Manimala Chakraborti
AstroCeNT, Warsaw

The new $(g-2)_\mu$ result and SUSY

28/07/2021 BASED ON : **2104.03287**, WITH SVEN HEINEMEYER AND IPSITA SAHA

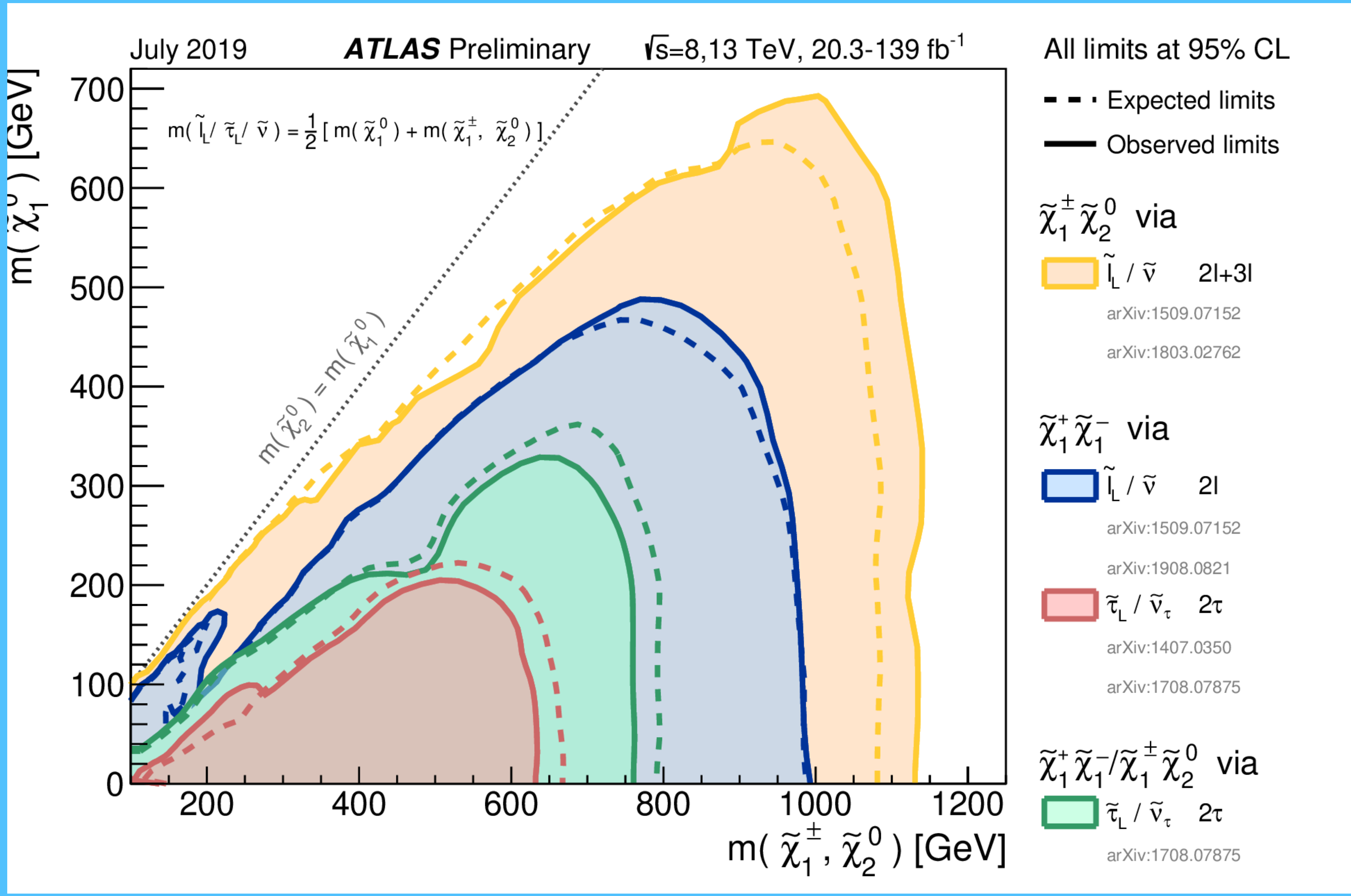
- EW sector may be hiding key to new physics

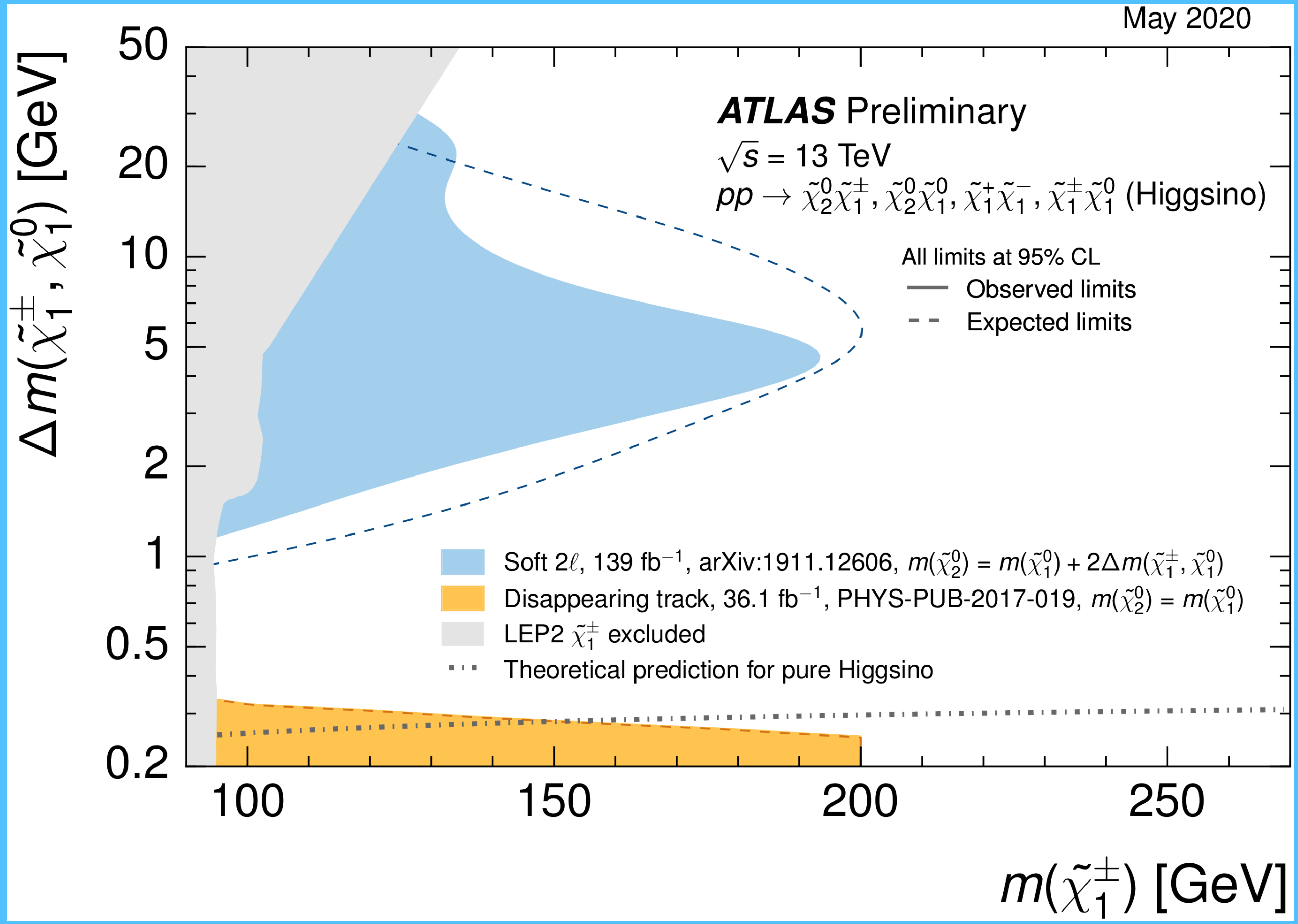
- Modest production cross section, mass bounds from the LHC comparably weak

- May show up elsewhere : DM experiments, $(g-2)_\mu$ …

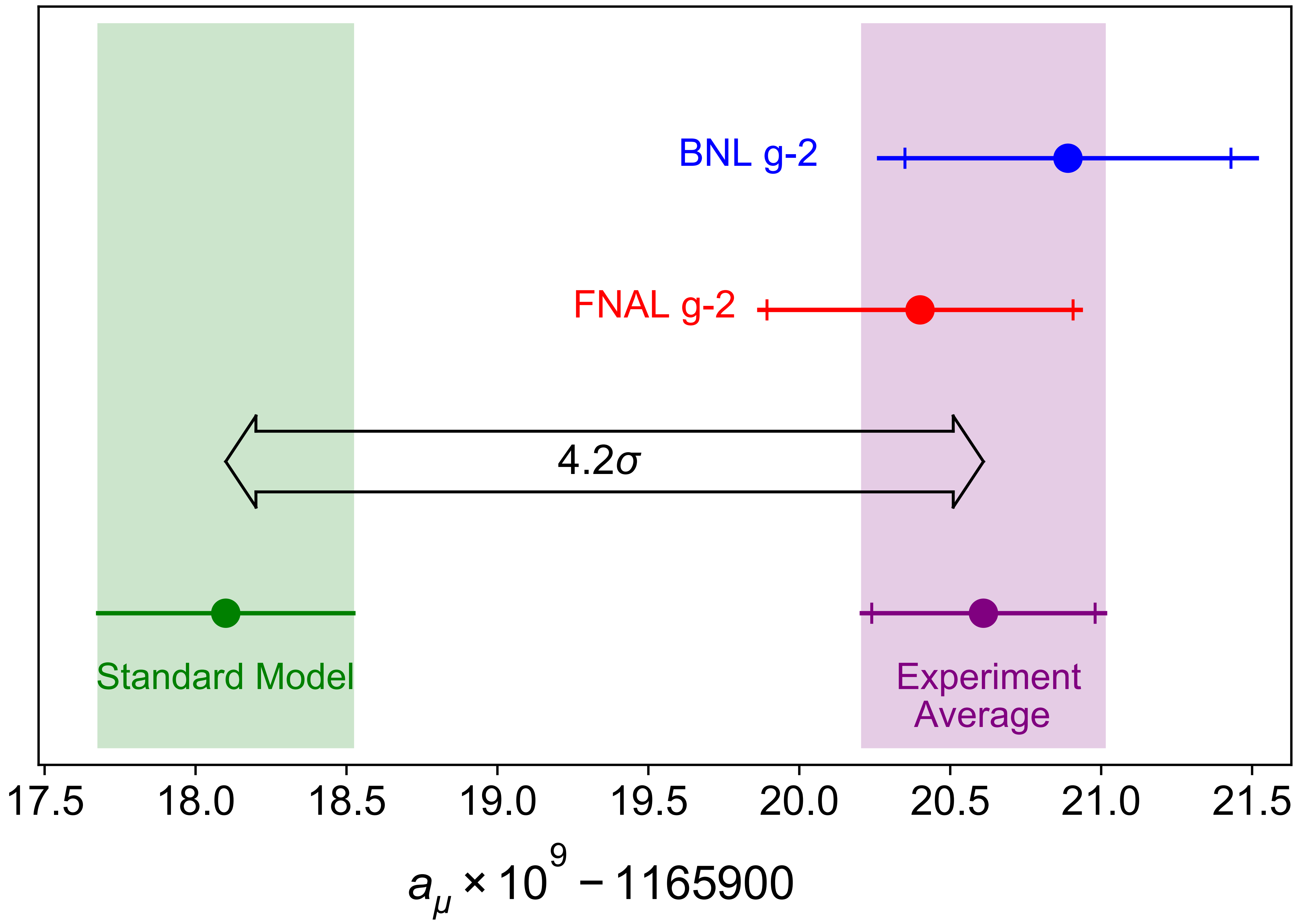
- 4.2σ discrepancy in $(g-2)_\mu$

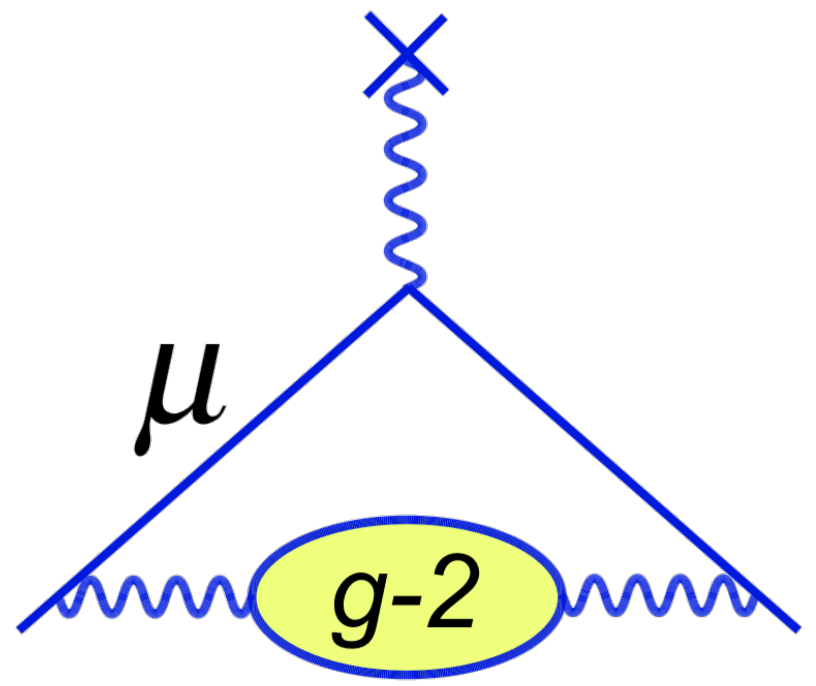
- New results from Fermilab 'MUON (g-2)' !





