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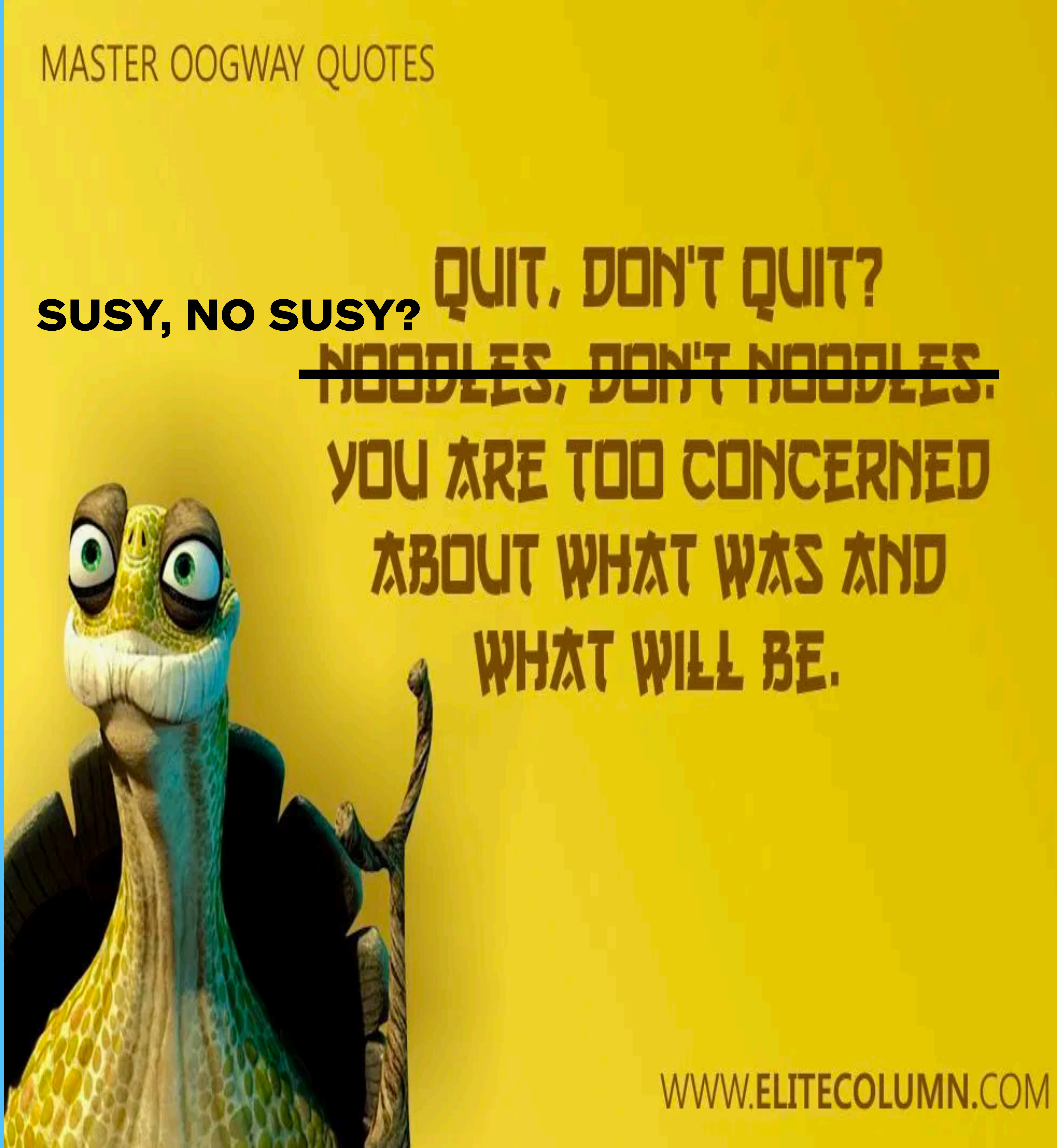
Improved $(g-2)_\mu$ measurements and Supersymmetry

ANOMALIES 2020 – 11/09/2020

BASED ON : 2006.15157 WITH SVEN HEINEMEYER AND MANIMALA CHAKRABORTI

Possibilities :

- EW Sector may be the hiding key to new physics!
- Modest production cross-section, mass bounds from LHC rather weak.
- May show up elsewhere : Dark Matter experiments, $(g-2)_\mu$ etc ..



MSSM Superpotential

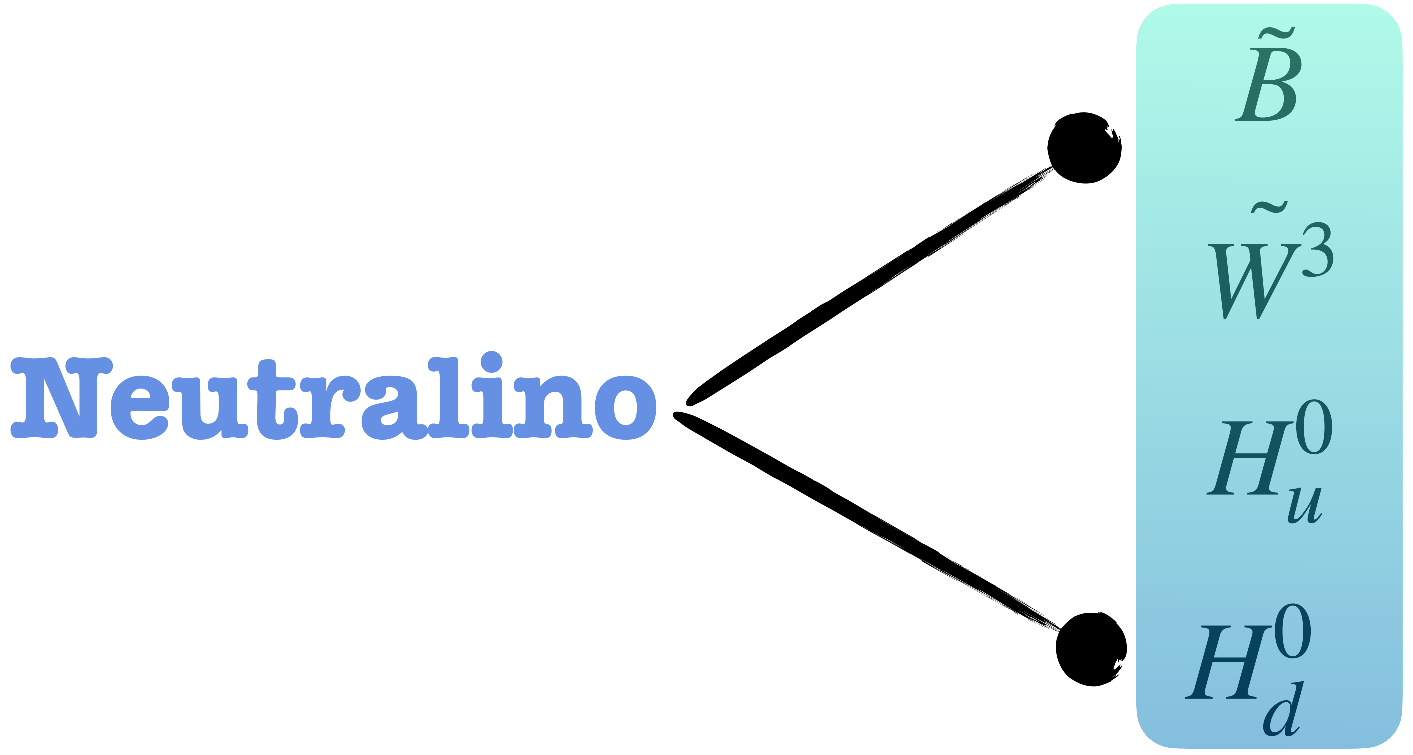
$$W_{\text{MSSM}} = \bar{u} Y_u Q H_u - \bar{d} Y_d Q H_d - \bar{e} Y_e L H_d + \mu H_u H_d$$

Soft Breaking Terms

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

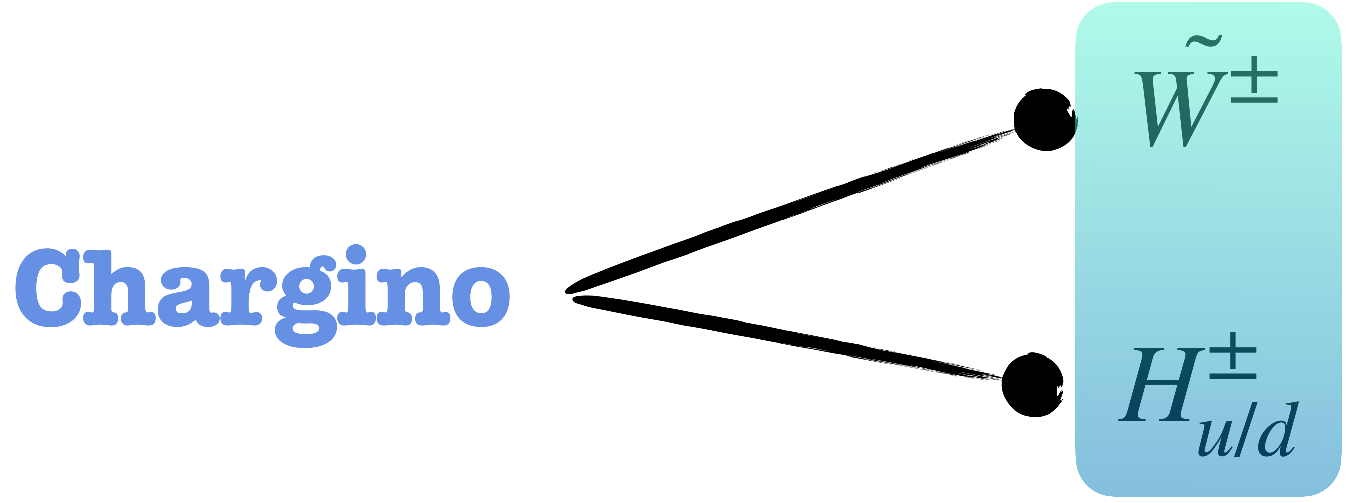
EW Gauginos

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

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

LSP in RPC

DM

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

Sleptons

Slepton Mass Matrix

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

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

$$m^2_{RR} = m^2_{\tilde{R}} + Q_f s_w^2 M_z^2 c_\beta^2$$

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

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

Constraints

Proper recasting is important.

Direct Searches at LHC

- LHC searches restricted to **simplified models**

  → sparticles except those relevant to the signal are taken to be decoupled.

- $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ are taken to be mass-degenerate and purely wino. $\tilde{\chi}_1^0$ is assumed to be purely bino.

- All three generations of sleptons and sneutrinos are assumed mass degenerate. In MSSM:

  $$m_{\tilde{\nu}}^2 = m_{\tilde{l}}^2 + \frac{1}{2} m_Z^2 cos2\beta$$

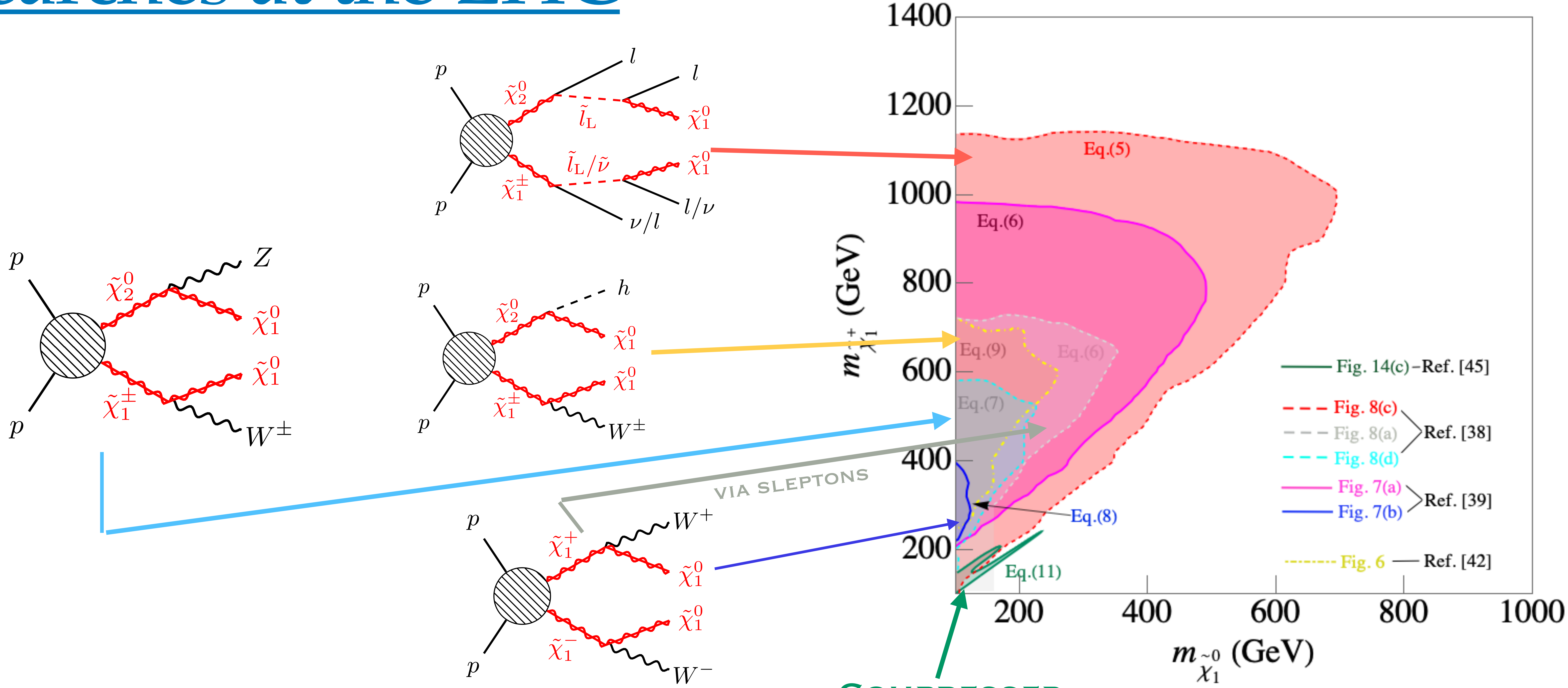
- Heavier gauginos $\tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_2^{\pm}$ assumed to be decoupled.

- No sensitivity to parameters like tan β.

