Manimala chakraborti
IFT, Madrid

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

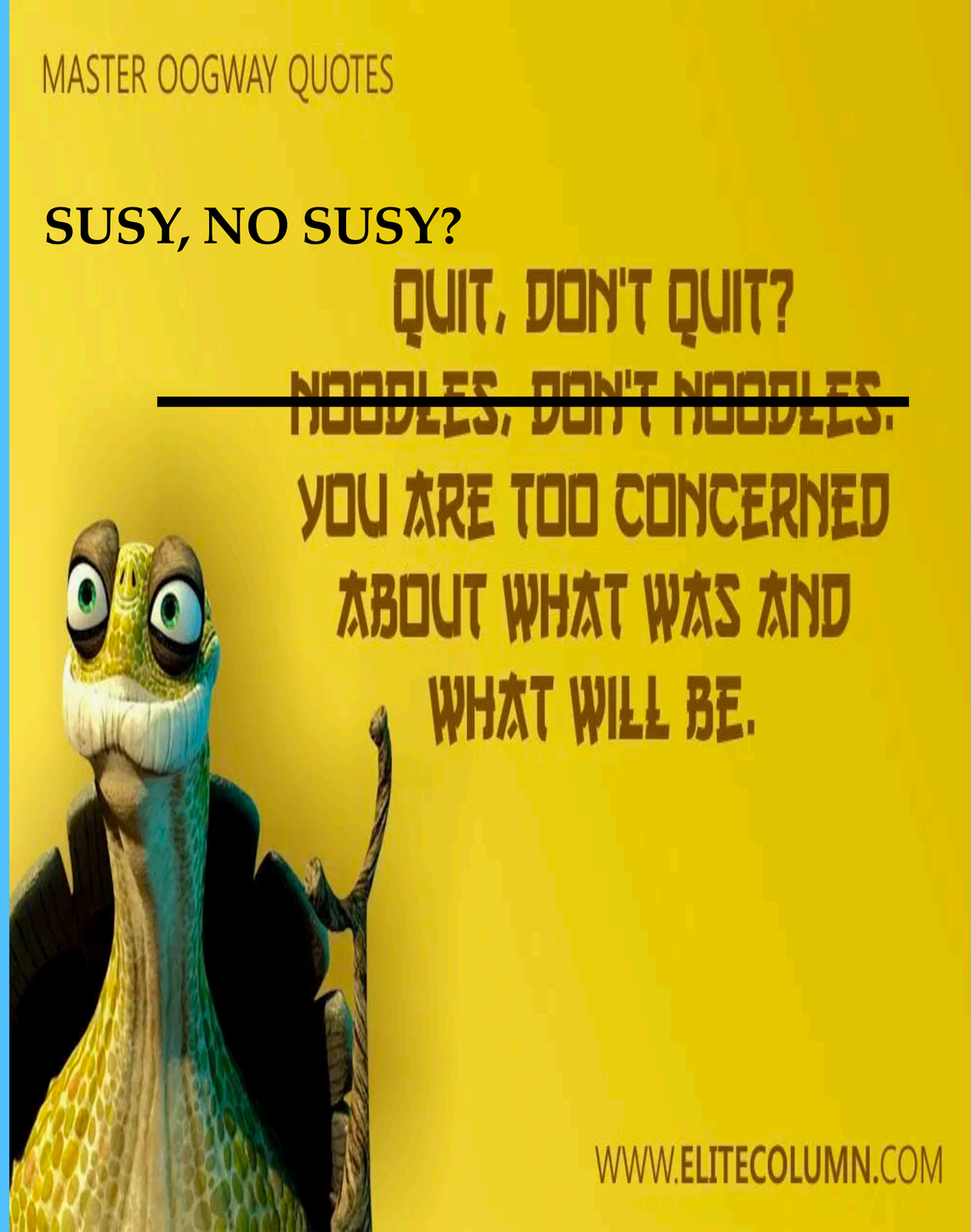
SNOWMASS 2020 – 07/07/2020

BASED ON : 2006.15157 WITH SVEN HEINEMEYER AND IPSITA SAHA

- EW sector may be hiding key to new physics

- Modest production cross section, mass bounds from the LHC rather week

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



MSSM Superpotential

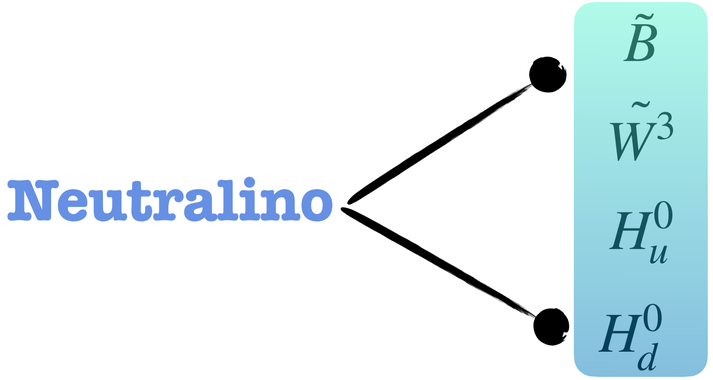
$$W_{\mathrm{MSSM}} = \bar{u} Y_u Q H_u - \bar{d} Y_d Q H_d - \bar{e} Y_e L H_d + \mu H_u H_d$$