Muon (g-2)





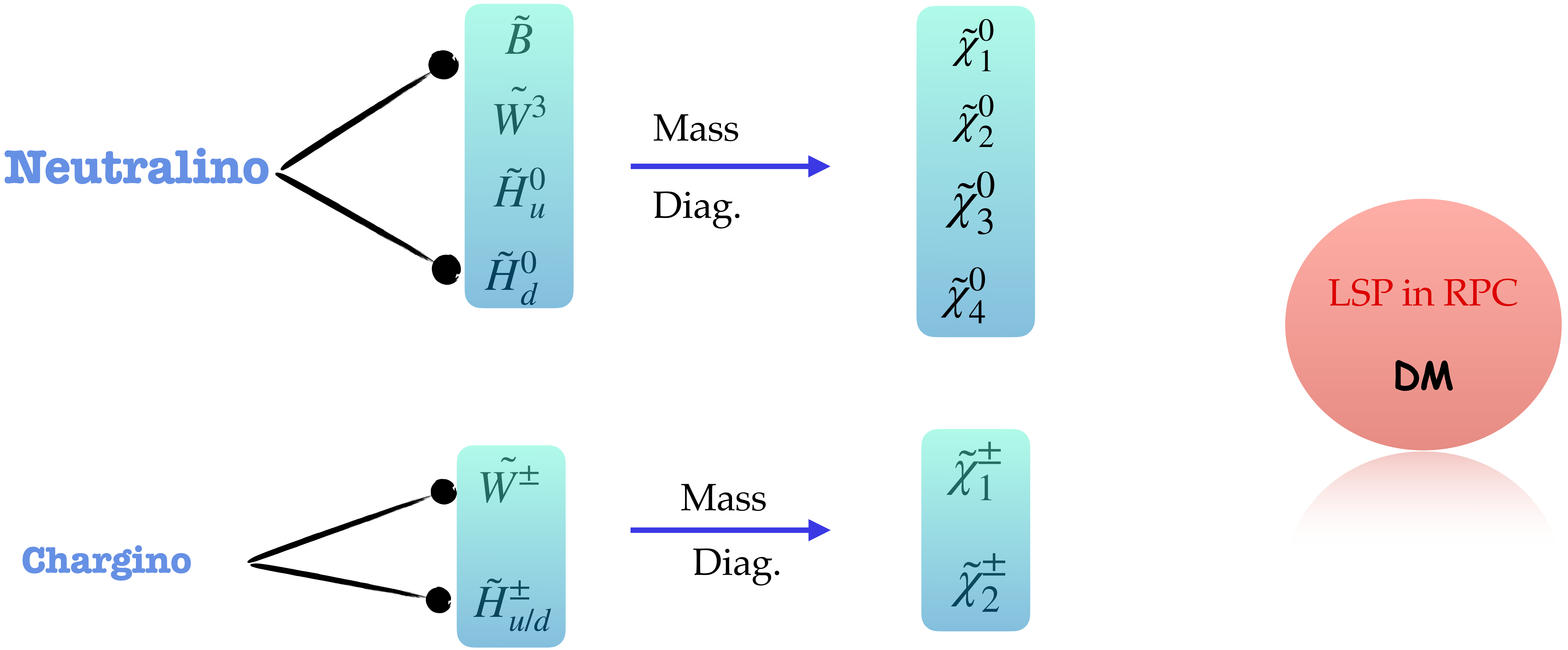
$$a_\mu^{exp} - a_\mu^{theo,SM} = (25.1 \pm 5.9) \times 10^{-10}$$

Muon g-2 experiment at Fermilab aims at 4 x BNL precision

- Abi *et al* PRL '21
- Aoyama *et al* '20

EW Gauginos

Masses and mixing determined by U(1) and SU(2) gaugino masses M_1, M_2 and Higgs mass parameter μ.



Sleptons

Slepton Mass Matrix

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

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

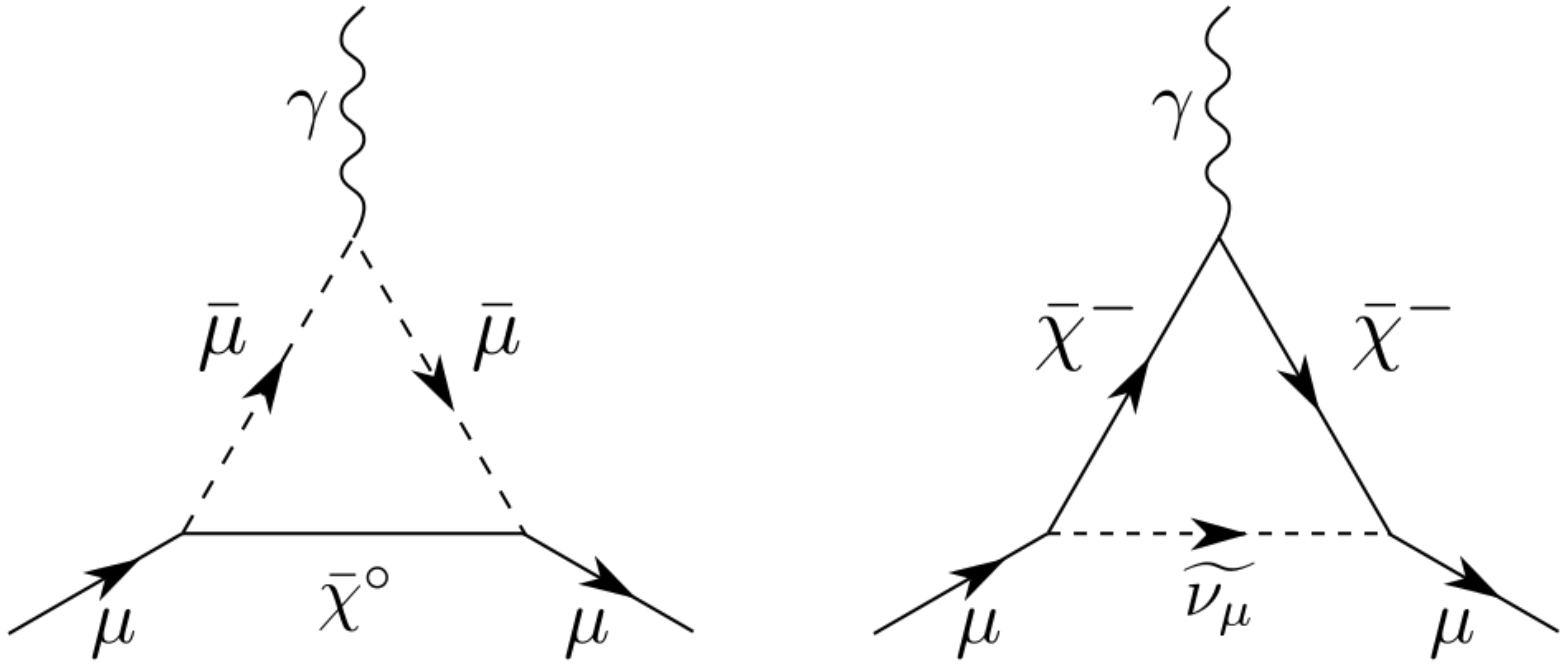
$$m_{RR}^2 = m_{\tilde{R}}^2 + Q_l s_w^2 M_z^2 c_{2\beta}$$

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

Parameters → $M_1, M_2, \mu, \tan\beta, m_{\tilde{L}}, m_{\tilde{R}}$

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

Muon (g-2)



- SUSY contributions from Chargino-Sneutrino and Smuon-Neutralino loop
- SM EW 1 loop : $\frac{\alpha}{\pi}\frac{m_\mu^2}{M_W^2}$.   MSSM , 1 loop : $\frac{\alpha}{\pi}\frac{m_\mu^2}{M_{SUSY}^2} \times tan\beta$
- SUSY can easily explain anomaly : upper limits on EW super partner masses

Constraints

Proper recasting is important

Direct Searches at LHC

- LHC searches restricted to **simplified models.**
- $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ taken to be mass-degenerate and purely wino. $\tilde{\chi}_1^0$ purely bino.
- All three generations of sleptons and sneutrinos assumed mass degenerate.
- Heavier gauginos $\tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_2^{\pm}$ assumed to be decoupled.
- No sensitivity to parameters like $\tan\beta$.

Indirect Constraints

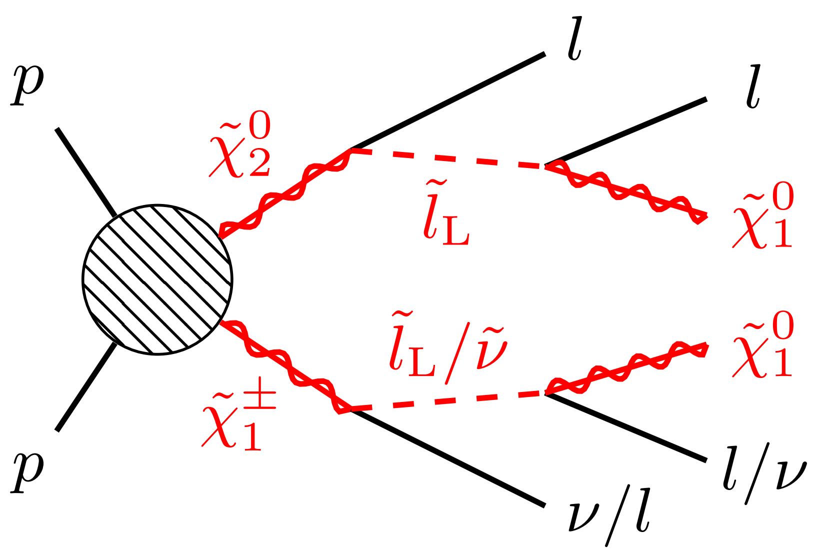
- Muon (g-2).
- WMAP/PLANCK relic density.
- Spin independent direct detection data from XENON/LUX.

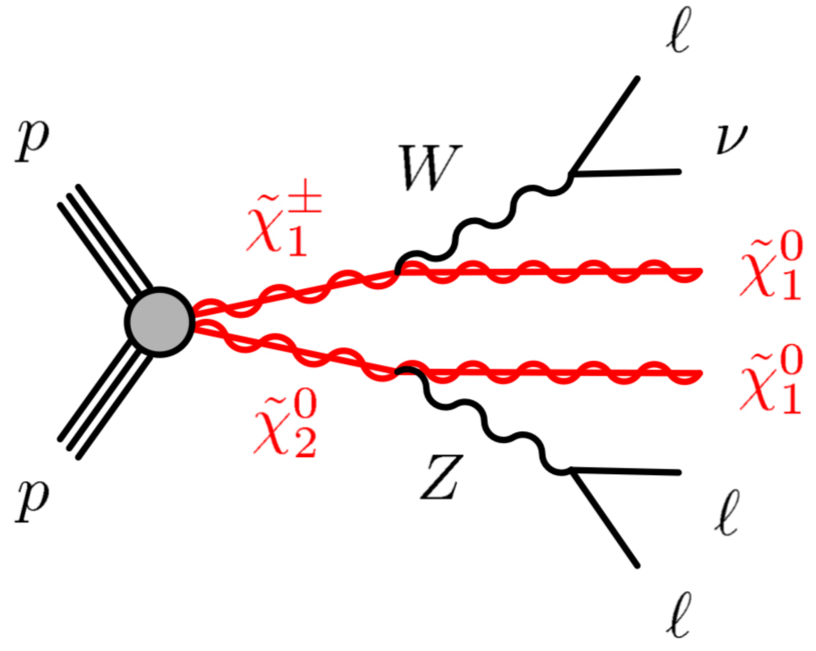
Searches at the LHC

- Trilepton searches

  ATLAS [1803.02762]

