Indian Association for the Cultivation of Science

Lepton magnetic moments in SUSY L_μ-L_τ model in light of CEνNS & LHC data

Heerak Banerjee

Based on work by HB, Bhaskar Dutta and Sourov Roy,
ArXiv: 2011.05083, 2011.xxxx

Magnificent CEνNS 2020

tphb@iacs.res.in
heerakb91@gmail.com

Motivation

- The experimental observation of the muon magnetic dipole moment stands at a ~3.7σ deviation from its theoretical prediction.

$$\delta a_\mu^{exp} = a_\mu^{exp} - a_\mu^{SM} = 2.79(0.76) \times 10^{-9}$$

G. W. Bennett et al. PRD73 (2006)
T.Aoyama et al. Phys. Rept. 887 (2020)

- The electron magnetic dipole moment is at a ~2.5σ deviation from its Standard Model prediction, but in the opposite direction.

$$\delta a_e^{exp} = -8.8(3.6) \times 10^{-13}$$

R. H. Parker, C. Yu, W. Zhong, B. Estey and H. Mller, Science 360, 191 (2018)

- Flavor-universality of leptons: both quantities would be of the same sign, and scale by the mass-squared of the corresponding leptons.

$$\frac{\delta a_\mu}{\delta a_e} = -3.1(1.5) \times 10^3 \qquad \frac{\delta a_\mu}{\delta a_e} \neq \frac{m_\mu^2}{m_e^2} \qquad \frac{m_\mu^2}{m_e^2} = 4.3 \times 10^4$$

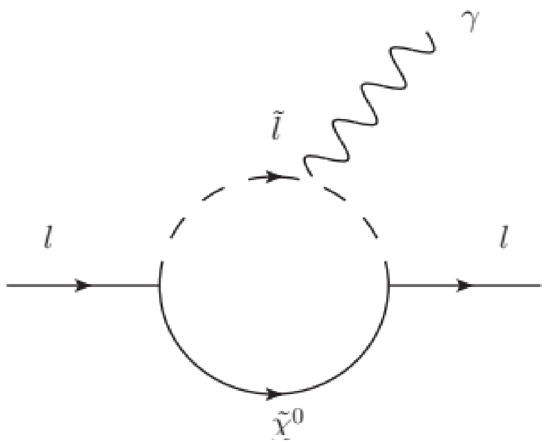
Motivation

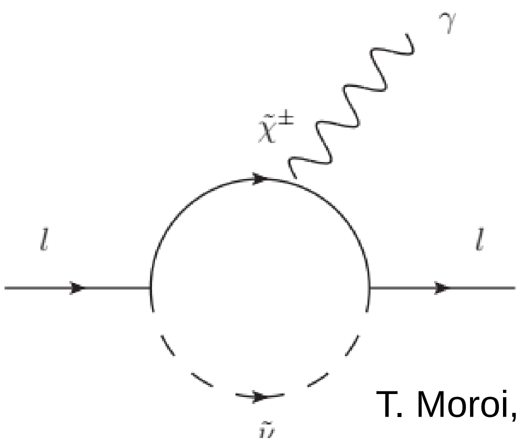
$\mathrm{U}(1)'$ → Lepton (g-2) are of the same sign! Unless coupling switches nature over generations.

SUSY → Requires lepton flavor-Violation. Leads to charged-lepton flavor violating decays.

$\mathrm{SUSY}\ \mathrm{U}(1)_{L_\mu - L_\tau}$ → Two distinct sources of lepton (g-2)! No dependence on Lepton flavor-violation.

SUSY L_μ-L_τ Contribution to Lepton (g-2)





T. Moroi, PRD 53 (1996)

S. P. Martin, J. D. Wells, PRD 64 (2001)

- Supersymmetric contribution to lepton MDMs

$$\delta a_l^{MSSM} \sim 14 \frac{m_l^2}{m_\mu^2} \; \mathrm{Sign}(\mu) \tan\beta \left(\frac{100 \text{ GeV}}{M_{SUSY}} \right)^2 10^{-10}$$

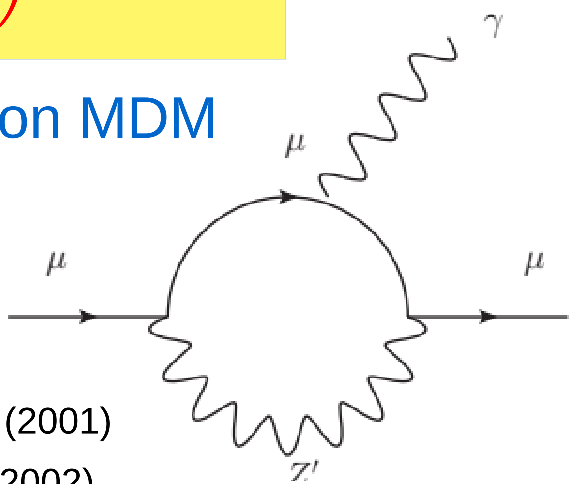
- Contribution of the L_μ-L_τ gauge boson to the muon MDM

$$\delta a_\mu^{Z'} = \frac{g_X^2 m_\mu^2}{4\pi^2} \int_0^1 dz \, \frac{z^2(1-z)}{m_\mu^2 z + M_{Z'}^2 (1-z)}$$

