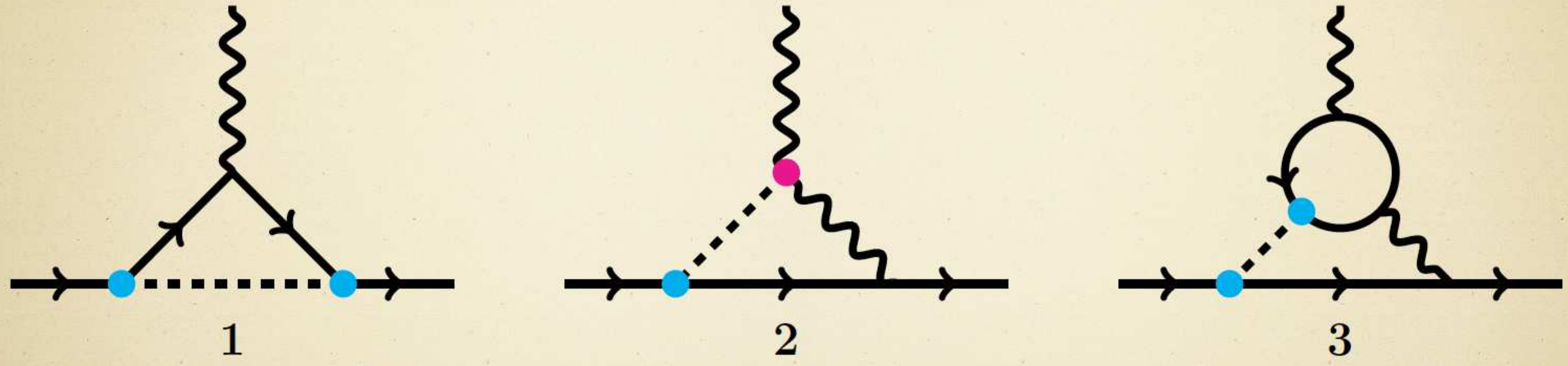
– ILC/CLIC needed to cover these scenario

4. “There is always the axion”

→ quote by Howie Baer on WIMP DM limits

Lagrangian and possible contributions (I):

$$\mathscr{L}_{\text{eff}} \supset \frac{c_{ii}}{2}\frac{\partial_\mu a}{f_a}\left(\bar{\ell}_i \gamma^\mu \gamma^5 \ell_i\right) + c_{\gamma\gamma}\frac{\alpha}{4\pi}\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu} + \cdots$$



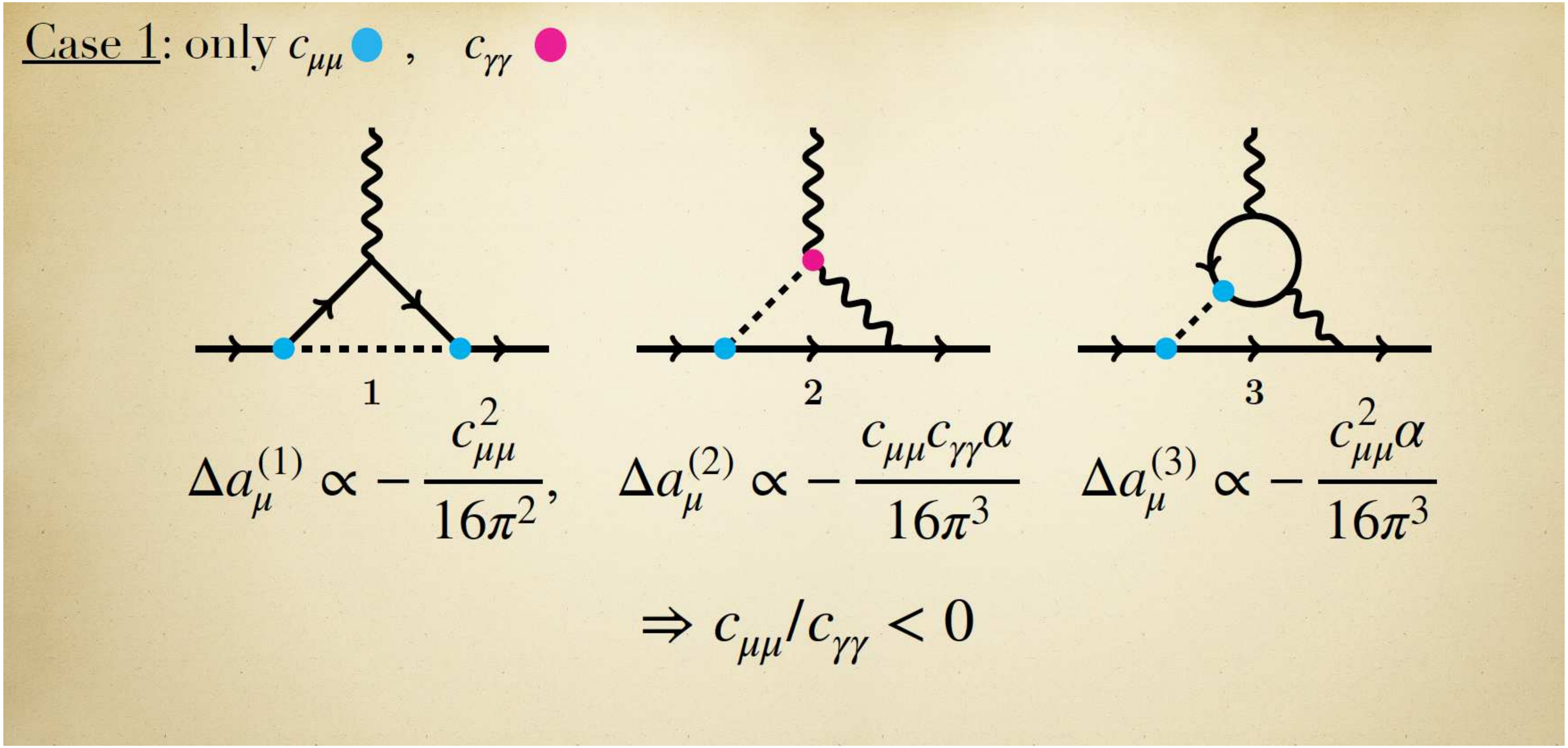
$$\Delta a_\mu^{(1)} \propto -\frac{c_{\mu\mu}^2}{16\pi^2}, \quad \Delta a_\mu^{(2)} \propto -\frac{c_{\mu\mu}c_{\gamma\gamma}\alpha}{16\pi^3}, \quad \Delta a_\mu^{(3)} \propto -\frac{c_{\mu\mu}c_{ii}\alpha}{16\pi^3},$$

Chang et.al 2001; Marciano et.al. 2016; Bauer et.al. 2017.

Different combinations of the axion couplings: Darme et.al 2020

[*taken from talk by JJ. Fan, g-2Days21*]

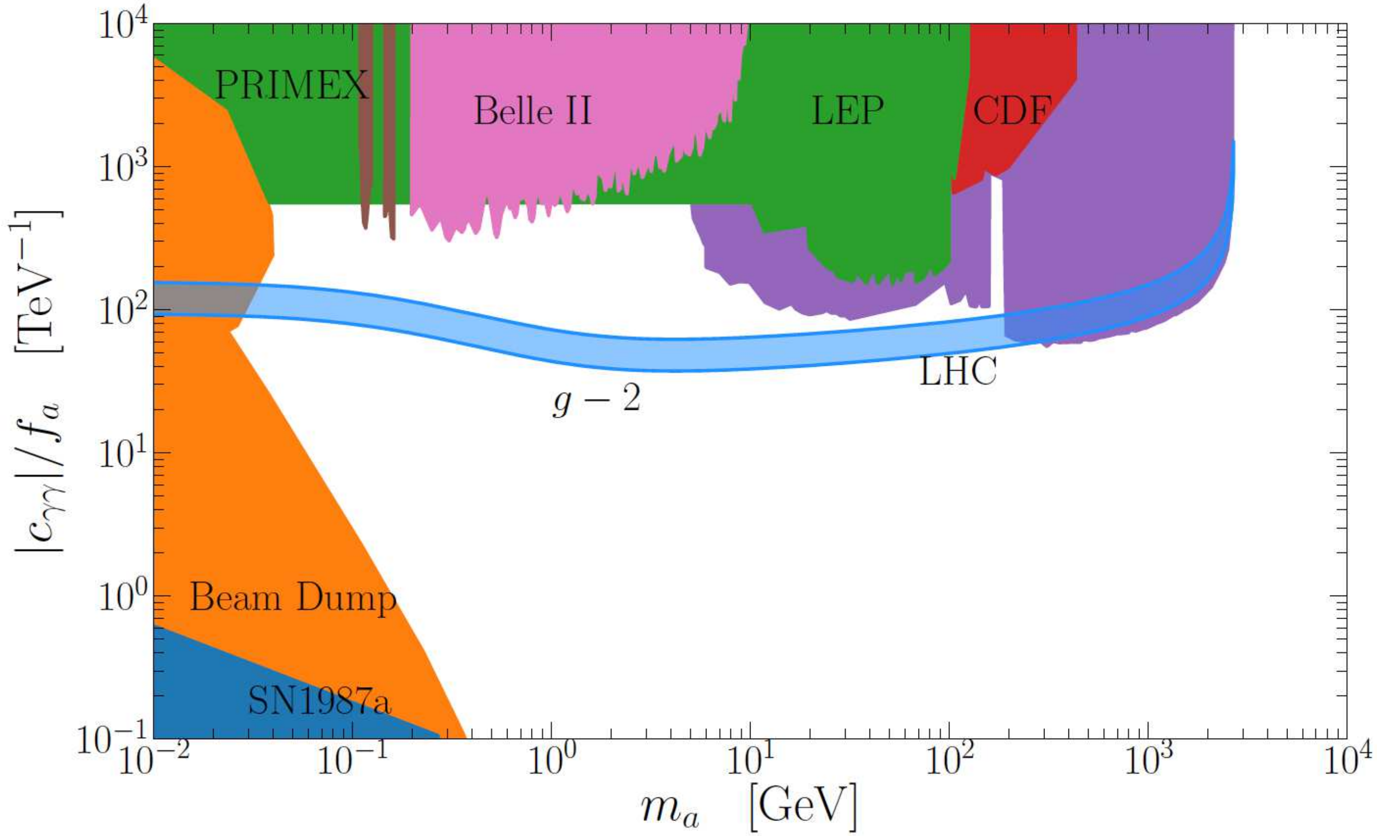
Lagrangian and possible contributions (II):



[*taken from talk by JJ. Fan, g-2Days21*]

Allowed parameter space for case 1:

[*M. Buen-Abad, JJ. Fan, M. Reece, C. Sun '21*]

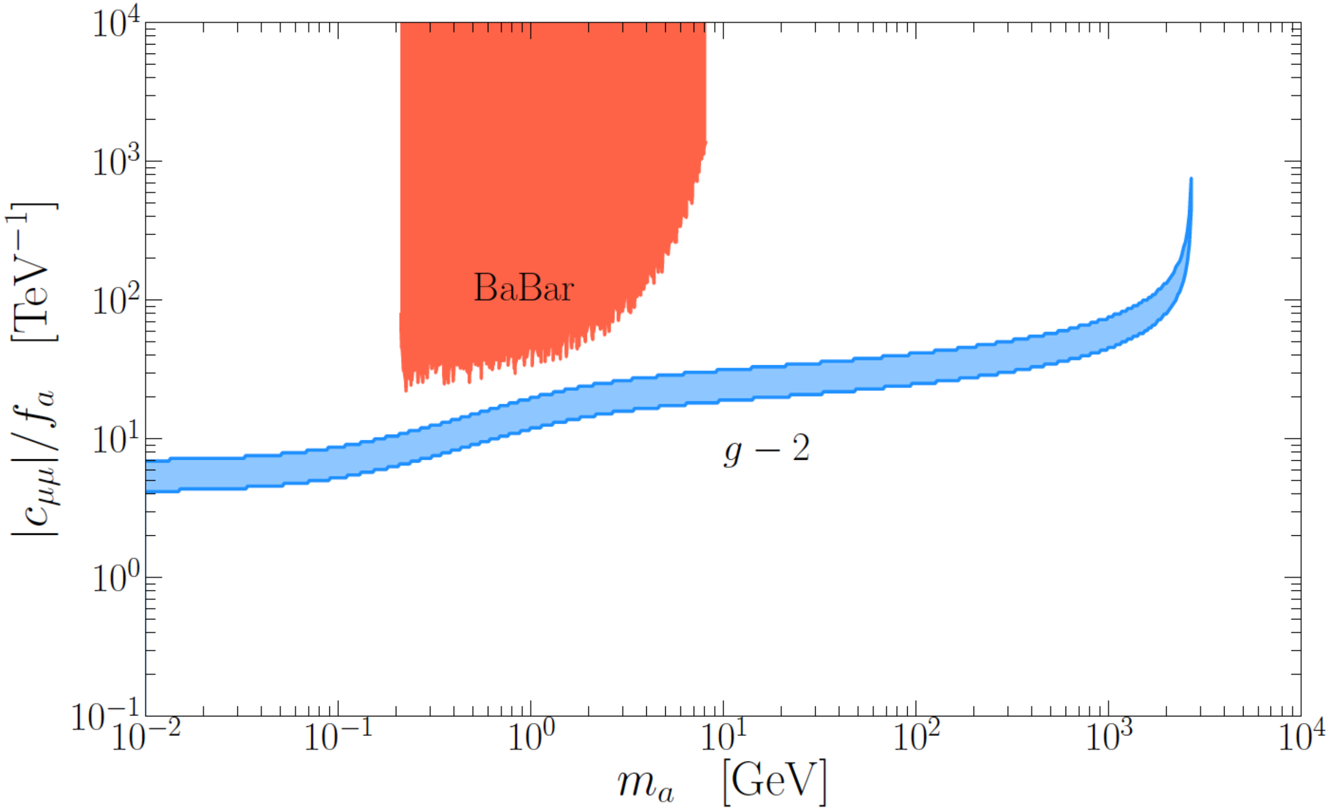


$$c_{\gamma\gamma}/c_{\mu\mu} < 0, \quad m_a \in [40\text{ MeV}, 200\text{ GeV}]$$

$$\left|\frac{f_a}{c_{\gamma\gamma}}\right| \lesssim 15\ldots25\text{ GeV}, \quad \left|\frac{f_a}{c_{\mu\mu}}\right| \lesssim 100\text{ GeV}$$

Allowed parameter space for case 1:

[M. Buen-Abad, JJ. Fan, M. Reece, C. Sun '21]



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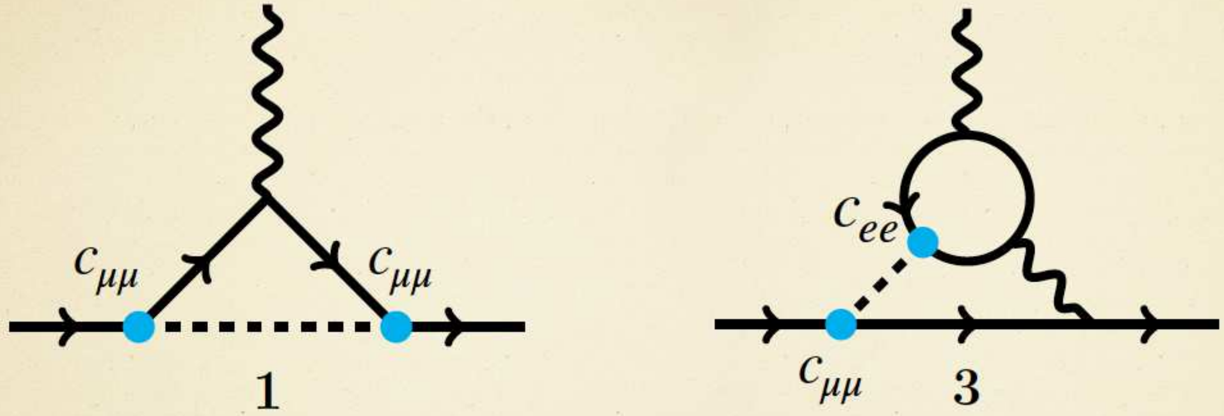
$$\left|\frac{f_a}{c_{\gamma\gamma}}\right| \lesssim 15\ldots 25\ \text{GeV}, \quad \left|\frac{f_a}{c_{\mu\mu}}\right| \lesssim 100\ \text{GeV}$$