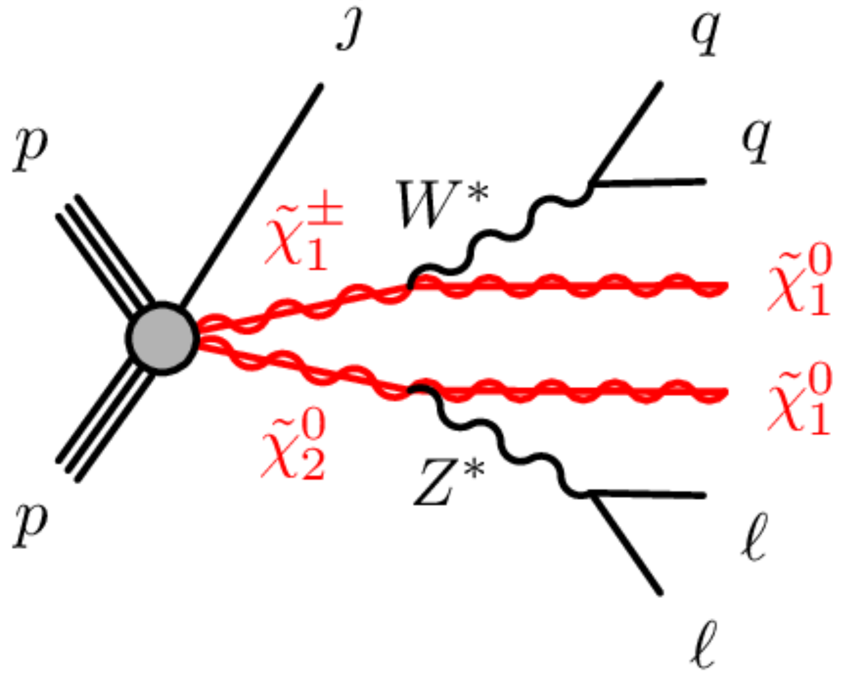
  13 TeV, 36 fb^{-1}

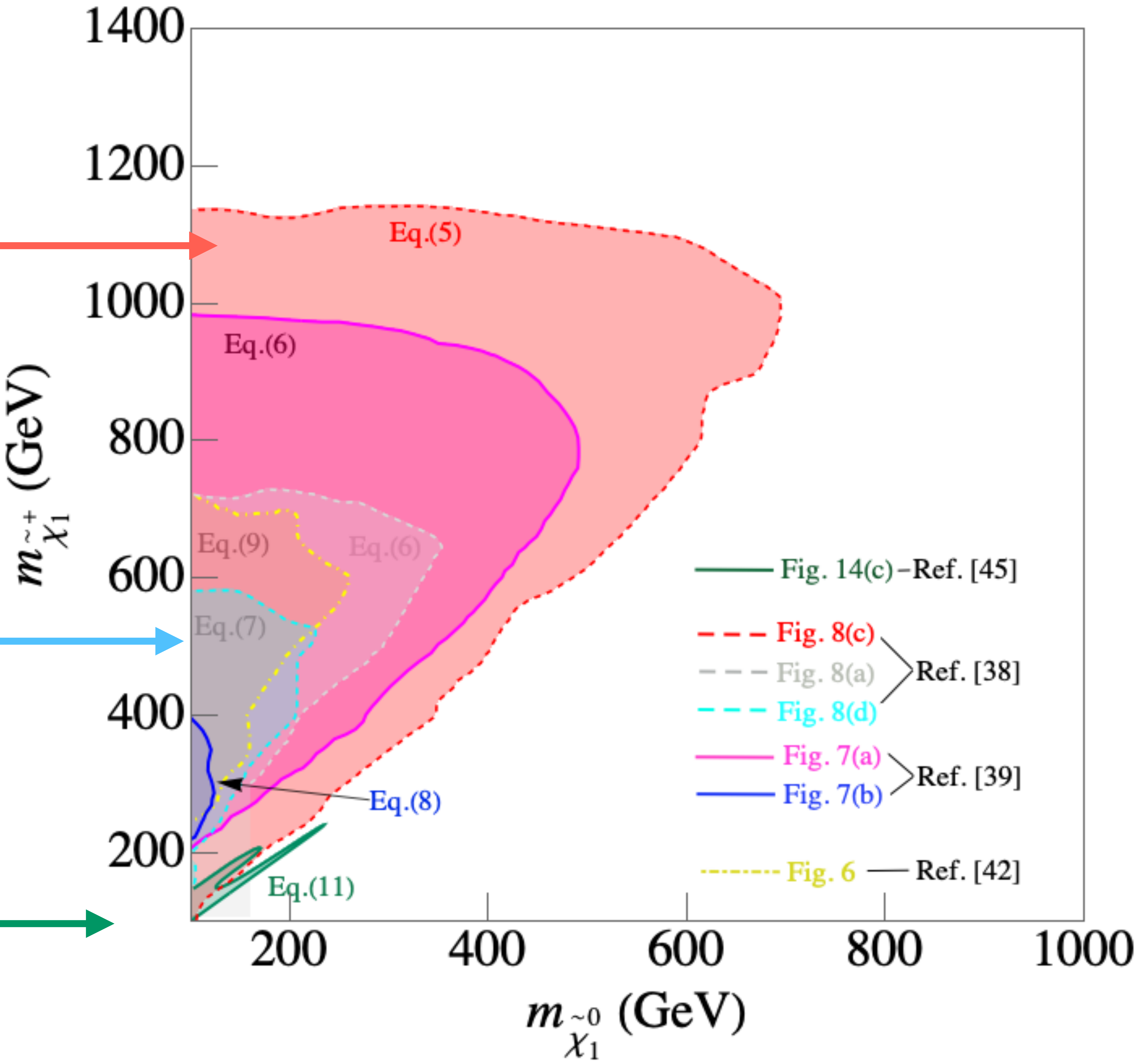




- Compressed spectra searches

  ATLAS 1911.12606





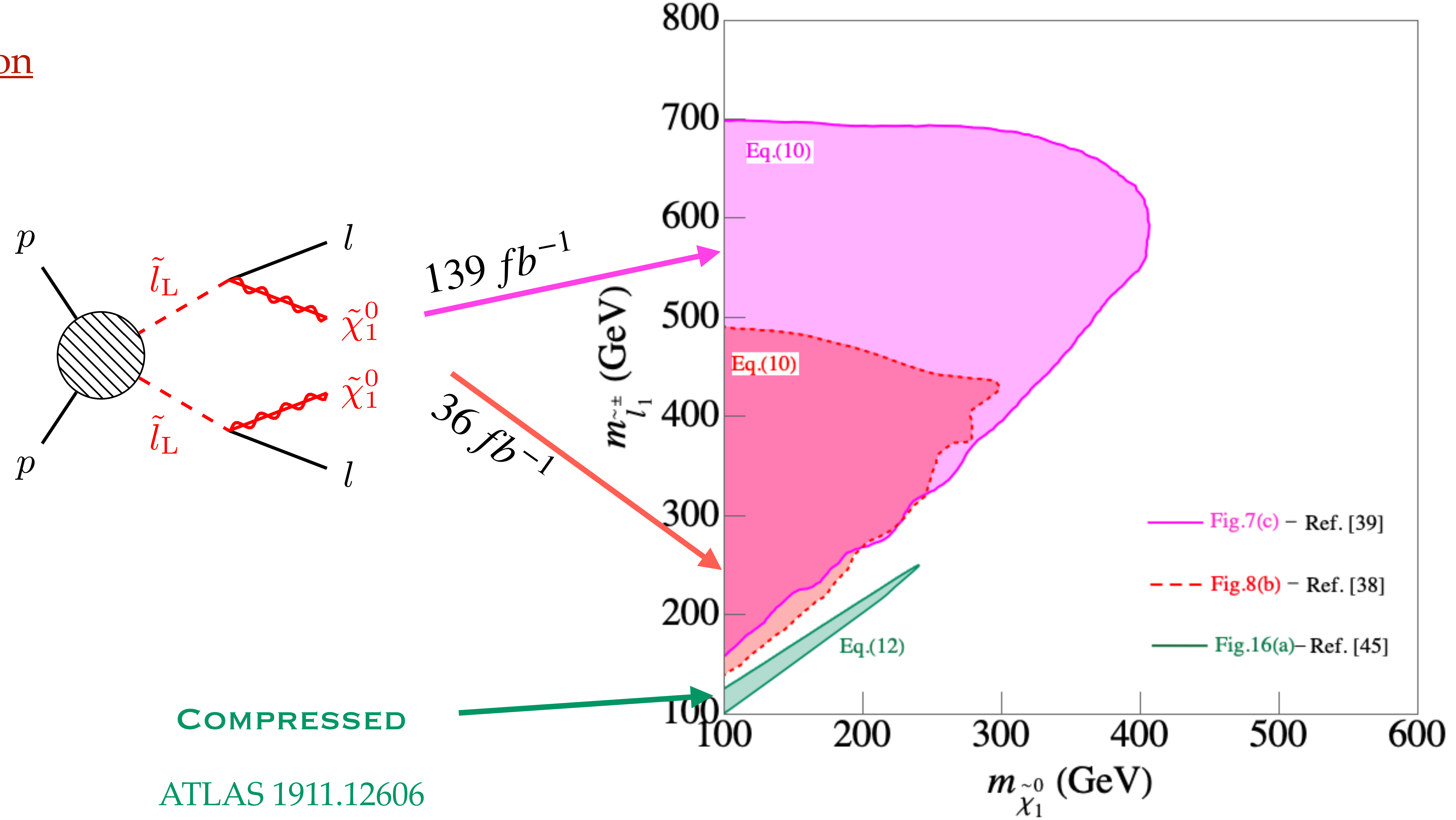
Proper recasting is important → checkMATE

Searches at the LHC

- Slepton pair production

ATLAS [1908.08215]