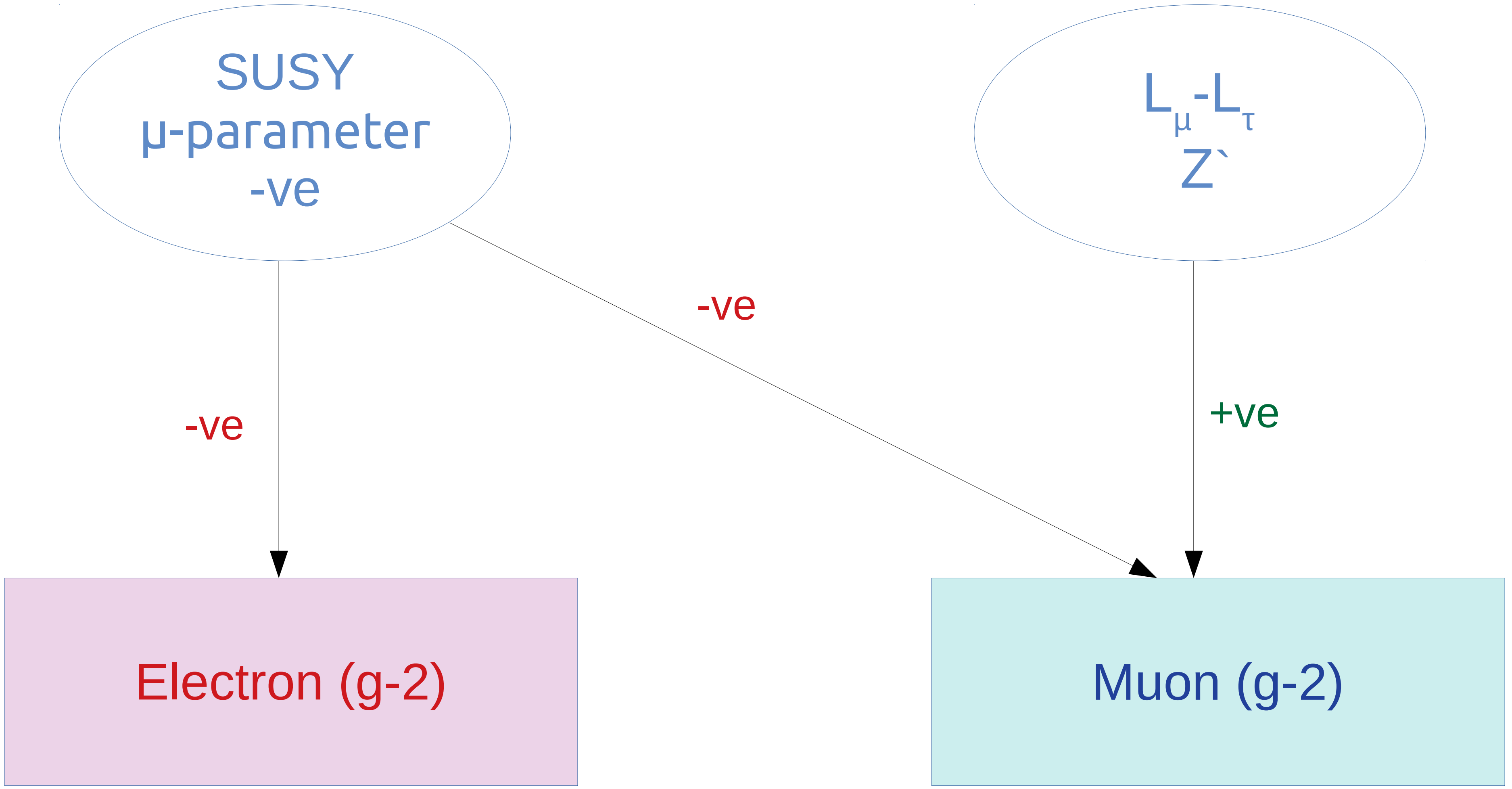
+ve

Baek, Deshpande, He, Ko, PRD 64 (2001)

E. Ma, D. P. Roy, S. Roy, PLB 525 (2002)



Basic Scheme



Kinetic Mixing

D. Suematsu PRD59 (1999)
Bauer, Foldenauer, Jaeckel JHEP07 (2018)
Dienes, Kolda, March-Russell, NPB492 (1997)

HB, S. Roy PRD99 (2019)

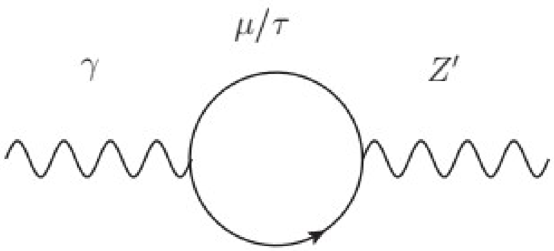
$$\mathcal{L} = -\tfrac{\epsilon}{2}\hat{B}_{\mu\nu}\hat{X}^{\mu\nu}$$

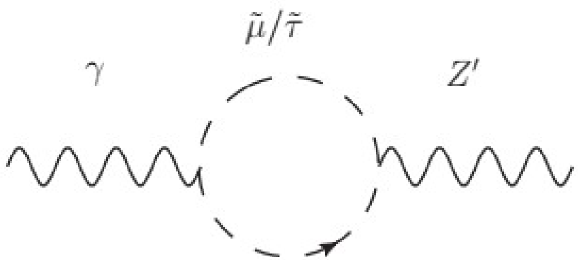
Assumed zero at Tree level

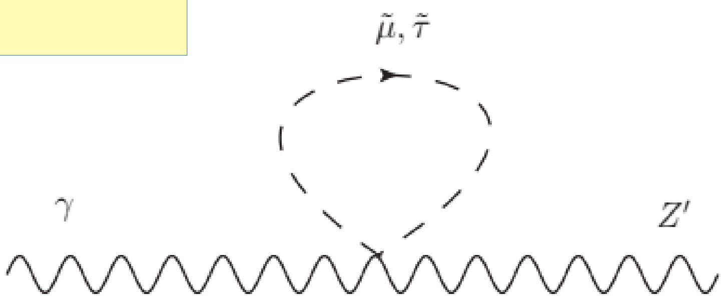
$$\left(e\mathrm{J}^{\mathrm{em}}_{\mu},\quad \mathrm{e}\,/\,\mathrm{s}_w c_w\; J^Z_\mu,\quad \mathrm{g}_X\; J^X_\mu\right)\begin{pmatrix} \mathrm{A}^\mu - \epsilon Z'^\mu \\ \mathrm{Z}^\mu - \epsilon\delta\tan\theta_w Z'^\mu \\ \mathrm{Z}'^\mu + (1+\delta)\tan\theta_w Z^\mu \end{pmatrix}$$

$$\begin{aligned}\Pi(q^2) &= \frac{8eg_X}{16\pi^2}\int_0^1 x(1-x)\ \mathrm{Ln}\left[\frac{m_\tau^2 - x(1-x)q^2}{m_\mu^2 - x(1-x)q^2}\right]dx \\ &+ \frac{2eg_X}{16\pi^2}\int_0^1 (1-2x)^2\ \mathrm{Ln}\left[\frac{m_{\tilde\tau}^2 - x(1-x)q^2}{m_{\tilde\mu}^2 - x(1-x)q^2}\right]dx \\ &= \epsilon\end{aligned}$$