Lagrangian and possible contributions (III):

Case 2: only $c_{\mu\mu}$, c_{ee}



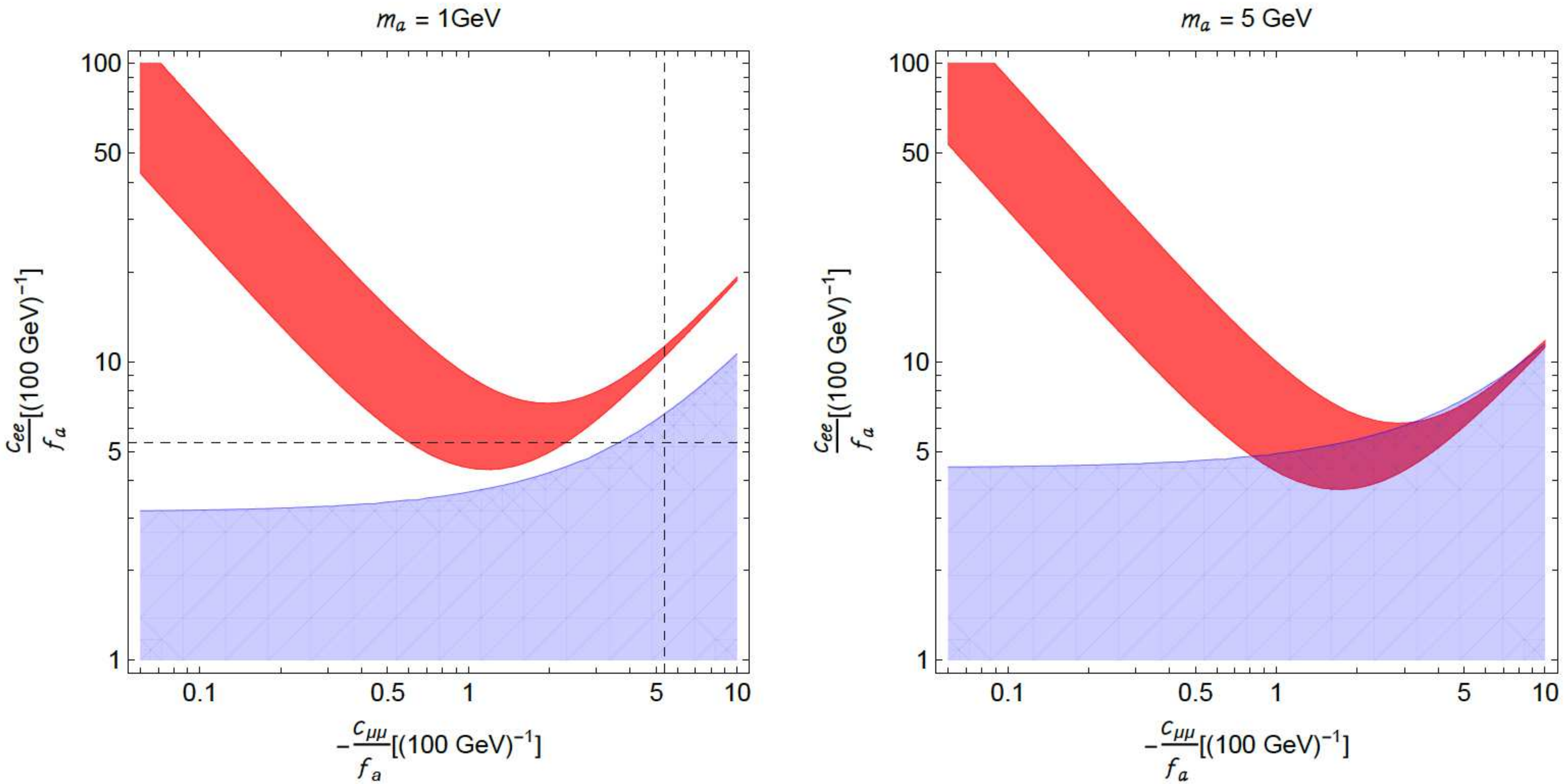
$$\Delta a_\mu^{(1)} \propto -\frac{c_{\mu\mu}^2}{16\pi^2}, \quad \Delta a_\mu^{(3)} \propto -\frac{c_{\mu\mu} c_{ee} \alpha}{16\pi^3}$$

$$\Rightarrow c_{\mu\mu}/c_{ee} < 0$$

[*taken from talk by J. Fan, g-2Days21*]

Allowed parameter space for case 2:

[*M. Buen-Abad, JJ. Fan, M. Reece, C. Sun '21*]



$$m_a \gtrsim 2\ \text{GeV}, \quad c_{ee}/c_{\mu\mu} < 0$$

$$\left|\frac{f_a}{c_{\mu\mu}}\right| \lesssim 100\ \text{GeV}, \quad \left|\frac{f_a}{c_{ee}}\right| \lesssim 25\ \text{GeV} \quad \text{for } m_a = 5\ \text{GeV}$$

Case 1:

$$c_{\gamma\gamma}/c_{\mu\mu} < 0, \quad m_a \in [40\text{ MeV}, 200\text{ GeV}]$$
$$\left|\frac{f_a}{c_{\gamma\gamma}}\right| \lesssim 15\ldots25\text{ GeV}, \quad \left|\frac{f_a}{c_{\mu\mu}}\right| \lesssim 100\text{ GeV}$$

Case 2:

$$m_a \gtrsim 2\text{ GeV}, \quad c_{ee}/c_{\mu\mu} < 0$$
$$\left|\frac{f_a}{c_{\mu\mu}}\right| \lesssim 100\text{ GeV}, \quad \left|\frac{f_a}{c_{ee}}\right| \lesssim 25\text{ GeV} \quad \text{for } m_a = 5\text{ GeV}$$

$\Rightarrow$ axion couplings to SM must be unnaturally large!

$\Rightarrow$ only achieved by integrating out additional matter content

$\Rightarrow$ consider full UV-complete model?!

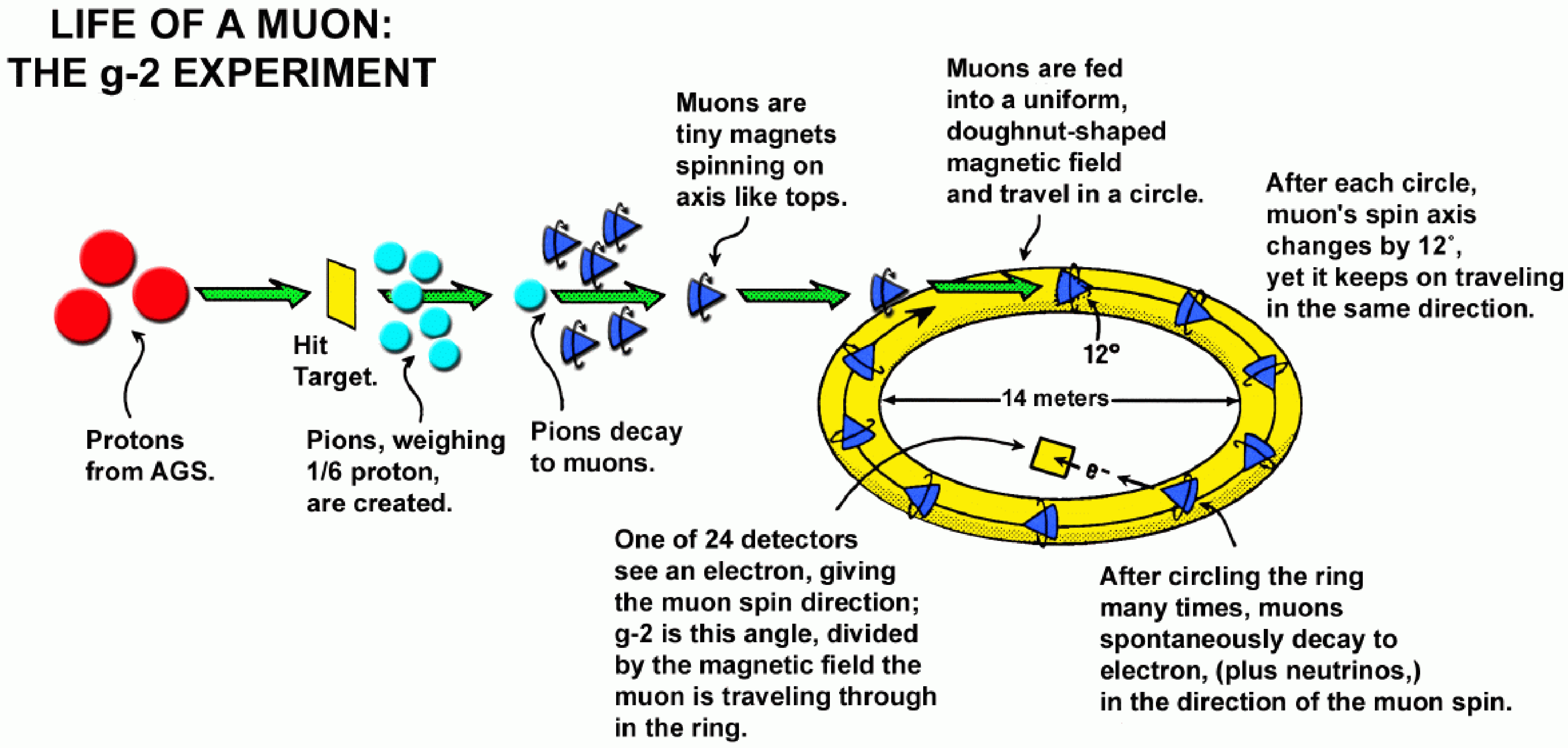
5. Conclusinos

- new $(g-2)_\mu$ result confirms old result and deviation from the SM
  $(g-2)_\mu$ is real $\Rightarrow$ (relatively) light EW particles
- 2HDM: only type X can be in agreement with $(g-2)_\mu$, EWPO, flavor
  $\Rightarrow m_A \lesssim 50$ GeV, $\tan\beta \gtrsim 40 \Rightarrow$ not taken into account (yet): $h_{125} \to AA$
- MSSM:
  - scan the EW sector of the MSSM with all constraints:
    $(g-2)_\mu$, DM relic density, DM DD, LHC EW searches
  - upper limits on EW masses $\Rightarrow$ evaluate future prospects

  LHC searches included via CheckMate $\Rightarrow$ crucial!
- A) bino/wino DM with chargino coann. (DM full)
  B/C) bino DM with slepton coann. (DM full)
  D) higgsino eDM $m_{\tilde\chi_1^0} \sim m_{\tilde\chi_2^0} \sim m_{\tilde\chi_1^\pm} \sim \mu$ (DM upper limit)
  E) wino DM $m_{\tilde\chi_1^0} \sim m_{\tilde\chi_1^\pm} \sim M_2$ (DM upper limit)
  $\Rightarrow$ clear upper limits, $m_{\text{(N)LSP}} \lesssim 600$ GeV confirmed
  compressed spectra: good HL-LHC prospects, but ILC/CLIC needed
- Axions: in principle possible
  $\Rightarrow$ axion couplings to SM must be unnaturally large!
  $\Rightarrow$ integrating out additional matter content, full UV-complete model?


Further Questions?

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

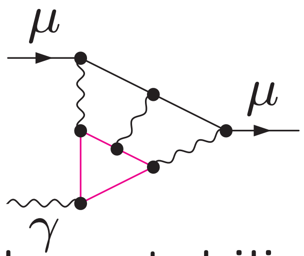


Coupling of muon to magnetic field : $\mu - \mu - \gamma$ coupling

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

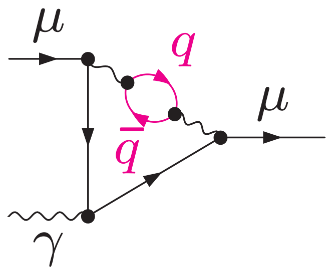
Theory of $(g-2)_\mu$:

– the light-by-light contribution:



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

– the hadronic vacuum contribution:



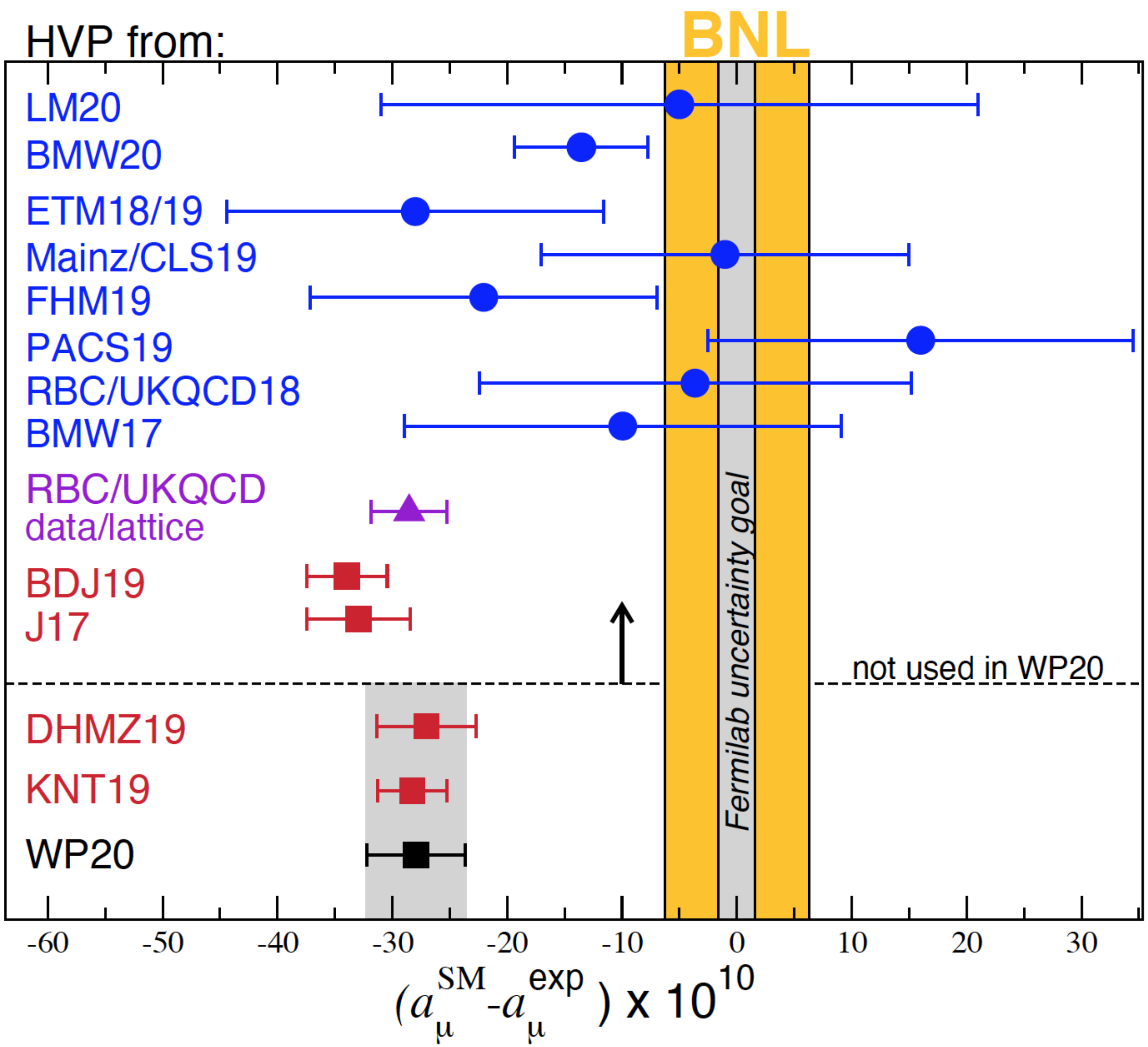
'direct' e^+e^- data:

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

τ data:

tended to be closer to experimental result
inclusion of γ-ρ mixing: agreement with e^+e^- *[F. Jegerlehner, R. Szafron '10]*
$\Rightarrow$ not used anymore

HVP summary:



⇒ 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

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

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

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

Compressed spectra

$$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to (W^*\tilde{\chi}_1^0)(Z^*\tilde{\chi}_1^0) \to 2l + \not{E}_T \; + \mathrm{ISR}\ , \tag{11}$$
$$\tilde{l}^+\tilde{l}^- \to (l^+\tilde{\chi}_1^0)(l^-\tilde{\chi}_1^0) \to 2l + \not{E}_T \; + \mathrm{ISR} \tag{12}$$

Searches involving Staus

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

Exception: compressed spectra ⇒ direct application

A) Bino/wino DM with chargino co-annihilation

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

Parameter scan:

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

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

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

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

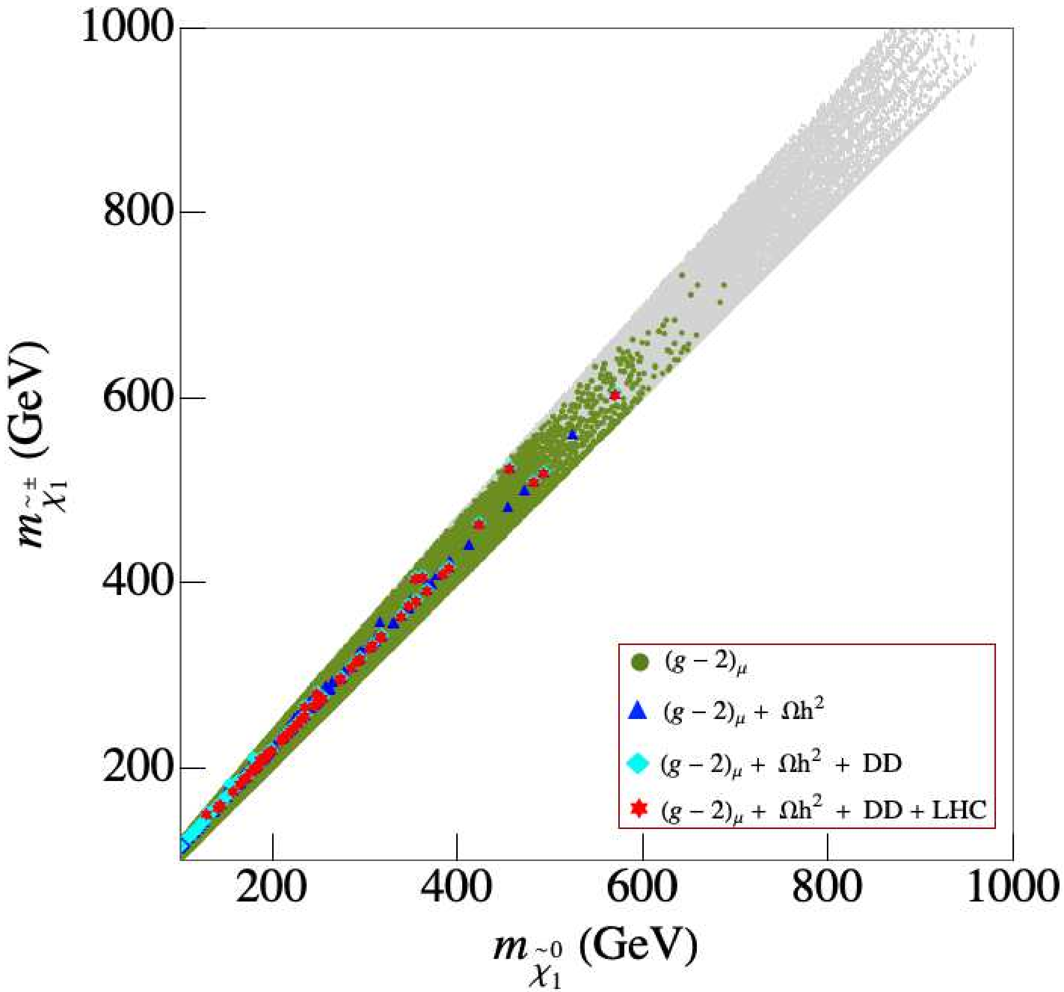
$$100\text{ GeV} \le m_{\tilde{L}} \le 1\text{ TeV},$$

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

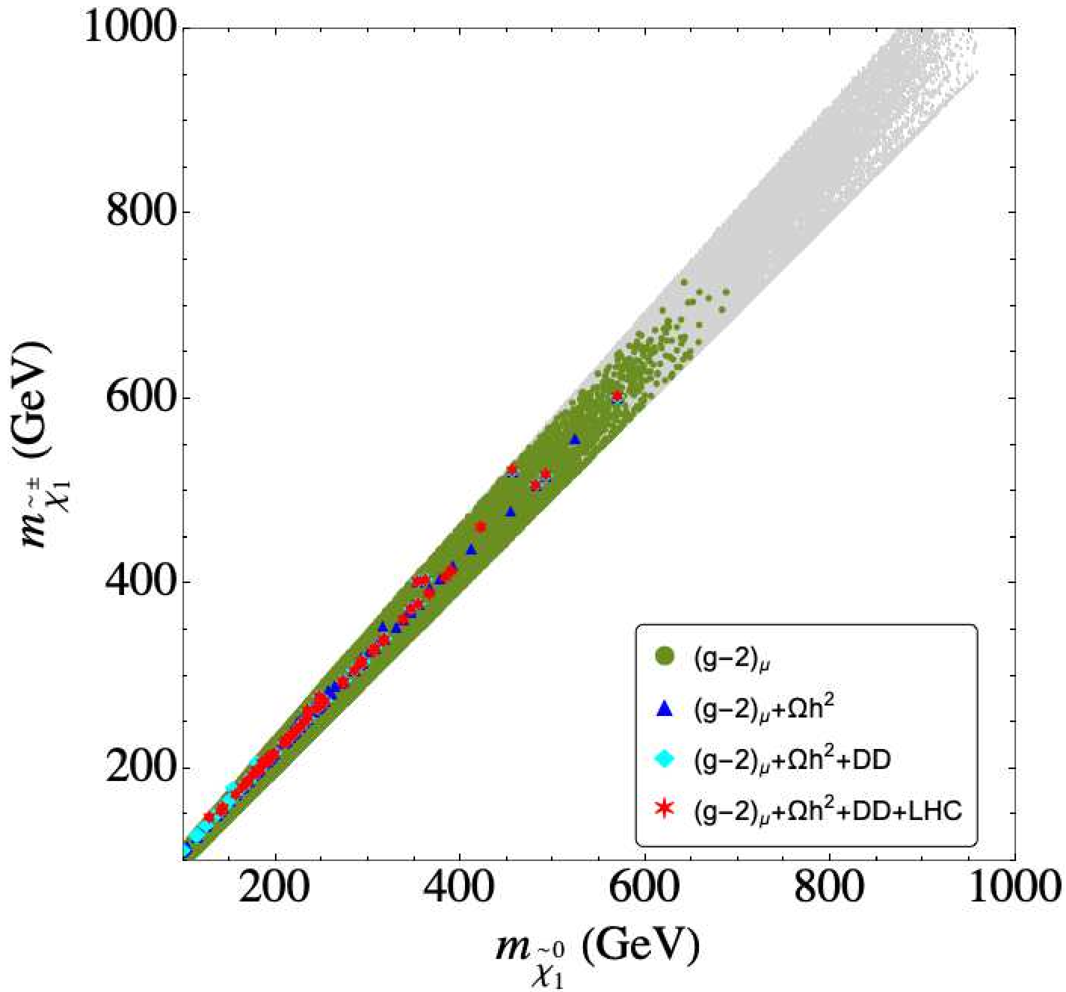
(latter condition only to make the analysis simpler, no relevant effect)