Soft Breaking Terms

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

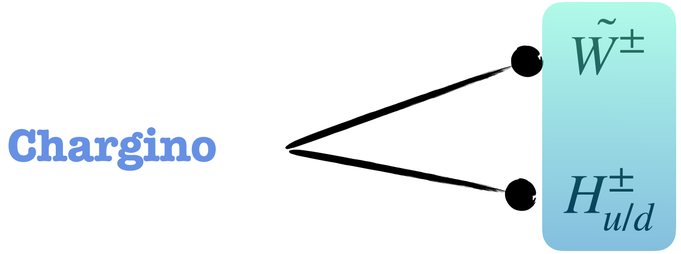
EW Gauginos

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

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

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

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

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

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

Constraints

Proper recasting is important

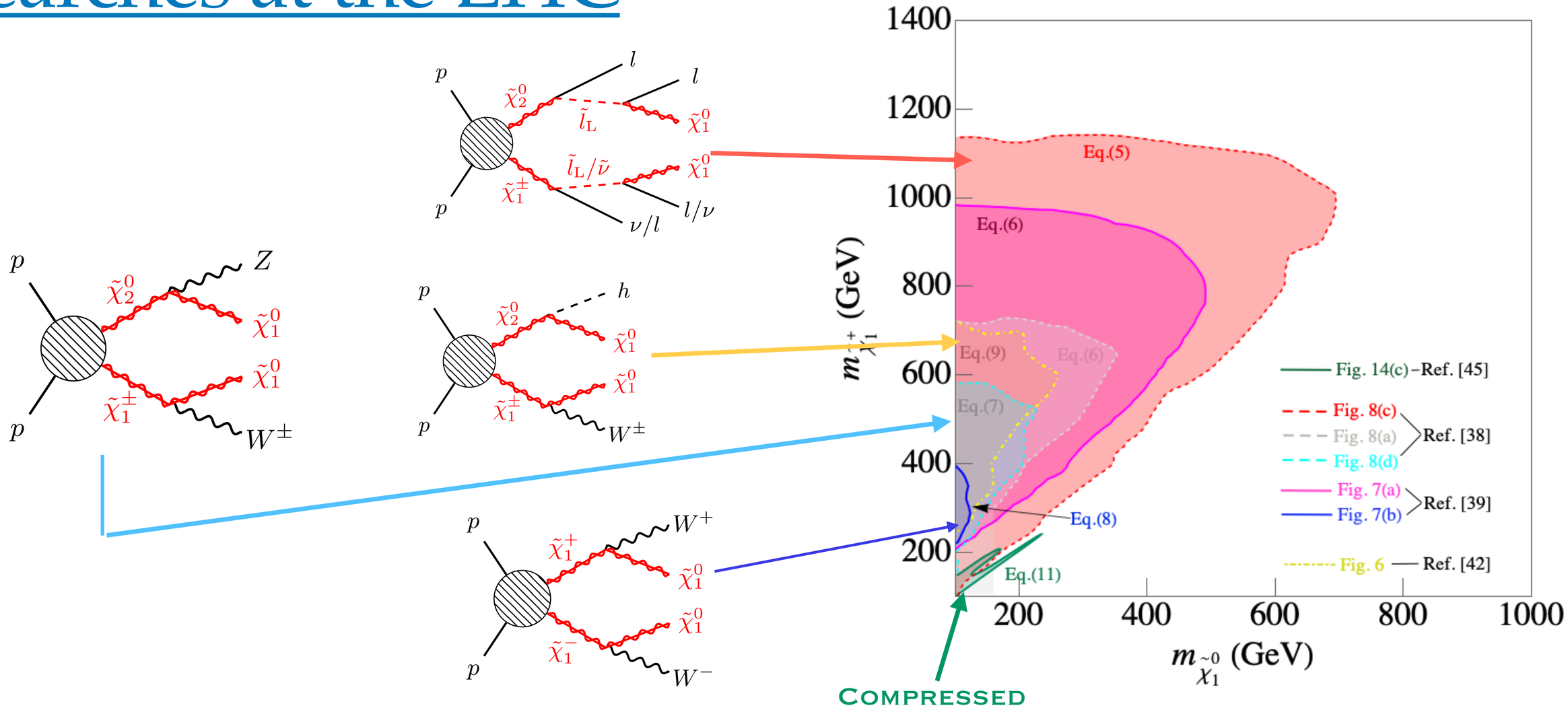
Direct Searches at LHC

- LHC searches restricted to **simplified models** → sparticles except those relevant to the signal are taken to be decoupled.
- $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ 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 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 $\tan\beta$.

Indirect Constraints

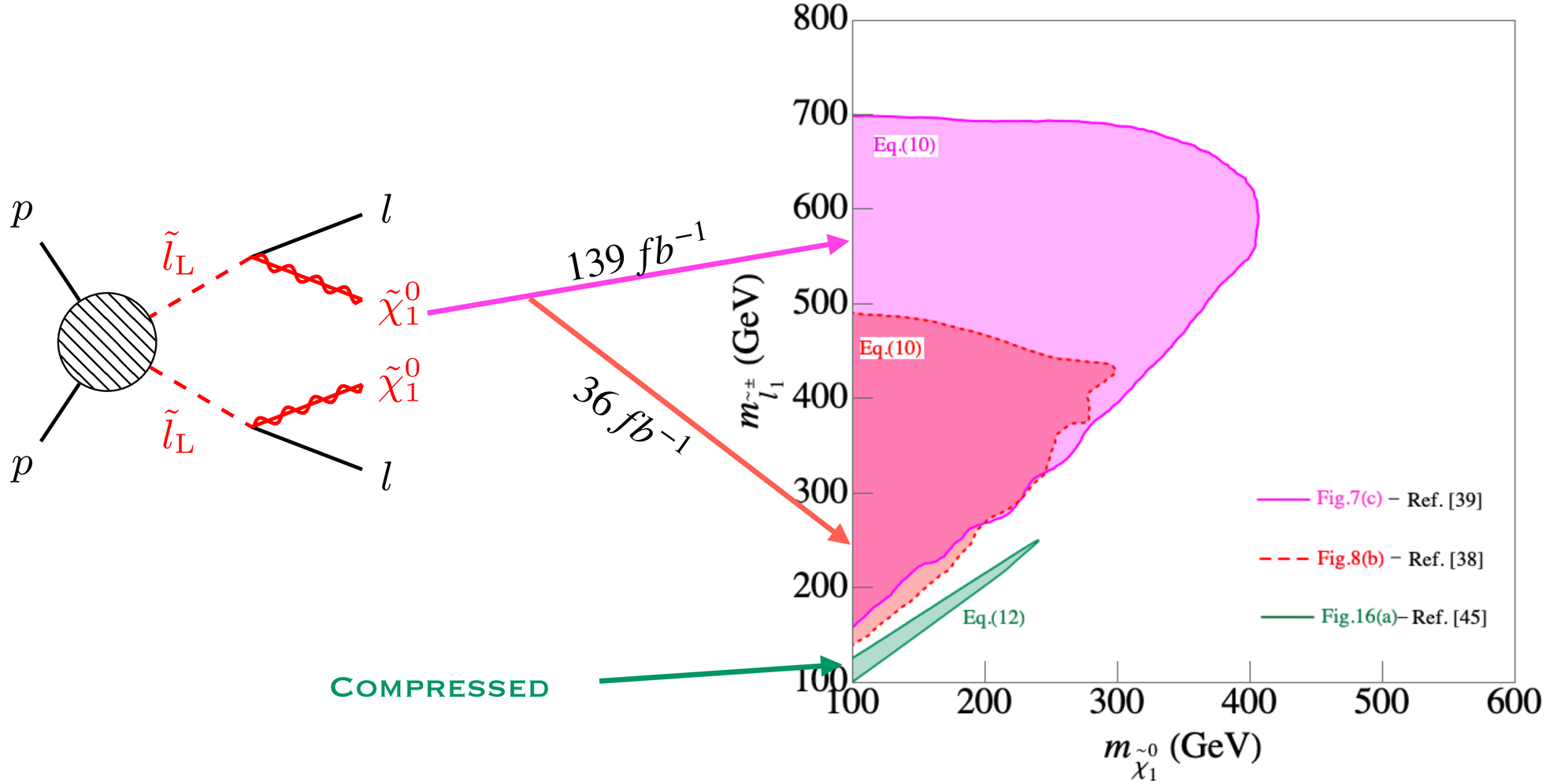
- Muon (g-2).
- WMAP/PLANCK relic density.
- Spin independent direct detection data from XENON/LUX.
- Indirect detection constraints of dark matter.

Searches at the LHC



Proper recasting is important → checkMATE

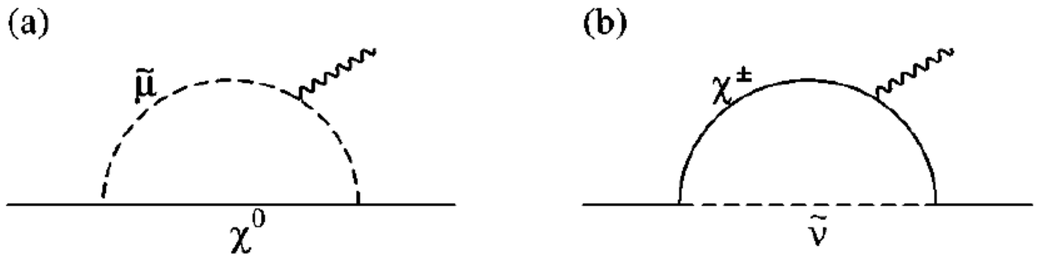
Searches at the LHC



Proper recasting is important → checkMATE

Muon (g-2)

- Currently large discrepancy from the SM $> (3\sigma)$.
  $a_\mu^{exp} - a_\mu^{SM} = (28.02 \pm 7.37) \times 10^{-10}$ Keshavarzi, Nomura, Teubner '19
- Assuming upcoming Fermilab Run-I result to have the same central value and same exp. uncertainty, combined data corresponds to $\sim 5.4\,\sigma$ 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

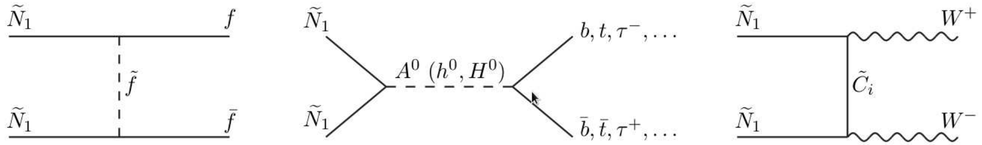


- SUSY contributions from Chargino-Sneutrino and Smuon-Neutralino loop
- Contribution ~ $\tan\beta$, can reconcile the anomaly