13 TeV, 139 fb^{-1}

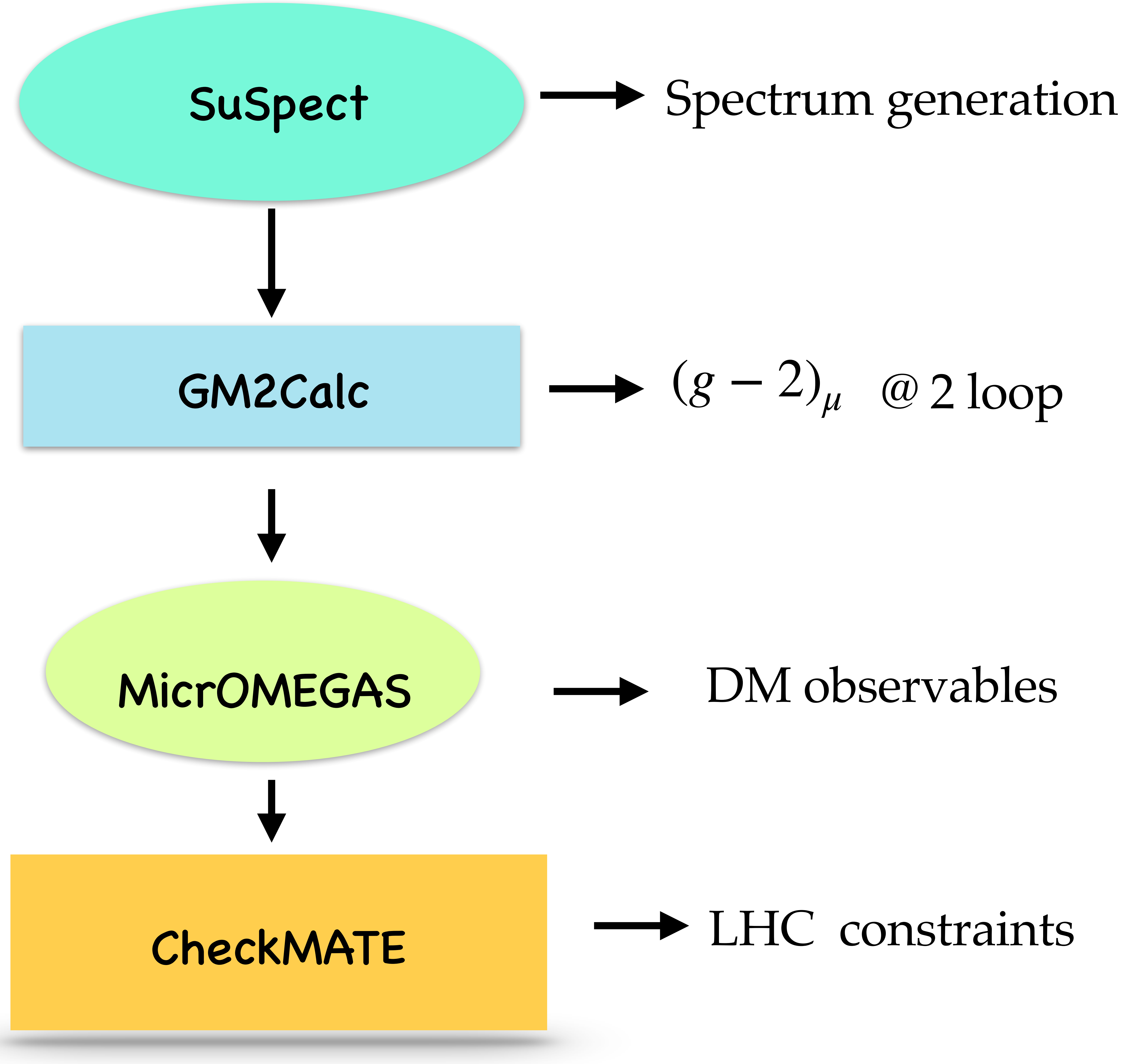


COMPRESSED

ATLAS 1911.12606

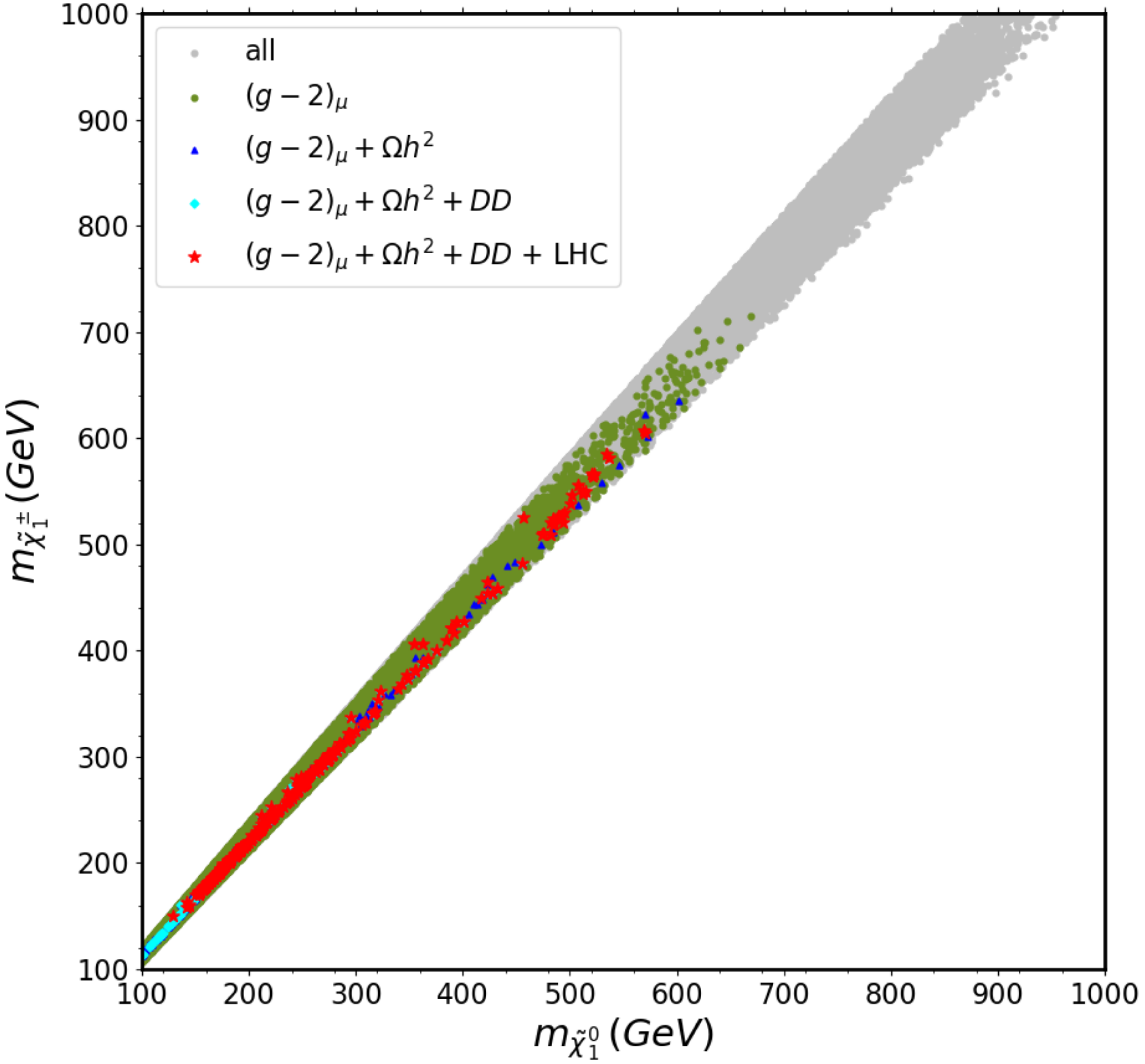
Proper recasting is important → checkMATE

Analysis flow



- $\Delta a_\mu = (25.1 \pm 5.9) \times 10^{-10}$
- $\Omega_{CDM} h^2 = 0.120 \pm 0.001$
- Direct detection SI bounds from XENON1T

Chargino Co-annihilation



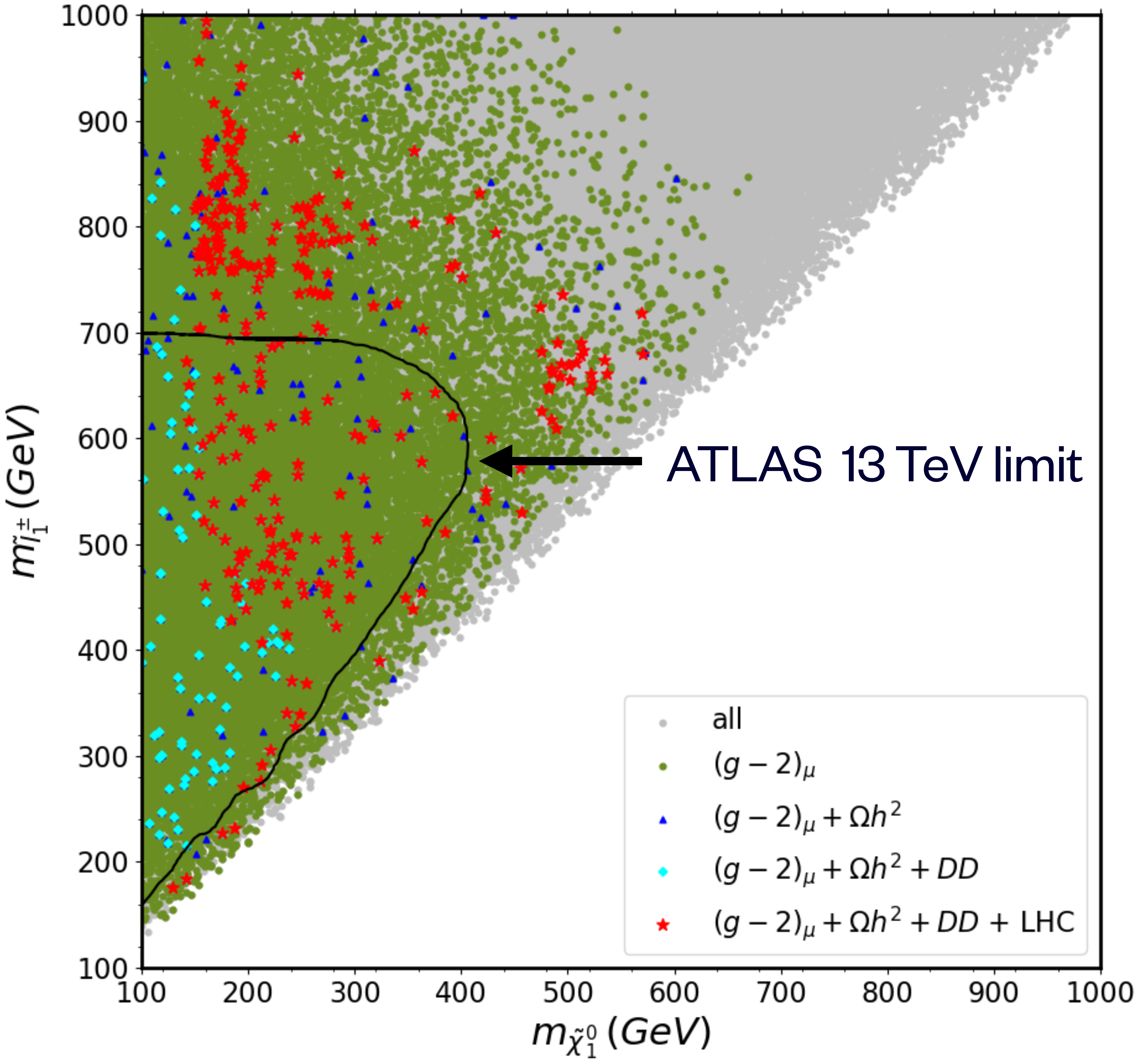
Bino-wino co-annihilation

$$100 \text{ GeV} \leq M_1 \leq 1 \text{ TeV}, \quad M_1 \leq M_2 \leq 1.1 M_1,$$
$$1.1 M_1 \leq \mu \leq 10 M_1, \quad 5 \leq \tan\beta \leq 60,$$
$$100 \text{ GeV} \leq m_{\tilde{l}_L} \leq 1 \text{ TeV}, \quad m_{\tilde{l}_R} = m_{\tilde{l}_L}.$$

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

LHC searches (for compressed spectrum)

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



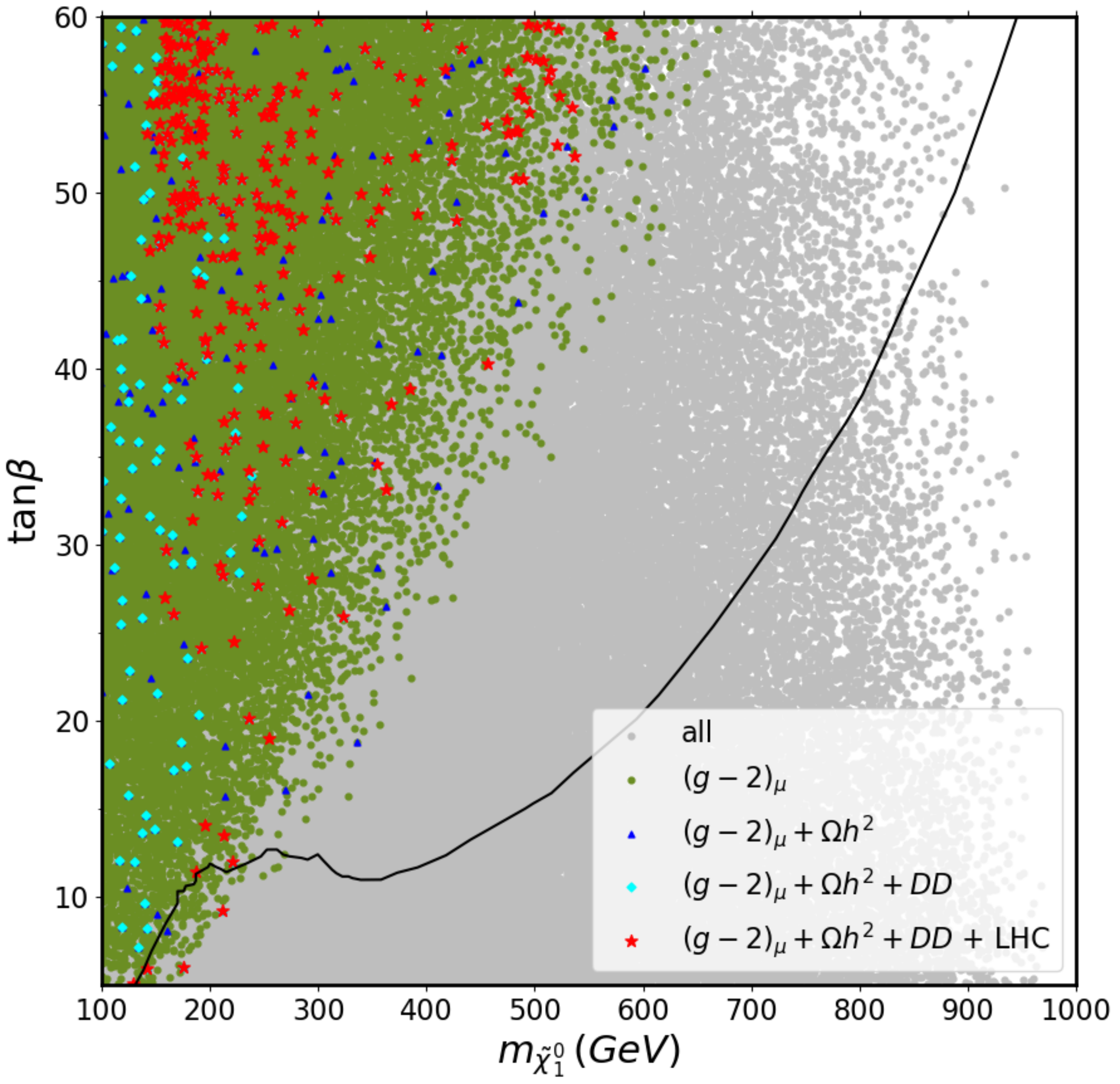
- Slepton-pair production →($2l$ + missing E_T) provides important search channel

- Considerable BR for $\tilde{e}_L(\tilde{\mu}_L) \rightarrow \tilde{\chi}_1^{\pm}\nu_e(\nu_\mu)$

→ Less no. of signal leptons.

Possibility of A-pole annihilation

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



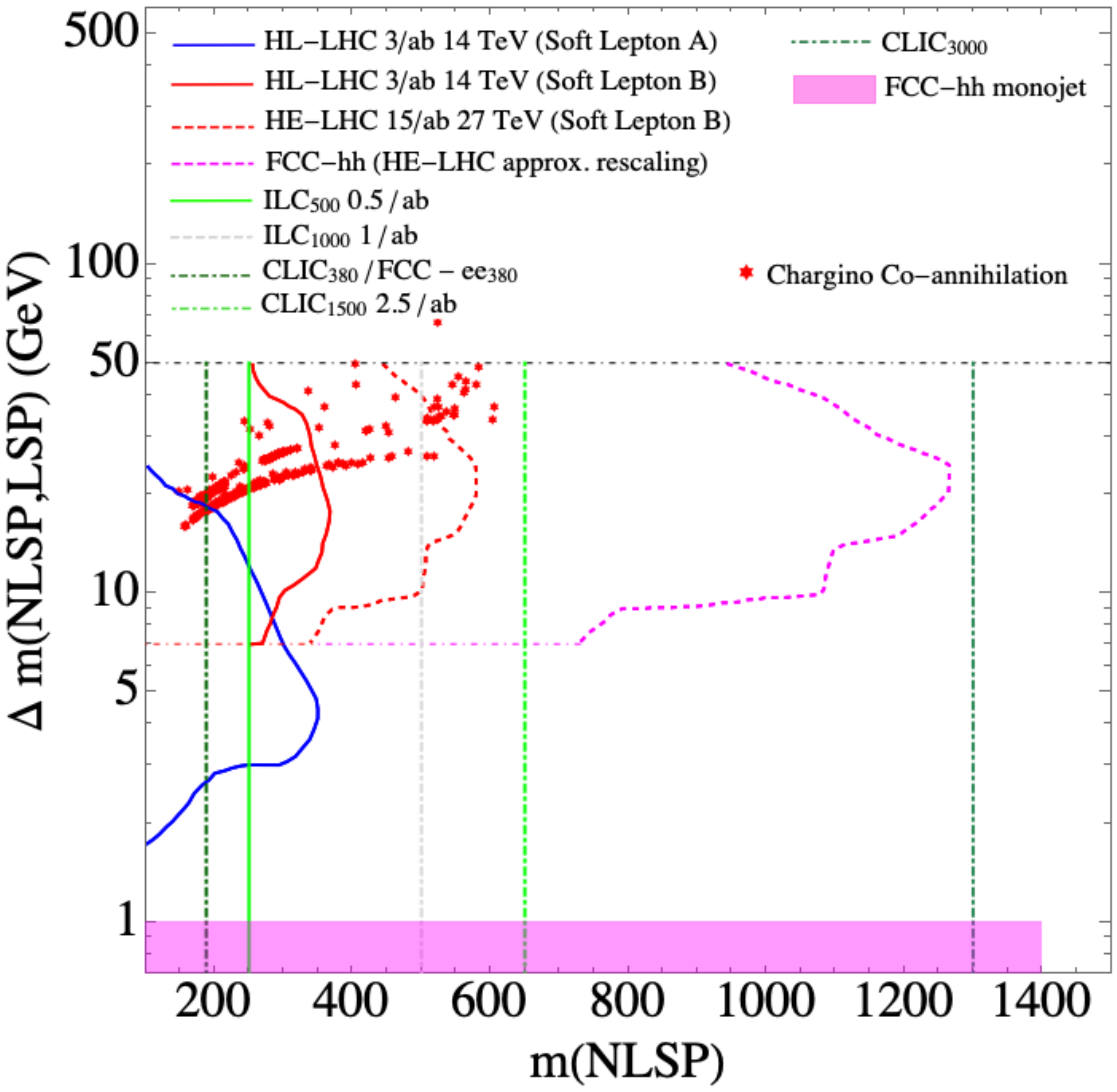
$$m_{\tilde{\chi}_1^0} = \frac{M_A}{2}$$