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

old $(g-2)_\mu$



new $(g-2)_\mu$

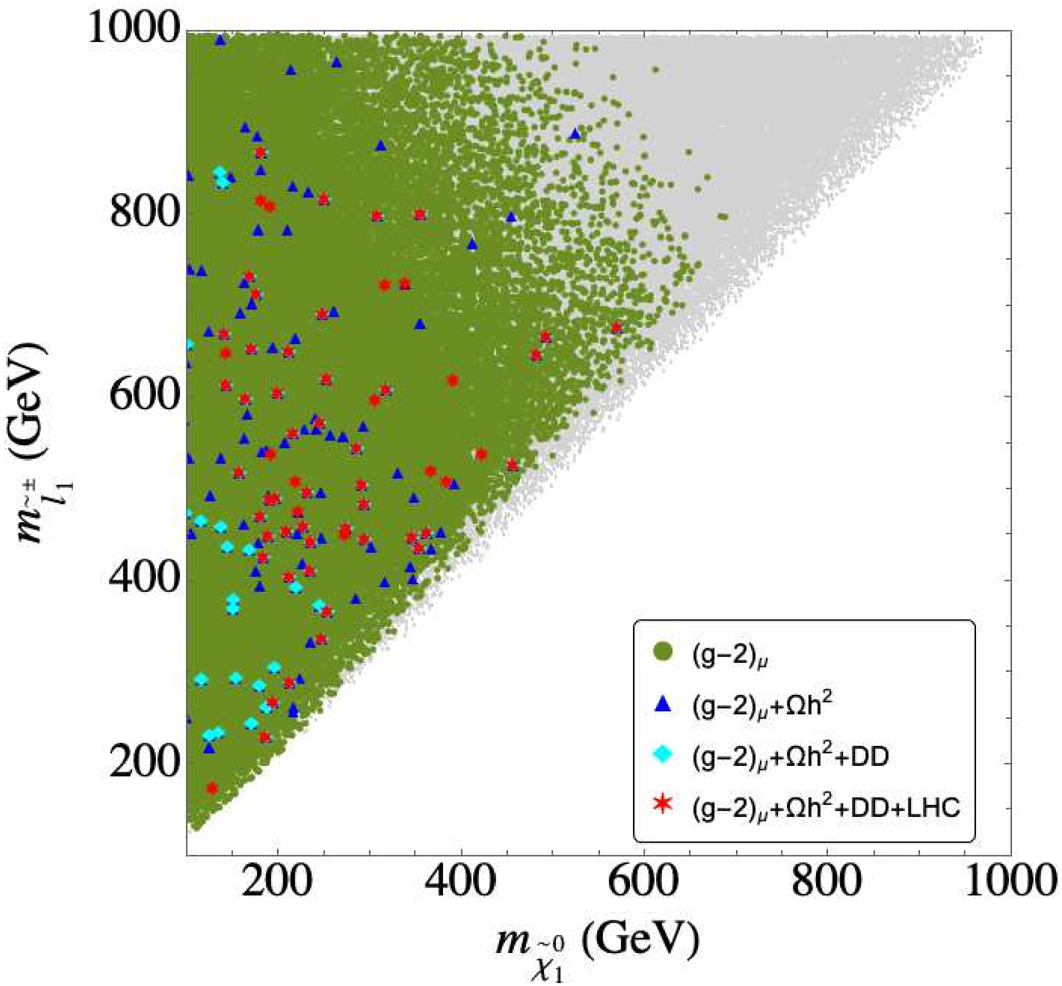


⇒ compressed spectrum as expected

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

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

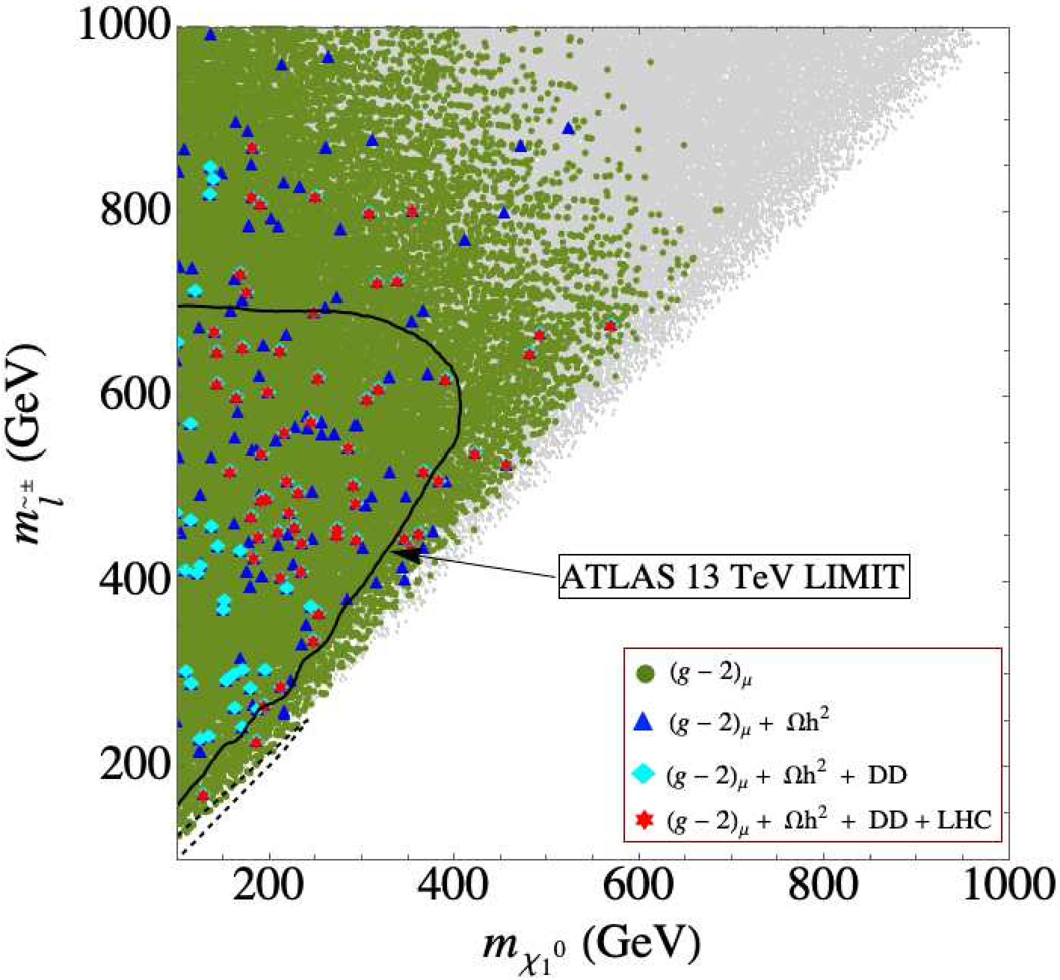
new $(g-2)_\mu$



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

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

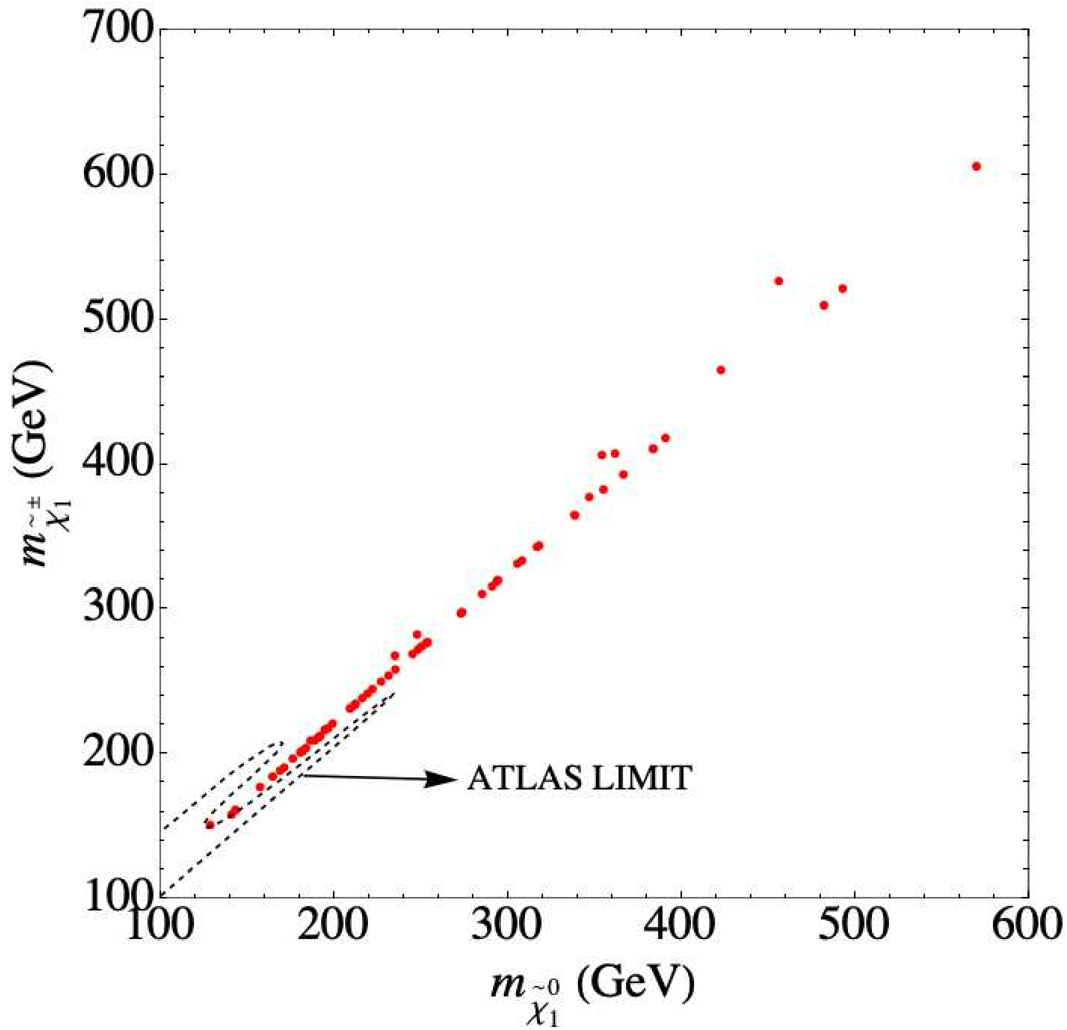
old $(g-2)_\mu$



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

⇒ naive application of LHC bounds fails

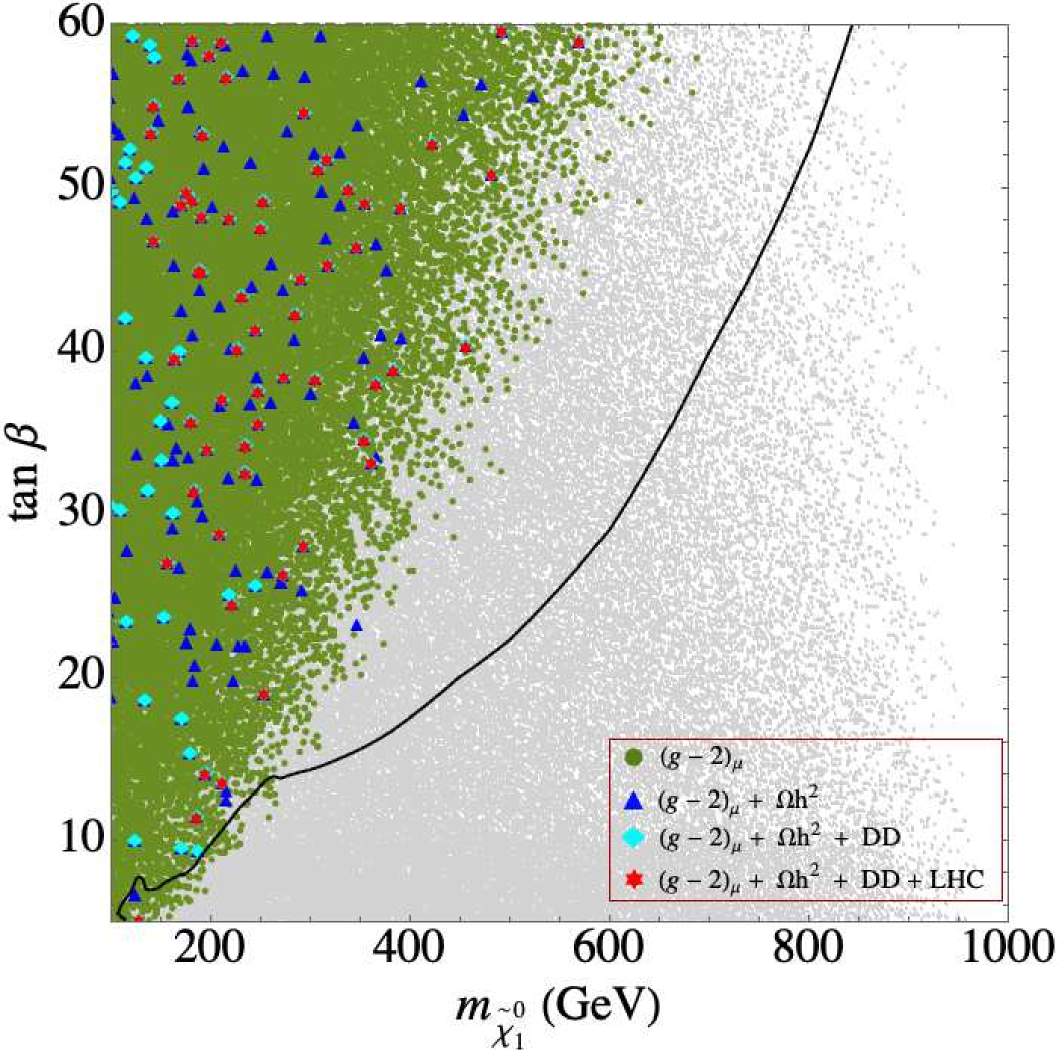
Comparison with the compressed spectra searches:



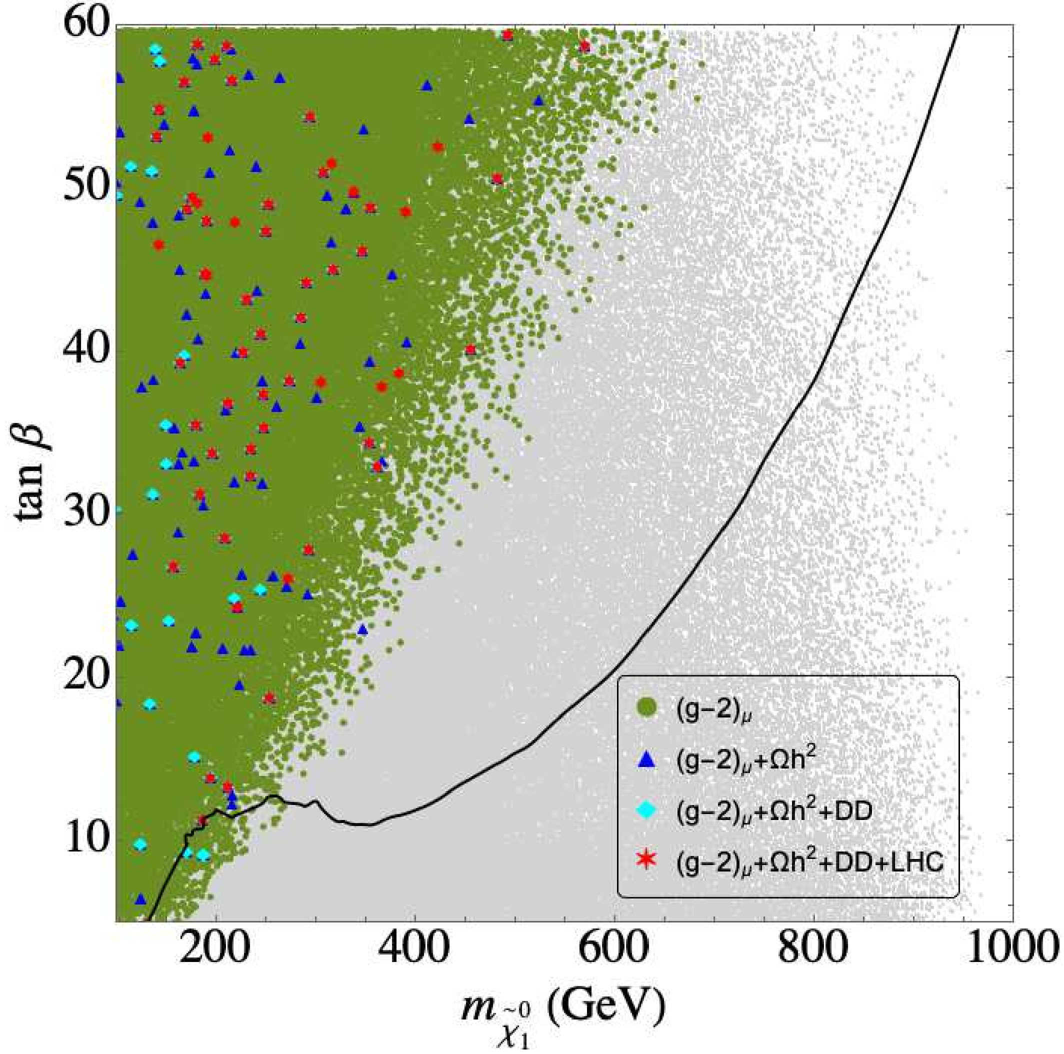
⇒ compressed spectrum avoids current bounds!

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

old $(g-2)_\mu$



new $(g-2)_\mu$

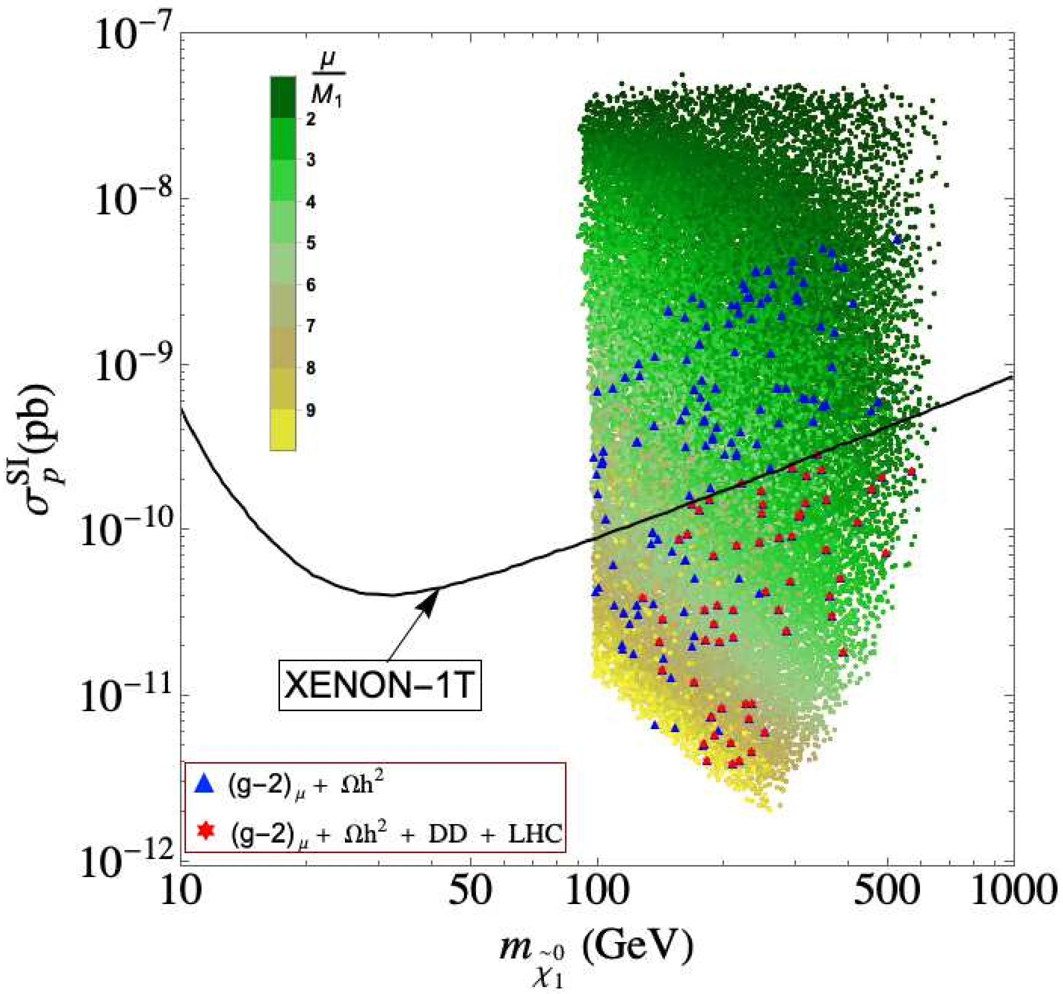


black contour: (simplified) application of $H/A \to \tau^+\tau^-$

$\Rightarrow$ A-pole annihilation effectively excluded

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

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

$$M_1 \le M_2 \le 10M_1 ,$$

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

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

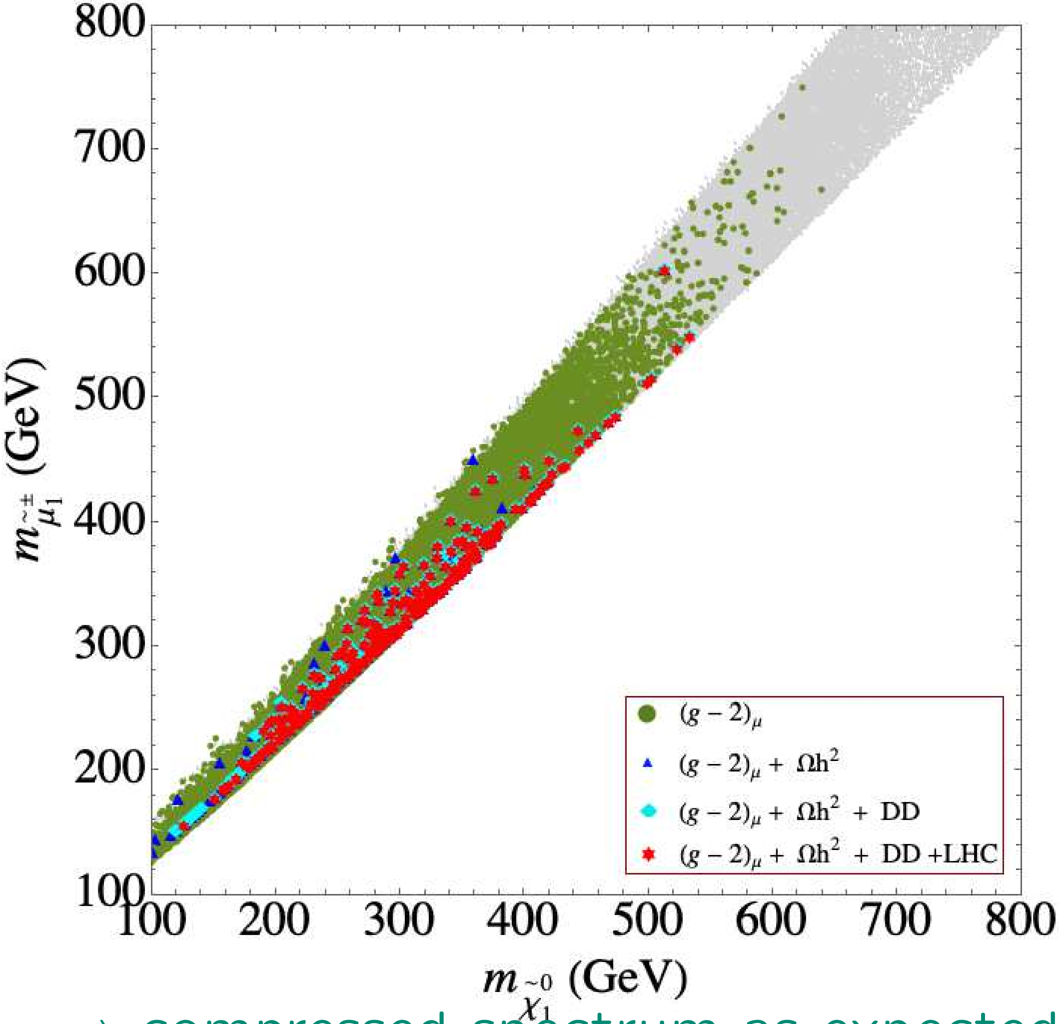
$$\text{Case-L:} \quad M_1 \le m_{\tilde{L}} \le 1.2M_1, \quad M_1 \le m_{\tilde{R}} \le 10M_1.$$