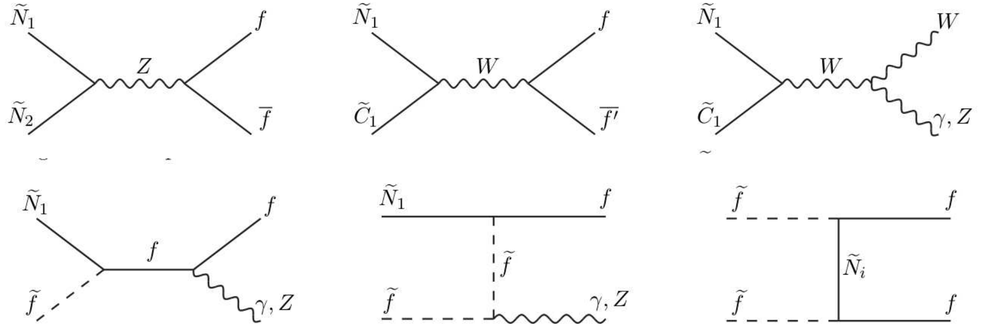
DM Constraints

Relic Density

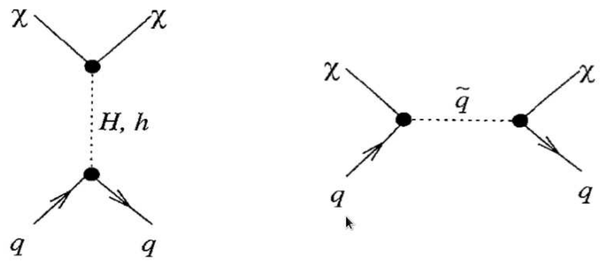
Some annihilation channels that could give right relic density :



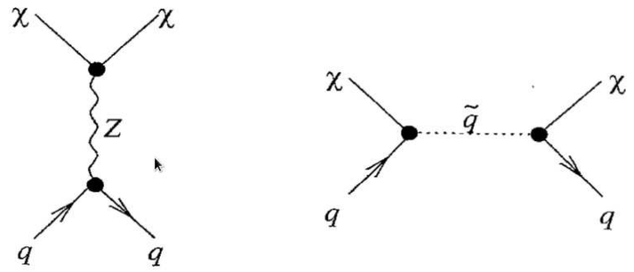
There can be coannihilations with sparticles of slightly heavier masses:



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:

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

Slepton co-annihilation region:

Case-L: SU(2) doublet

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

Case-R: SU(2) singlet

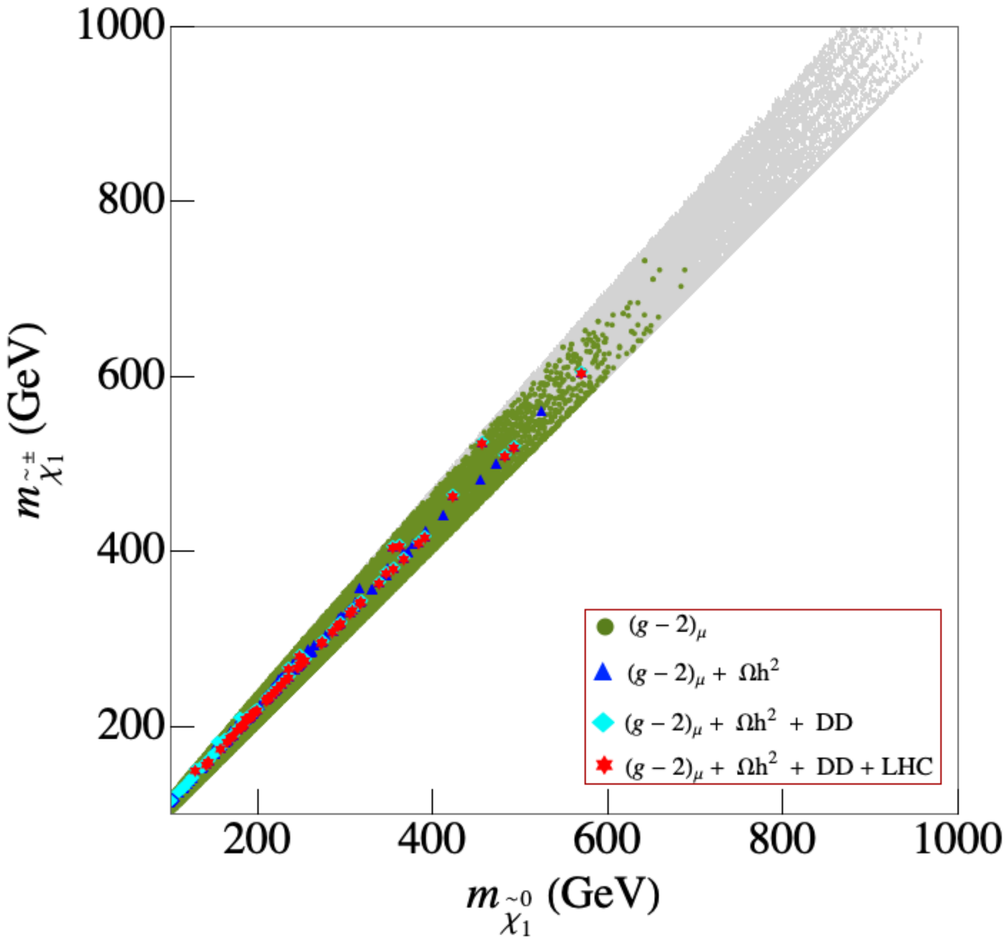
$$100 \text{ GeV} \leq M_1 \leq 1 \text{ TeV}, \quad M_1 \leq M_2 \leq 10 M_1,$$
$$1.1 M_1 \leq \mu \leq 10 M_1, \quad 5 \leq \tan\beta \leq 60,$$
$$M_1 \text{ GeV} \leq m_{\tilde{l}_R} \leq 1.2 M_1, \quad M_1 \leq m_{\tilde{l}_L} \leq 10 M_1.$$

MC, S.Heinemeyer, I.Saha 2006.15157

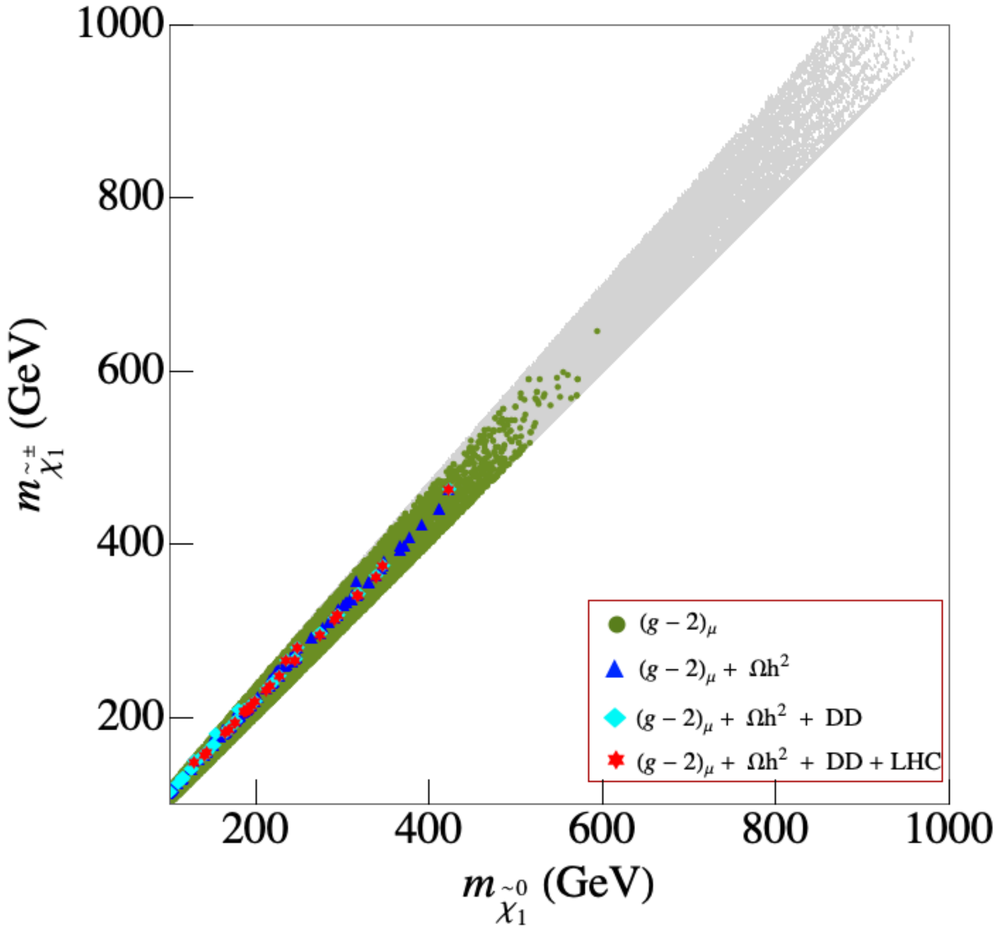
Packages used → SuSpect, SUSYHIT, GM2Calc, micrOMEGAs, CheckMATE.