Indirect Constraints

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

Searches at the LHC

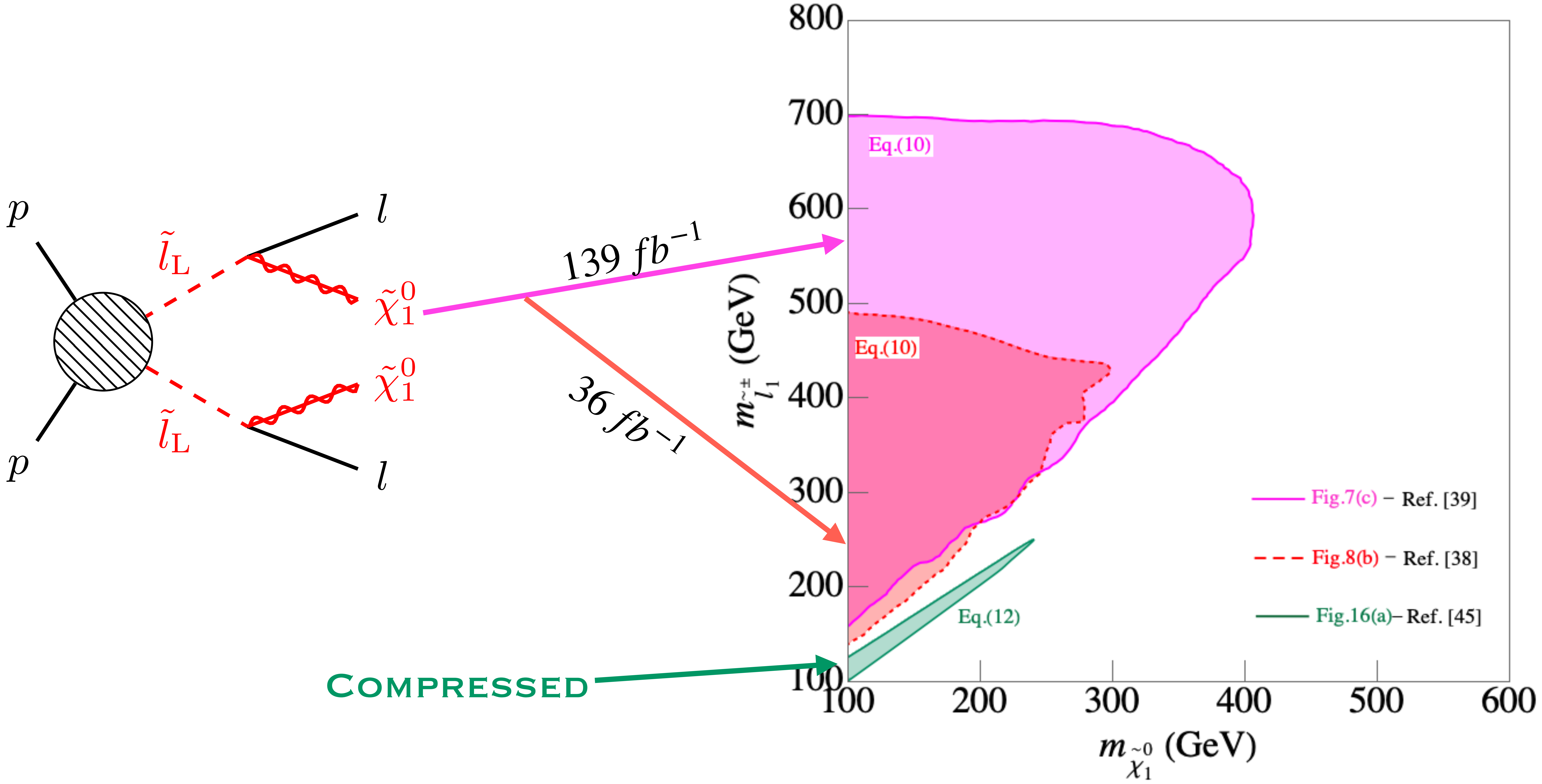


VIA SLEPTONS

COMPRESSED

Proper recasting is important. → CheckMATE

Searches at the LHC

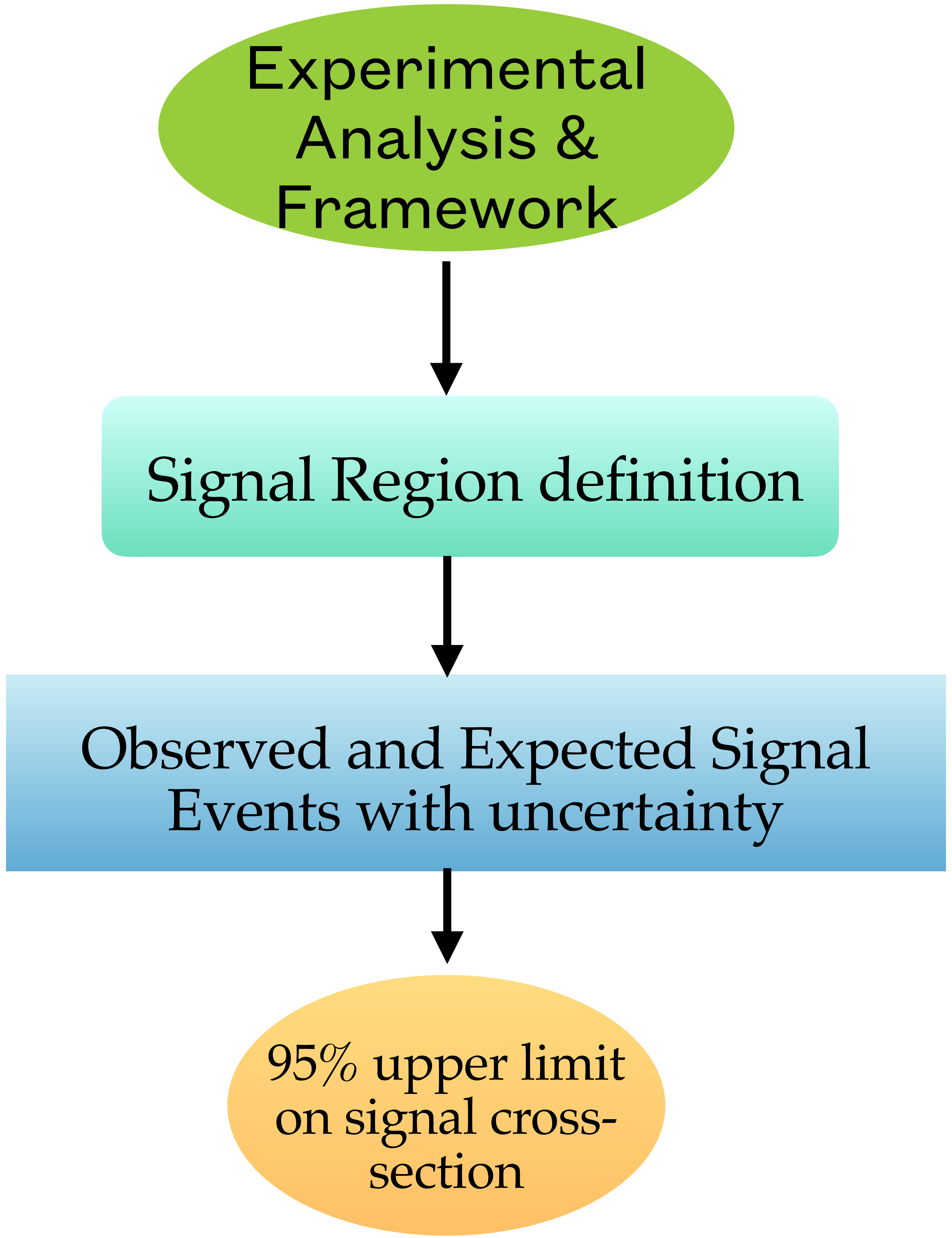


Proper recasting is important. → CheckMATE

CheckMATE in brief

J. S. Kim, D. Schmeier, J. Tattersall and K. Rolbiecki, *Comput. Phys. Commun.* **196** (2015), 535-562 [arXiv:1503.01123 [hep-ph]].

M. Drees, H. Dreiner, D. Schmeier, J. Tattersall and J. S. Kim, *Comput. Phys. Commun.* **187** (2015), 227-265 [arXiv:1312.2591 [hep-ph]].



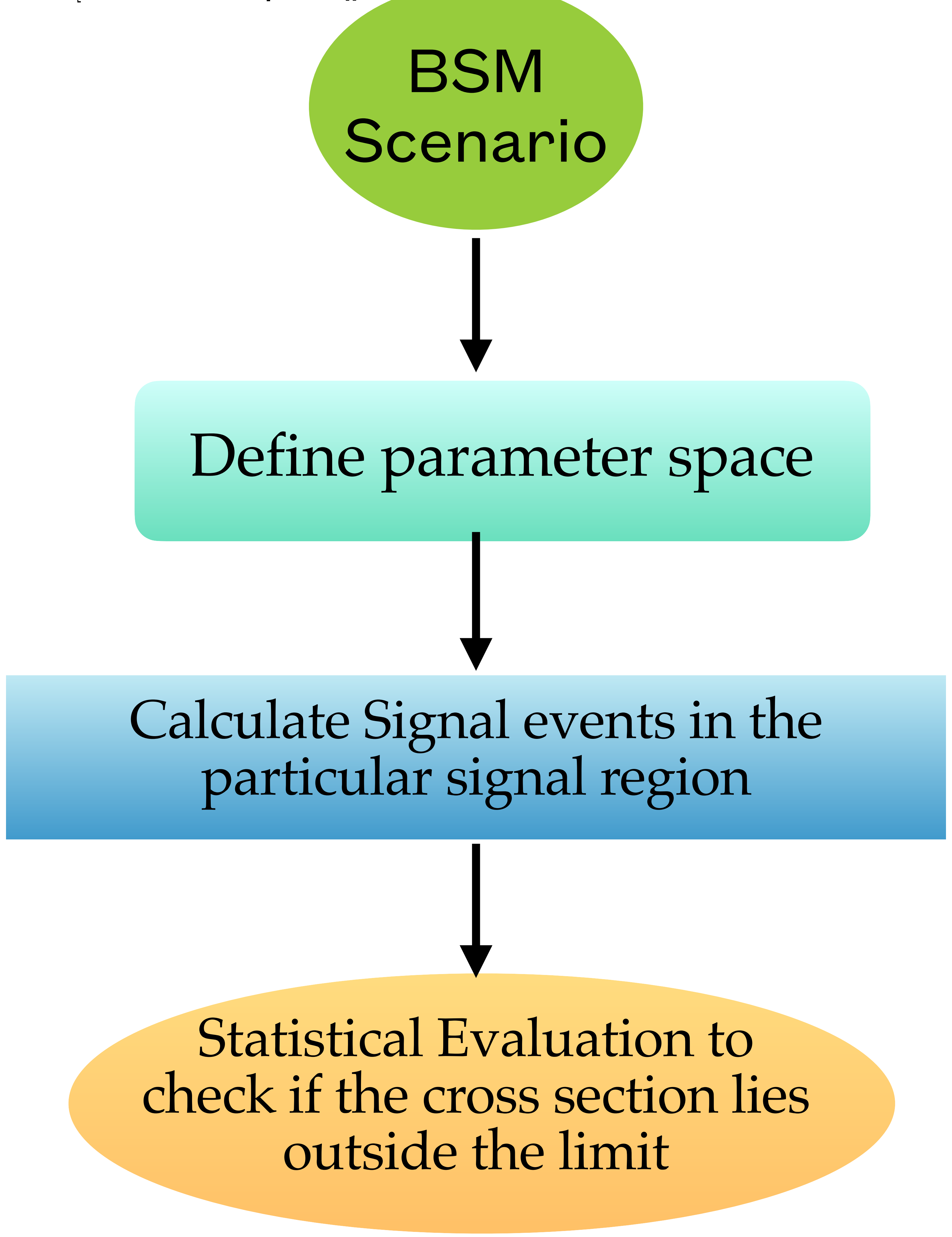
Experimental Analysis & Framework

Signal Region definition

Observed and Expected Signal Events with uncertainty

95% upper limit on signal cross-section

Input for Implementation of new analysis



BSM Scenario

Define parameter space

Calculate Signal events in the particular signal region

Statistical Evaluation to check if the cross section lies outside the limit

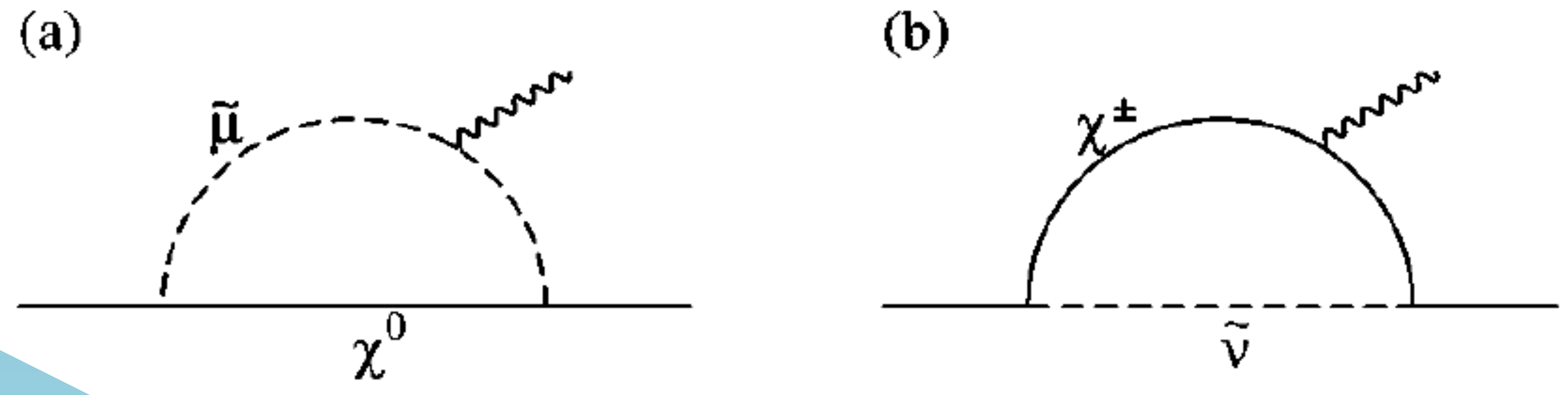
Model parameter test

Muon (g-2)

- Currently large discrepancy from the SM $> (3\sigma)$.
  $a_\mu^{exp} - a_\mu^{SM} = (28.02 \pm 7.37) \times 10^{-10}$
  Kashavarzi, Nomura, Teubner '19

- Assuming upcoming Fermilab Run-I result to have the same central value and reduced exp uncertainty combined data corresponds to 5.4σ discrepancy.
  $a_\mu^{exp} - a_\mu^{SM} = (28.02 \pm 5.2) \times 10^{-10}$

- New "World average" appeared
  → modest impact on our analysis
  Aoyama *et al* '20



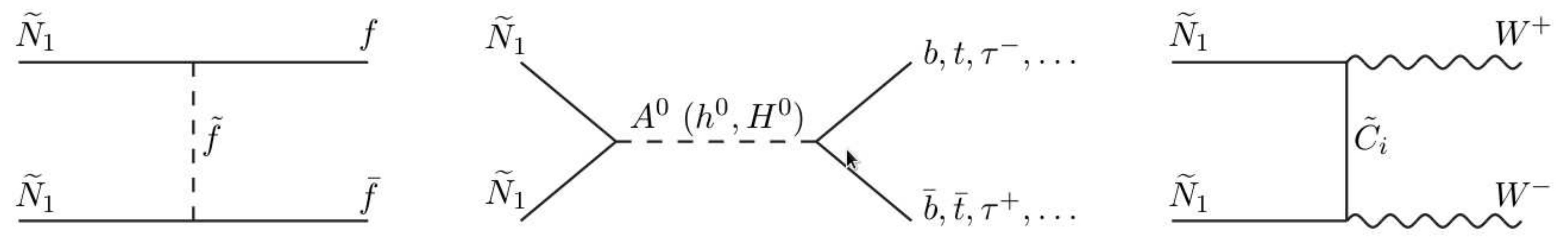
- SUSY contributions from Chargino-Sneutrino and Smuon-Neutralino loop