$$r = \frac{m_{\tilde\tau}}{m_{\tilde\mu}}$$

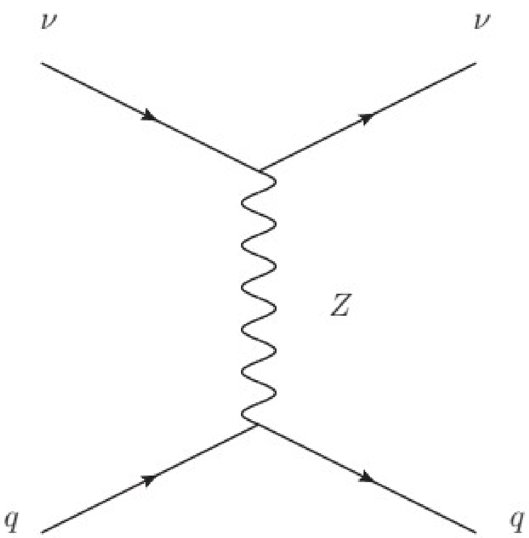






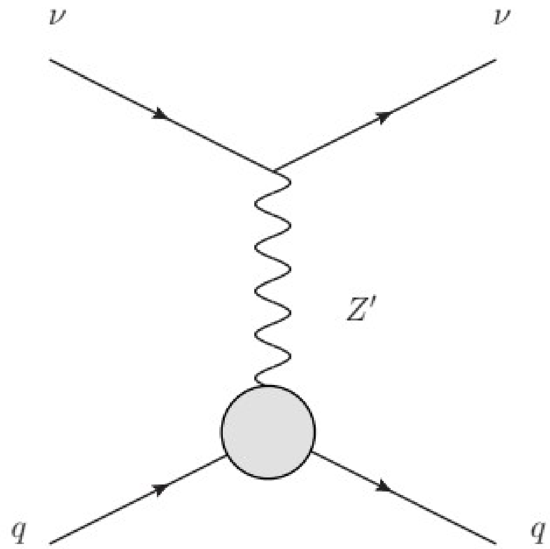
CEνNS

SM



+

BSM

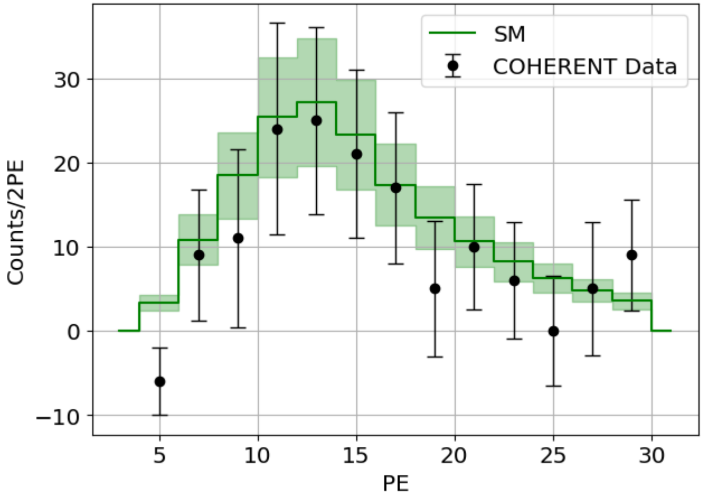


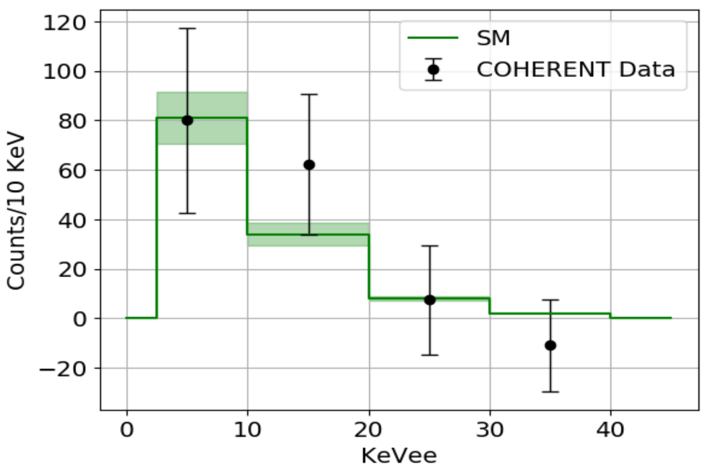
$$\frac{d\sigma}{dE} = \frac{G_F^2 Q_V^2}{2\pi} m_N \left(1 - \left(\frac{m_N E}{E_\nu^2}\right) + \left(1 - \frac{E}{E_\nu}\right)^2\right) F(q^2)$$

$$Q_V \equiv Z\left(2g^u + g^d\right) + N\left(g^u + 2g^d\right)$$

D. Freedman PRD9 (1974)
Drukier, Stodolsky PRD30 (1984)
Dutta, Liao, Sinha, Strigari, PRL123 (2019)

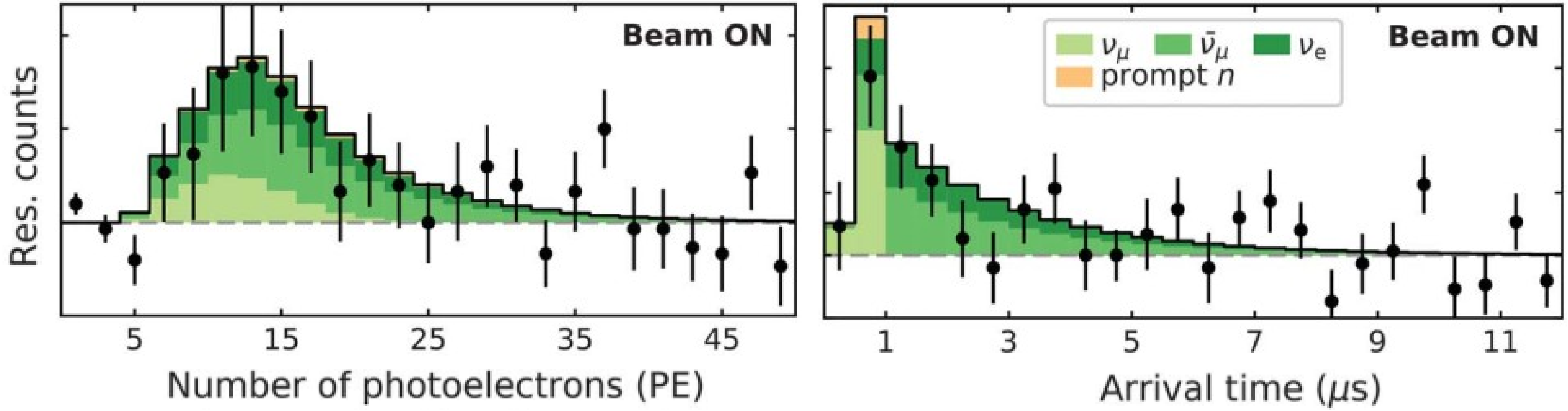
$$g^i \Rightarrow g^i + \frac{Q^X Q^i_{em} g_X \epsilon e}{2\sqrt{2} G_F \left(q^2 + M_{Z'}^2\right)}$$





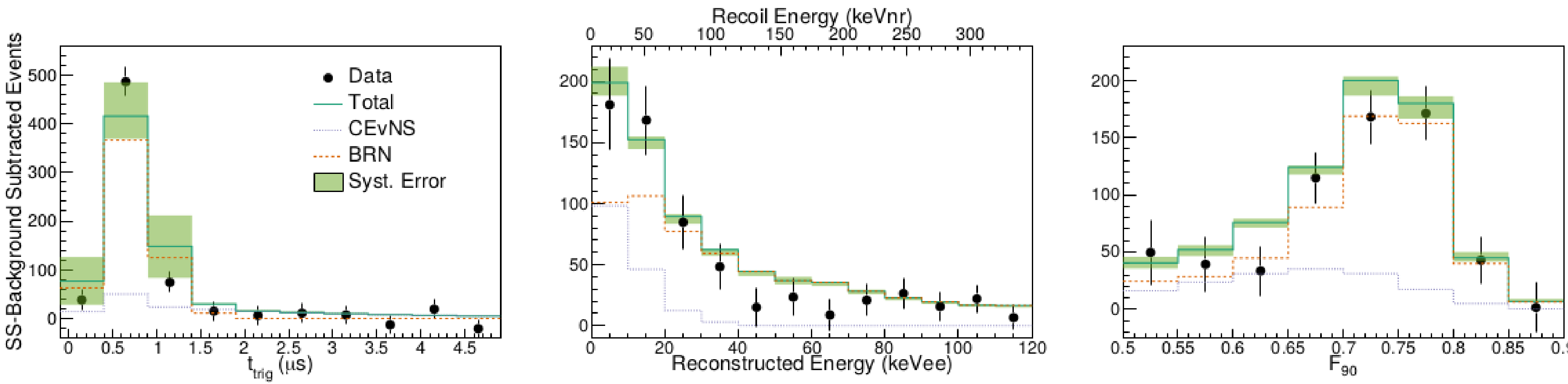
COHERENT data

CEνNS on CsI D. Akimov et al. [COHERENT Collab.], Science 357, 1123 (2017)



173 ± 48 predicted, 134 ± 22 observed 128 ± 17 predicted, 159 ± 43 observed

CEνNS on liquid Ar D. Akimov et al. [COHERENT Collab.],arXiv: 2003.10630, 2006.12659



Likelihood Test

$$\mathcal{L}_{\rm CsI} \propto \quad \prod_{\rm bins} \quad \int \mathcal{P}\left[N_{obs}, (1+\alpha)N_i + N_{\rm BG}\right] \mathcal{P}\left[N_{obs}^{\rm BG}, N_{\rm BG}\right] \times \mathcal{N}\left[\alpha, 0, \sigma\right] d\alpha dN_{\rm BG}$$

Dutta, Liao, Sinha, Strigari, PRL123 (2019)