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

Bagnaschi et al. '18

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

Future prospects



Berggren ' 20

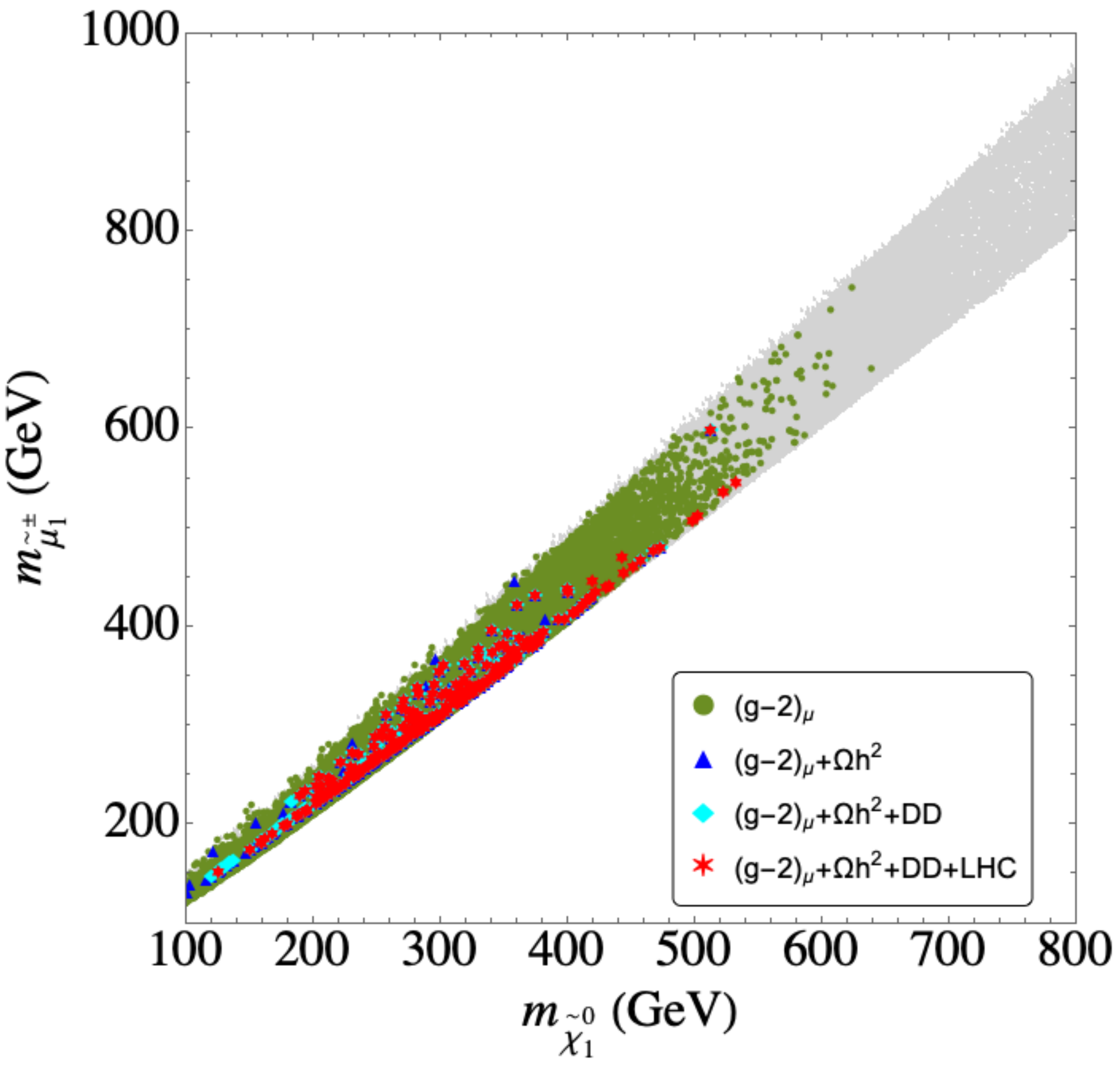
Conclusions

- It is possible to constrain the EW MSSM with the help of indirect constraints along with the direct collider limits.
- DM and muon (g-2) constraints put effective upper limit on EW SUSY masses.
- LHC limits restrict the mass ranges from below.
- Proper recasting of ATLAS/CMS analyses important !
- Future collider searches will be conclusive.
- More results for $(g-2)_\mu$ from Fermilab STAY TUNED!!!

THANK YOU!

BACKUP

Slepton Co-annihilation: Case-L



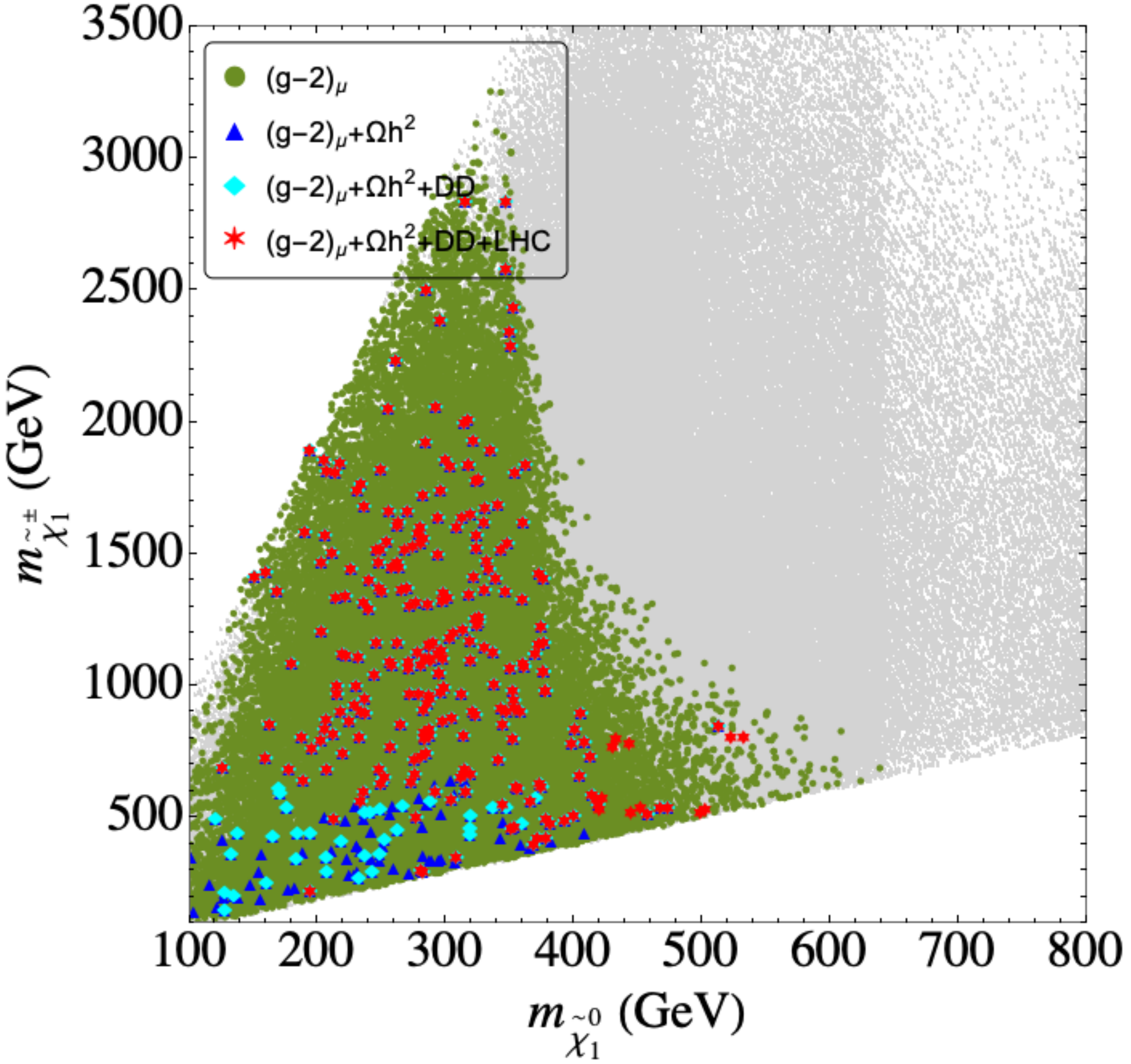
Case-L: SU(2) doublet

$$100\ \text{GeV} \le M_1 \le 1\ \text{TeV}\ , \quad M_1 \le M_2 \le 10 M_1\ ,$$
$$1.1 M_1 \le \mu \le 10 M_1, \quad 5 \le \tan\beta \le 60,$$
$$M_1\ \text{GeV} \le m_{\tilde{l}_L} \le 1.2 M_1, \quad M_1 \le m_{\tilde{l}_R} \le 10 M_1\ .$$

The left-sleptons and sneutrinos are close in mass to the LSP

Compressed search bounds effective

Slepton Co-annihilation: Case-L



Case-L: SU(2) doublet

$$100 \text{ GeV} \leq M_1 \leq 1 \text{ TeV}\ , \quad M_1 \leq M_2 \leq 10M_1\ ,$$
$$1.1M_1 \leq \mu \leq 10M_1, \quad 5 \leq \tan\beta \leq 60,$$
$$M_1 \text{ GeV} \leq m_{\tilde{l}_L} \leq 1.2M_1, \quad M_1 \leq m_{\tilde{l}_R} \leq 10M_1\ .$$

$\mathrm{BR}(\tilde{\chi}_1^\pm \to \tilde{\tau}_1\nu_\tau)$ and $\mathrm{BR}(\tilde{\chi}_2^0 \to \tilde{\tau}_1\tau)$, $\mathbf{BR}(\tilde{\chi}_2^0 \to \tilde{\nu}\nu)$

($3l$ + missing E_T) exclusion limit weakens

Recasting with CM

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

Event generation → MG5_aMC@NLO

↓

Showering and hadronization → Pythia8

↓

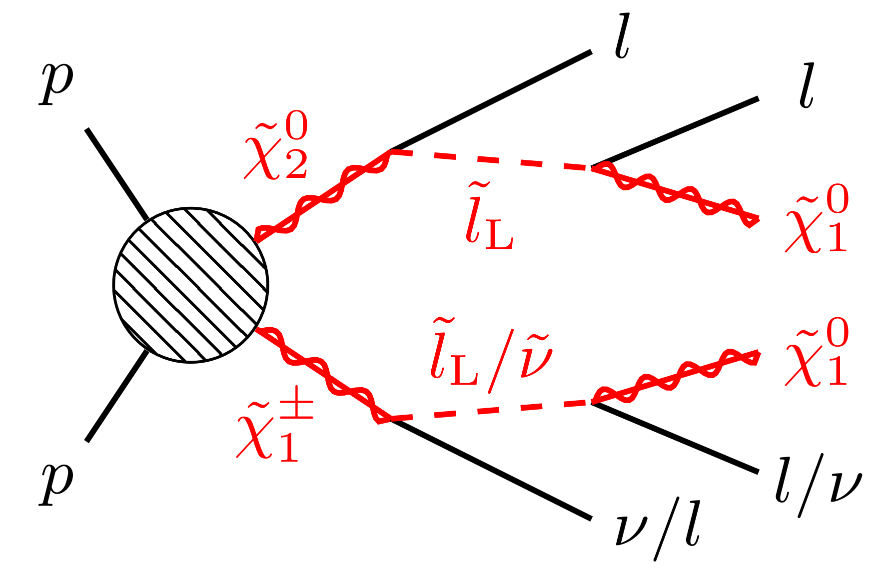
Detector effect → Delphes

↓

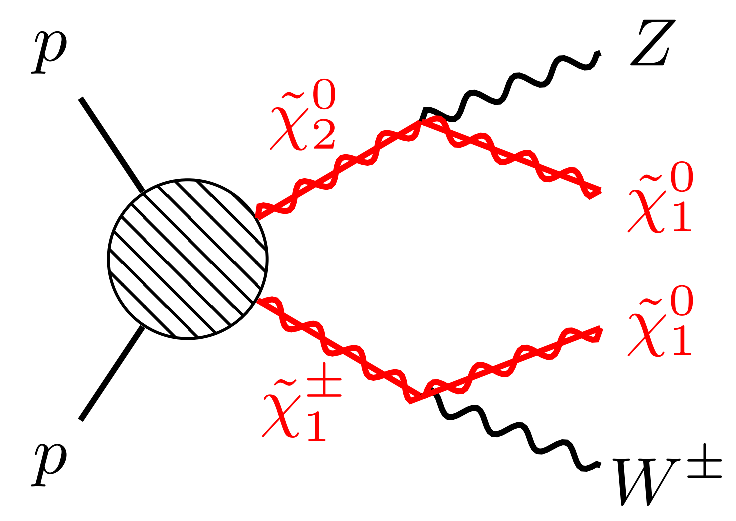
SR definition and statistical evaluation