- Contribution ~ $\tan\beta$, can reconcile the anomaly

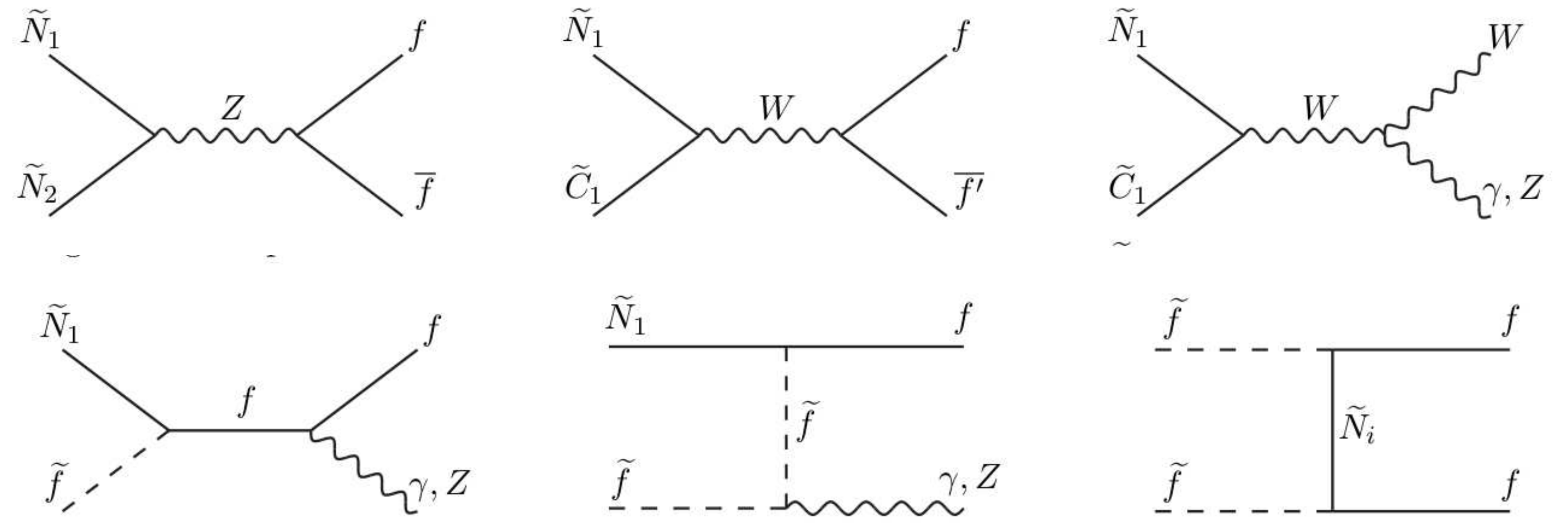
DM Constraints

Relic Density

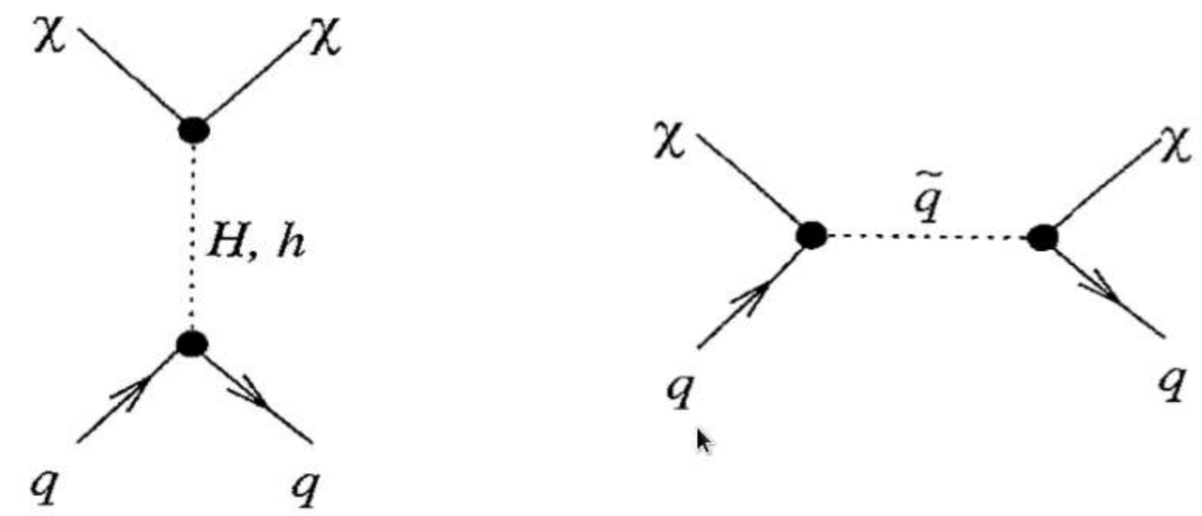
Some annihilation channels that could give right relic density :



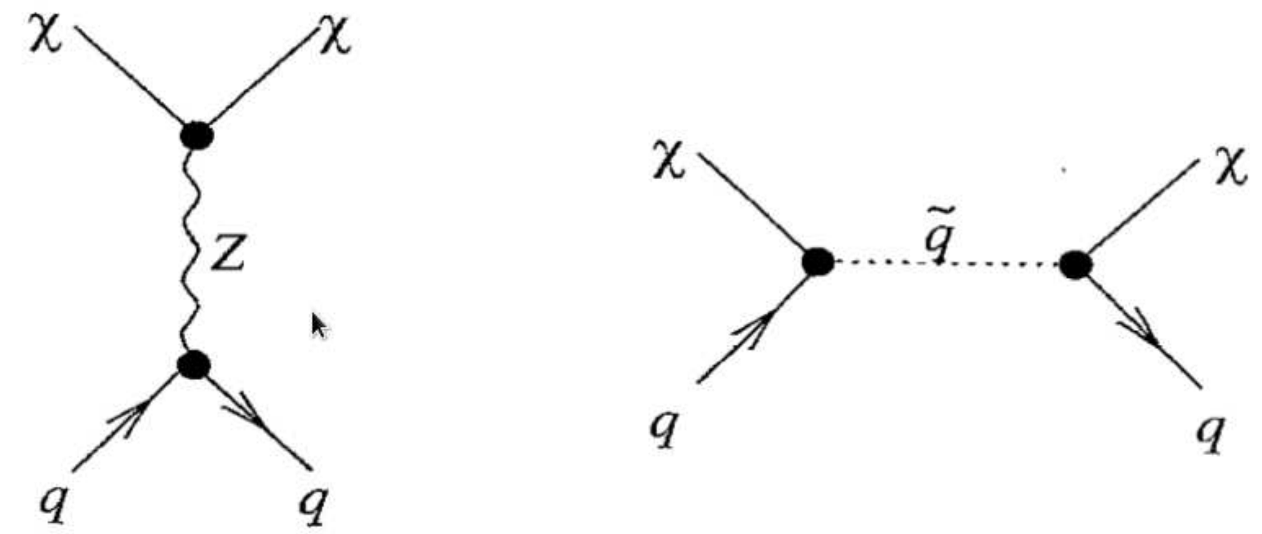
There can be coannihilations with sparticles of slightly heavier masses:



Direct Detection



Diagrams contributing to SI interactions



Diagrams contributing to SD interactions

A well-tempered bino-wino or bino-higgsino LSP is favorable for chargino co-annihilation while a bino dominated LSP will work for slepton co-annihilation.

Parameter Scanning

Chargino co-annihilation region:

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

Slepton co-annihilation region:

Case-L: SU(2) doublet

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

Case-R: SU(2) singlet

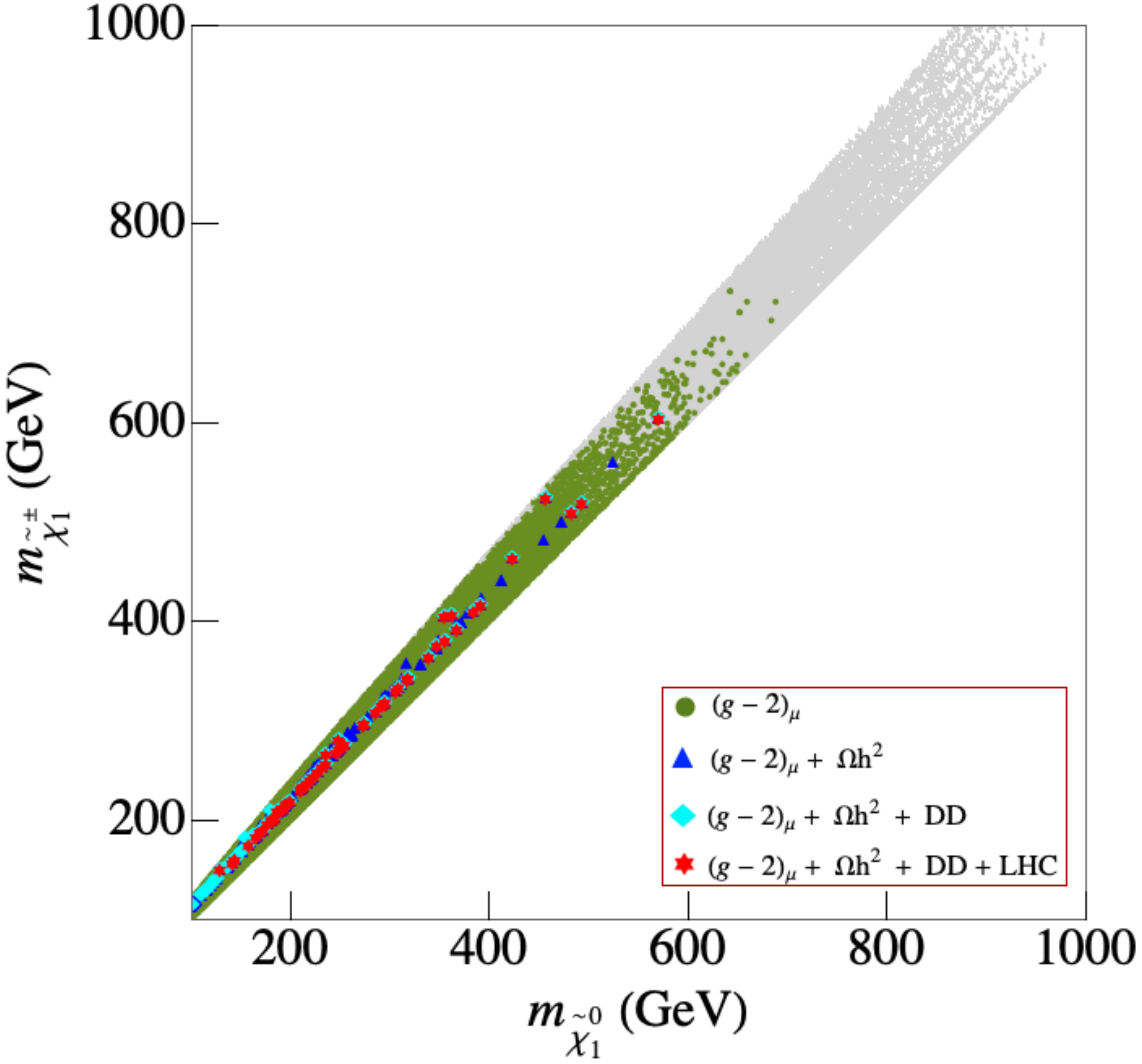
$$
\begin{aligned}
100\ \text{GeV} \leq M_1 \leq 1\ \text{TeV}\ , \quad & M_1 \leq M_2 \leq 10 M_1\ , \\
1.1 M_1 \leq \mu \leq 10 M_1, \quad & 5 \leq \tan\beta \leq 60, \\
M_1\ \text{GeV} \leq m_{\tilde{l}_R} \leq 1.2 M_1, \quad & M_1 \leq m_{\tilde{l}_L} \leq 10 M_1\ .
\end{aligned}
$$

MC, S.Heinemeyer, I.Saha 2006.15157

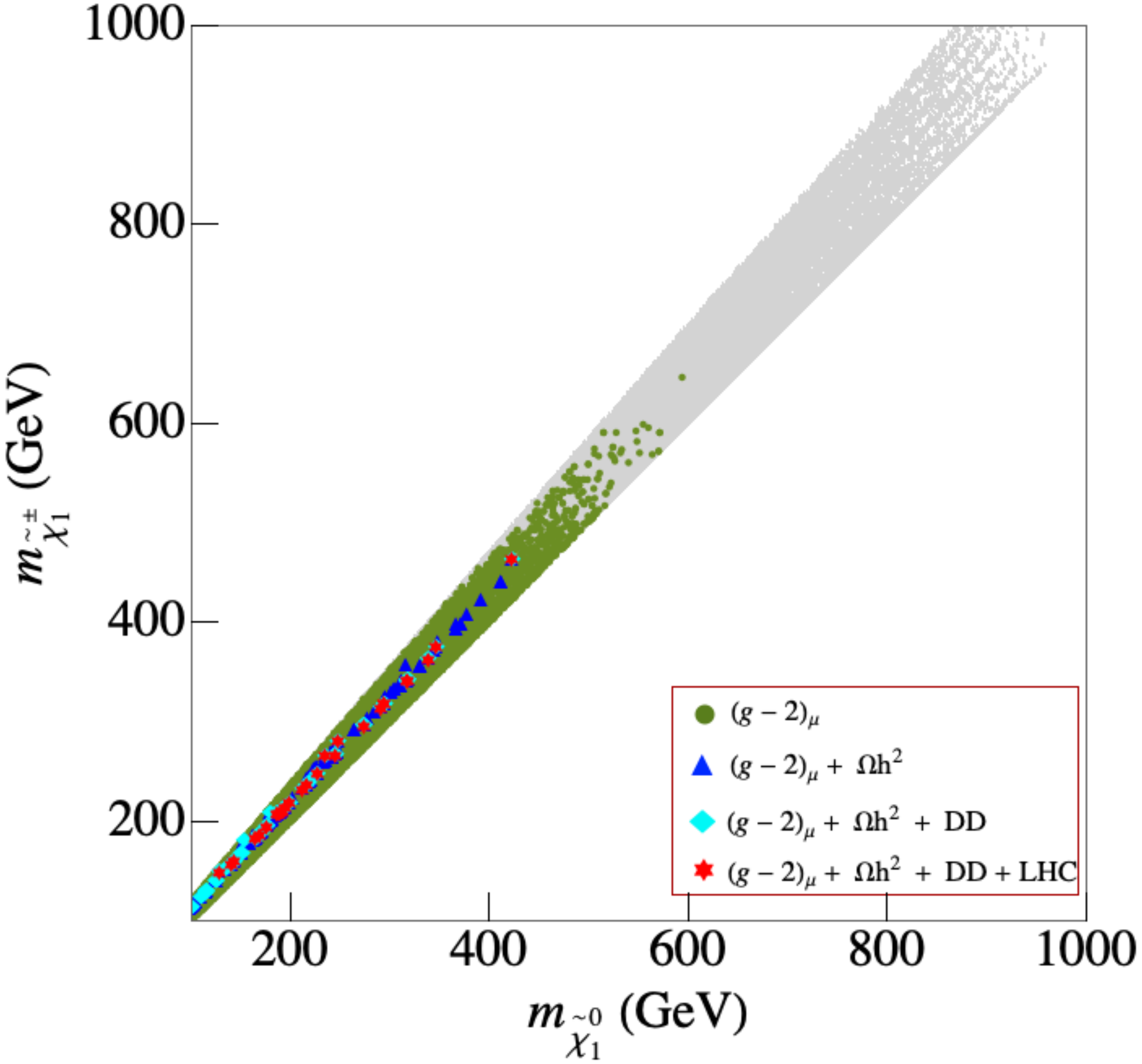
Packages used → SuSpect, SUSYHIT, GM2Calc, micrOMEGAs, CheckMATE etc.