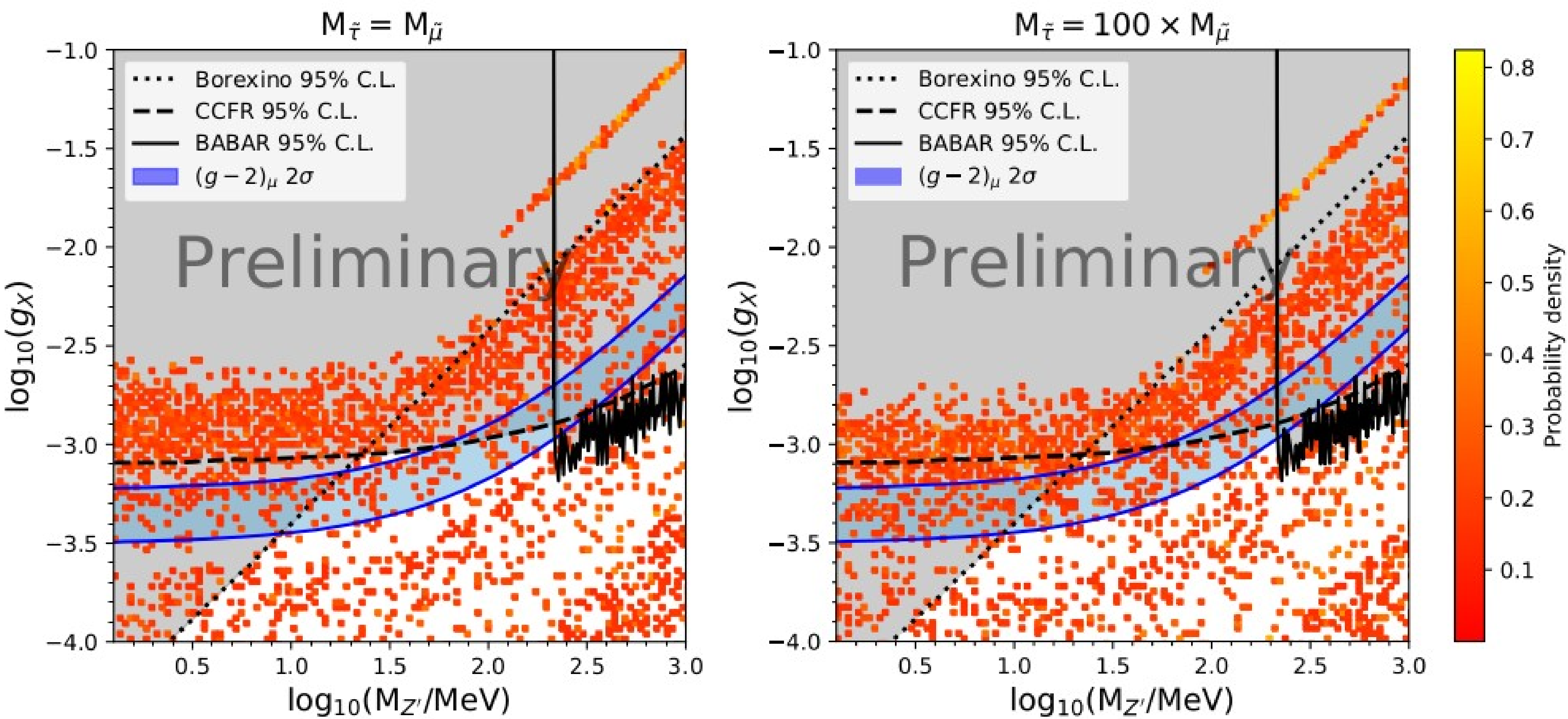
$$\begin{aligned}\mathcal{L}_{\rm Ar} \propto \quad \prod_{\rm bins} \quad & \int_{-3\sigma_i}^{3\sigma_i} \mathcal{P}\left[N_{obs}, (1+\alpha)N_i + (1+\beta_1)N_{ss} + (1+\beta_2)N_{pBRN} + (1+\beta_3)N_{dBRN}\right] \\ \times \quad & \mathcal{N}\left[\alpha, 0, \sigma\right] \mathcal{N}\left[\beta_1, 0, \sigma_1\right] \mathcal{N}\left[\beta_2, 0, \sigma_2\right] \mathcal{N}\left[\beta_3, 0, \sigma_3\right] d\alpha d\beta_1 d\beta_2 d\beta_3\end{aligned}$$

$\mathcal{P}[k, \lambda] \rightarrow$ Poisson distribution
$\mathcal{N}[x, \mu, \sigma] \rightarrow$ Normal distribution

$$\mathcal{L} \propto \mathcal{L}_{\rm CsI} \times \mathcal{L}_{\rm Ar}$$

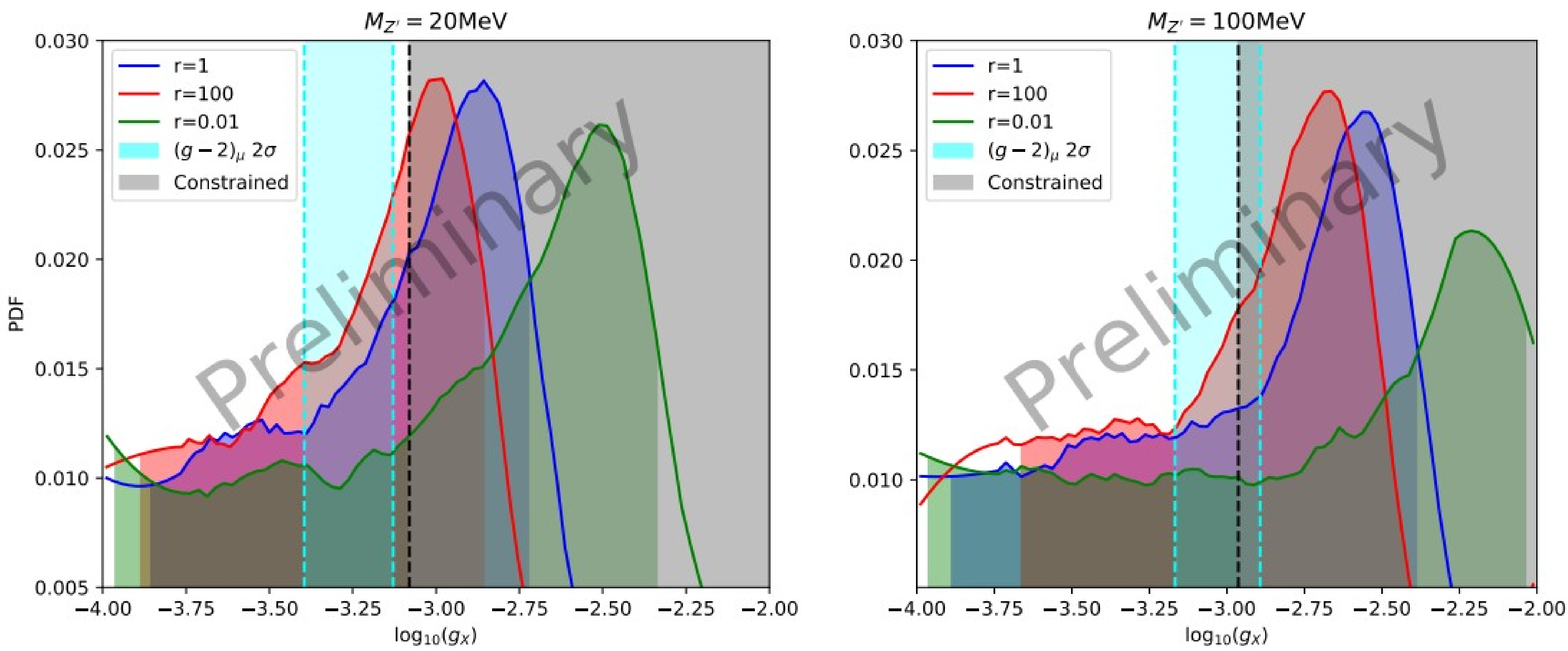
$N_{CE\nu NS}$	159 ± 41
N_{pBRN}	555 ± 33
N_{dBRN}	11 ± 11
N_{SS}	3131 ± 22
Sig.(stat.)	3.89σ