Chargino Co-annihilation

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



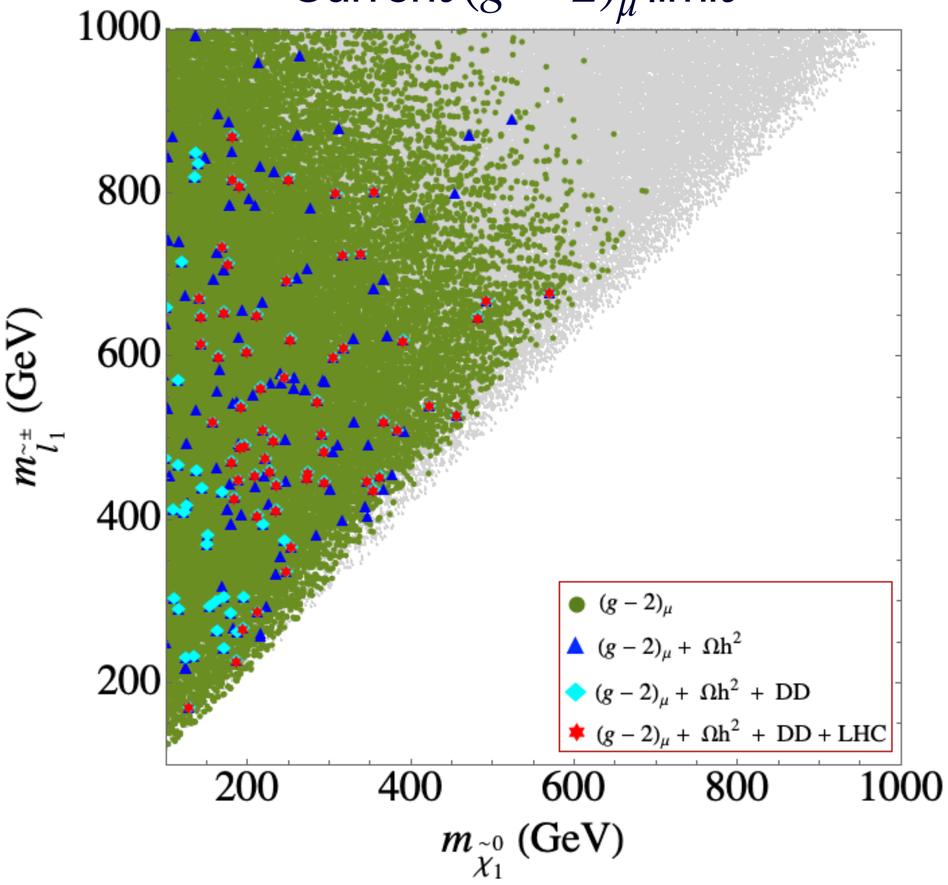
Anticipated future $(g-2)_\mu$ limit



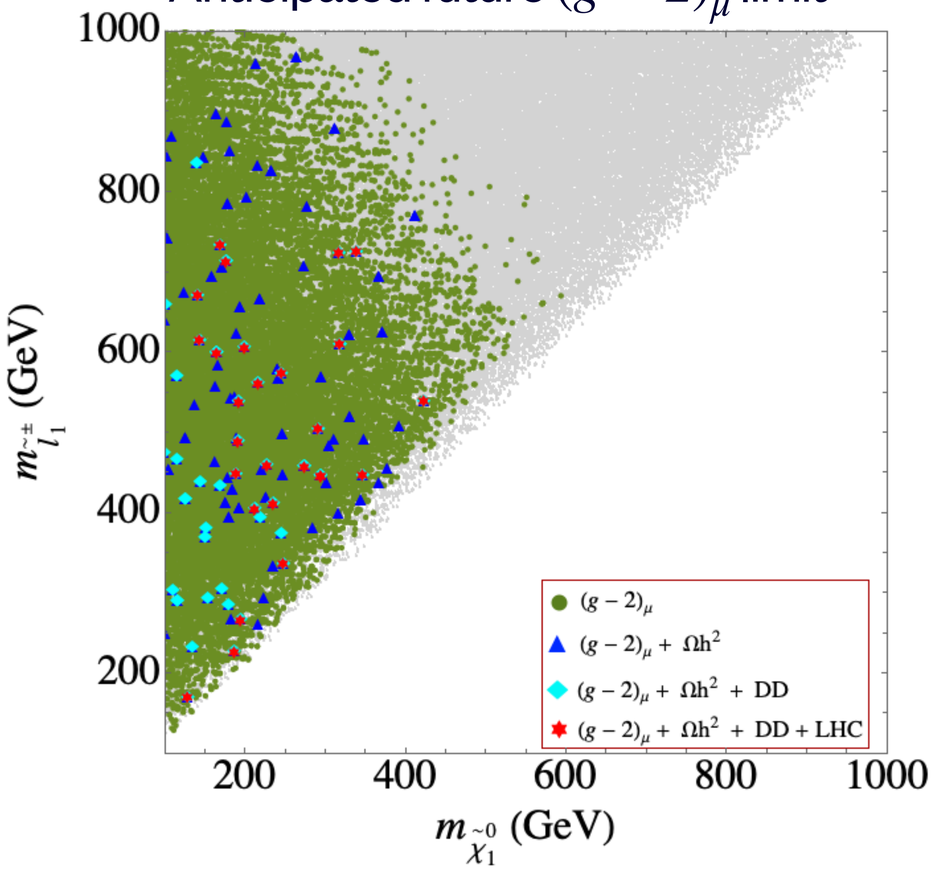
Upper and lower bounds from $(g-2)_\mu$ and LHC searches (for compressed spectrum)

Chargino Co-annihilation

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



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

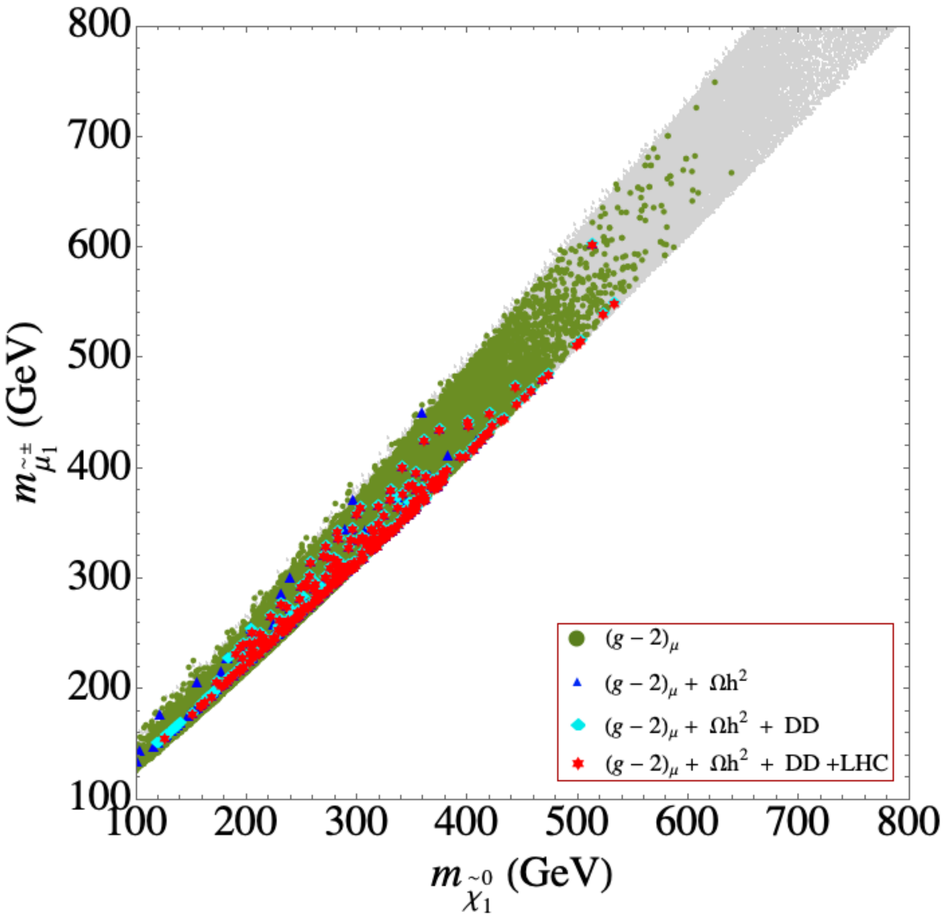


Slepton-pair production →(*2l* + missing E_T) provides important search channel ....