Chargino Co-annihilation

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



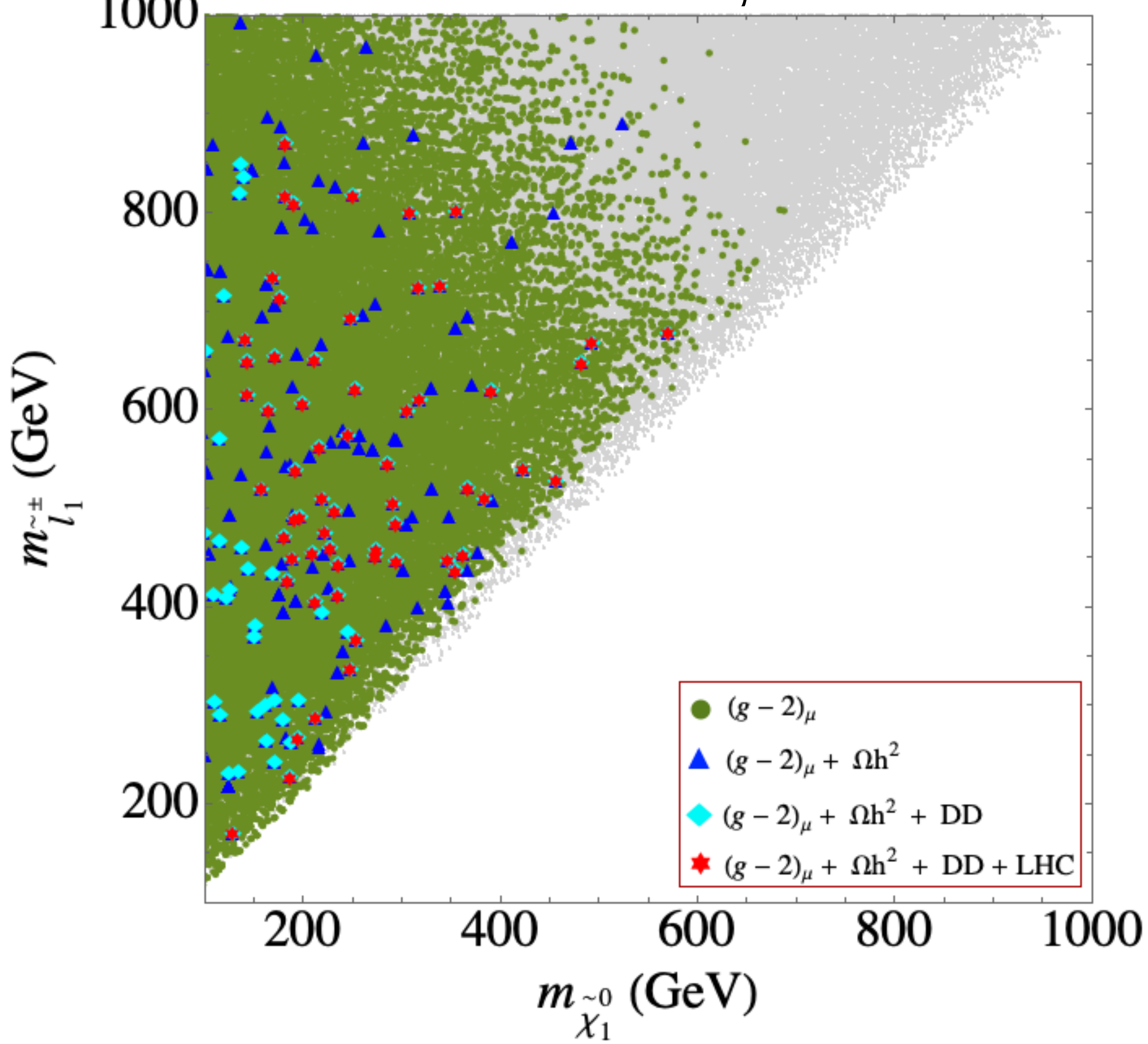
Anticipated future $(g-2)_\mu$ limit



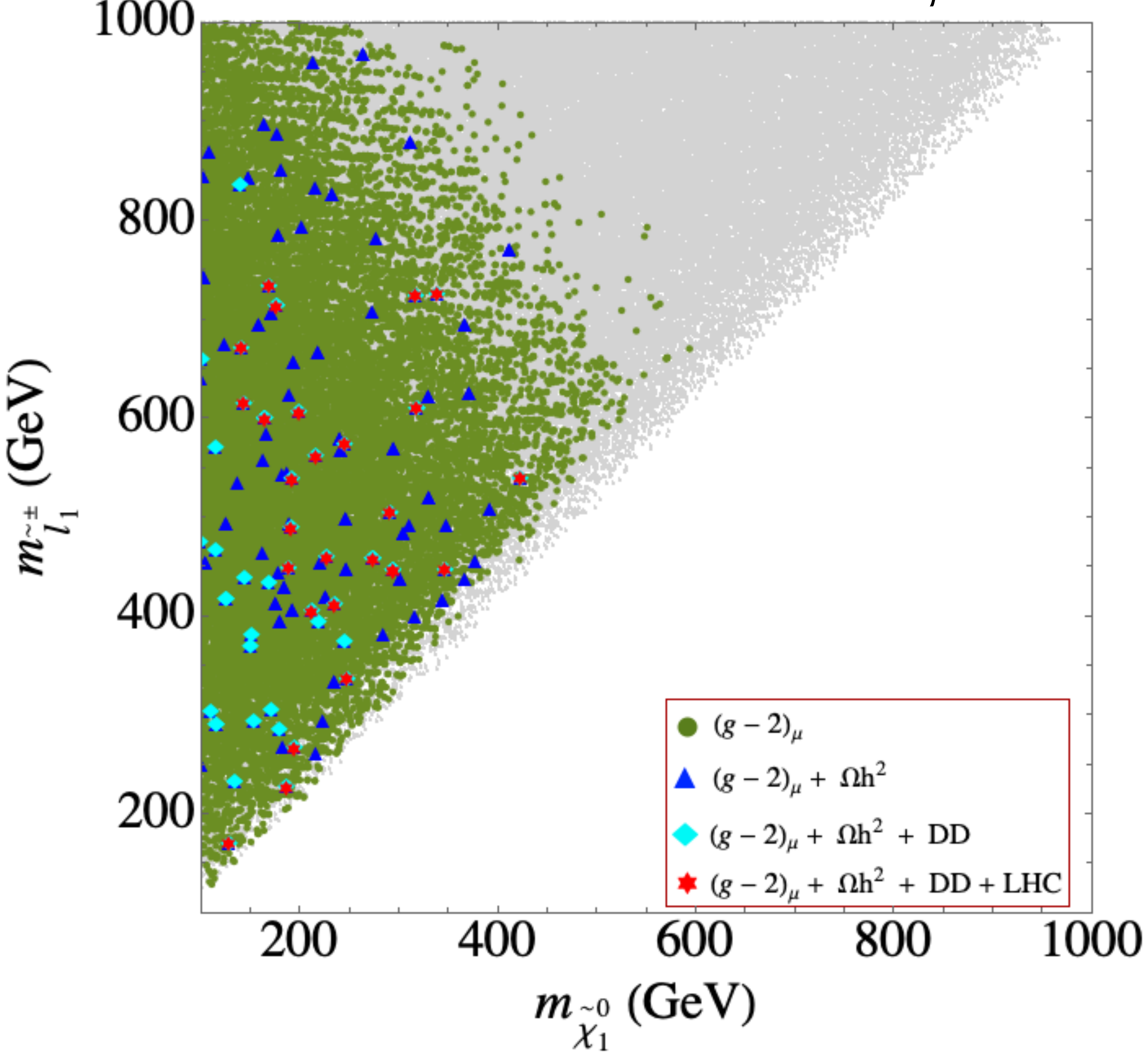
Upper and lower bounds from $(g-2)_\mu$ and LHC searches (for compressed spectrum)

Chargino Co-annihilation

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



Anticipated future $(g-2)_\mu$ limit

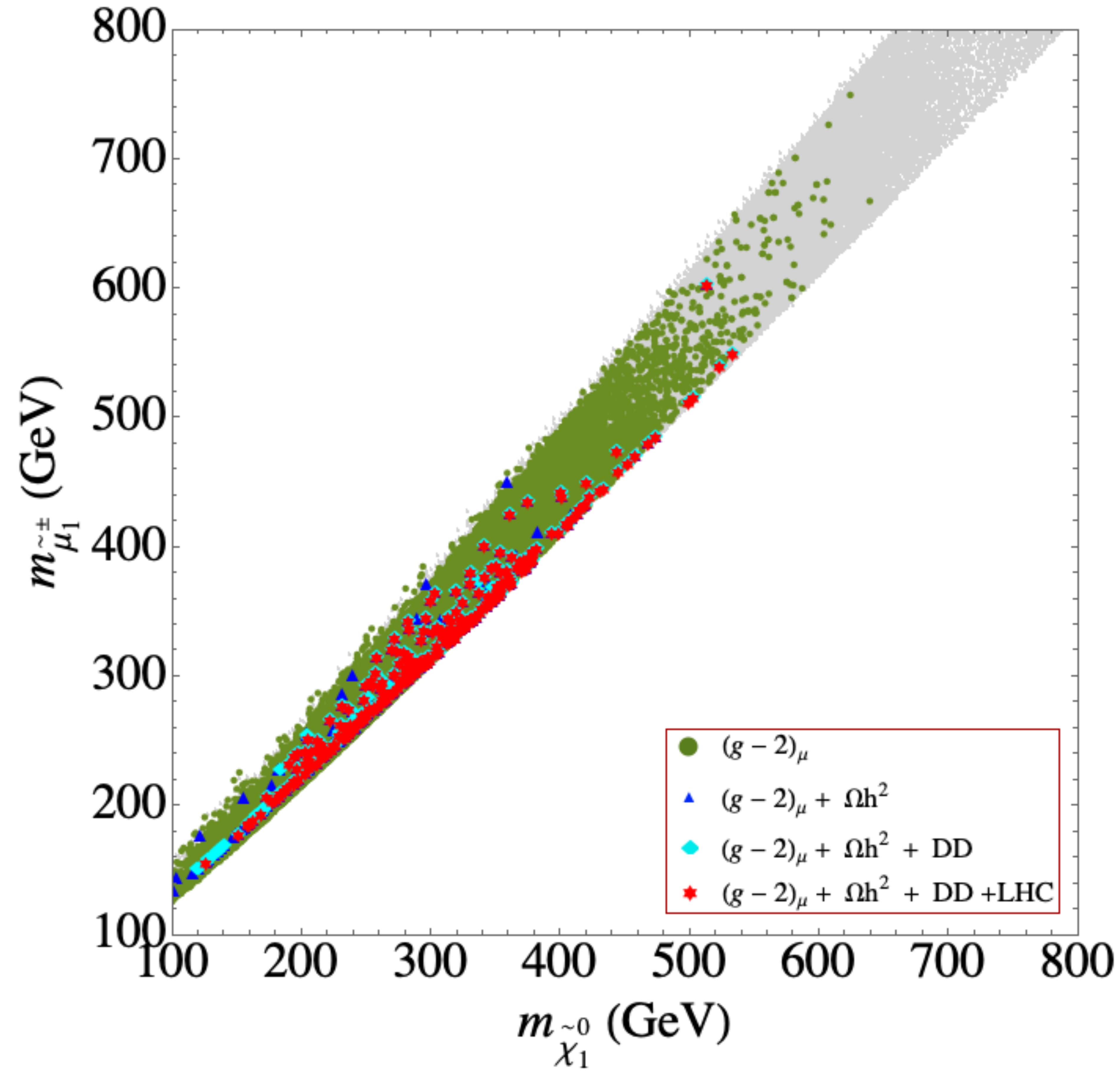


Slepton-pair production→($2l$+missingE_T) provides important search channel.

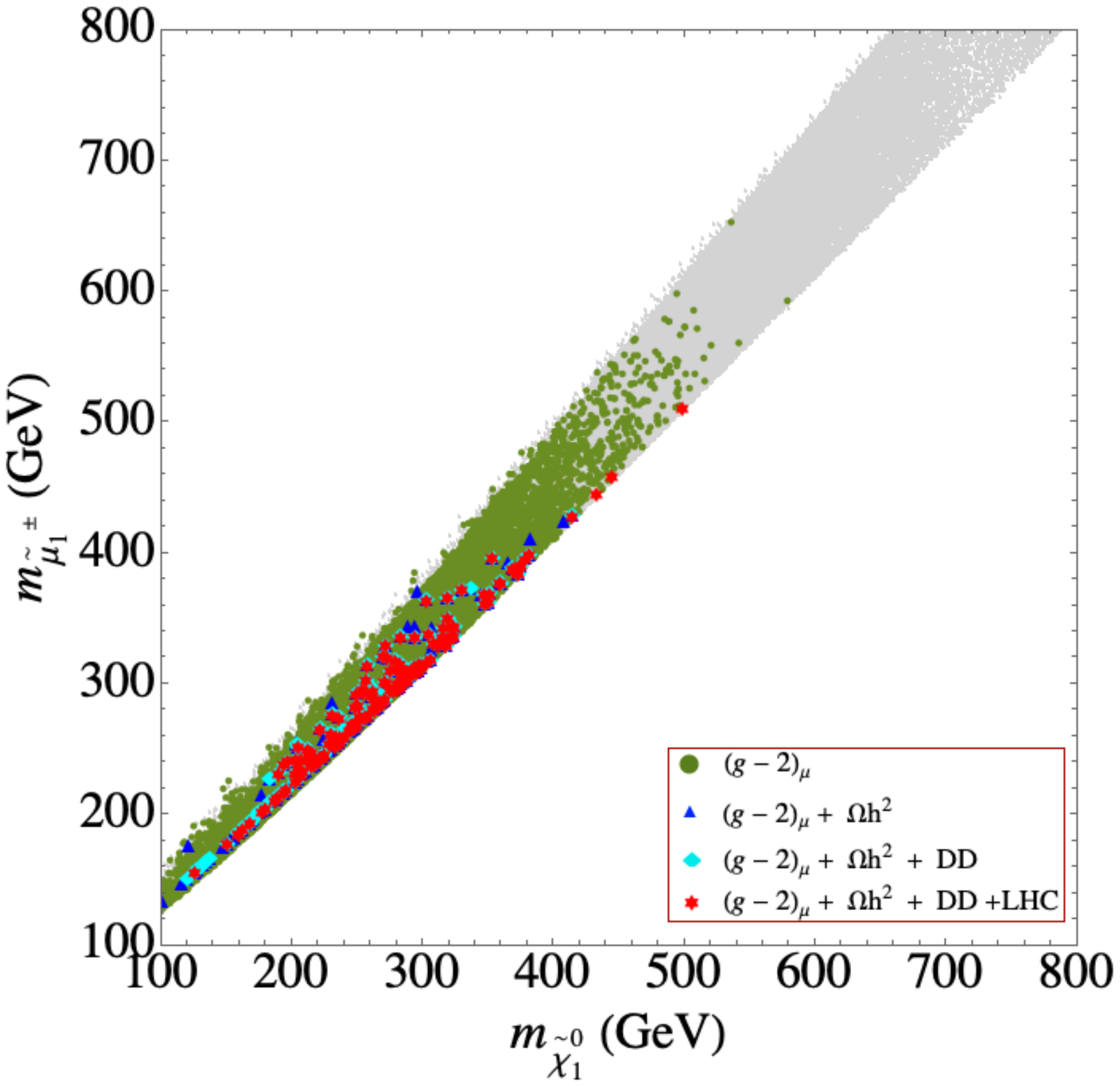
Right-sleptons are significantly heavy, Considerable BR for $\tilde{e}_L(\tilde{\mu}_L) \to \tilde{\chi}_1^\pm e(\mu)$ → Less no. of signal leptons.