New analysis implementation

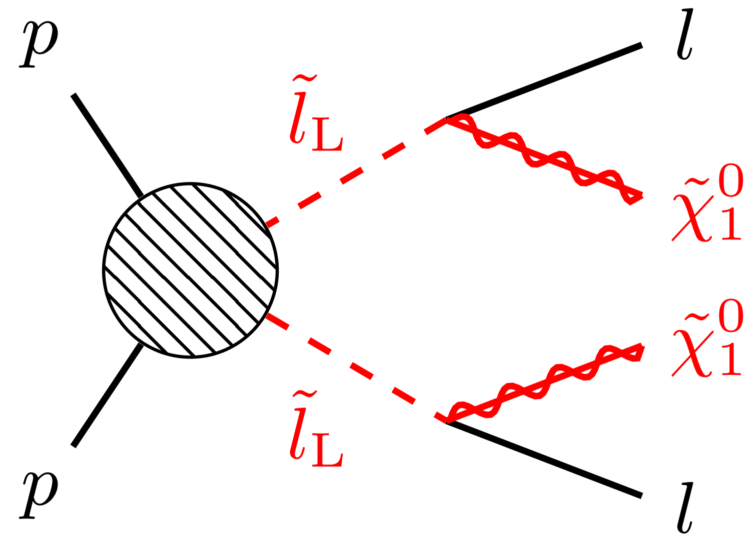
- ATLAS [1803.02762]



- ATLAS [1803.02762]



- ATLAS [1908.08215]

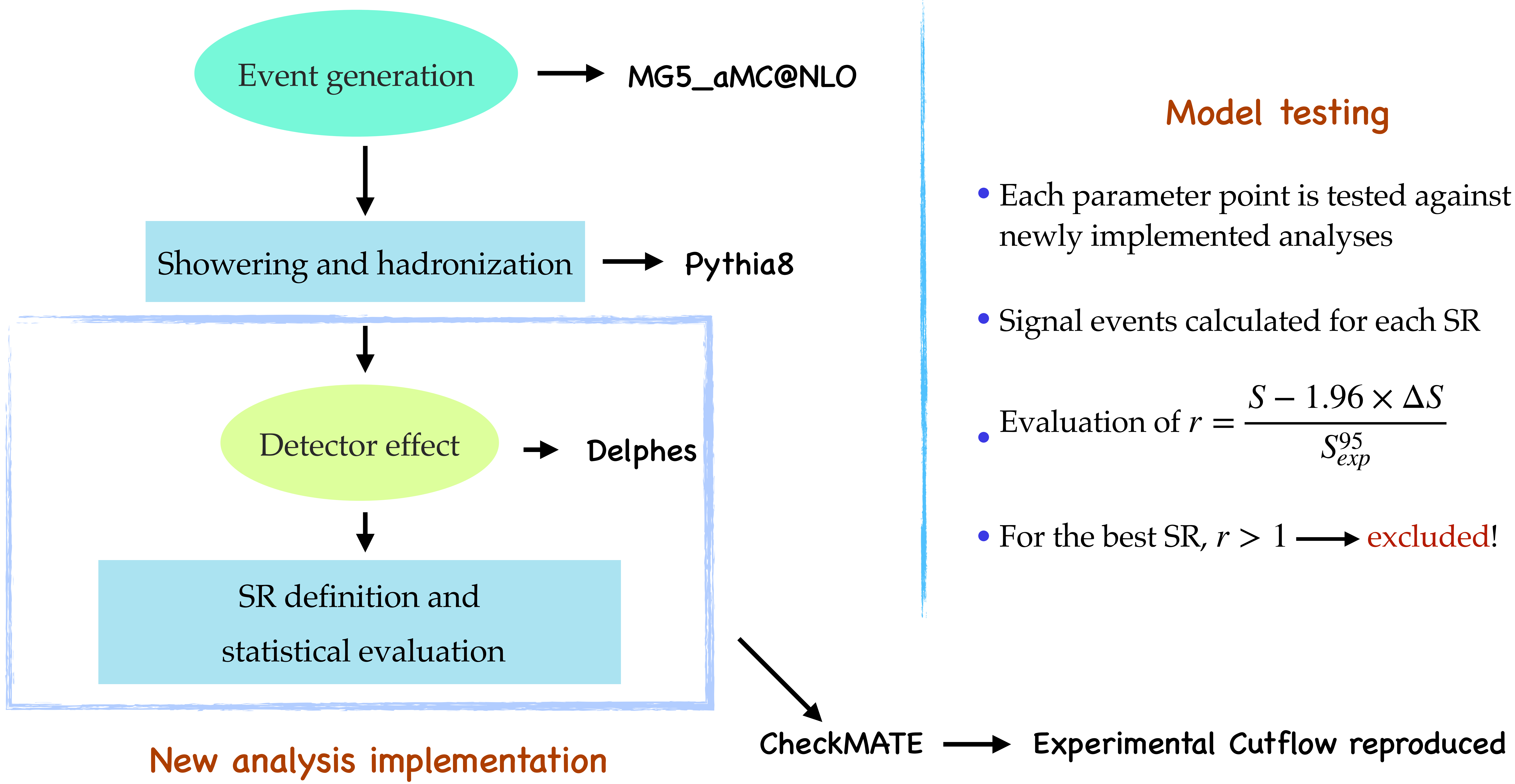


Compressed spectra searches applied directly

Most relevant in our case

Recasting with CM

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

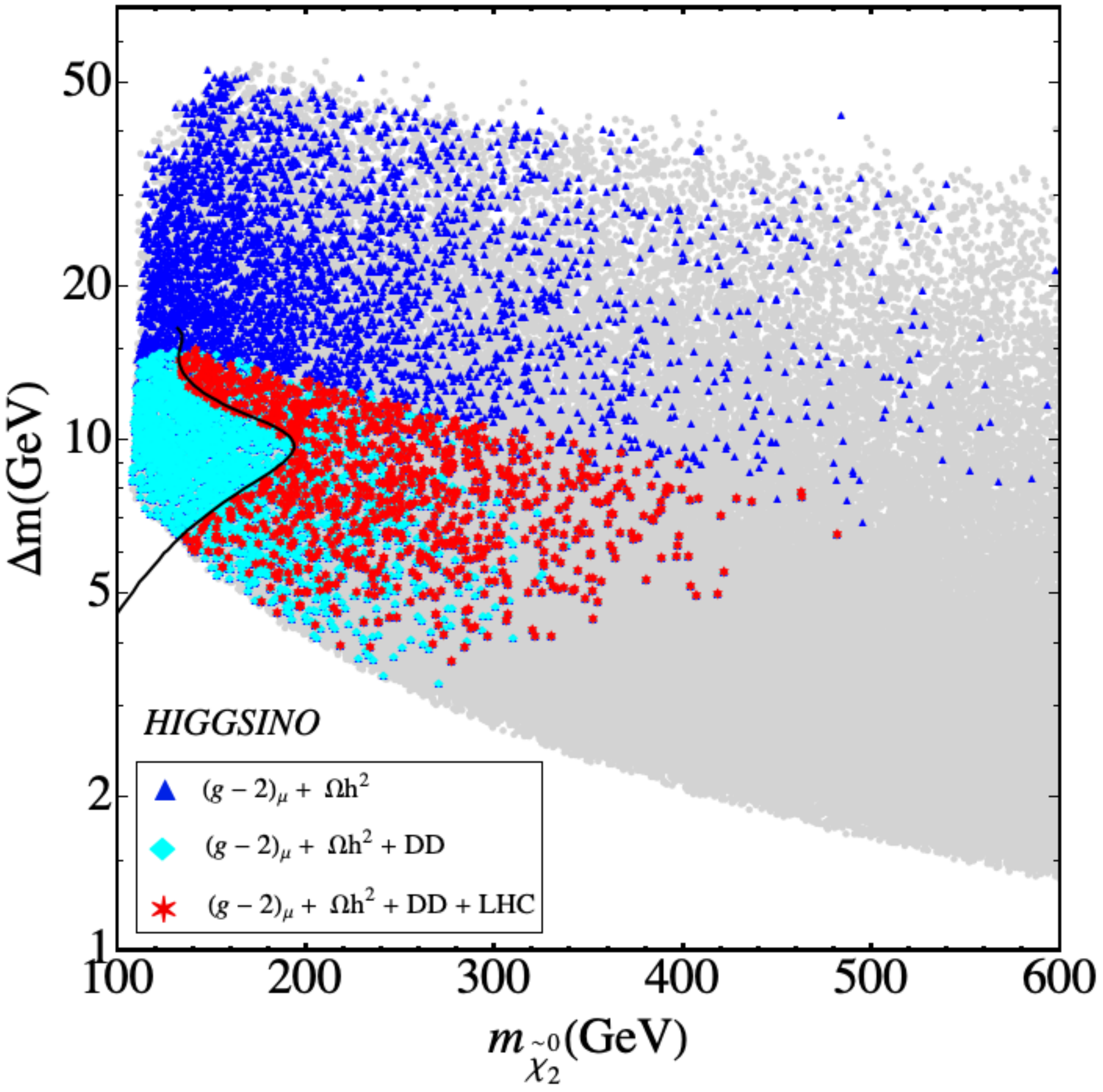


Model testing

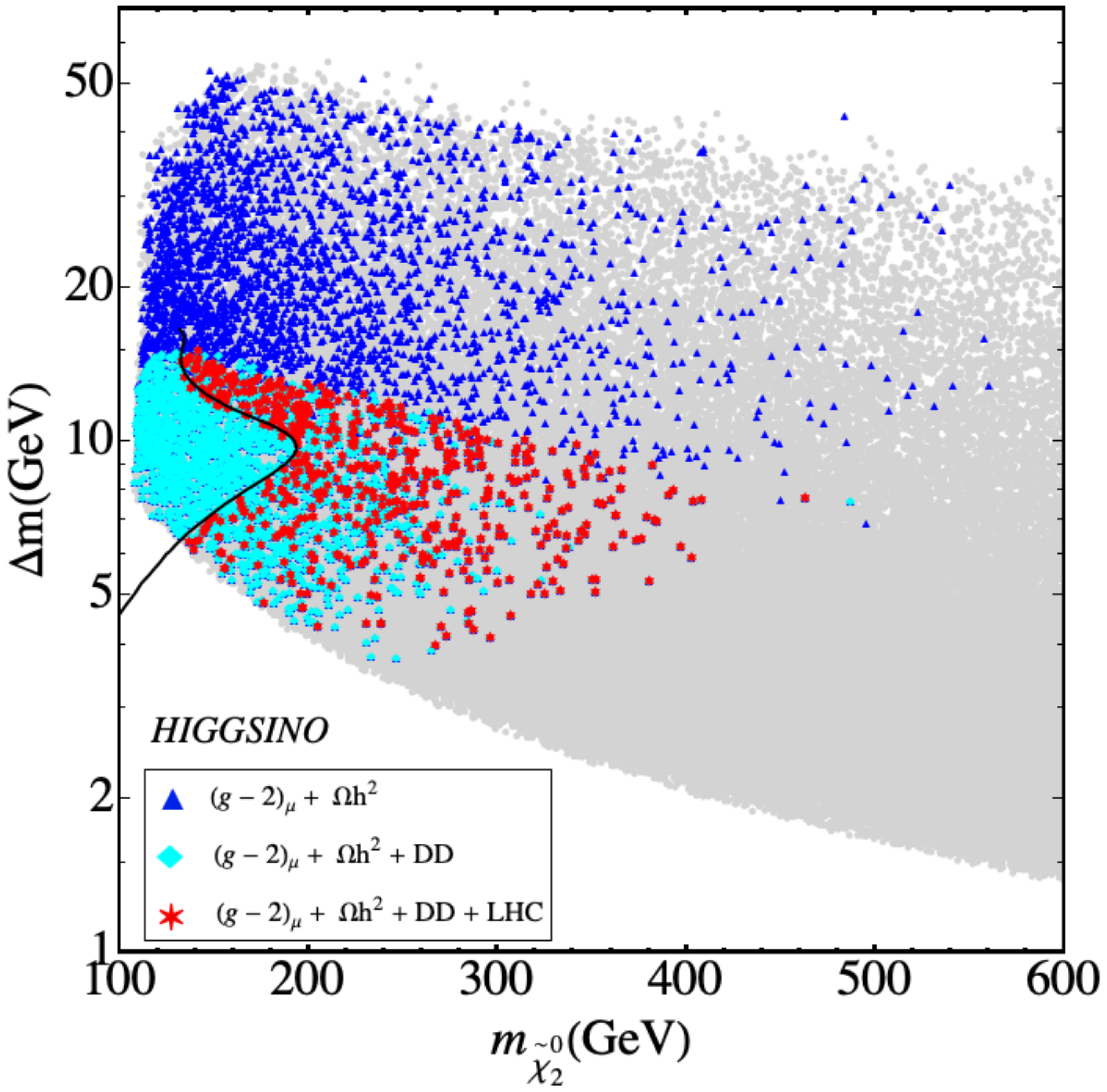
- Each parameter point is tested against newly implemented analyses
- Signal events calculated for each SR
- Evaluation of $r = \dfrac{S - 1.96 \times \Delta S}{S^{95}_{exp}}$
- For the best SR, $r > 1 \longrightarrow$ excluded!