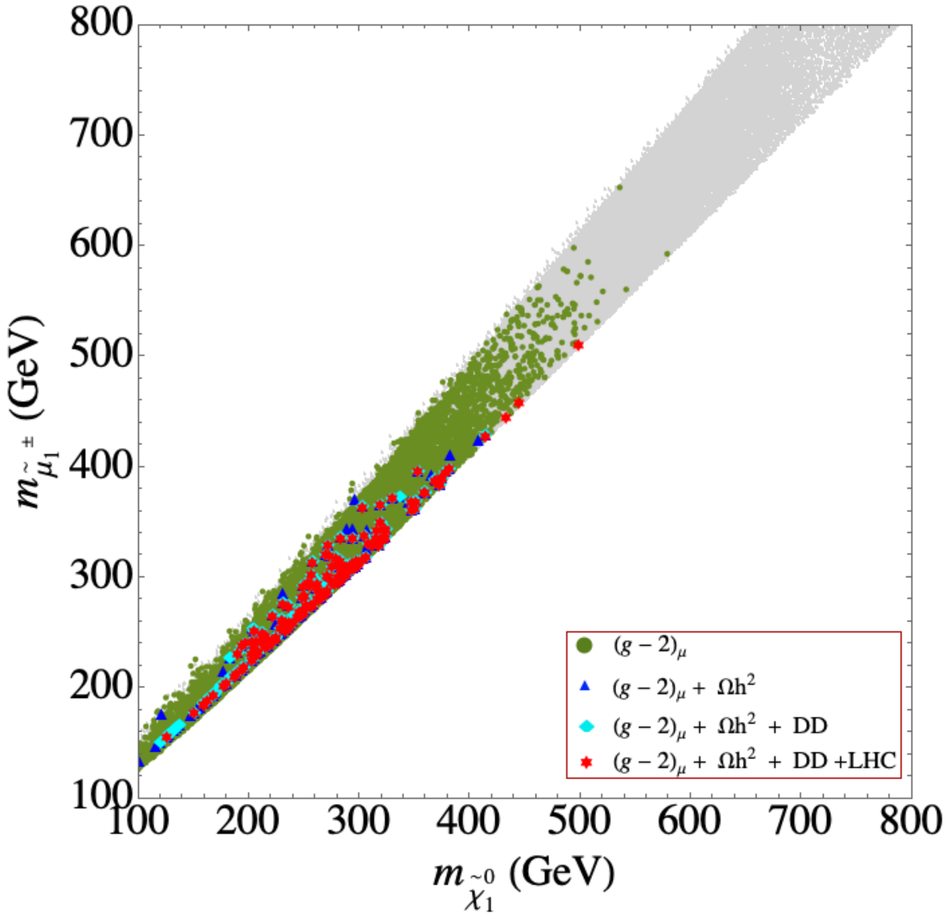
R-sleptons heavy, Considerable BR for $\tilde{e}_L(\tilde{\mu}_L) \to \tilde{\chi}_1^\pm e(\mu)$ → Less no. of signal leptons.

Slepton Co-annihilation: Case-L

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



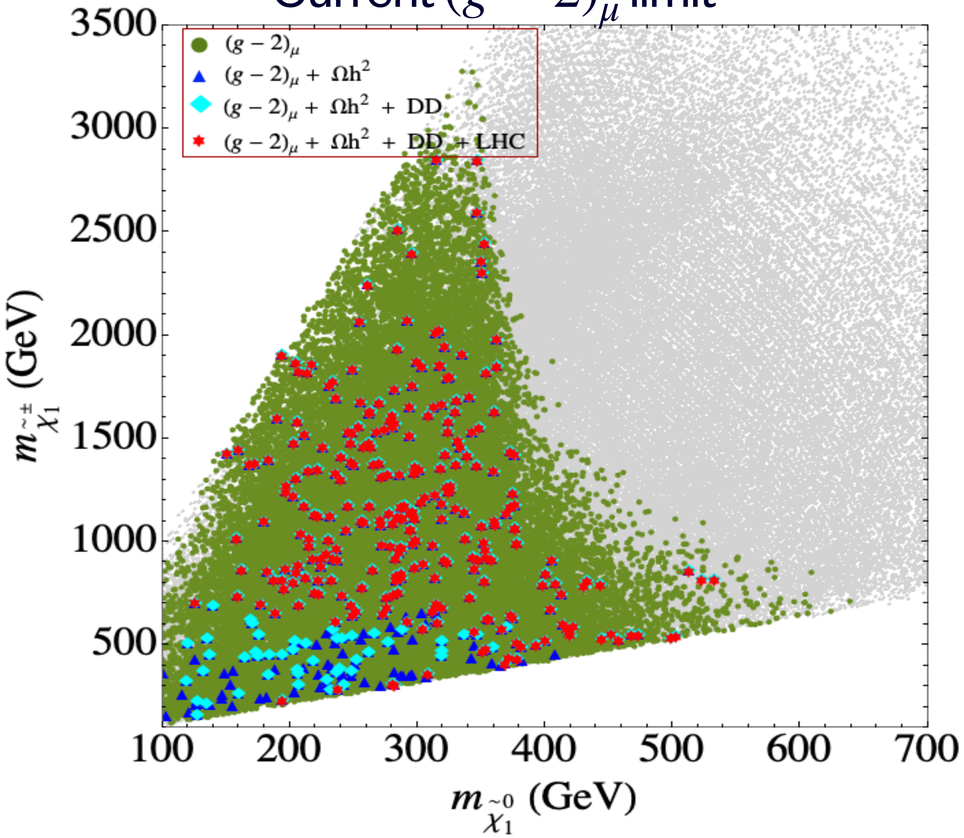
Anticipated future $(g-2)_\mu$ limit



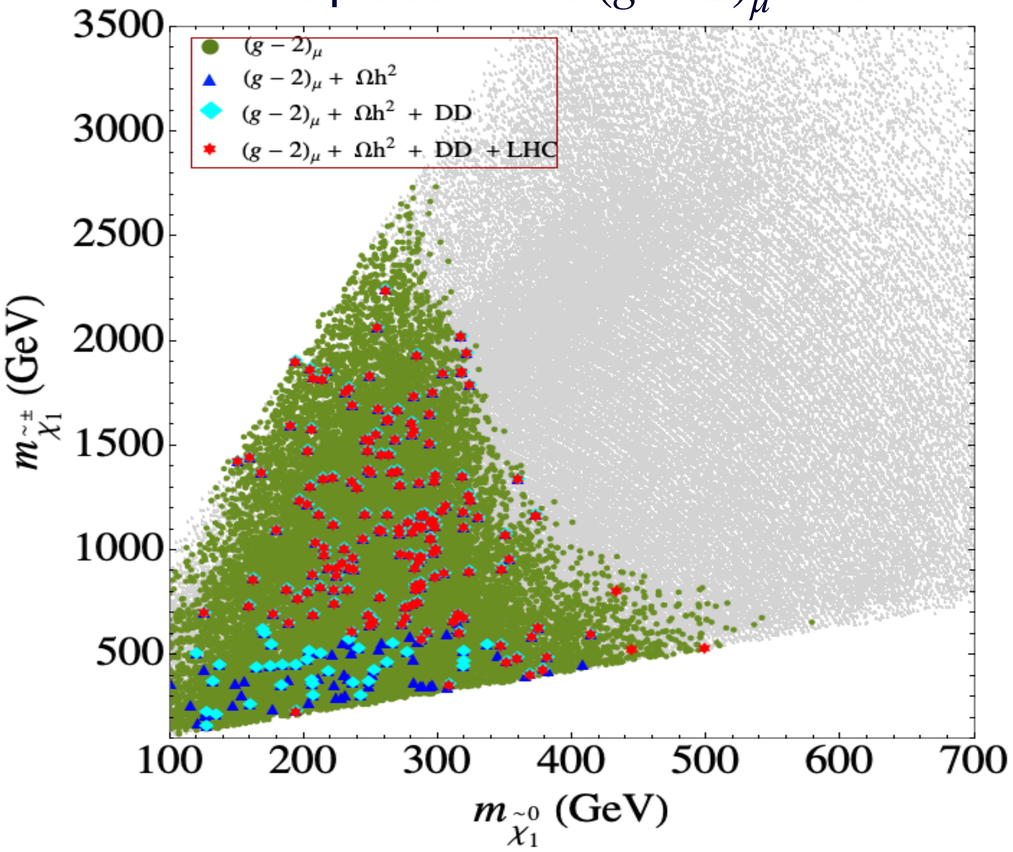
The left-sleptons and sneutrinos are close in mass to the LSP → stau not far away