Combined Results



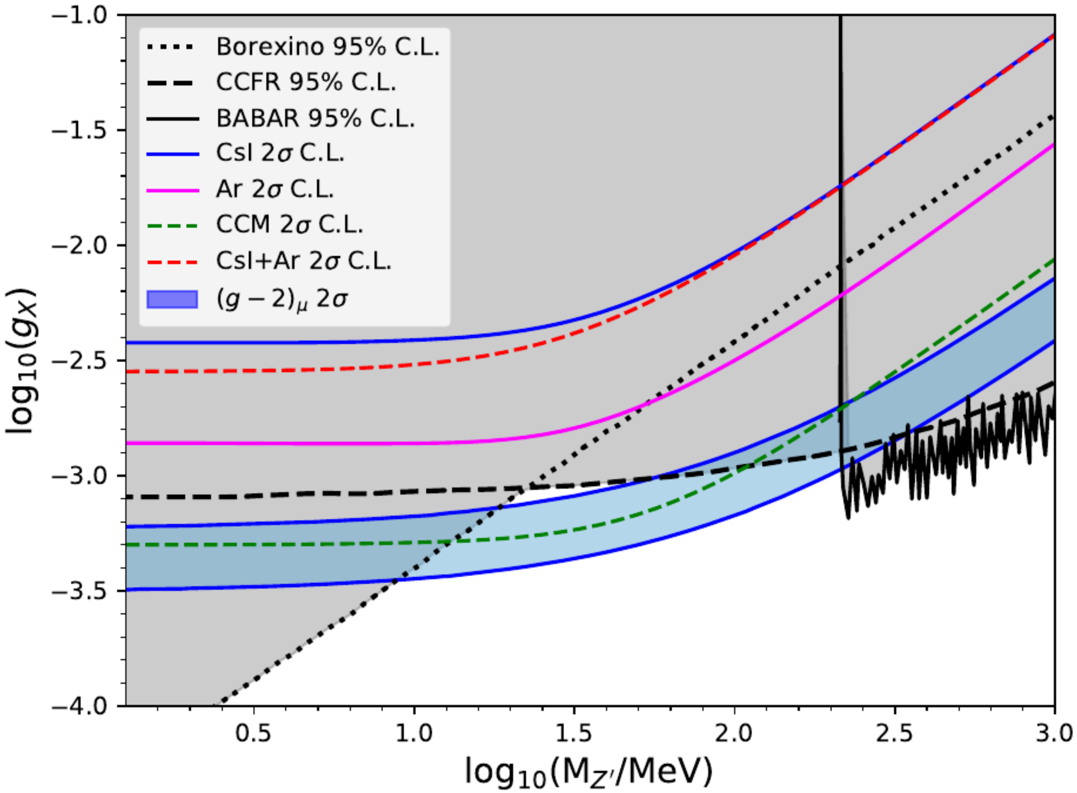
HB, B. Dutta, S. Roy, arXiv:2011.xxxxx

Combined Results



HB, B. Dutta, S. Roy, arXiv: 2011.xxxxx

Combined Results



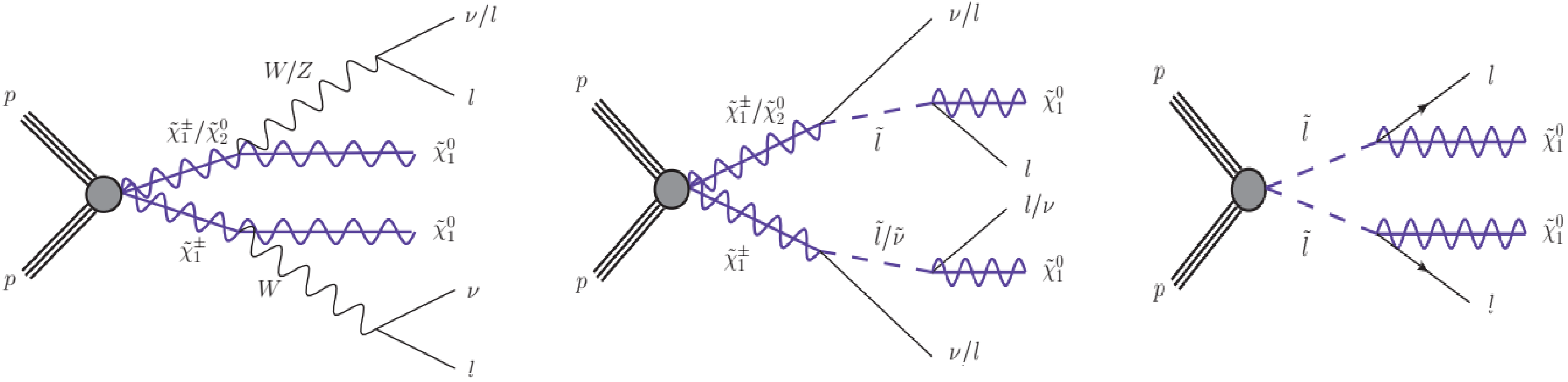
CCM
5000 hours of operation per year,
equivalent to ~ 3 × 10^{22} POT
0.0425 neutrinos per proton per flavor,
KeVee window of 25- 150 KeV.
Poisson likelihood in each bin
Only CevNS prediction used.

$$t = -2\log\left(\frac{\mathcal{L}_0}{\mathcal{L}_1}\right)$$

$$M_{Z'} = 20 \text{ MeV} \rightarrow 1.4\sigma$$
$$M_{Z'} = 100 \text{ MeV} \rightarrow 1.3\sigma$$

HB, B. Dutta, S. Roy, arXiv:2011.05083, 2011.xxxx

LHC Constraints:



$$\tilde{\chi}_i^0 \equiv \left(\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{B}', \tilde{\eta}, \tilde{\bar{\eta}}\right) \qquad \tilde{\chi}_i^{\pm} \equiv \left(\tilde{W}^-, \tilde{H}_d^-\right), \left(\tilde{W}^+, \tilde{H}_u^+\right)$$

$$\tan\beta = \langle h_u^0 \rangle / \langle h_d^0 \rangle$$

$\mathrm{M}_0,\ \mathrm{M}_1,\ \mathrm{M}_2,\ \mu$

$\mathrm{M}_{\tilde{l}_L},\ \mathrm{M}_{\tilde{l}_R}$

$\mathrm{M}_2,\ \mu$

Numerical Scan

Numerical Scan:

Parameter	Range
M_0	100 GeV - 1 TeV
M_1	100 GeV - 1 TeV
M_2	100 GeV - 1 TeV
μ	100 GeV - 1 TeV
tan β	10 - 50
$\mathrm{M}_{\tilde{L}_e}$	100 GeV - 1 TeV
$\mathrm{M}_{\tilde{L}_\mu}/M_{\tilde{L}_e}$	1 - 100