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

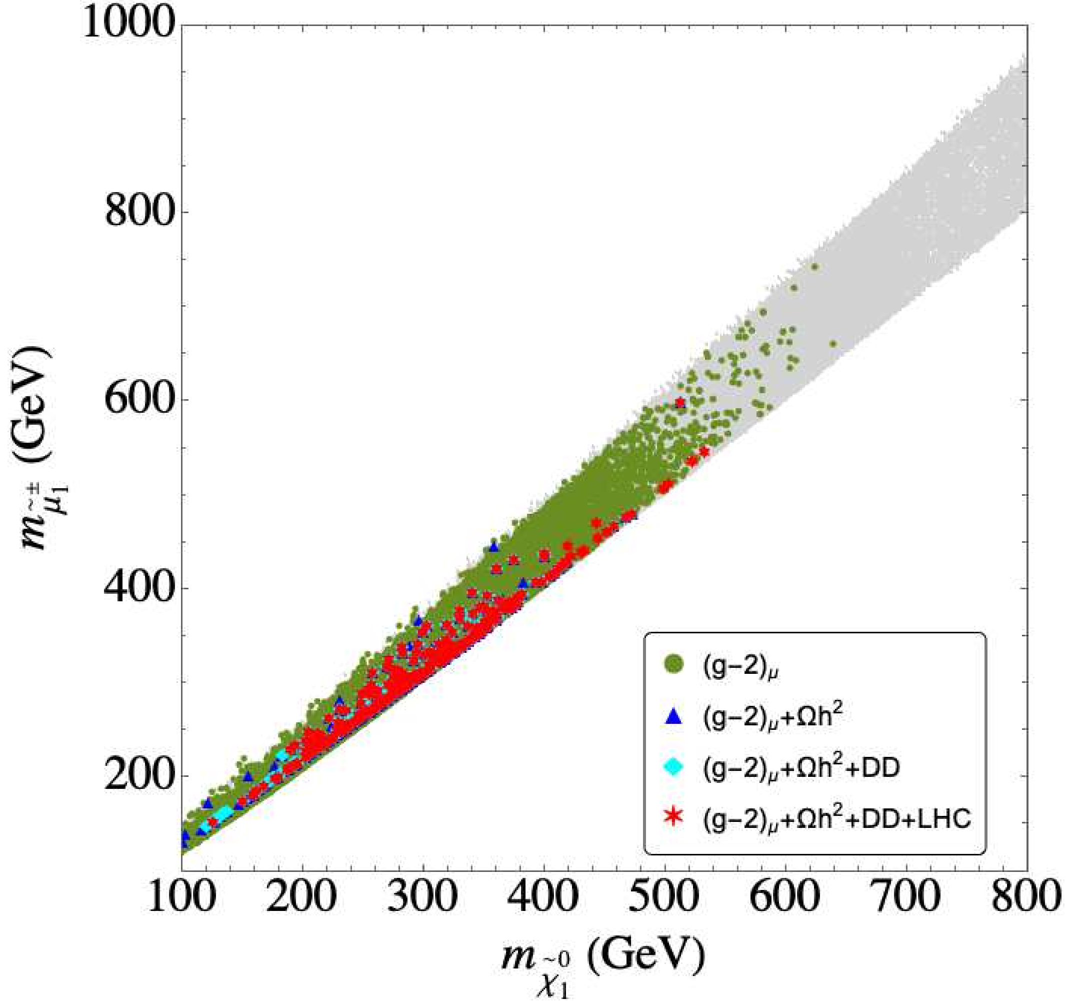
$\Rightarrow$ here focus on Case-L

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

old $(g-2)_\mu$



new $(g-2)_\mu$

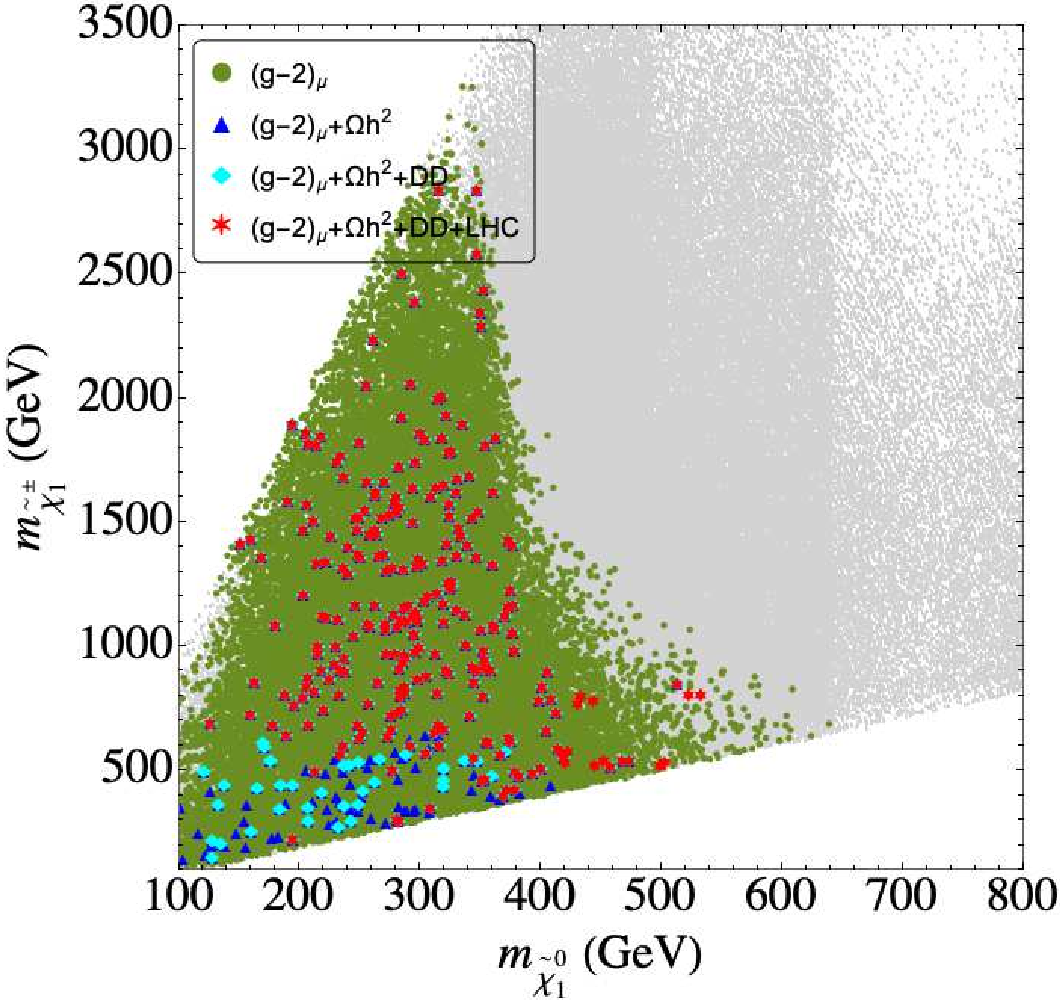


⇒ compressed spectrum as expected

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

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

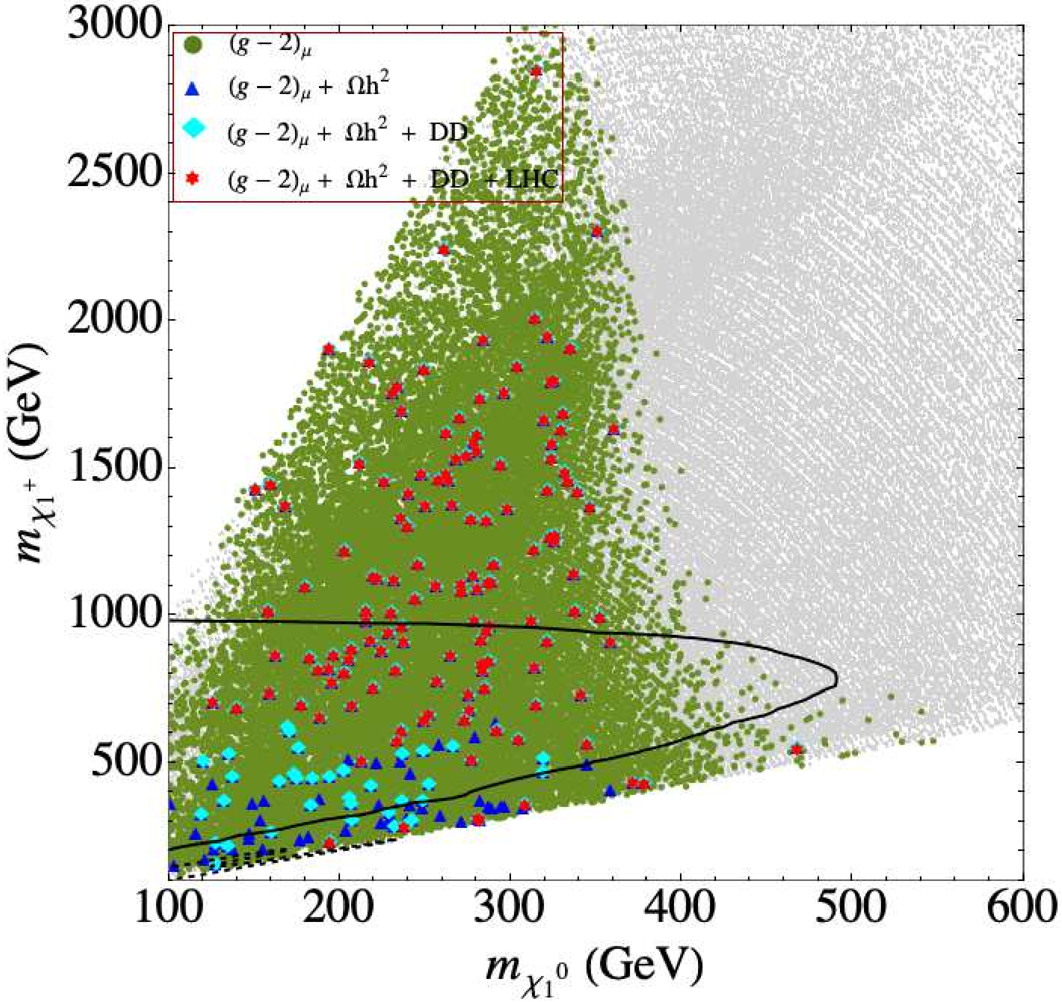
new $(g-2)_\mu$



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

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

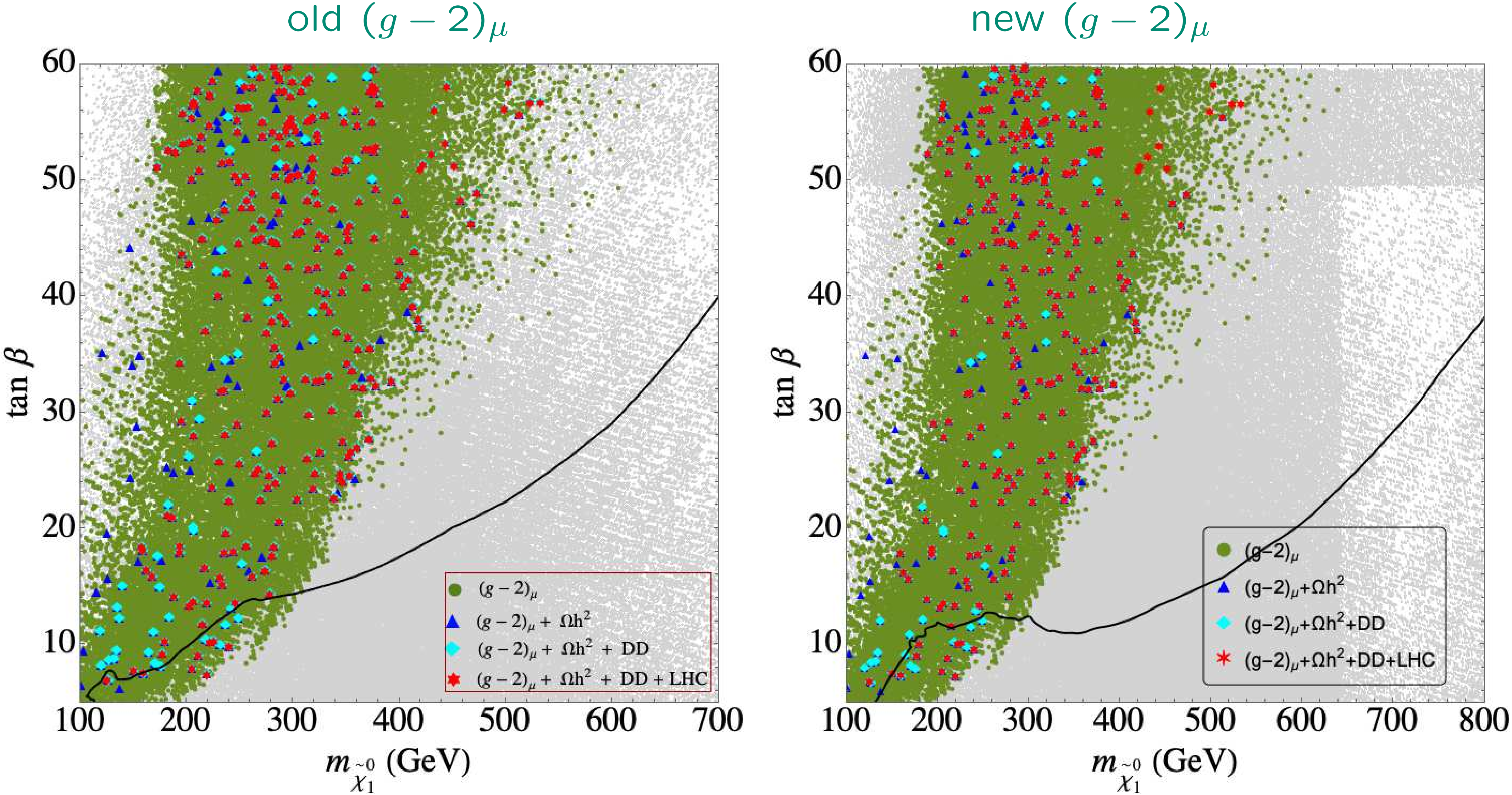
old $(g-2)_\mu$



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

⇒ naive application of LHC bounds fails

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 largely excluded

D) Higgsino DM

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

Parameter scan:

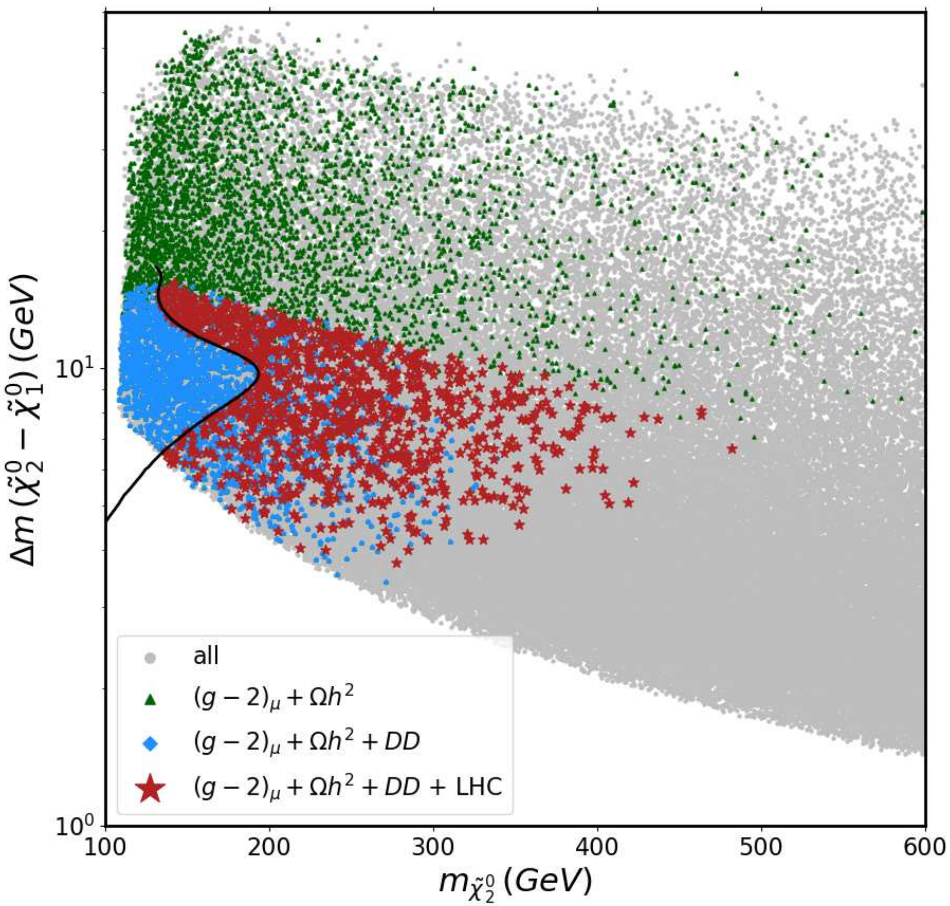
$$
\begin{aligned}
100\text{ GeV} \le \mu &\le 1.2\text{ TeV}\,, \\
1.1\mu \le M_1 &\le 10\mu\,, \\
1.1 M_2 \le \mu &\le 10\mu\,, \\
5 \le \tan\beta &\le 60, \\
100\text{ GeV} \le m_{\tilde{L}}, m_{\tilde{R}} &\le 2\text{ TeV},
\end{aligned}
$$

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

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

Results in the $m_{\tilde{\chi}_2^0}$-Δm plane:

old $(g-2)_\mu$

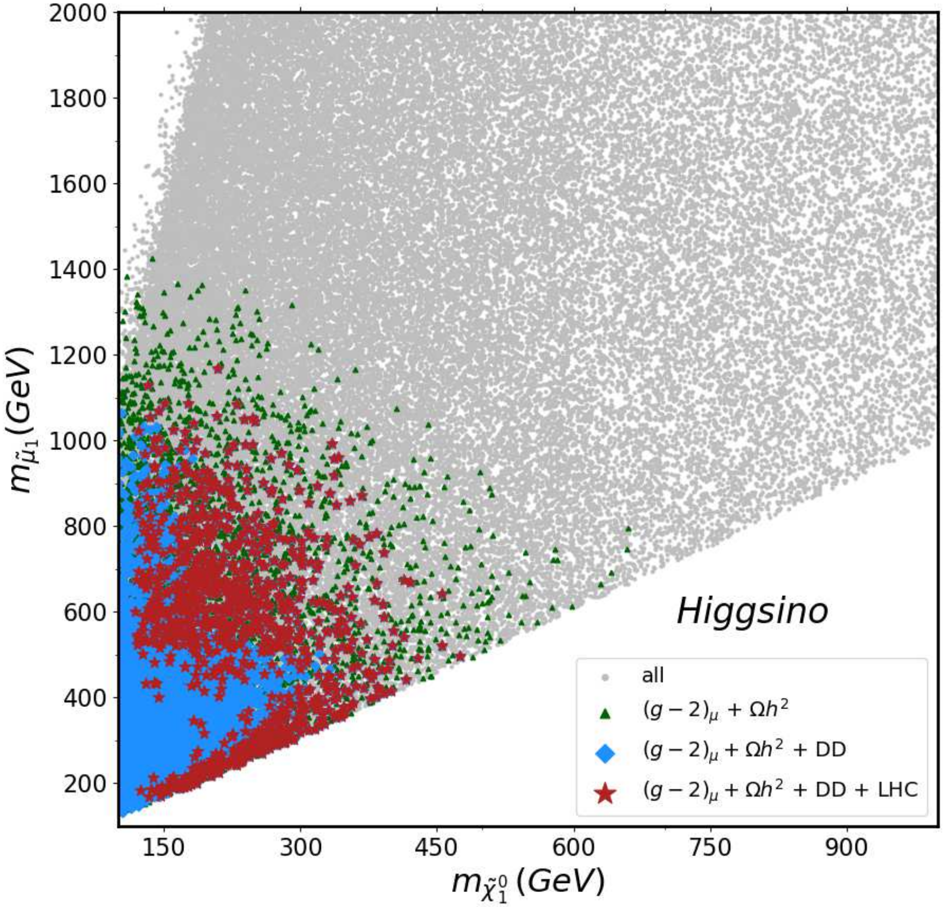


$\Rightarrow$ important: compressed spectra searches (11)

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

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

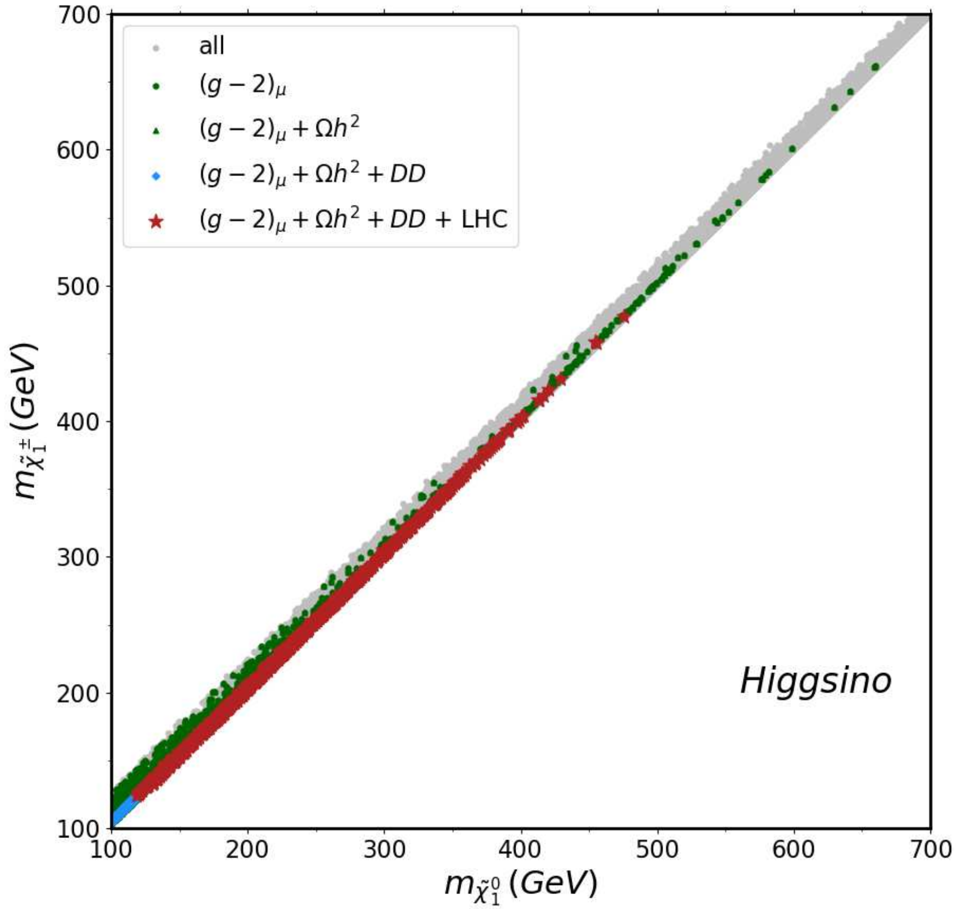
old $(g-2)_\mu$



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

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

old $(g-2)_\mu$

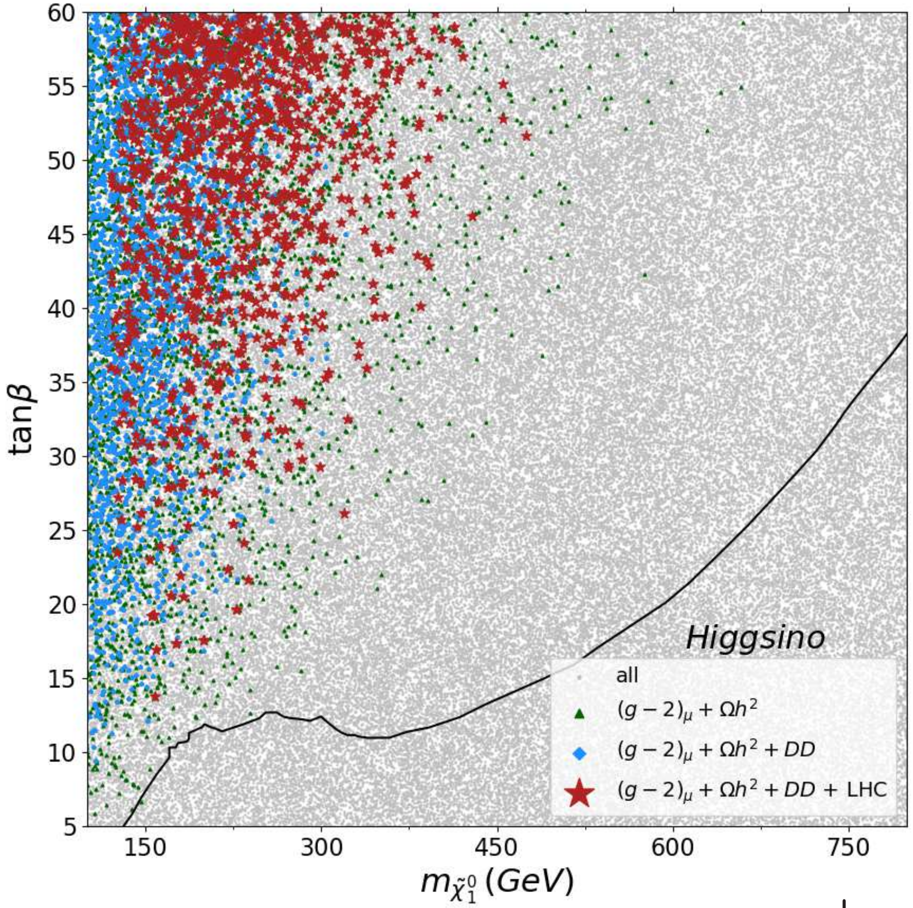


$\Rightarrow$ important: compressed spectra searches (11)

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

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:

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

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

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

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

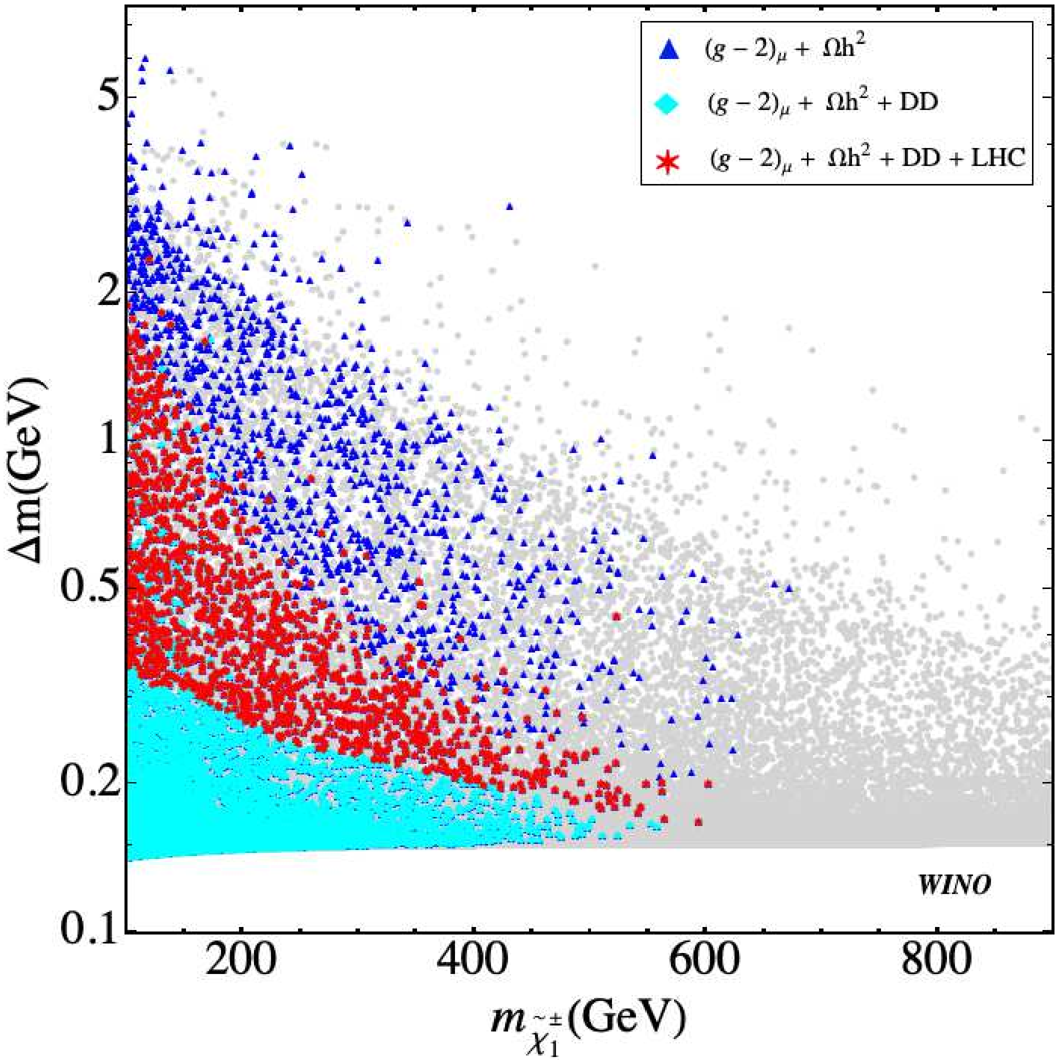
$$100\ \text{GeV} \leq m_{\tilde{L}}, m_{\tilde{R}} \leq 2\ \text{TeV},$$