Slepton Co-annihilation: Case-L

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



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

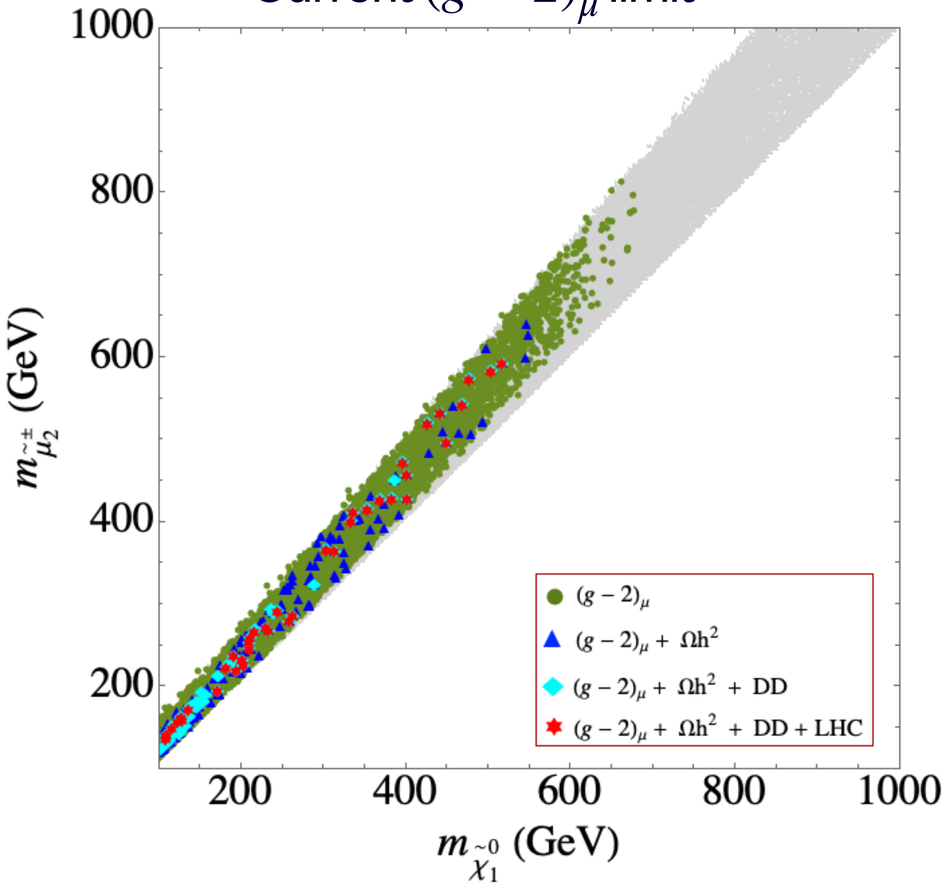


Large $\mathrm{BR}(\tilde{\chi}_1^\pm \to \tilde{\tau}_1 \nu_\tau)$ and $\mathrm{BR}(\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau)$, $\mathrm{BR}(\tilde{\chi}_2^0 \to \tilde{\nu}\nu)$

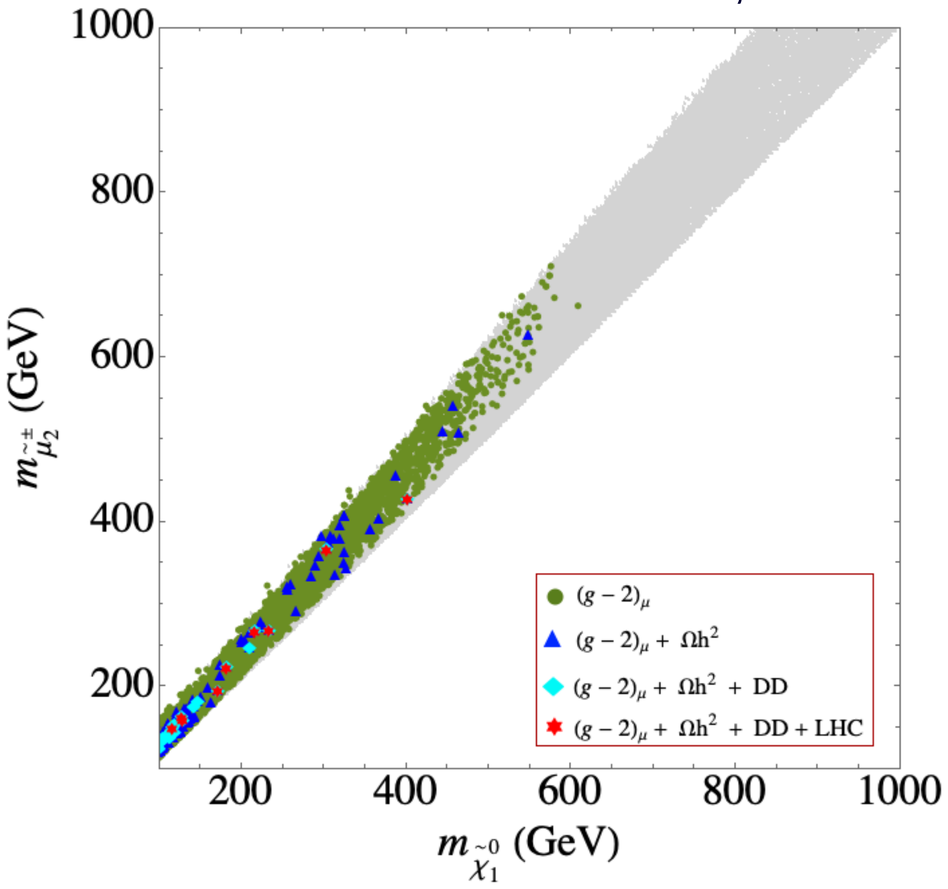
(*3l* + missing E_T) exclusion limit weakens ...