Slepton Co-annihilation: Case-L

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



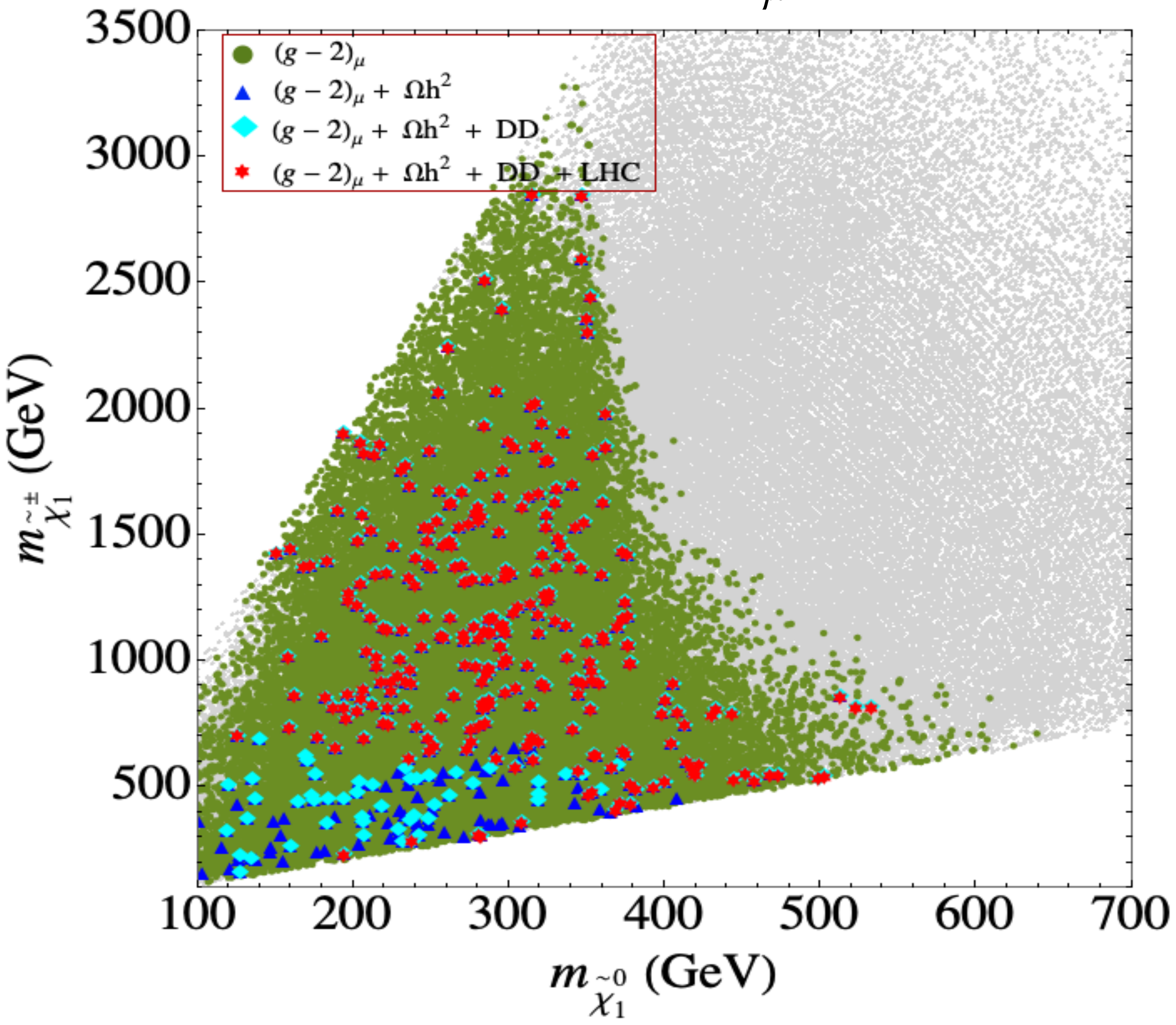
Anticipated future $(g-2)_\mu$ limit



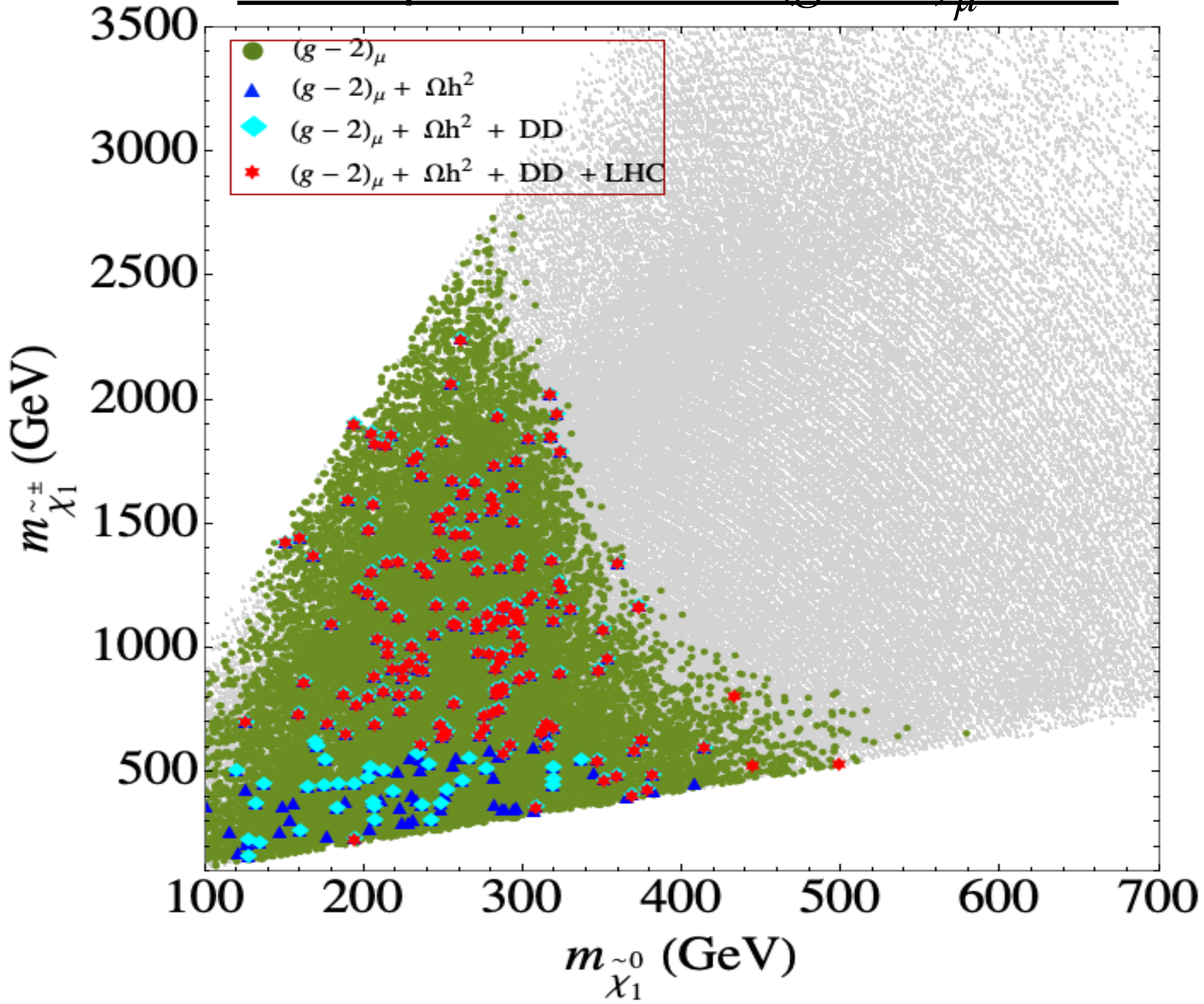
The left-sleptons and sneutrinos are close in mass to the LSP → stau not far away

Slepton Co-annihilation: Case-L

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



Anticipated future $(g-2)_\mu$ limit

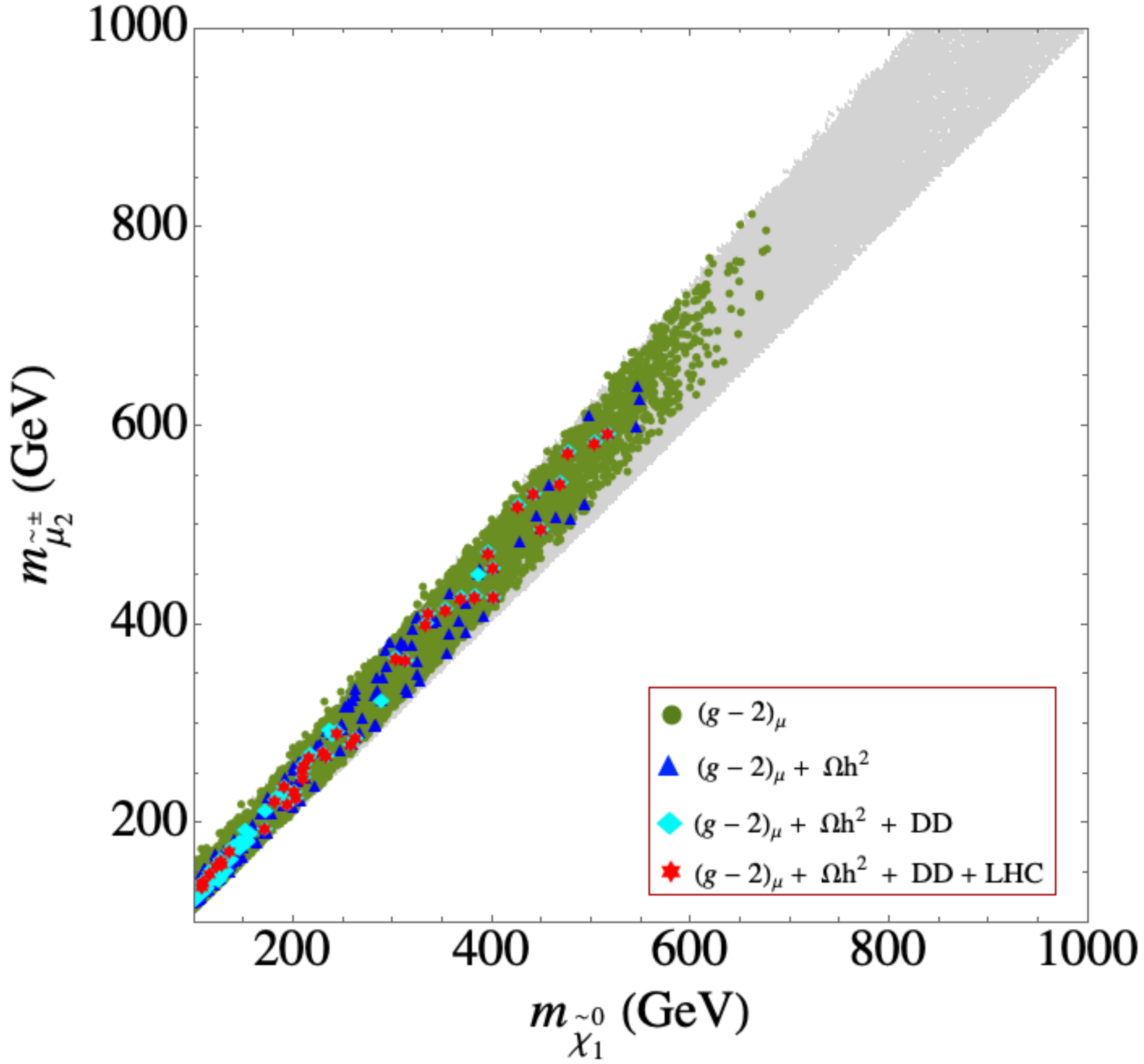


Reduced limit attributed by significant $\mathrm{BR}(\tilde{\chi}_1^\pm \to \tilde{\tau}_1 \nu_\tau)$ and $\mathrm{BR}(\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau)$, $\mathbf{BR}(\tilde{\chi}_2^0 \to \tilde{\nu}\nu)$

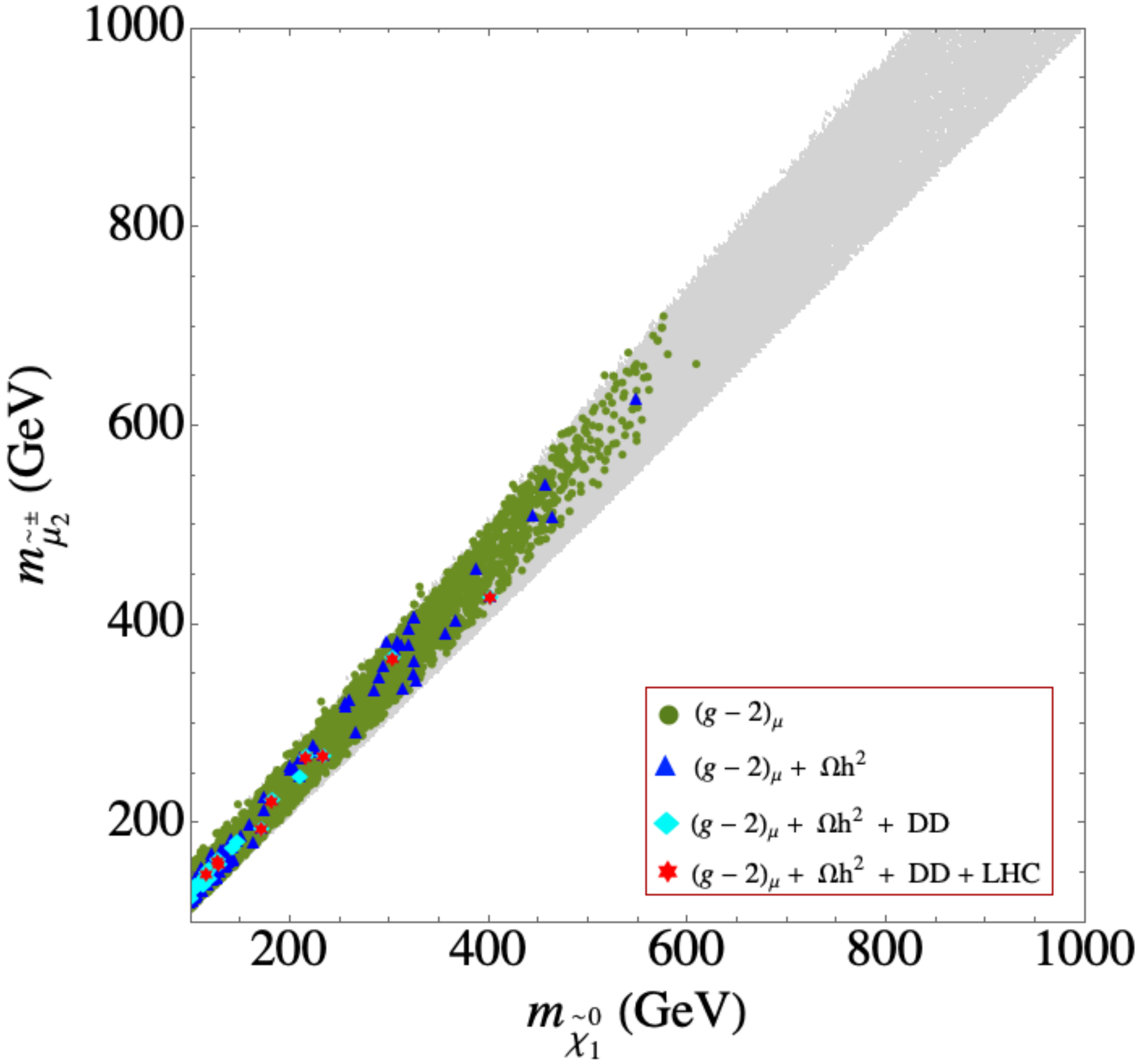
($3l$ + missingET)exclusion limit weakens