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

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

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

old $(g-2)_\mu$

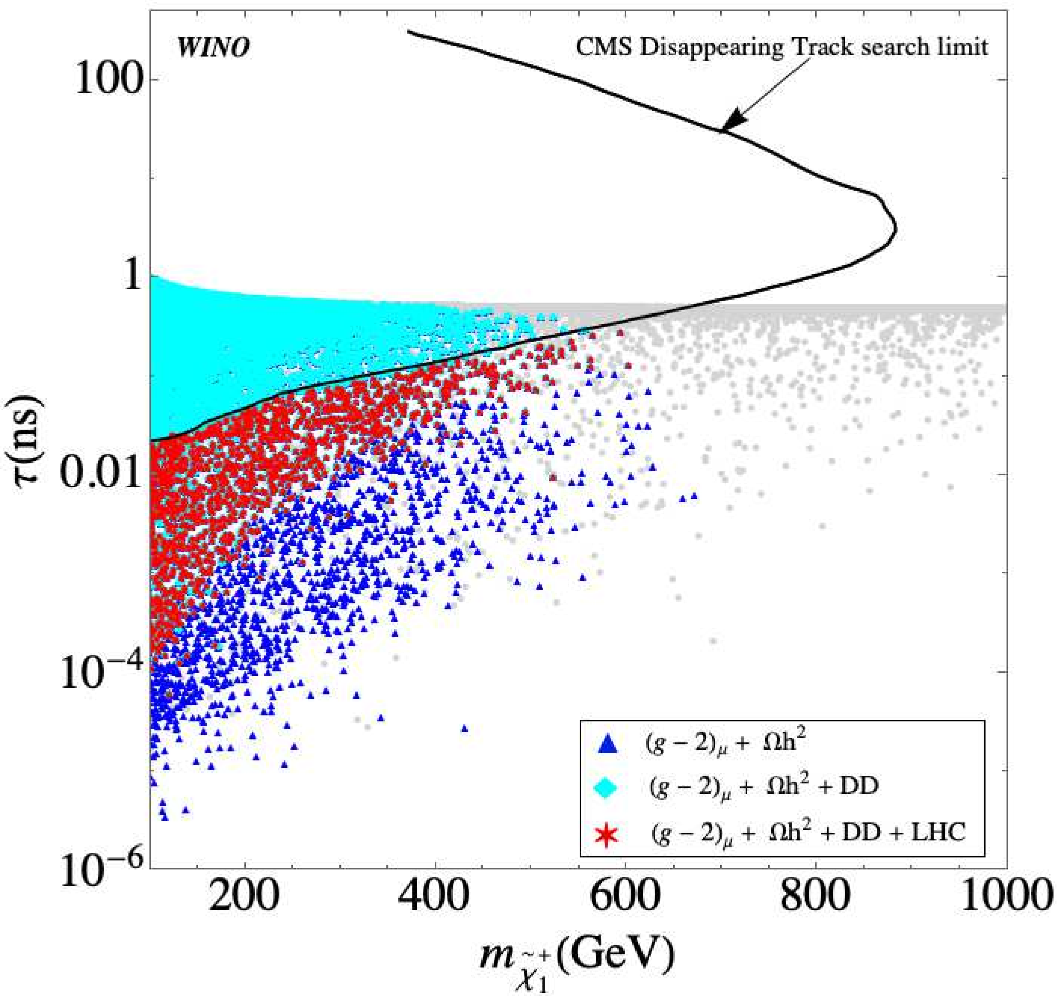


⇒ important: disappearing track limit ⇒ $m_{\text{(N)LSP}} \lesssim 600$ GeV

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

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

old $(g-2)_\mu$

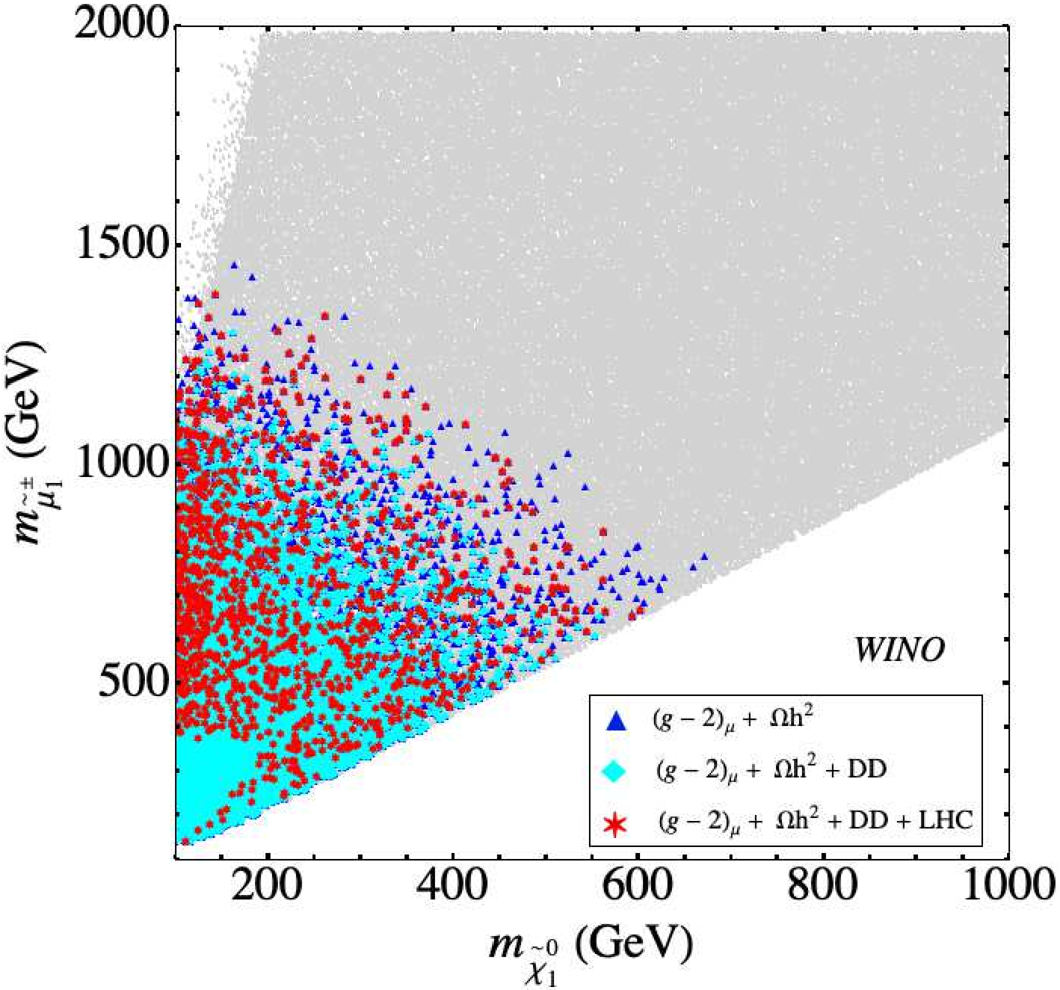


$\Rightarrow$ important: disappearing track limit $\Rightarrow m_{\text{(N)LSP}} \lesssim 600$ GeV