Higgsino LSP

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

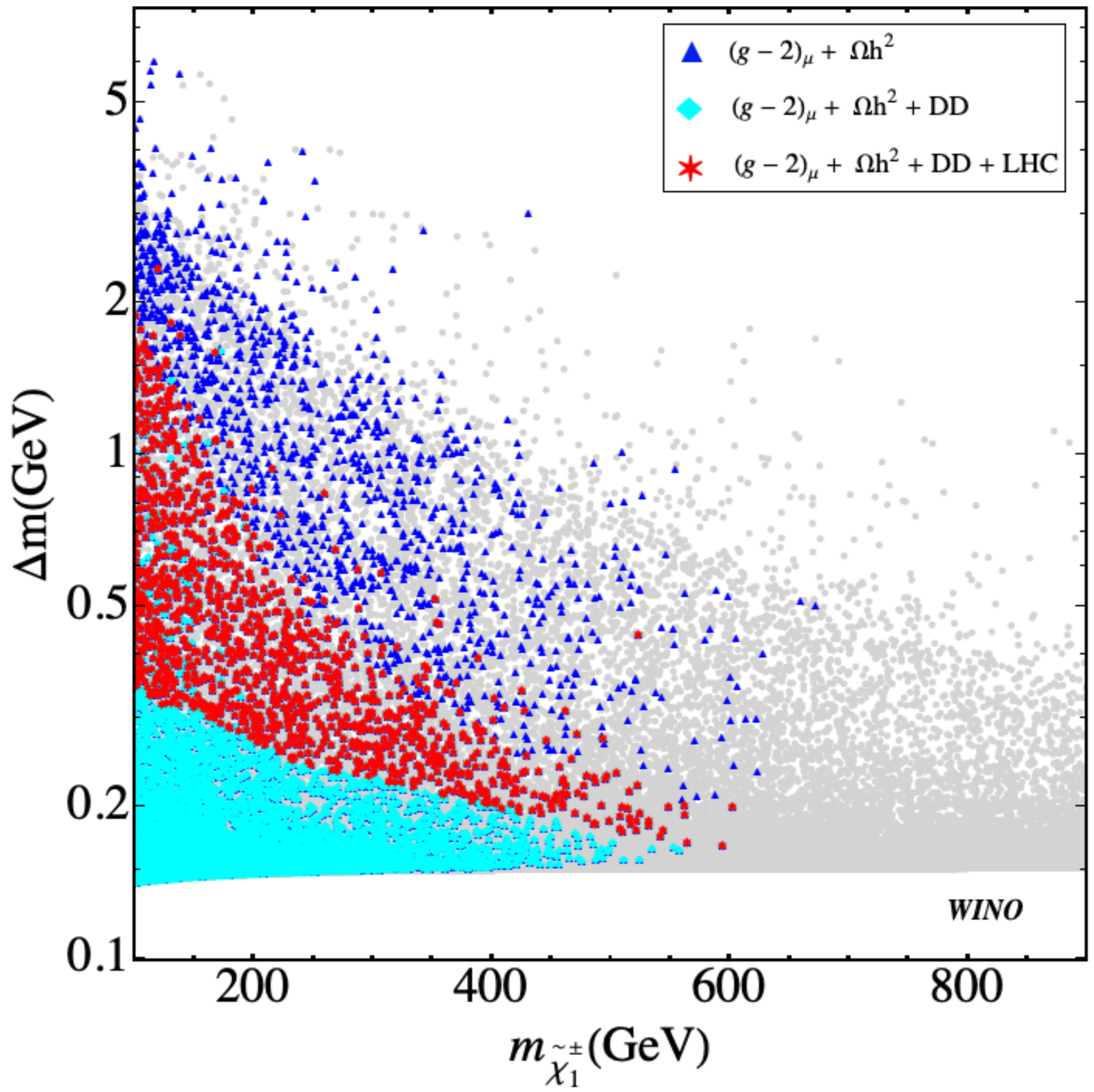


Future $(g-2)_\mu$ limit

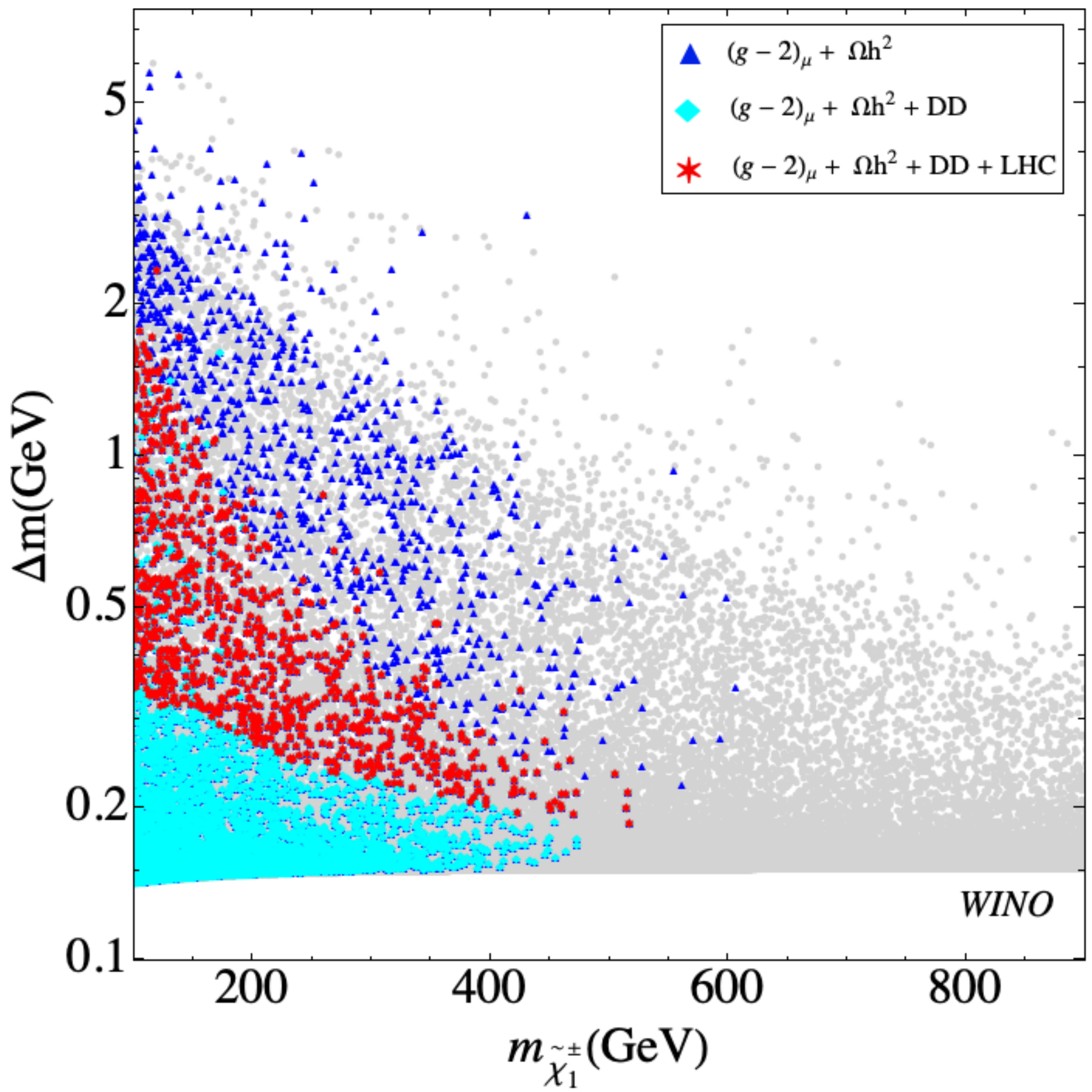


Wino LSP

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

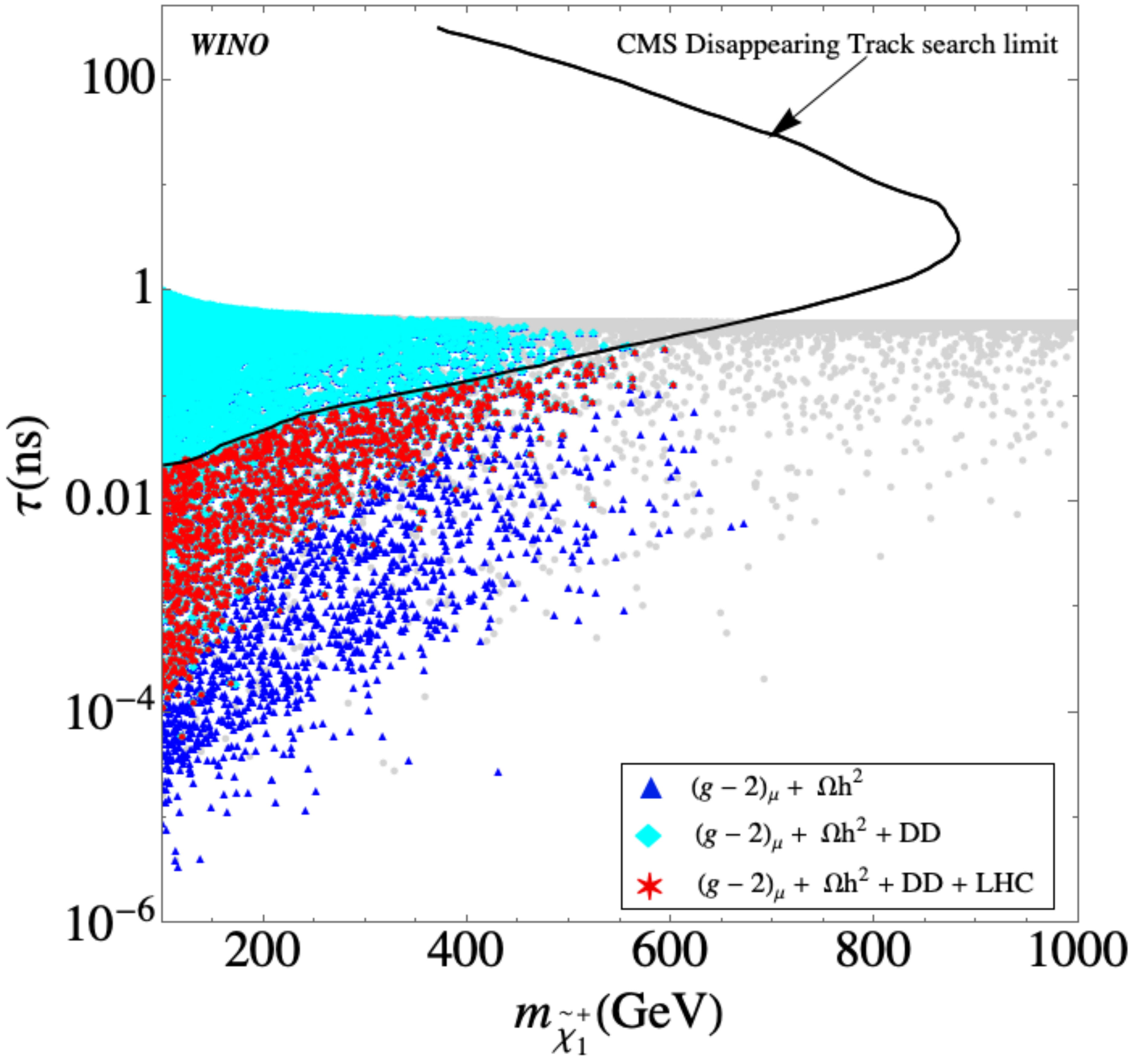


Future $(g-2)_\mu$ limit



Wino LSP lifetime

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



$$\Gamma(\tilde{\chi}^\pm \to \tilde{\chi}^0\pi^\pm) = \Gamma(\pi^\pm \to \mu^\pm\nu_\mu) \times \frac{16\delta m^3}{m_\pi m_\mu^2}\left(1-\frac{m_\pi^2}{\delta m^2}\right)^{1/2}\left(1-\frac{m_\mu^2}{m_\pi^2}\right)^{-2}$$

$$\Gamma(\tilde{\chi}^\pm \to \tilde{\chi}^0 e^\pm \nu_e) \simeq \frac{2G_F^2}{15\pi^3}\delta m^5.$$

- Disappearing track searches most important.

$(g-2)_\mu$

- 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

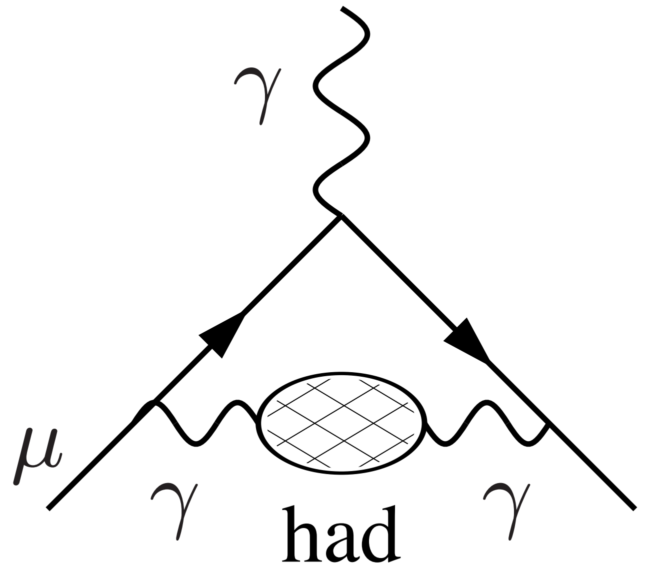
- Important probe for new physics. $\frac{\delta a_l}{a_l} \sim \frac{m_l^2}{\Lambda^2}$.