Slepton Co-annihilation: Case-R

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



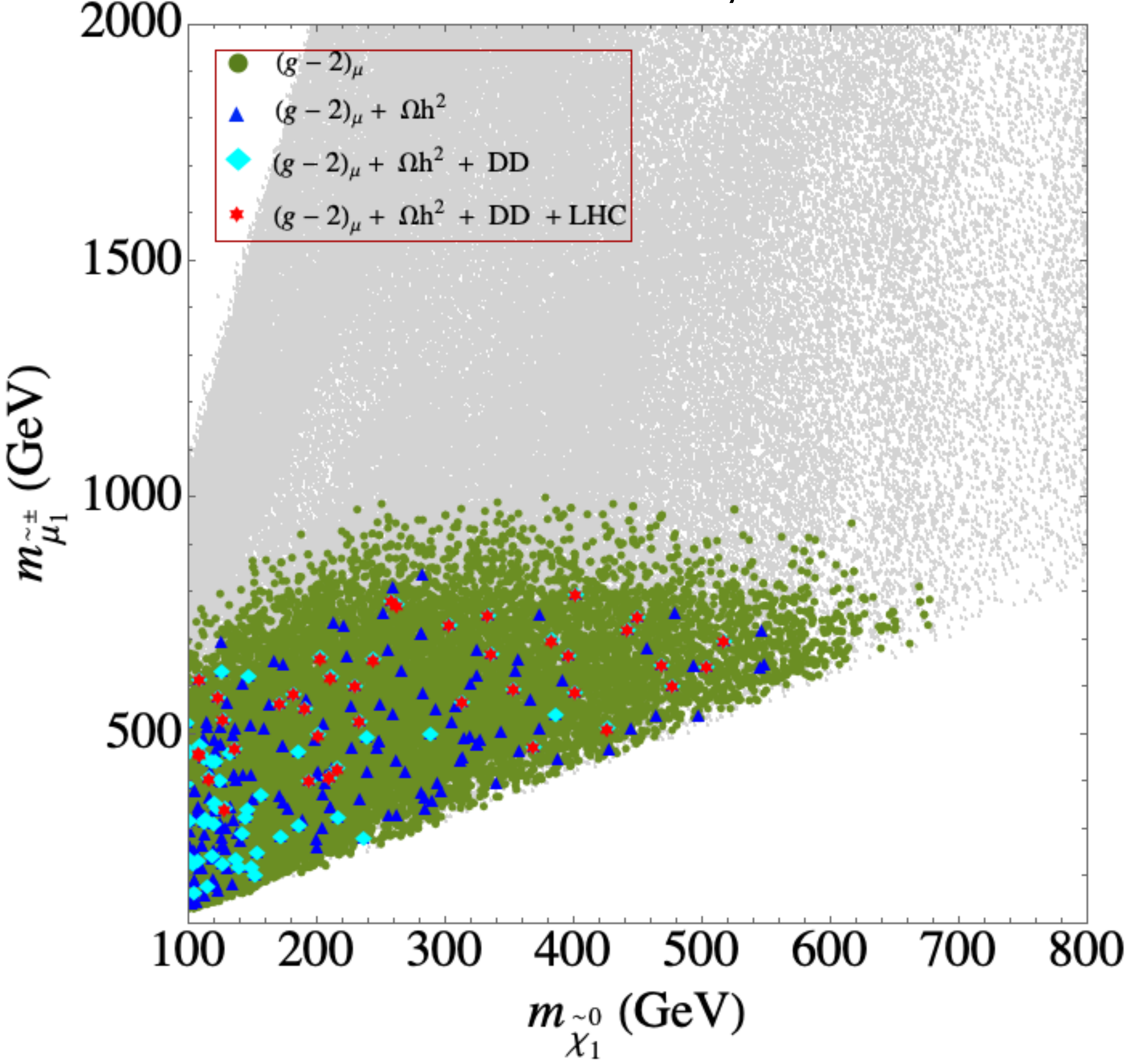
Anticipated future $(g-2)_\mu$ limit



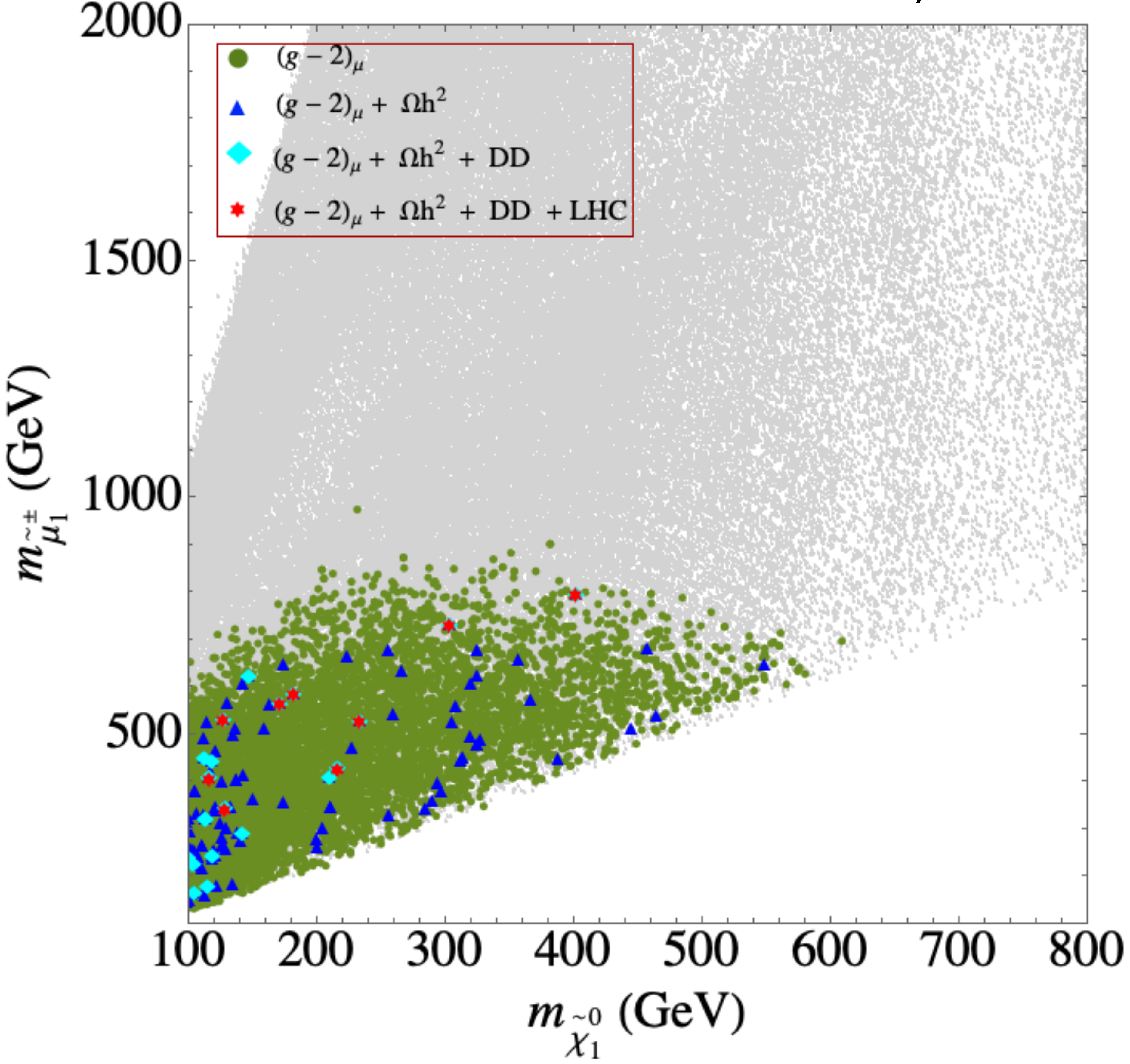
Right-sleptons are close in mass to LSP.

Small μ is favored, tension between DD and $(g-2)_\mu$.

Slepton Co-annihilation: Case-R



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

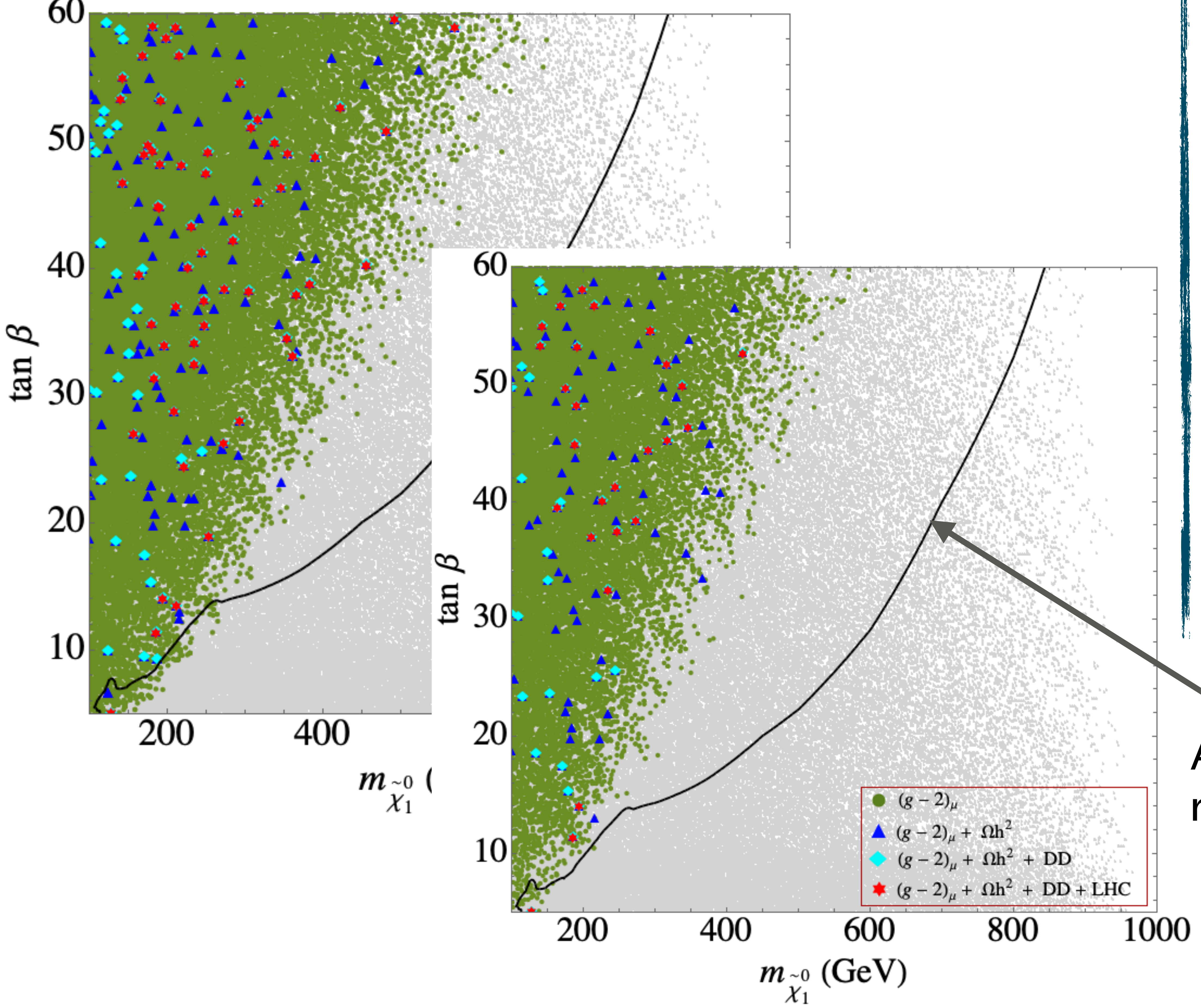


Anticipated future $(g-2)_\mu$ limit

Left-sleptons can not be too heavy to have relevant contribution to $(g-2)_\mu$.

Get stringent constraint from LHC.

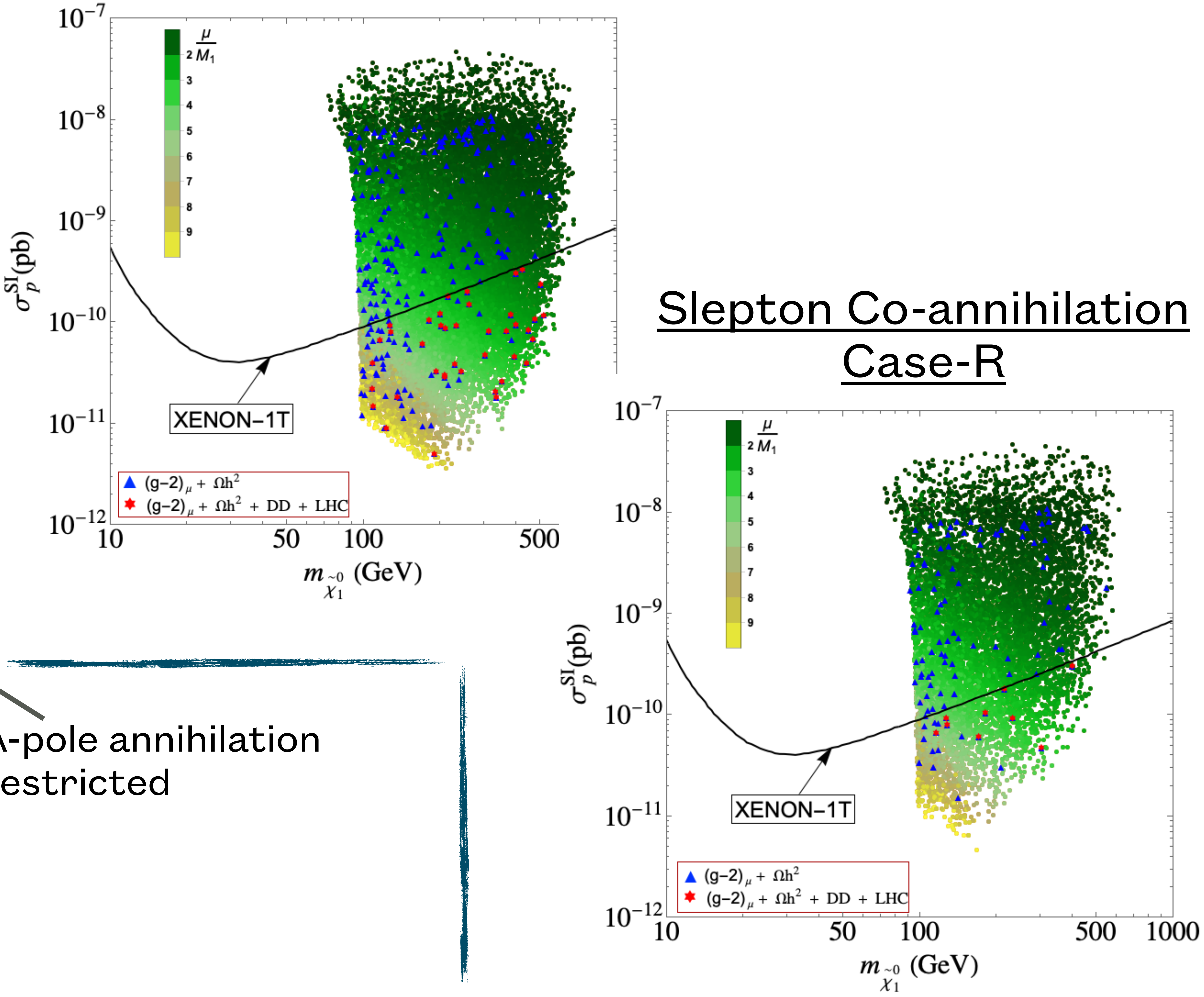
Further Comments



Chargino co-annihilation

A-pole annihilation restricted

Slepton Co-annihilation Case-R



Larger $\tan\beta$ can easily satisfy $(g-2)_\mu$.

Tension between DD and $(g-2)_\mu$.