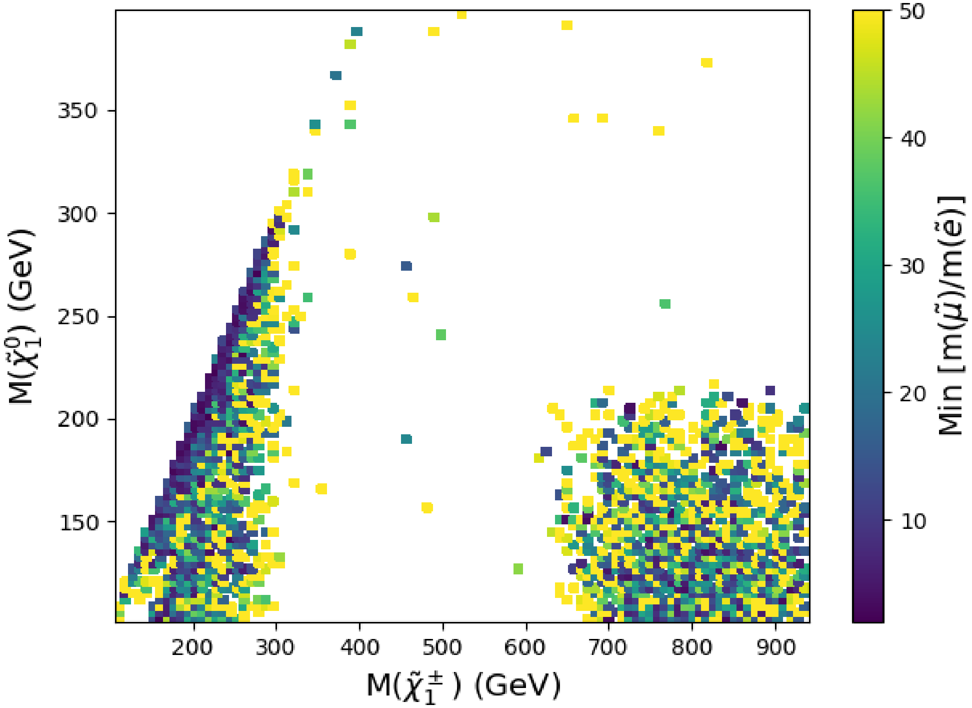
HB, B. Dutta, S. Roy, arXiv:2011.05083

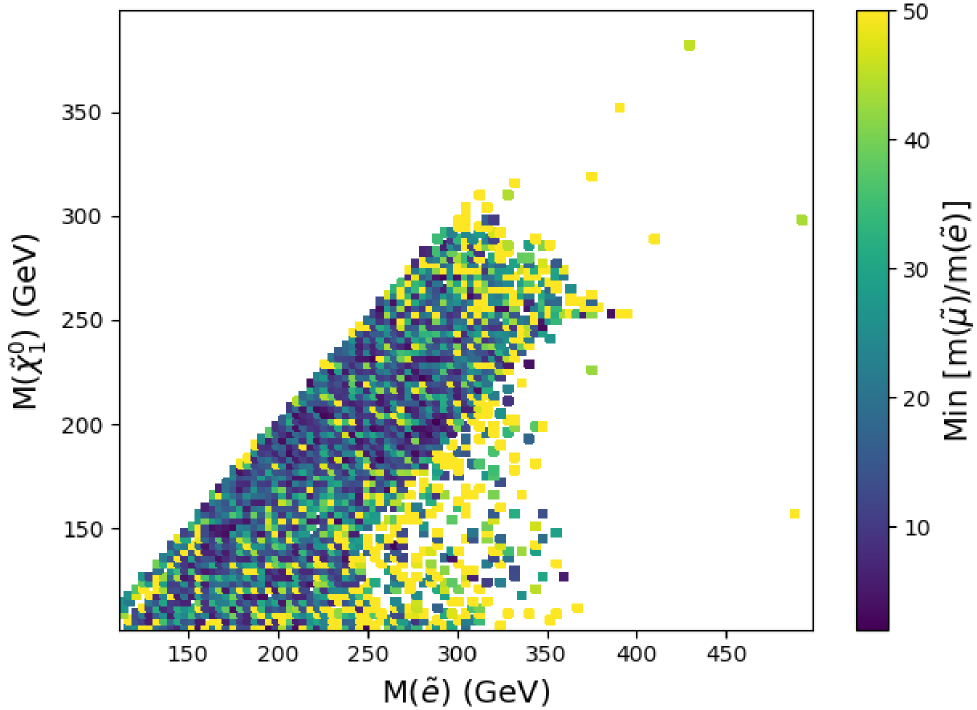
Broad Results:

Parameter	Range
$\mathrm{M}_{\tilde{\chi}_1^0}$	$\lesssim 400$ GeV
$\mathrm{M}_{\tilde{e}}$	$\lesssim 400$ GeV
$\mathrm{M}_{\tilde{\mu}}/M_{\tilde{e}}$	$\gtrsim 2.5$
$\mathrm{M}_{\tilde{\mu}}$	$\gtrsim 600$ GeV

Results of the scan

Upper limit on selectron and lightest neutralino mass: From (g-2)





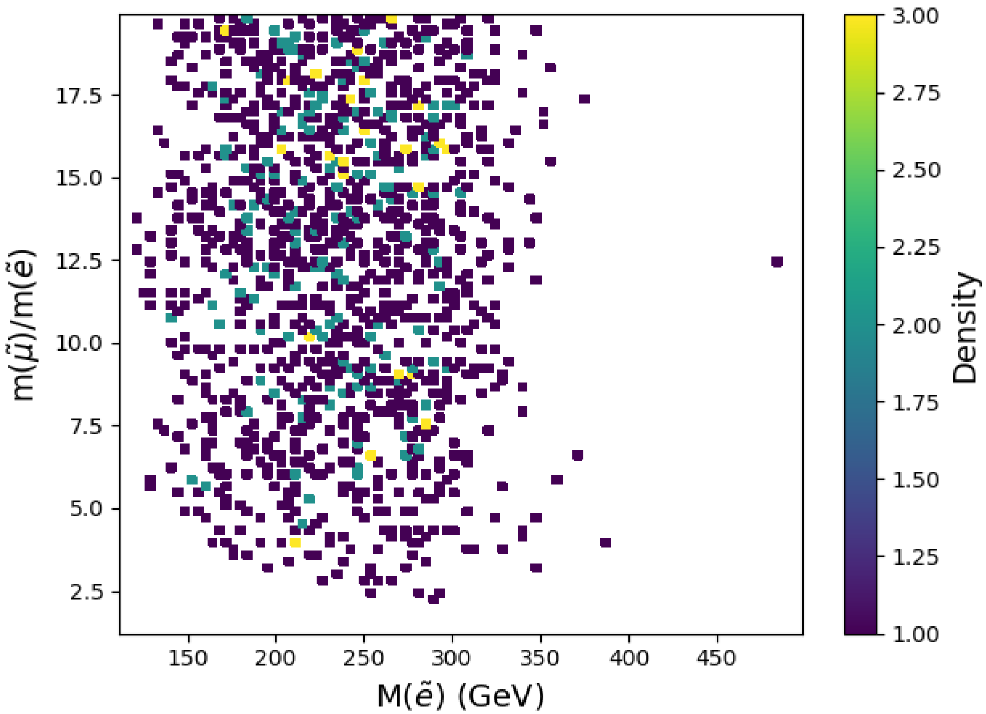
Gaps in spectrum: From collider constraints. Binos are light when chargino/selectron is heavy!