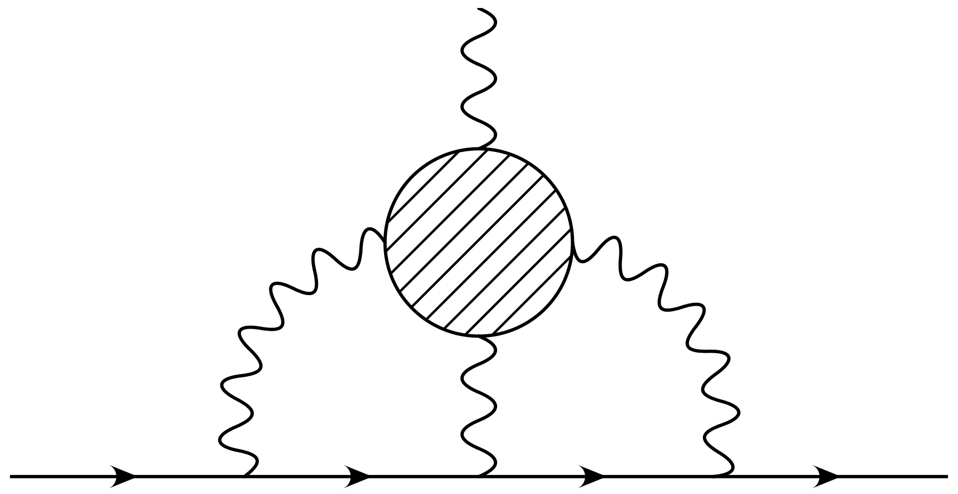
- SM contributions : QED, weak, hadronic vacuum polarization, hadronic light by light scattering.

- 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.





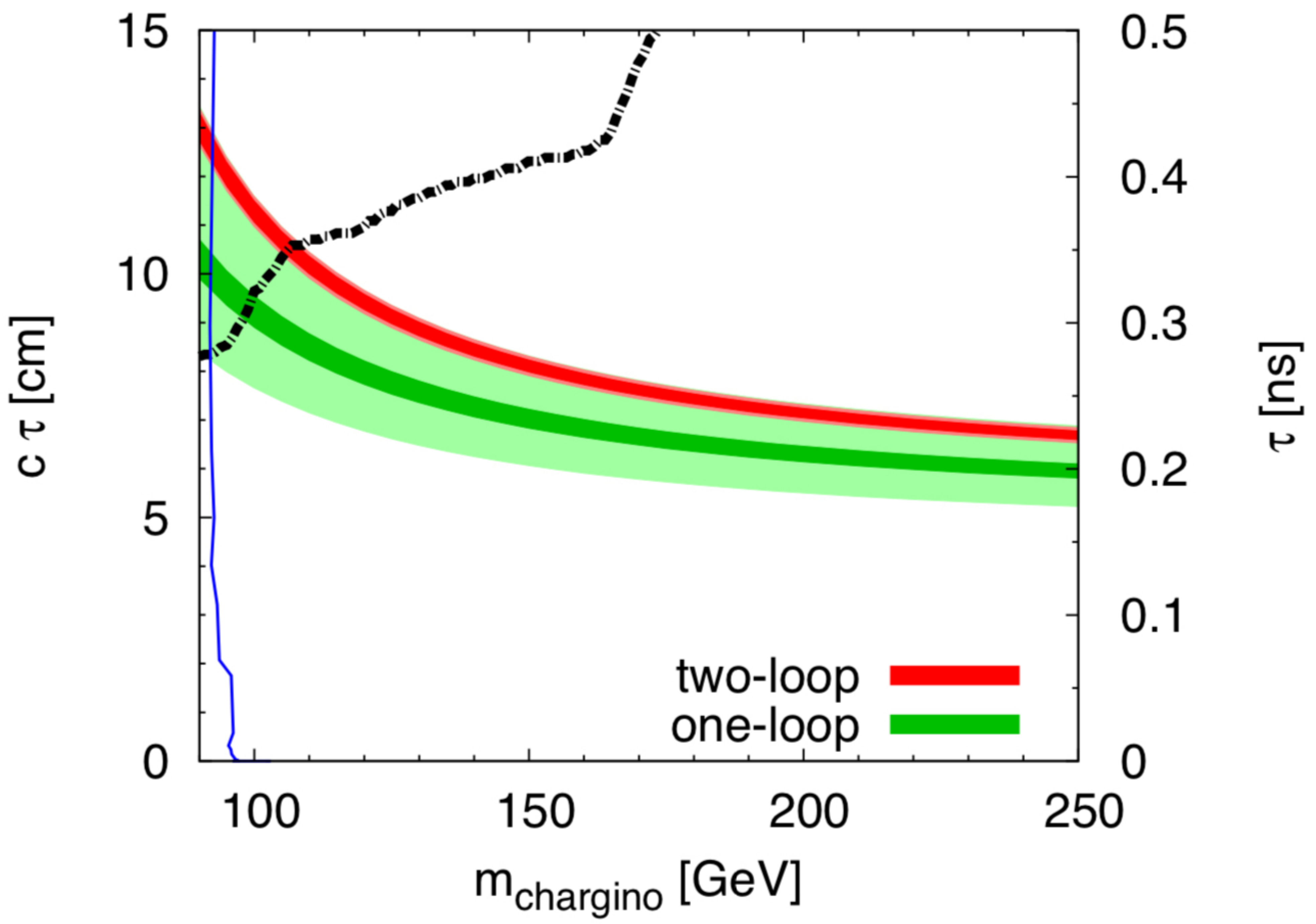


Figure 6: The lifetime of charged wino evaluated by using δm at the one-loop (green band) and two-loop (red band). We neglected the next-to-leading order corrections to the lifetime of the charged wino estimated in terms of the pion decay rate, which is expected to be a few percent correction. The black 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].

MSSM Superpotential

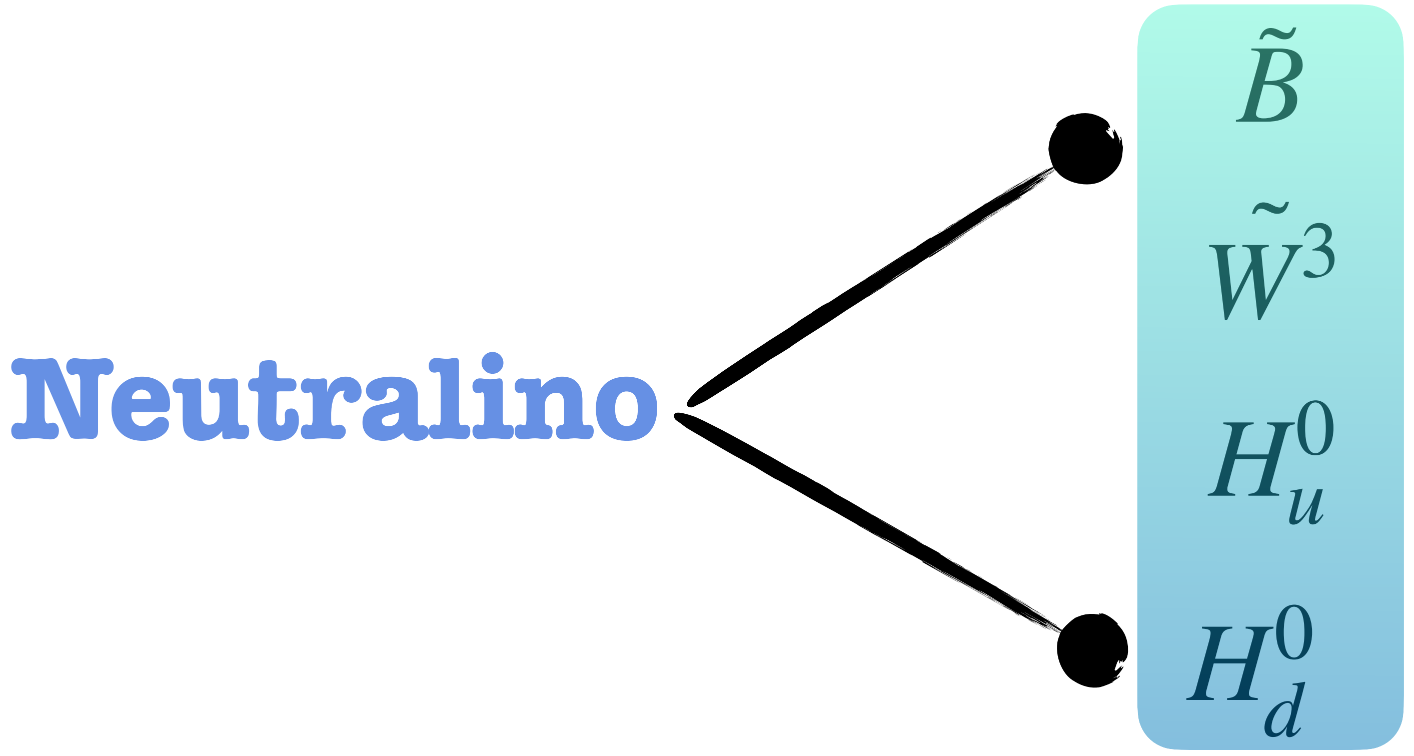
$$W_{\text{MSSM}} = \bar{u} Y_u Q H_u - \bar{d} Y_d Q H_d - \bar{e} Y_e L H_d + \mu H_u H_d$$

Soft Breaking Terms

$$\mathcal{L}_{\text{soft}}^{\text{MSSM}} = -\frac{1}{2}\left(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B} + c.c\right)$$
$$-\left(\tilde{\bar{u}}\,\mathbf{a_u}\,\tilde{Q}H_u - \tilde{\bar{d}}\,\mathbf{a_d}\,\tilde{Q}H_d - \tilde{\bar{e}}\,\mathbf{a_e}\,\tilde{L}H_d + c.c\right)$$
$$-\tilde{Q}^\dagger \mathbf{m_Q^2}\,\tilde{Q} - \tilde{L}^\dagger\,\mathbf{m_L^2}\,\tilde{L} - \tilde{\bar{u}}\,\mathbf{m_{\bar{u}}^2}\,\tilde{\bar{u}}^\dagger - \tilde{\bar{d}}\,\mathbf{m_{\bar{d}}^2}\,\tilde{\bar{d}}^\dagger - \tilde{\bar{e}}\,\mathbf{m_{\bar{e}}^2}\,\tilde{\bar{e}}^\dagger$$
$$-\,m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - \left(bH_uH_d + c.c\right)$$

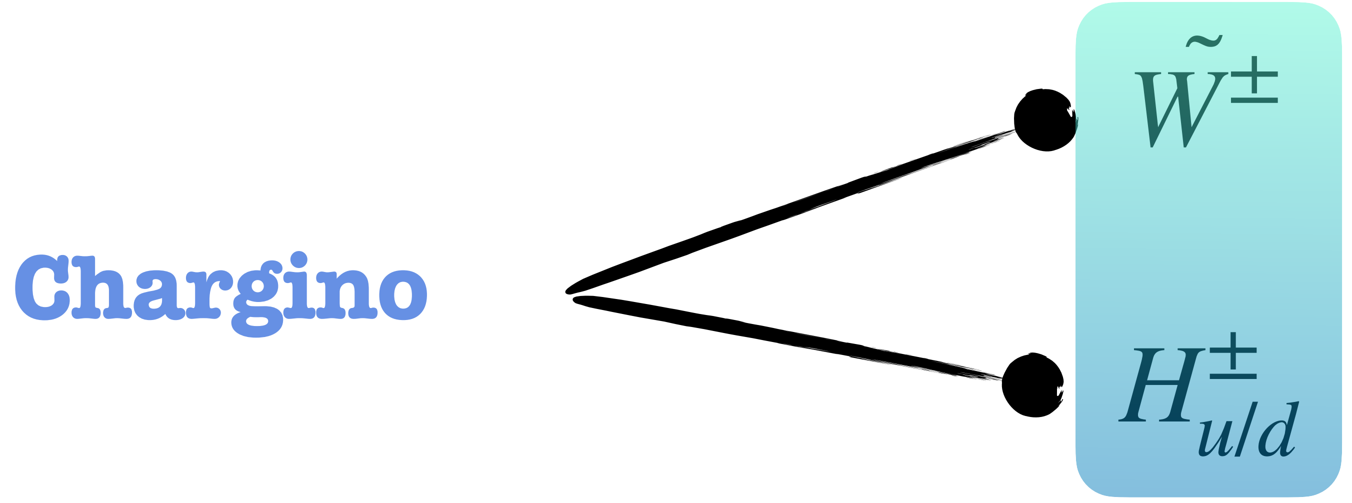
EW Gauginos

Masses and mixing are determined by U(1) and SU(2) gaugino masses M_1, M_2 and Higgs mass parameter μ.



Neutralino Mass Matrix

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



Chargino Mass Matrix

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

FOUR PARAMETERS $M_1, M_2, \mu, \tan\beta$