Lowest and highest LSP : chargino coannihilation

Lowest LSP in Current (g-2)

Highest LSP in Current (g-2)

Highest LSP in Future (g-2)

Sample points	C1	C2	C3	Sample points	C1	C2	C3
M_1	133	579	430	$\mathrm{BR}(\tilde\chi_2^0 \to \tilde\tau_1 \tau)$	100	100	100
M_2	144	583	444				
μ	1329	1081	1024				
$\tan\beta$	5.1	59	52.7	$\mathrm{BR}(\tilde\chi_1^\pm \to \tilde\tau_1 \nu_\tau)$	100	100	100
$m_{\tilde l_L} = m_{\tilde l_R}$	170	678	540				
$m_{\tilde\chi_1^0}$	129	570	423				
$m_{\tilde\chi_2^0}$	150	605	464				
$m_{\tilde\chi_3^0}$	1338	1087	1032				
$m_{\tilde\chi_4^0} \sim m_{\tilde\chi_2^\pm}$	1341	1093	1036	$\mathrm{BR}(\tilde e_1 \to \tilde\chi_1^0 e$	20	14	16.4
$m_{\tilde\chi_1^\pm}$	150	605	464	$\to \tilde\chi_2^0 e$	28	30	28.9
$m_{\tilde e_1, \tilde\mu_1}$	176	680	542	$\to \tilde\chi_1^\pm \nu_e)$	52	55	54.6
$m_{\tilde e_2, \tilde\mu_2}$	176	680	541				
$m_{\tilde\tau_1}$	140	582	437				
$m_{\tilde\tau_2}$	205	765	629				
$m_{\tilde\nu}$	159	675	536	$\mathrm{BR}(\tilde e_2 \to \tilde\chi_1^0 e$	99.9	99.7	99.9
$\Omega_{\tilde\chi} h^2$	0.118	0.121	0.118	$\to \tilde\chi_2^0 e)$	0.1	0.3	0.1
$a_\mu^{\mathrm{SUSY}} \times 10^{10}$	21.1	15.6	20.14				
$\sigma_p^{\mathrm{SI}} \times 10^{10}$	0.39	2.3	1.12				

Searches for τ rich final states will be beneficial for further study.

BR in %

Lowest and highest LSP : Slepton coannihilation

Sample points	L1	L2	L3	Sample points	L1	L2	L3
M_1	131	541	508	$\mathrm{BR}(\tilde\chi_2^0 \to \tilde l_1 l$	32	32.4	28
M_2	838	793	515	$\to \tilde\tau_1 \tau$	17	18.4	17.4
μ	720	1365	1012	$\to \tilde\nu \nu$	34.5	49.2	54.6
$\tan\beta$	6.95	56.7	56	$\to \tilde\chi_1^0 h$	13	-	-
$m_{\tilde l_L}$	149	548	509	$\to \tilde\chi_1^0 Z)$	3.43	-	-
$m_{\tilde l_R}$	1172	1278	2349				
$m_{\tilde\chi_1^0}$	126	533	499				
$m_{\tilde\chi_2^0}$	706	816	535				
$m_{\tilde\chi_3^0}$	731	1369	1019				
$m_{\tilde\chi_4^0} \sim m_{\tilde\chi_2^\pm}$	889	1374	1025	$\mathrm{BR}(\tilde\chi_1^\pm \to \tilde\nu_{l_1} l$	32	33.2	39.4
$m_{\tilde\chi_1^\pm}$	706	816	535	$\to \tilde\nu_{\tau_1} \tau$	17	17	20.4
$m_{\tilde e_1, \tilde\mu_1}$	155	549	511	$\to \tilde l_1 \nu_l$	23.2	31.8	25.2
$m_{\tilde e_2, \tilde\mu_2}$	1173	1279	2349	$\to \tilde\tau_1 \nu_\tau$	11.7	17.7	15
$m_{\tilde\tau_1}$	155	534	509	$\to W \tilde\chi_1^0)$	16	-	-
$m_{\tilde\tau_2}$	1173	1286	2350				
$m_{\tilde\nu}$	135	544	505				
$\Omega_{\tilde\chi} h^2$	0.119	0.121	0.12	$\mathrm{BR}(\tilde e_1 \to \tilde\chi_1^0 e)$	100	100	100
$a_\mu^{\mathrm{SUSY}} \times 10^{10}$	19.7	14.06	21.1	$\mathrm{BR}(\tilde e_2 \to \tilde\chi_1^0 e$	100	100	99.2
$\sigma_p^{\mathrm{SI}} \times 10^{10}$	0.8	0.46	2.13	$\to \tilde\chi_2^0 e)$	-	-	0.5

Case-L

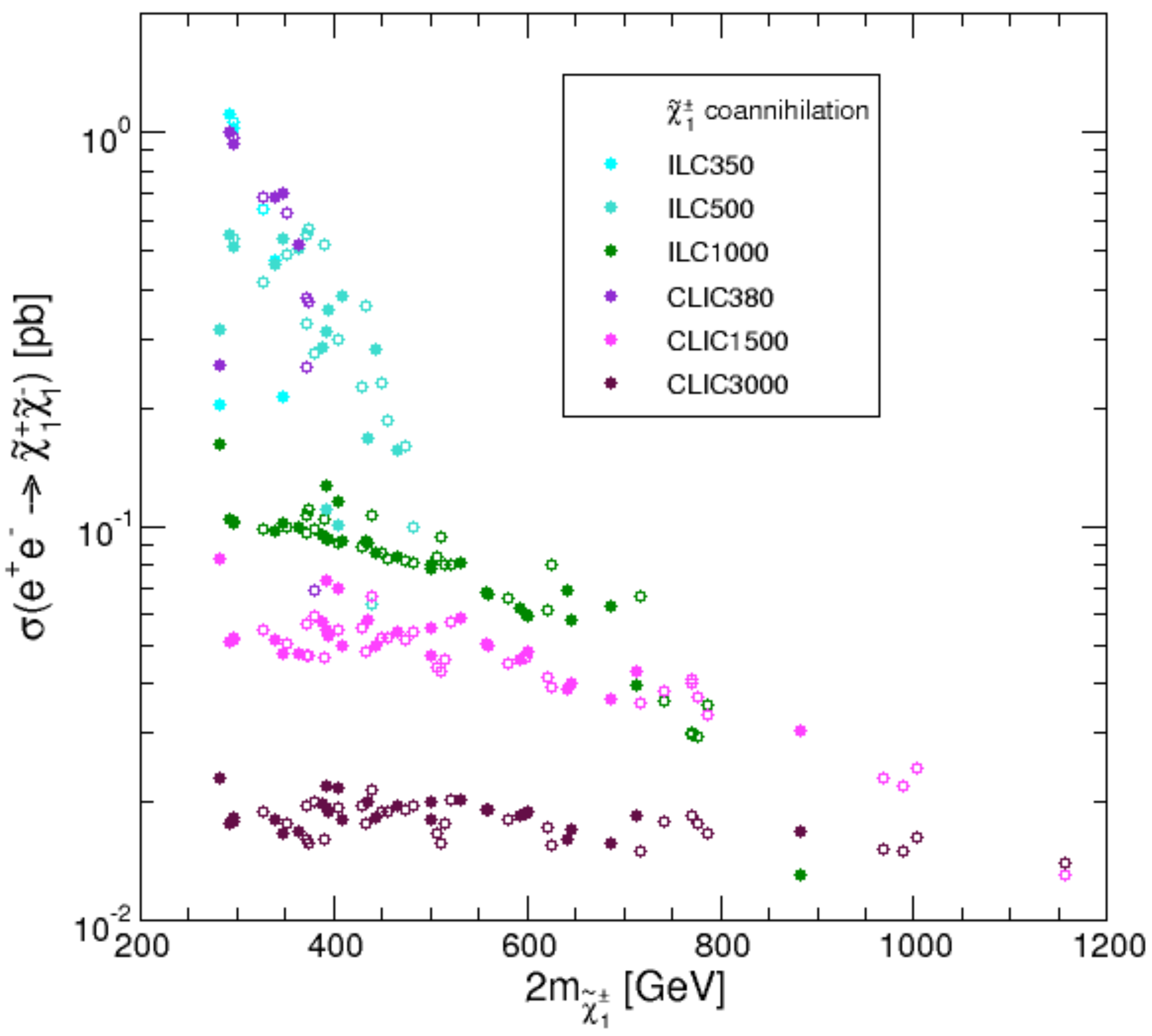
Sample points	R1	R2	R3	Sample points	R1	R2	R3
M_1	111	525	408	$\mathrm{BR}(\tilde\chi_2^0 \to \tilde l_2 l$	0.72	-	2.4
M_2	352	662	429	$\to \tilde\tau_2 \tau$	93.7	96.8	97.6
μ	812	1091	822	$\to \tilde\chi_1^0 h$	4.5	2.92	-
$\tan\beta$	20.5	58.5	59	$\to \tilde\chi_1^0 Z)$	0.99	-	-
$m_{\tilde l_L}$	458	695	794				
$m_{\tilde l_R}$	128	591	425				
$m_{\tilde\chi_1^0}$	109	518	402				
$m_{\tilde\chi_2^0}$	367	685	448	$\mathrm{BR}(\tilde\chi_1^\pm \to \tilde l_1 \nu_l$	-	-	-
$m_{\tilde\chi_3^0}$	823	1098	830	$\to \tilde\tau_2 \nu_\tau$	94.3	97	100
$m_{\tilde\chi_4^0} \sim m_{\tilde\chi_2^\pm}$	828	1105	838	$\to W \tilde\chi_1^0)$	5.7	2.8	-
$m_{\tilde\chi_1^\pm}$	367	685	448				
$m_{\tilde e_1, \tilde\mu_1}$	460	696	795				
$m_{\tilde e_2, \tilde\mu_2}$	136	592	428	$\mathrm{BR}(\tilde e_1 \to \tilde\chi_1^0 e)$	42	95	9.2
$m_{\tilde\tau_2}$	119	526	406	$\to \tilde\chi_2^0 e$	19.6	1.7	32
$m_{\tilde\tau_1}$	464	747	807	$\to \tilde\chi_1^\pm \nu_e)$	38.3	3.2	58.7
$m_{\tilde\nu}$	453	692	792				
$\Omega_{\tilde\chi} h^2$	0.121	0.121	0.121				
$a_\mu^{\mathrm{SUSY}} \times 10^{10}$	17.5	14.8	17.8	$\mathrm{BR}(\tilde e_2 \to \tilde\chi_1^0 e)$	100	100	100
$\sigma_p^{\mathrm{SI}} \times 10^{10}$	0.23	1.2	3.1				

Case-R

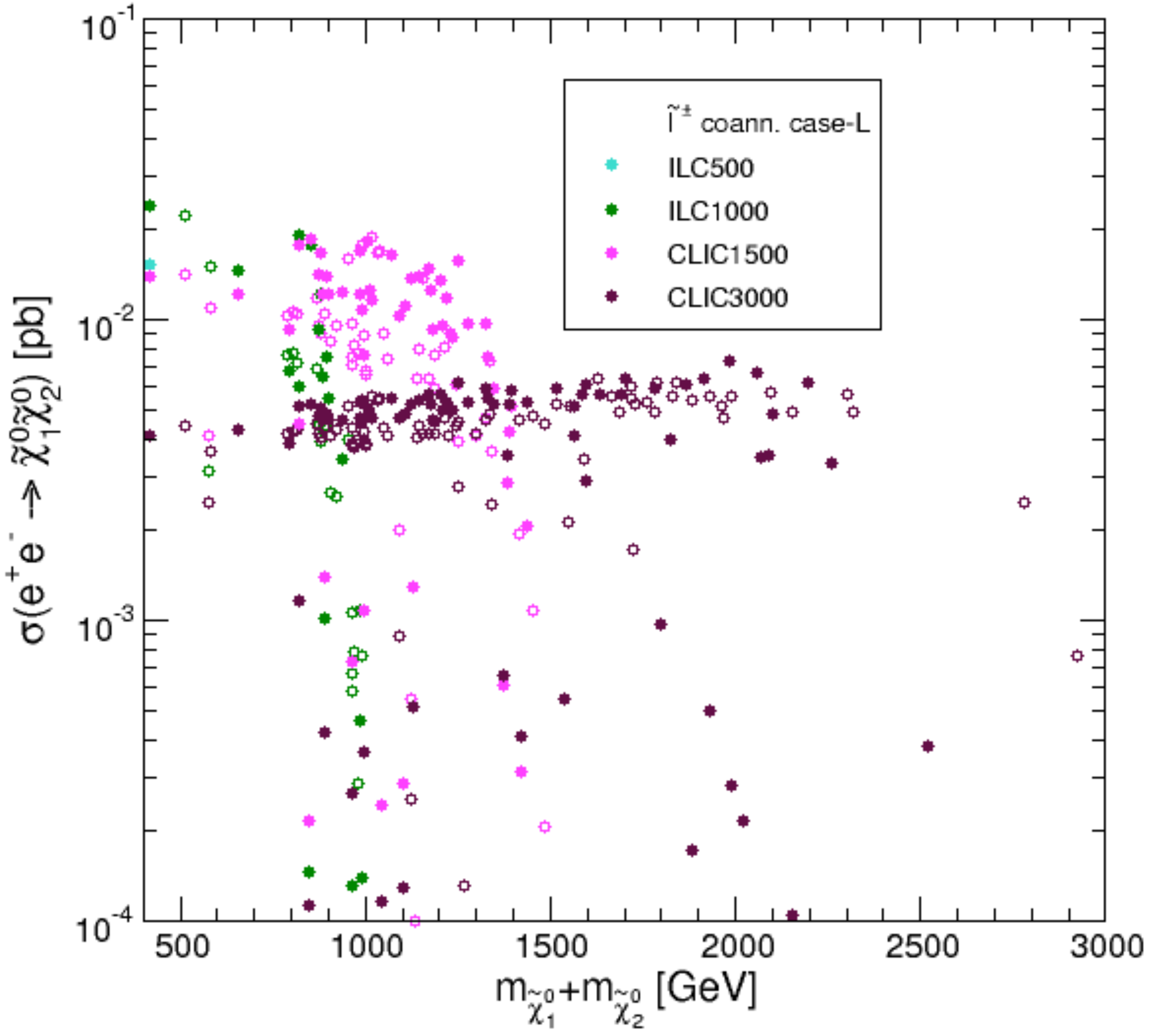
Lowest & Highest LSP mass in current (g-2) : L1, L2 (R1,R2)

Highest LSP mass in Future (g-2) : L3 (R3)