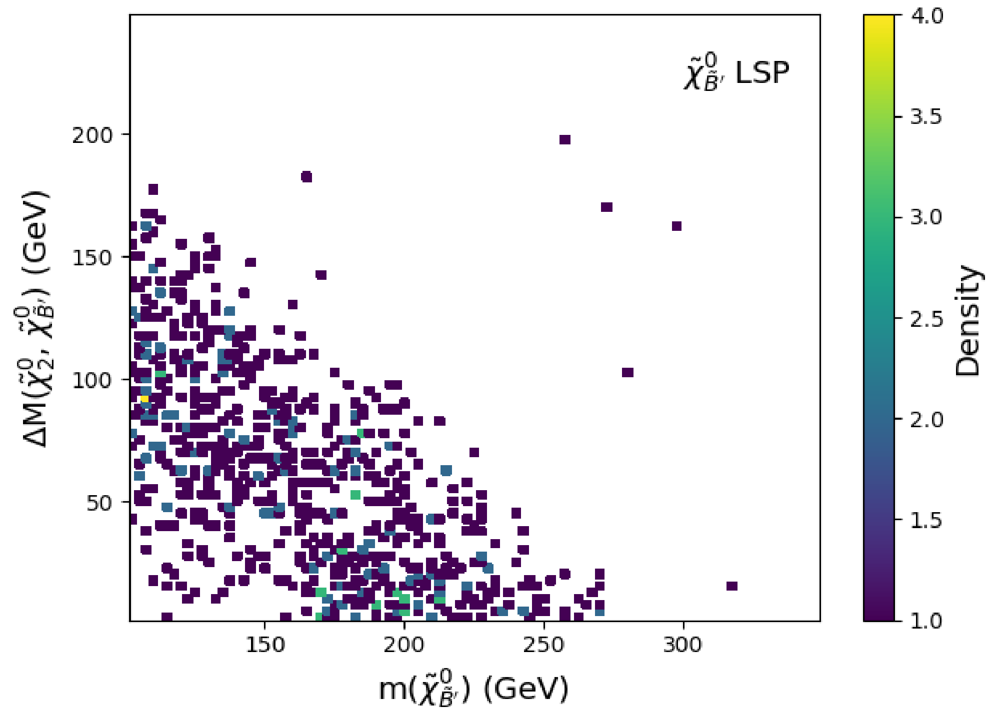
HB, B. Dutta, S. Roy, arXiv:2011.05083

Results of the scan

HB, B. Dutta, S. Roy, arXiv:2011.05083

Upper limit on selectron mass, lower limit on slepton hierarchy:
From (g-2)





The NL neutralino is the lightest stable (consequential) field as far as the collider and (g-2) is concerned when LSP is B`ino dominated.

Summary

- COHERENT CsI and Ar data have pulls in opposite directions.
- CsI data has preference for deductive BSM effect. Combined data still prefers it slightly.
- Exclusion from combined data on $L_\mu - L_\tau$ parameter space adheres to CsI exclusion.
- Work on general NSI forthcoming. Present data seems to favor deductive effect.
- The additional gauge boson may be as light as 10 MeV but no heavier than 200 MeV.
- The additional gauge coupling is constrained to between 0.0005 and 0.002.

Summary

- Possible to explain both lepton MDMs in a simple scenario.
- No lepton-flavor violation required whatsoever.
- A large variety of SUSY scenarios may accomodate the scheme. Important gaps observed in allowed spectrum.
- No hierarchy imposed on the slepton masses during scan, but it clearly shows up in the results. However, a hierarchy between second and first generation sleptons of as low as 2.5 is still possible.
- Values of tan β as low as 15 or lower is possible.

Thank You!

Backup slides

Summary

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- No lepton-flavor violation required whatsoever.
- A large variety of SUSY scenarios may accomodate the scheme. Important gaps observed in allowed spectrum.
- No hierarchy imposed on the slepton masses during scan, but it clearly shows up in the results. However, a hierarchy between second and first generation sleptons of as low as 2.5 is still possible.
- Values of tan β as low as 15 or lower is possible.
- The additional gauge boson may be as light as 10 MeV but no heavier than 200 MeV.
- The additional gauge coupling is constrained to between 0.0005 and 0.002.

Motivation

- Contribution of extra gauge boson to the lepton magnetic dipole moments (MDMs) are always of the same sign.

  A. E. Carcamo Hernandez, S. F. King, H. Lee and S. J. Rowley, Phys. Rev. D **101**, no.11, 115016 (2020)

  N. Haba, Y. Shimizu and T. Yamada, [arXiv:2002.10230 [hep-ph]]

  C. H. Chen and T. Nomura, [arXiv:2003.07638 [hep-ph]].

  C. Hati, J. Kriewald, J. Orloff and A. M. Teixeira, JHEP **07**, 235 (2020)

- Explanations within SUSY: large, flavor-nonuniversal, or explicitly flavor-violating trilinear soft SUSY-breaking terms.

  B. Dutta and Y. Mimura, Phys. Lett. B **790**, 563-567 (2019)

- Our attempt: no dependence on flavor violation, flavor-universal A-terms. Decouple the electron and muon (g-2) source?

  A. Crivellin, M. Hoferichter and P. Schmidt-Wellenburg, Phys. Rev. D **98**, no.11, 113002 (2018)

SUSY L_μ-L_τ Model for Electron and Muon (g-2)

Superfields	$\hat{L}_\mu$	$\hat{E}^c_\mu$	$\hat{L}_\tau$	$\hat{E}^c_\tau$	$\hat{\eta}$	$\hat{\bar{\eta}}$
$U(1)_{L_\mu - L_\tau}$	1	-1	-1	1	-1	1

$$W = \hat{U}^c Y_u \hat{Q} \hat{H}_u - \hat{D}^c Y_d \hat{Q} \hat{H}_d - \hat{E}^c Y_l \hat{L} \hat{H}_d - \mu \hat{H}_d \hat{H}_u - \mu_\eta \hat{\eta} \hat{\bar{\eta}}$$

- The additional superfields are R-Parity positive and must be equal and oppositely charged under the additional gauge symmetry.
- The leptonic yukawa sector is flavor-diagonal as a consequence of this additional symmetry.
- R-parity is conserved. This rules out additional terms that may still be gauge singlets. We assume zero tree-level kinetic mixing.

SUSY L_μ-L_τ Model for Electron and Muon (g-2)

$$
\begin{aligned}
-\mathcal{L}_{\rm soft} \;=\;& \left(\frac{M_3}{2}(i\tilde{g})(i\tilde{g}) + \frac{M_2}{2}(i\tilde{W})(i\tilde{W}) + \frac{M_1}{2}(i\tilde{B})(i\tilde{B}) + \frac{M_0}{2}(i\tilde{B}')(i\tilde{B}') + h.c\right) - M_{10}(i\tilde{B})(i\tilde{B}') \\
& + A\left(y_u^{ij} H_u \tilde{Q}_j \tilde{U}_i - y_d^{ij} H_d \tilde{Q}_j \tilde{D}_i - y_l^{i} H_d \tilde{L}_i \tilde{E}_i + h.c\right) \\
& + M_Q^2\left(\tilde{Q}^\dagger \tilde{Q} + \tilde{U}^{c\dagger}\tilde{U}^c + \tilde{D}^{c\dagger}\tilde{D}^c\right) + \sum_{l=e,\mu,\tau} \left(M_{\tilde{l}_L}^2 \tilde{L}_l^\dagger \tilde{L}_l + M_{\tilde{l}_R}^2 \tilde{E}_l^{c\dagger}\tilde{E}_l^c\right) \\
& + M_{H_d}^2 H_d^\dagger H_d + M_{H_u}^2 H_u^\dagger H_u + M_\eta^2(\eta^\dagger\eta + \bar{\eta}^\dagger\bar{\eta}) - (B_0 H_d H_u + B_\eta \eta\bar{\eta} + H.c.)
\end{aligned}
$$

$$
\tilde{\chi}_i^0 \equiv \left(\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{B}', \tilde{\eta}, \tilde{\bar{\eta}}\right) \qquad \tilde{\chi}_i^\pm \equiv \left(\tilde{W}^-, \tilde{H}_d^-\right), \left(\tilde{W}^+, \tilde{H}_u^+\right)
$$