Slepton Co-annihilation: Case-R

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



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

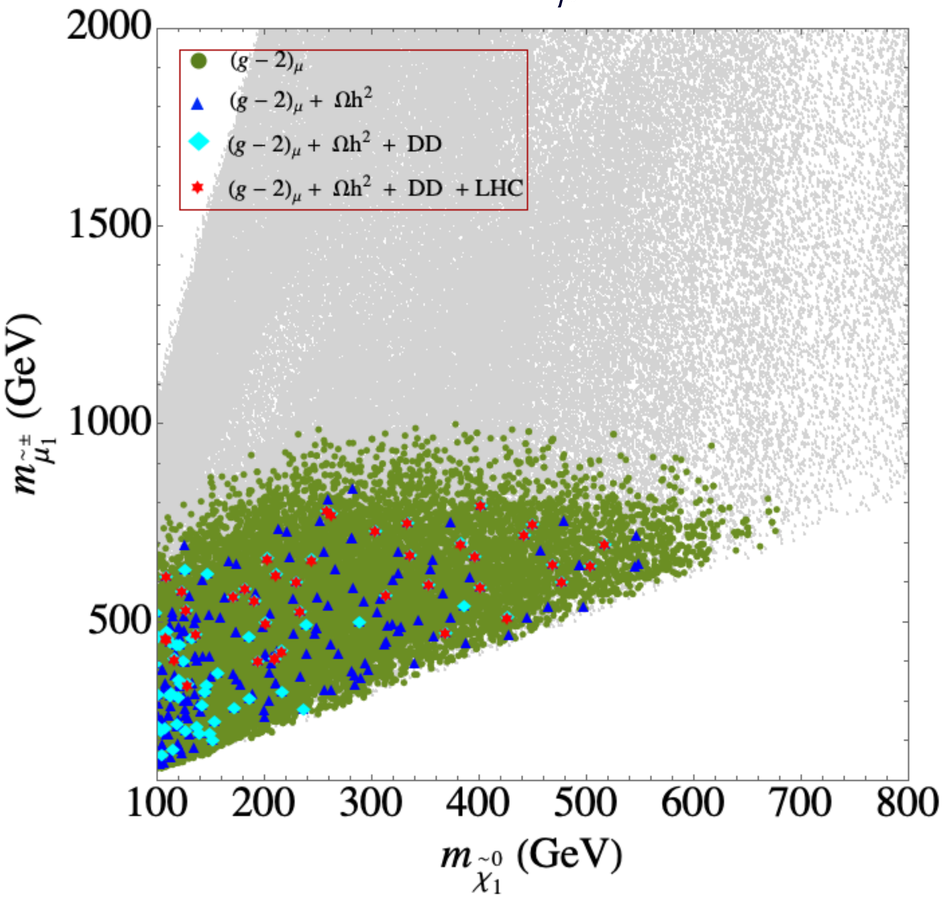


Right-sleptons are close in mass to LSP.

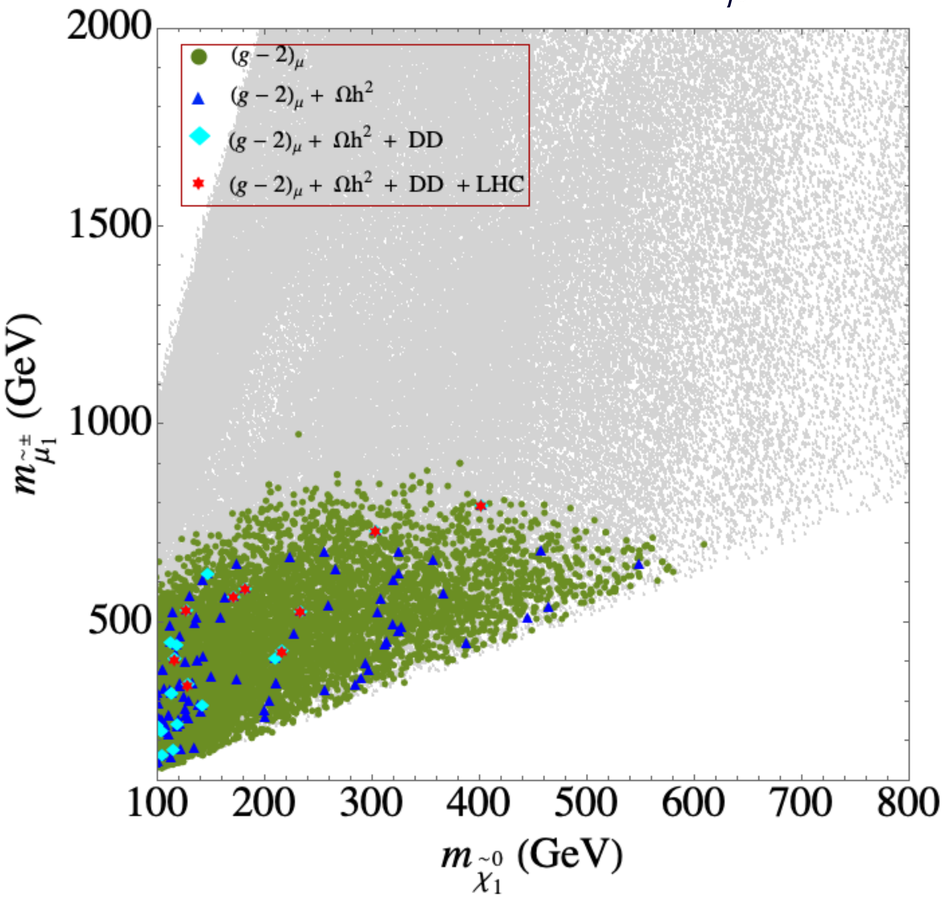
Small μ is favored, tension between DD and $(g-2)_\mu$.