$\Rightarrow$ allowed parameter space squeezed by DD limits and disapp. tracks

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

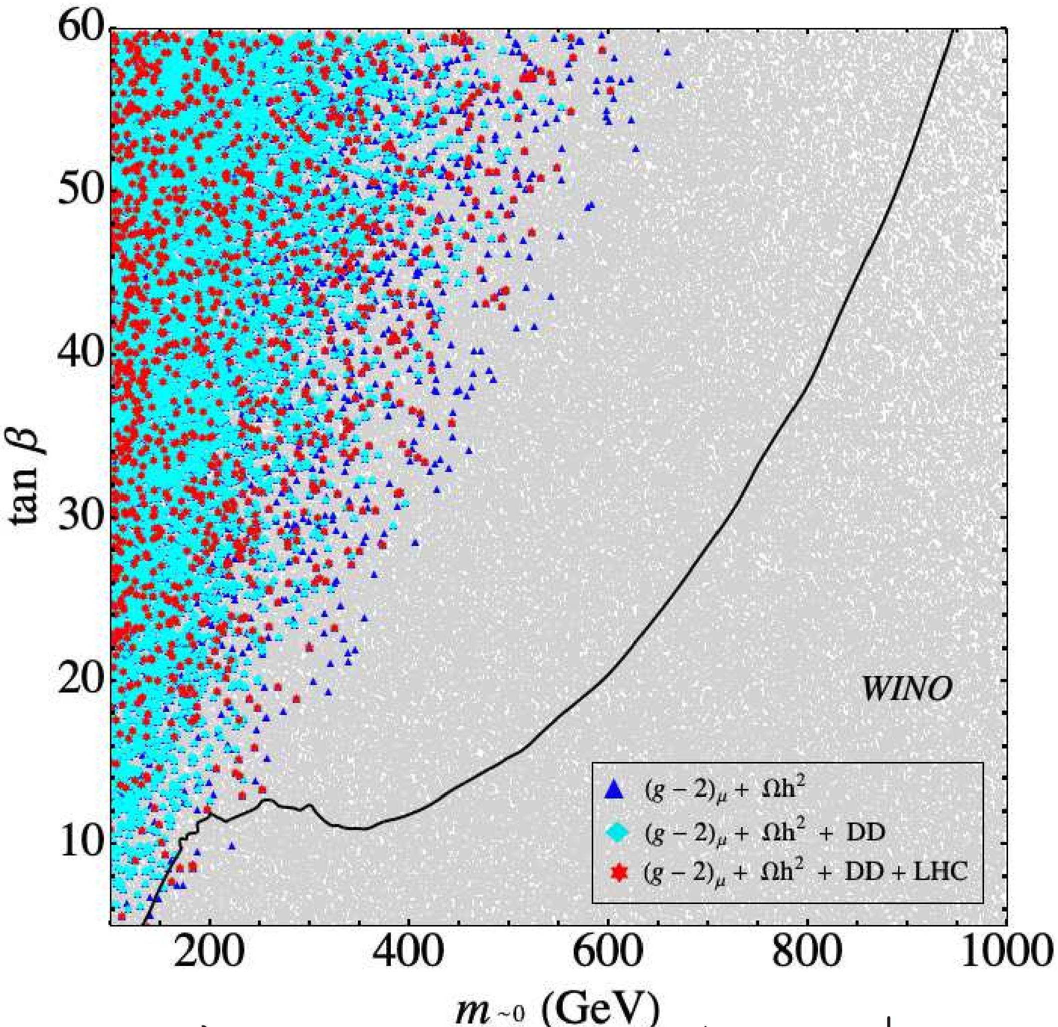
old $(g-2)_\mu$



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

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

old $(g-2)_\mu$

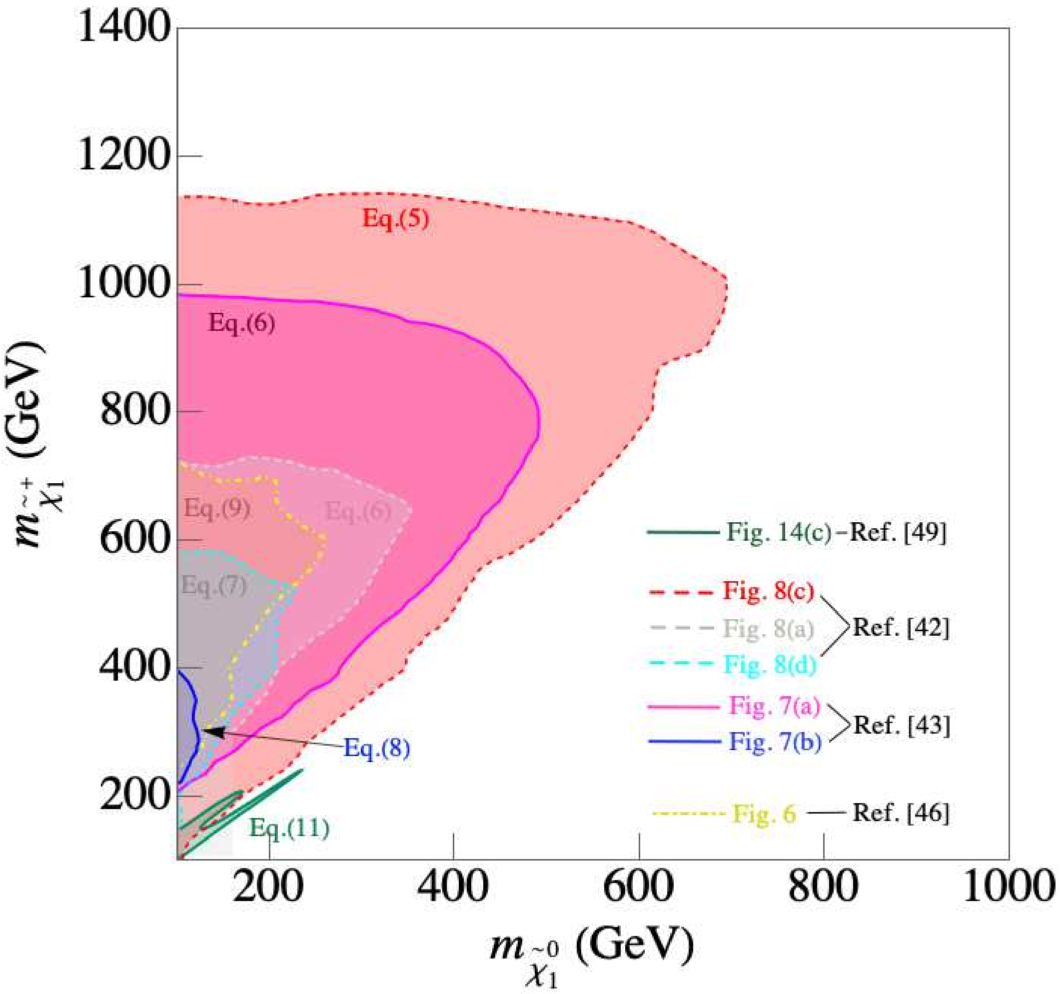


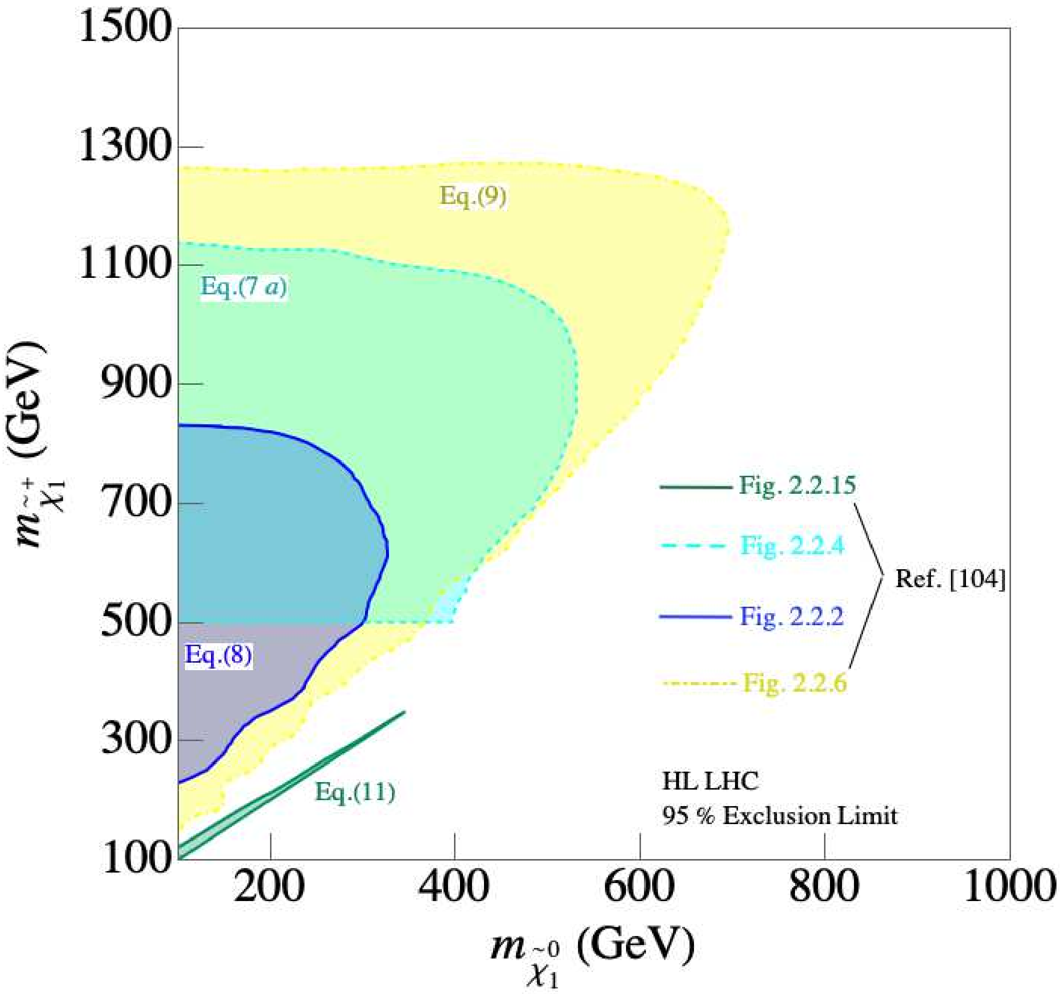
black contour: (simplified) application of $H/A \to \tau^+\tau^-$

$\Rightarrow$ A-pole annihilation largely excluded

LHC exclusion bounds vs. HL-LHC exclusion bounds

not all channels available [*YR18*]



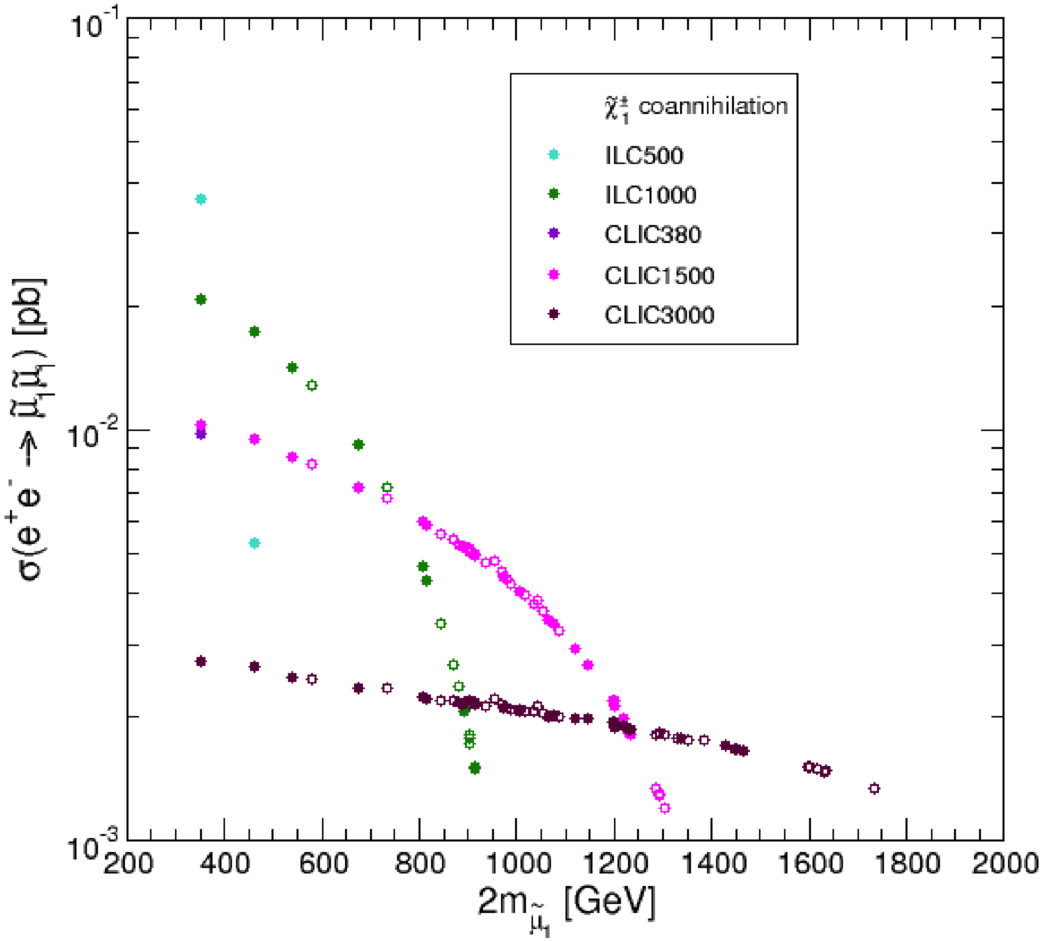


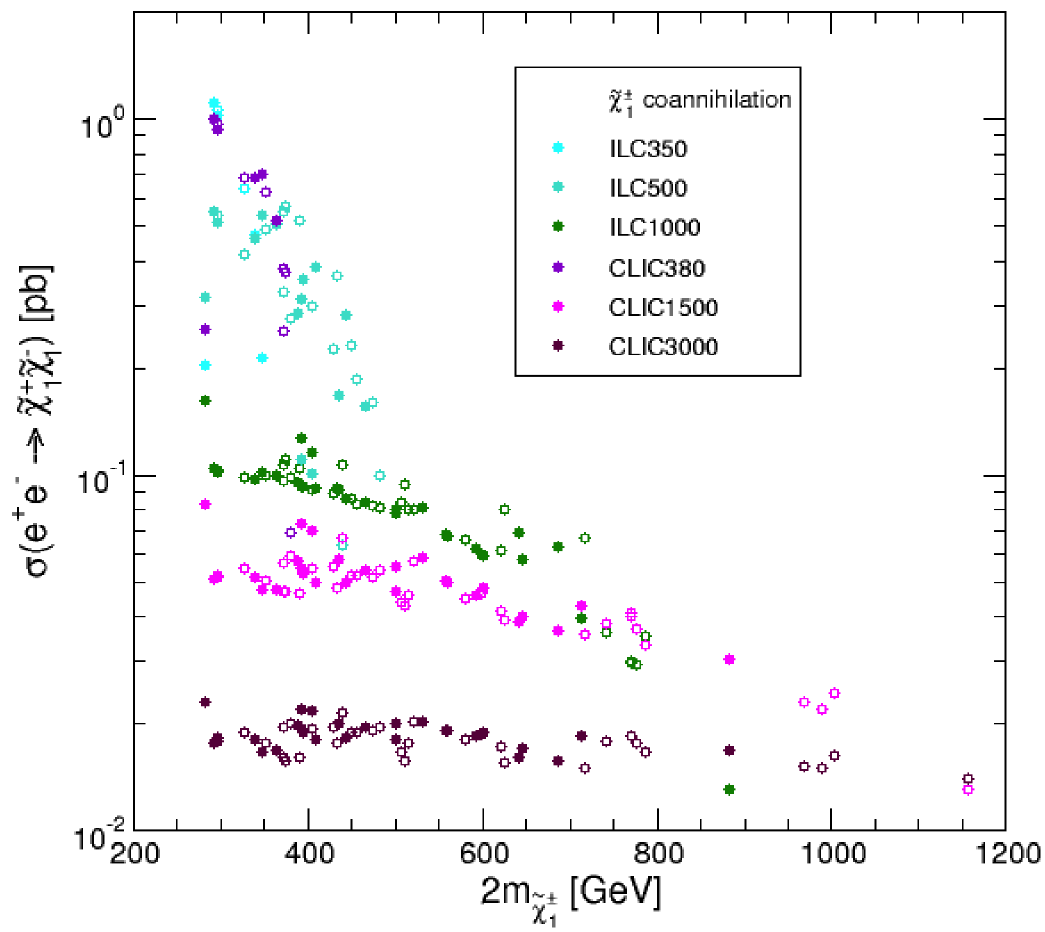
⇒ exclusion reach can be important

⇒ no CheckMate inclusion available . . .

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

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



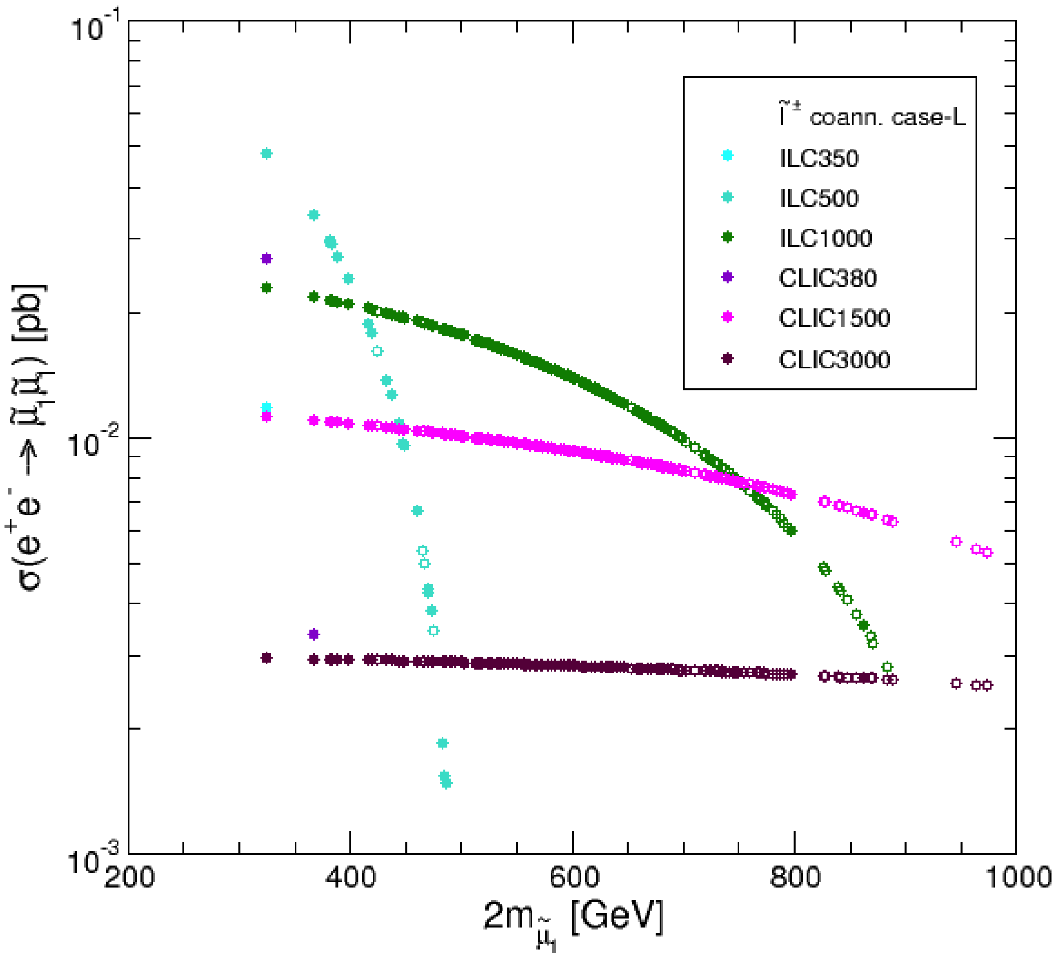


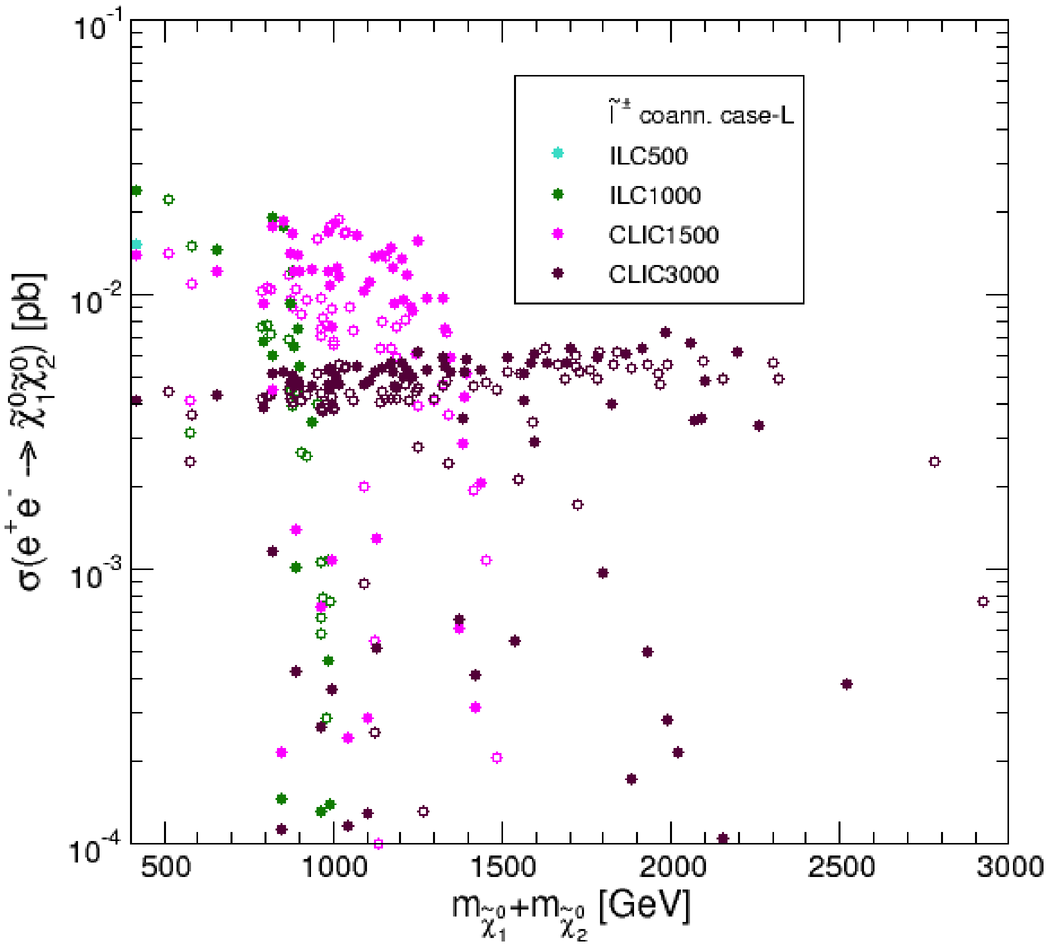
$\Rightarrow$ ILC has good prospects (particularly for $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$)

$\Rightarrow$ 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