Target for future collider : ILC/CLIC

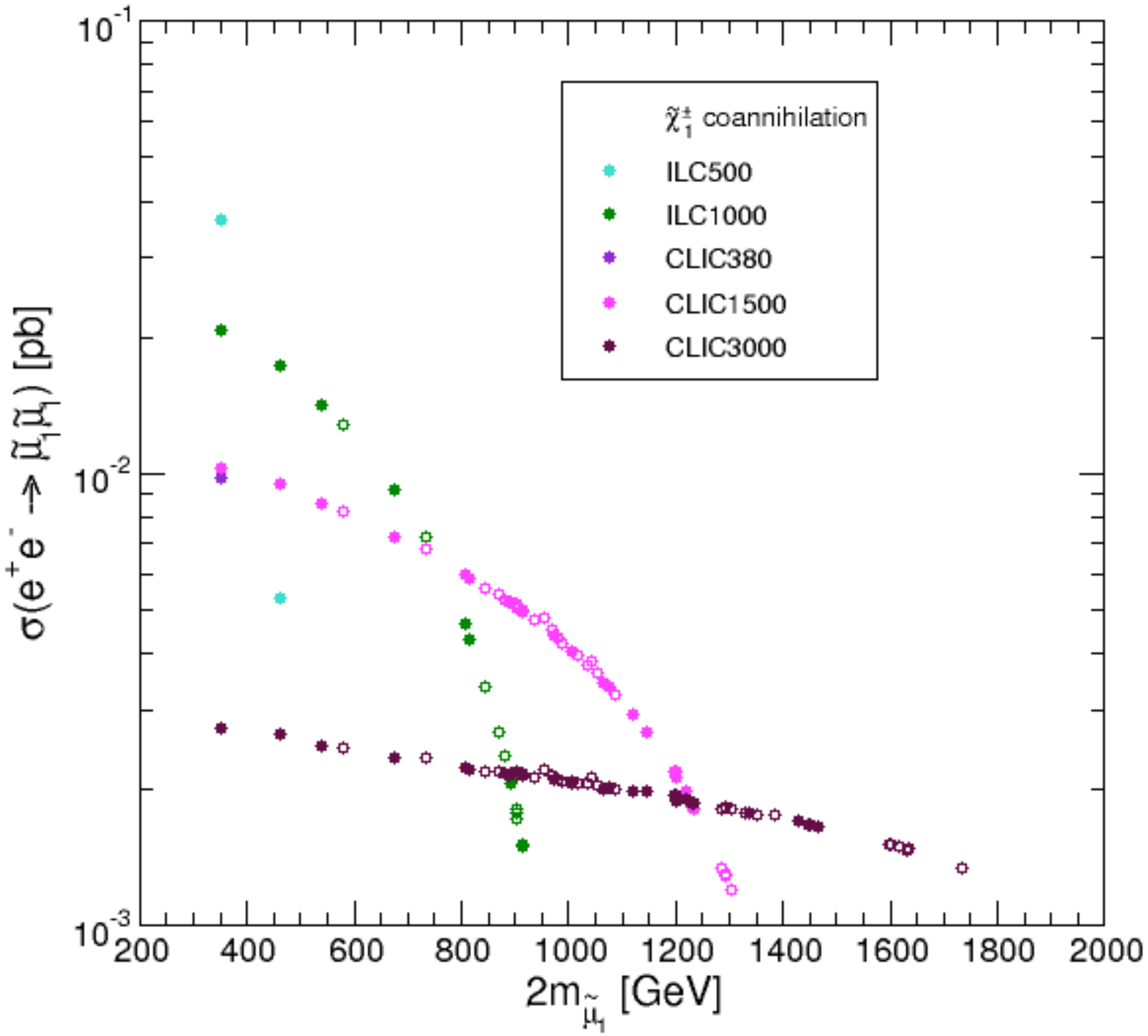


Chargino coannihilation

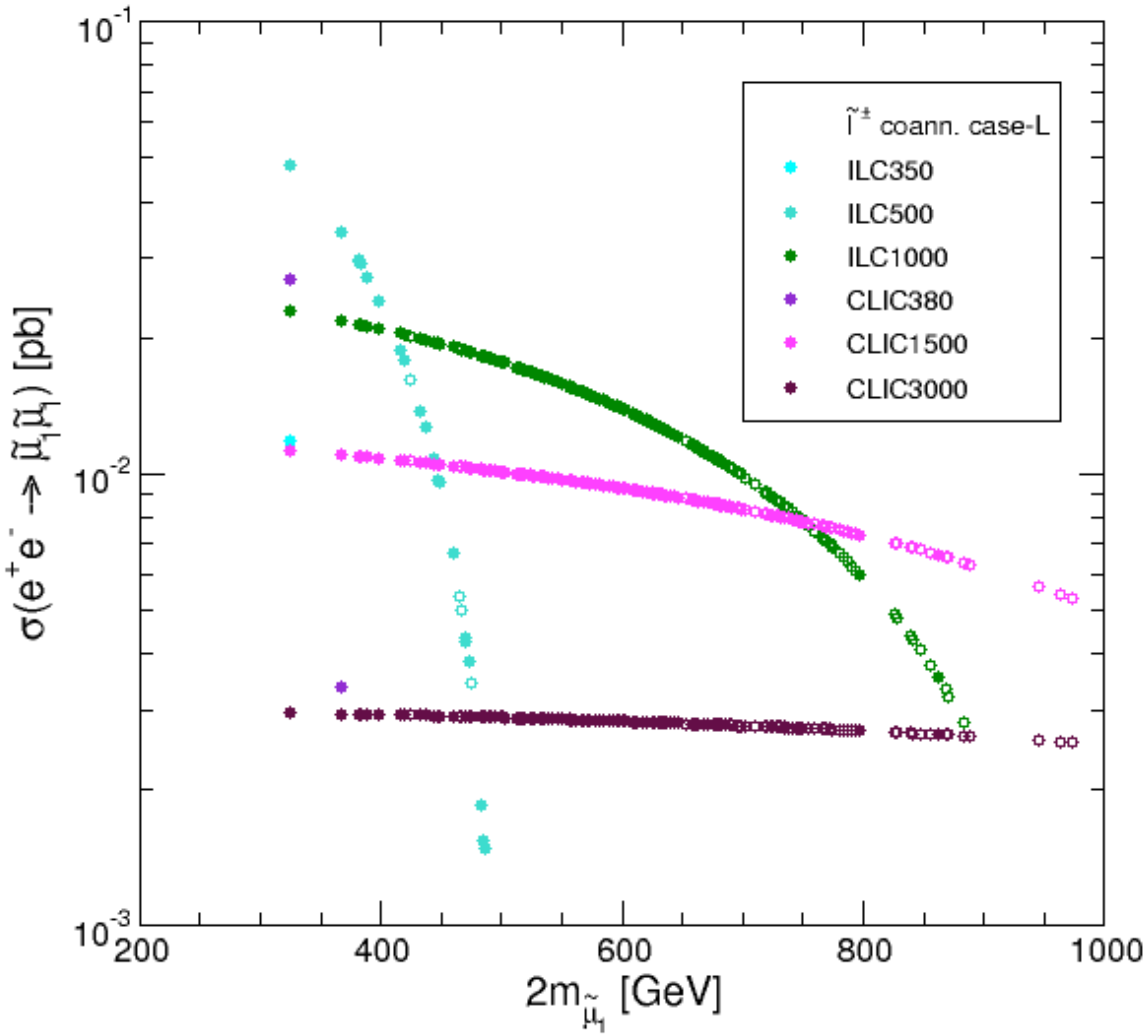


Slepton coannihilation : Case L

Target for future collider : ILC / CLIC



Chargino coannihilation



Slepton coannihilation : Case L

Conclusions

- Direct LHC bounds still have ample room for sub-TeV EW SUSY particles.
- 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) constraint put effective upper limit on EW SUSY masses while LHC limits restrict the mass ranges from below.
- LHC exclusion bound strongly depends on EW gaugino composition. Proper recasting of ATLAS/CMS analysis relaxes the existing bound.
- Searches for τ rich final states will be beneficial for further study.
- Future colliders, HL-LHC, ILC/CLIC also have significant prospect for detection.
- We await the new experiments results on muon (g-2) from Fermilab, J-PARC.
  STAY TUNED!!!

THANK YOU!

BACKUP

$(g-2)_\mu$

- 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

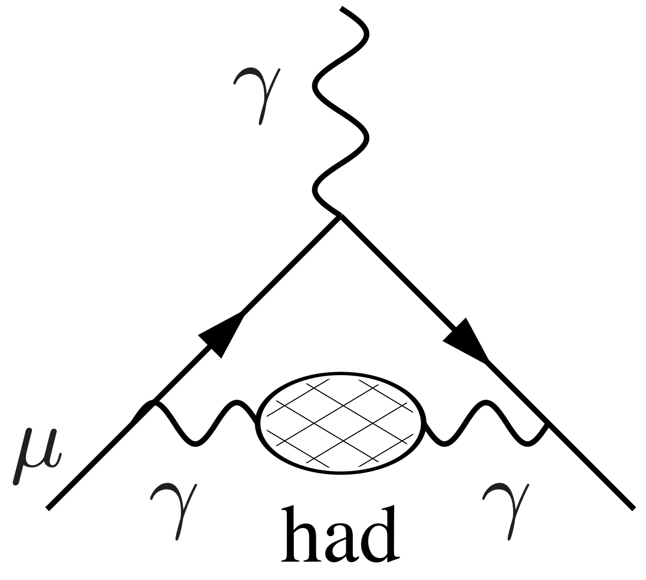
- Important probe for new physics. $\frac{\delta a_l}{a_l} \sim \frac{m_l^2}{\Lambda^2}$.

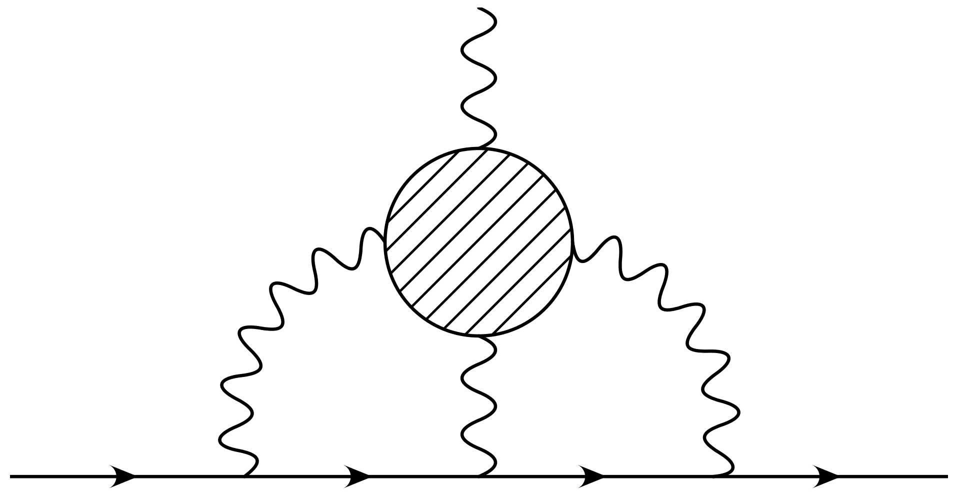
- SM contributions : QED, weak, hadronic vacuum polarization, hadronic light by light scattering.

- QED : complete calculation upto 5 loops. EW : two loops.

  Aoyama, Hayakawa, Kinoshita, Nio '17, Ishikawa, Nakazawa, Yasu '18, Heinemeyer, Stökinger, Weiglein '04

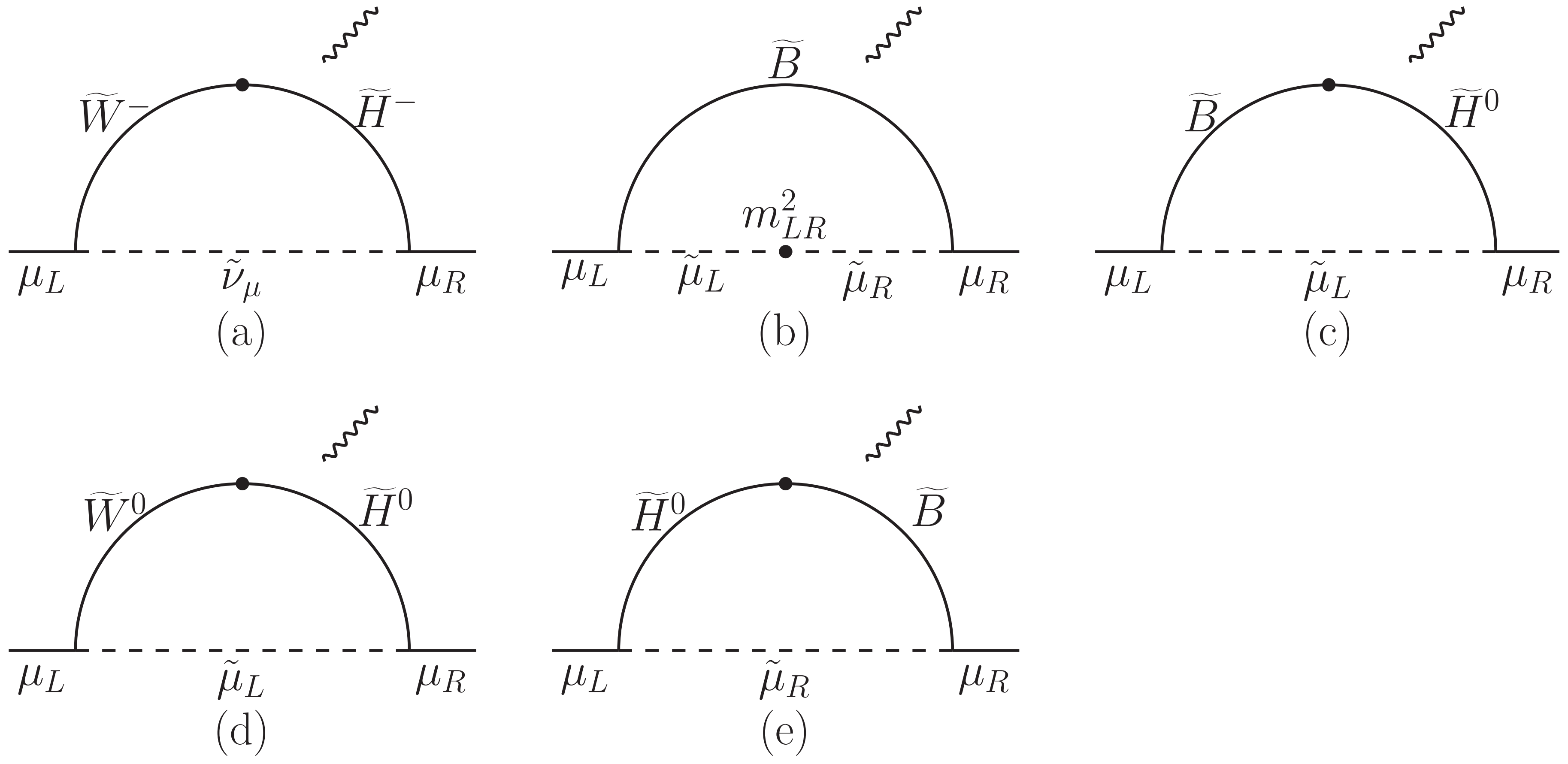
- Uncertainty dominated by non-perturbative, hadronic sector.





SUSY contributions to $(g-2)_\mu$

$$
\begin{aligned}
\Delta a_\mu(\tilde{W}, \tilde{H}, \tilde{\nu}_\mu) &\simeq 15 \times 10^{-9} \left(\frac{\tan\beta}{10}\right) \left(\frac{(100\,\mathrm{GeV})^2}{M_2 \mu}\right) \left(\frac{f_C}{1/2}\right), \\
\Delta a_\mu(\tilde{W}, \tilde{H}, \tilde{\mu}_L) &\simeq -2.5 \times 10^{-9} \left(\frac{\tan\beta}{10}\right) \left(\frac{(100\,\mathrm{GeV})^2}{M_2 \mu}\right) \left(\frac{f_N}{1/6}\right), \\
\Delta a_\mu(\tilde{B}, \tilde{H}, \tilde{\mu}_L) &\simeq 0.76 \times 10^{-9} \left(\frac{\tan\beta}{10}\right) \left(\frac{(100\,\mathrm{GeV})^2}{M_1 \mu}\right) \left(\frac{f_N}{1/6}\right), \\
\Delta a_\mu(\tilde{B}, \tilde{H}, \tilde{\mu}_R) &\simeq -1.5 \times 10^{-9} \left(\frac{\tan\beta}{10}\right) \left(\frac{(100\,\mathrm{GeV})^2}{M_1 \mu}\right) \left(\frac{f_N}{1/6}\right), \\
\Delta a_\mu(\tilde{\mu}_L, \tilde{\mu}_R, \tilde{B}) &\simeq 1.5 \times 10^{-9} \left(\frac{\tan\beta}{10}\right) \left(\frac{(100\,\mathrm{GeV})^2}{m_{\tilde{\mu}_L}^2 m_{\tilde{\mu}_R}^2 / M_1 \mu}\right) \left(\frac{f_N}{1/6}\right).
\end{aligned}
$$



Endo, Hamaguchi, Iwamoto, Yoshinaga'13