Slepton Co-annihilation: Case-R

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



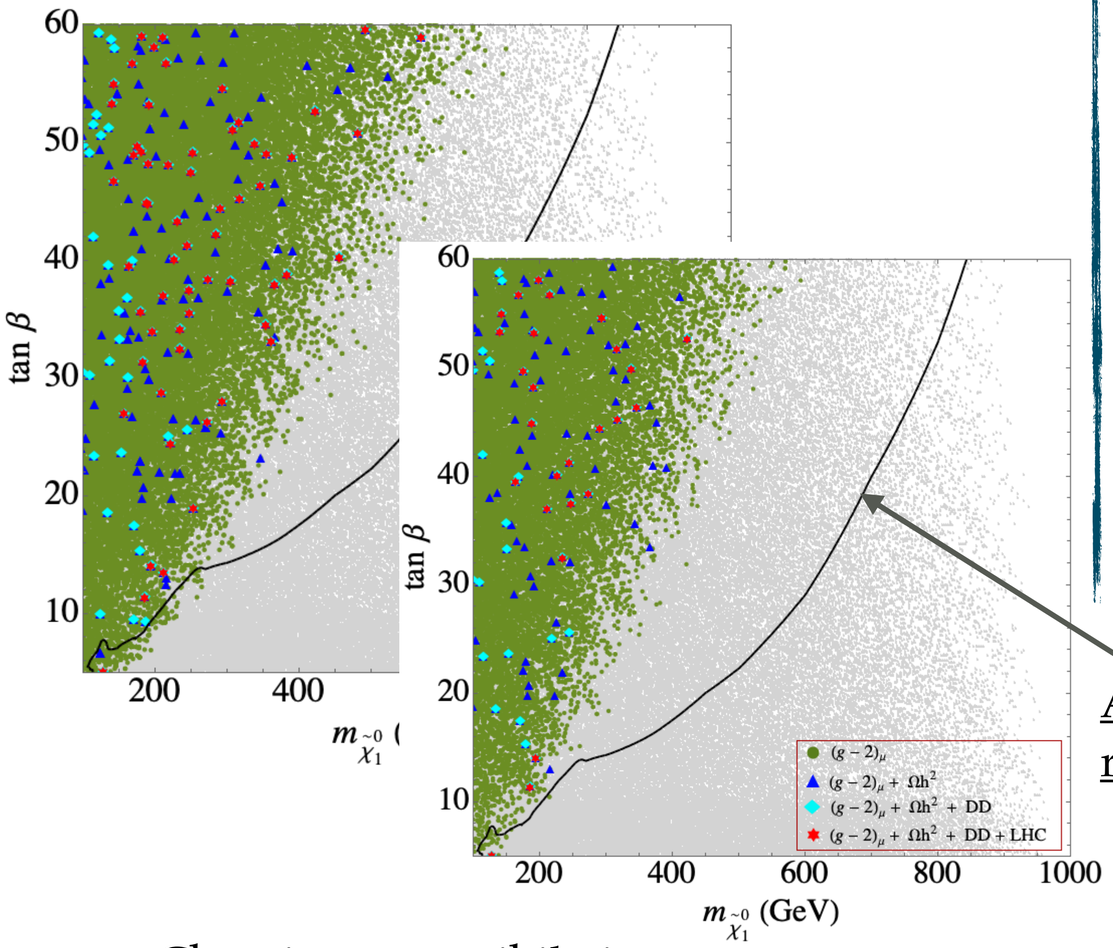
Anticipated future $(g-2)_\mu$ limit



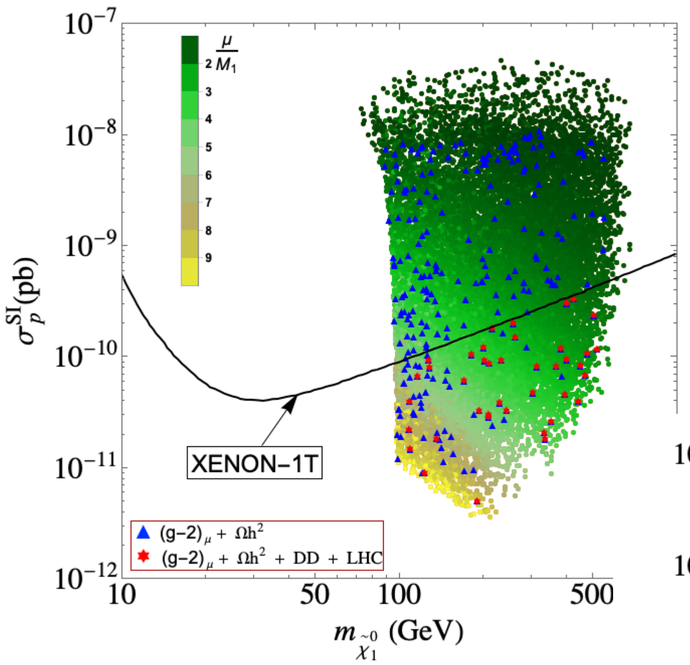
Left-sleptons can not be too heavy to have relevant contribution to $(g-2)_\mu$.

Get stringent constraint from LHC.

Further Comments

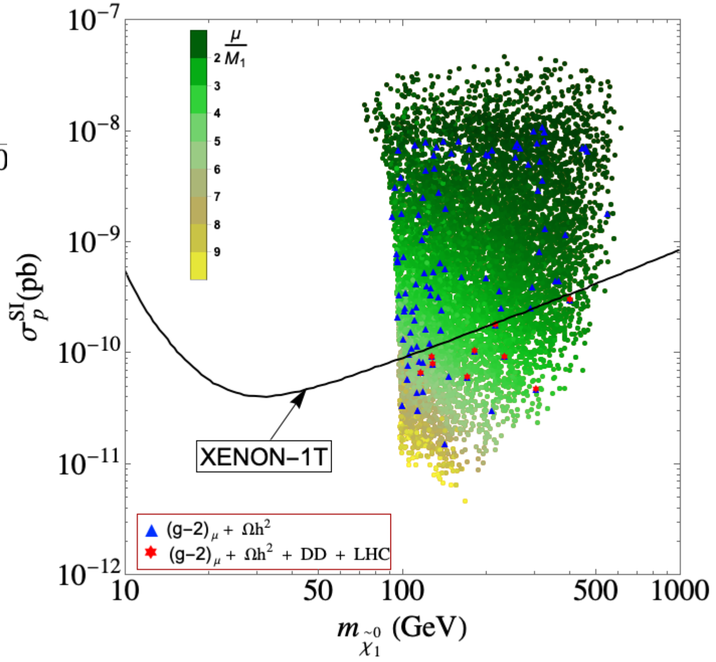


Chargino co-annihilation



A-pole annihilation restricted

Slepton Co-annihilation Case-R



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

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

Highest mass points

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

Coannihilation	$\tilde{\chi}_1^\pm$	$\tilde{l}^\pm$ (Case-L)	$\tilde{l}^\pm$ (Case-R)
$m_{\tilde{\chi}_1^0}$	570	533	518
$m_{\tilde{\chi}_2^0}$	605	816	685
$m_{\tilde{\chi}_3^0}$	1087	1370	1098
$m_{\tilde{\chi}_1^\pm}$	605	816	685
$m_{\tilde{e}_1,\tilde{\mu}_1}$	680	549	696
$m_{\tilde{e}_2,\tilde{\mu}_2}$	680	1279	592
$m_{\tilde{\tau}_1}$	582	534	747
$m_{\tilde{\tau}_2}$	765	1286	526
$m_{\tilde{\nu}}$	675	544	692

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

Coannihilation	$\tilde{\chi}_1^\pm$	$\tilde{l}^\pm$ (Case-L)	$\tilde{l}^\pm$ (Case-R)
$m_{\tilde{\chi}_1^0}$	423	499	402
$m_{\tilde{\chi}_2^0}$	464	535	448
$m_{\tilde{\chi}_3^0}$	1032	1019	830
$m_{\tilde{\chi}_1^\pm}$	464	535	448
$m_{\tilde{e}_1,\tilde{\mu}_1}$	542	511	795
$m_{\tilde{e}_2,\tilde{\mu}_2}$	541	2349	428
$m_{\tilde{\tau}_1}$	437	509	807
$m_{\tilde{\tau}_2}$	629	2350	406
$m_{\tilde{\nu}}$	536	505	792

Points satisfying $(g-2)_\mu$, DM and LHC constraints, masses in GeV.

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 constraints 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 bounds.
- Future colliders, HL-LHC, ILC/CLIC also have significant prospect for detection.
- New experimental results for $(g-2)_\mu$ from Fermilab, J-PARC .... STAY TUNED!!!

THANKYOU!

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

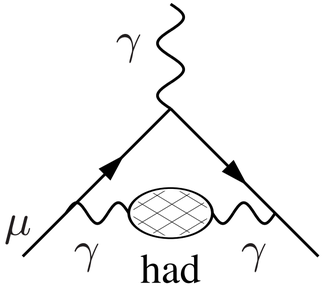
- Important probe for new physics. $\frac{\delta a_l}{a_l} \sim \frac{m_l^2}{\Lambda^2}$.

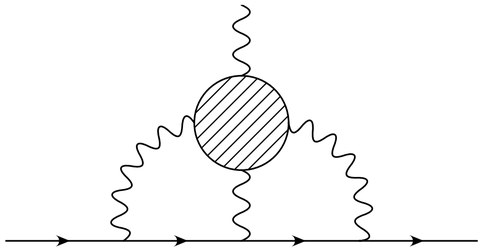
- SM contributions : QED, weak, hadronic vacuum polarization, hadronic light by light scattering.

- 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 $(g-2)_\mu$

$$\Delta a_\mu(\tilde{W},\tilde{H},\tilde{\nu}_\mu) \simeq \quad 15 \quad \times 10^{-9} \left(\frac{\tan\beta}{10}\right)\left(\frac{(100\,\mathrm{GeV})^2}{M_2\mu}\right)\left(\frac{f_C}{1/2}\right),$$

$$\Delta a_\mu(\tilde{W},\tilde{H},\tilde{\mu}_L) \simeq -2.5 \quad \times 10^{-9} \left(\frac{\tan\beta}{10}\right)\left(\frac{(100\,\mathrm{GeV})^2}{M_2\mu}\right)\left(\frac{f_N}{1/6}\right),$$

$$\Delta a_\mu(\tilde{B},\tilde{H},\tilde{\mu}_L) \simeq \quad 0.76 \times 10^{-9} \left(\frac{\tan\beta}{10}\right)\left(\frac{(100\,\mathrm{GeV})^2}{M_1\mu}\right)\left(\frac{f_N}{1/6}\right),$$

$$\Delta a_\mu(\tilde{B},\tilde{H},\tilde{\mu}_R) \simeq -1.5 \quad \times 10^{-9} \left(\frac{\tan\beta}{10}\right)\left(\frac{(100\,\mathrm{GeV})^2}{M_1\mu}\right)\left(\frac{f_N}{1/6}\right),$$

$$\Delta a_\mu(\tilde{\mu}_L,\tilde{\mu}_R,\tilde{B}) \simeq \quad 1.5 \quad \times 10^{-9} \left(\frac{\tan\beta}{10}\right)\left(\frac{(100\,\mathrm{GeV})^2}{m^2_{\tilde{\mu}_L} m^2_{\tilde{\mu}_R}/M_1\mu}\right)\left(\frac{f_N}{1/6}\right).$$

Endo, Hamaguchi, Iwamoto, Yoshinaga'13