$M_0,\ M_1,\ M_2,\ \mu$

$\tan\beta = \langle h_u^0\rangle / \langle h_d^0\rangle$

$M_{\tilde{l}_L},\ M_{\tilde{l}_R}$

$M_2,\ \mu$

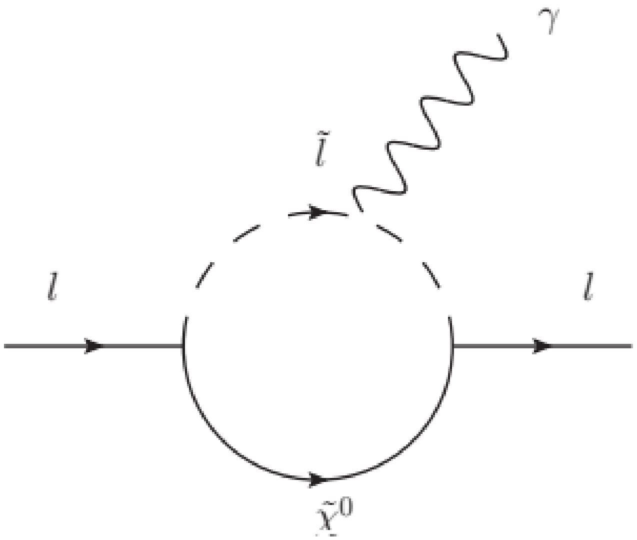
Lepton anomalous magnetic moments in SUSY

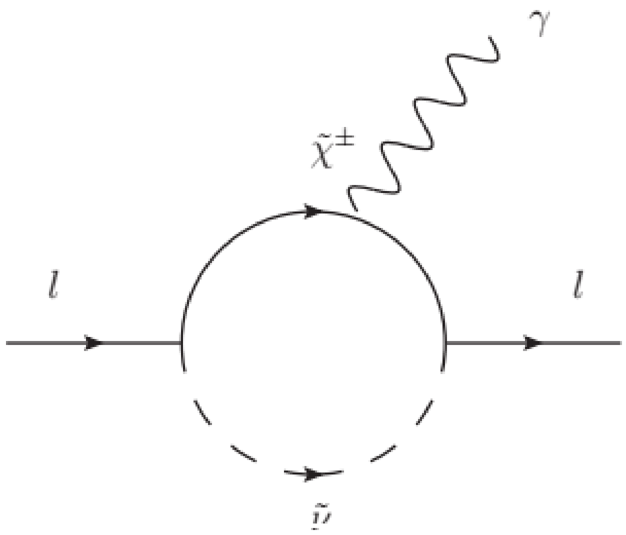
- Supersymmetric contribution to lepton MDMs

$$a_l^{\tilde{\chi}^0_{\tilde{B}}},\ a_l^{\tilde{\chi}^{\pm}}\ \text{dominate}$$

$$a_l^{\tilde{\chi}^0_{\tilde{B}}},\ a_l^{\tilde{\chi}^{\pm}} \propto (M_1, M_2)\mu \tan\beta$$

- The sign of $(M_1, M_2)\mu$ control the sign of SUSY contribution to lepton magnetic moment.
- Light Winos can provide for a larger magnetic moment even with heavy Higgsinos, while the converse is not true.
- Heavy Winos require a light Bino to make up for the loss in leptonic MDM.



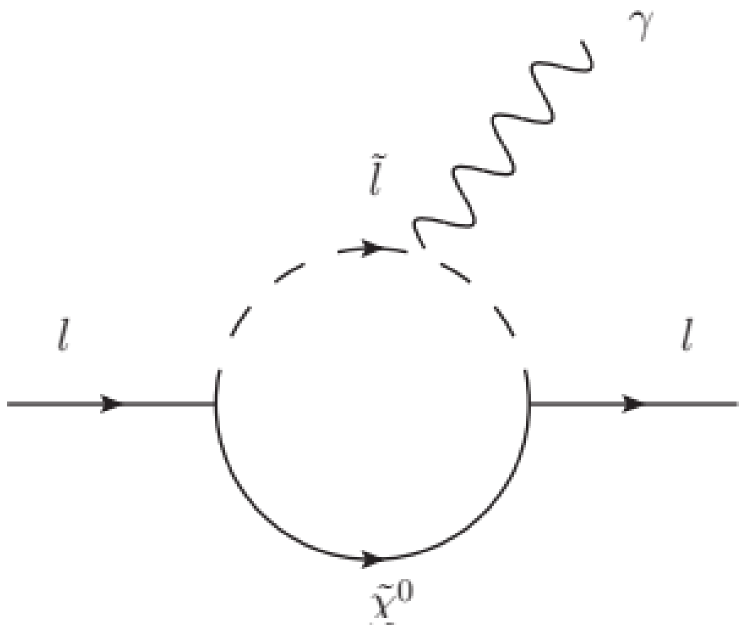


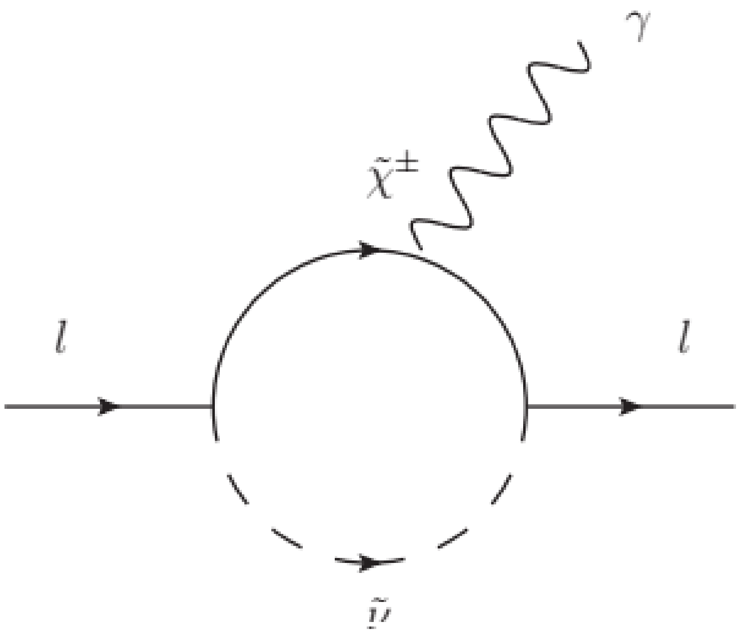
T. Moroi, Phys. Rev. D 53, 6565 (1996)
S. P. Martin and J. D. Wells, Phys. Rev. D 64, 035003 (2001)

Lepton anomalous magnetic moments in SUSY

- Supersymmetric contribution to lepton MDMs

$$\delta a_l^{MSSM} = 14\frac{m_l^2}{m_\mu^2}\ \mathrm{Sign}(\mu)\tan\beta\left(\frac{100\ \mathrm{GeV}}{M_{SUSY}}\right)^2 10^{-10}$$





Lepton anomalous magnetic moments in SUSY

- Supersymmetric contribution to lepton MDMs

$$a_l^{\tilde{\chi}^0} = -\frac{m_l}{16\pi^2}\sum_{i=1}^{7}\sum_{j=1}^{2}\left[\left(|n_{ij}^L|^2+|n_{ij}^R|^2\right)\frac{m_l}{12m_{\tilde{l}\,j}^2}F_1^N(x_{ij})\right.$$
$$\left.+\frac{m_{\tilde{\chi}^0\,i}}{3m_{\tilde{l}\,j}^2}\mathrm{Real}\left(n_{ij}^L n_{ij}^R\right)F_2^N(x_{ij})\right]$$

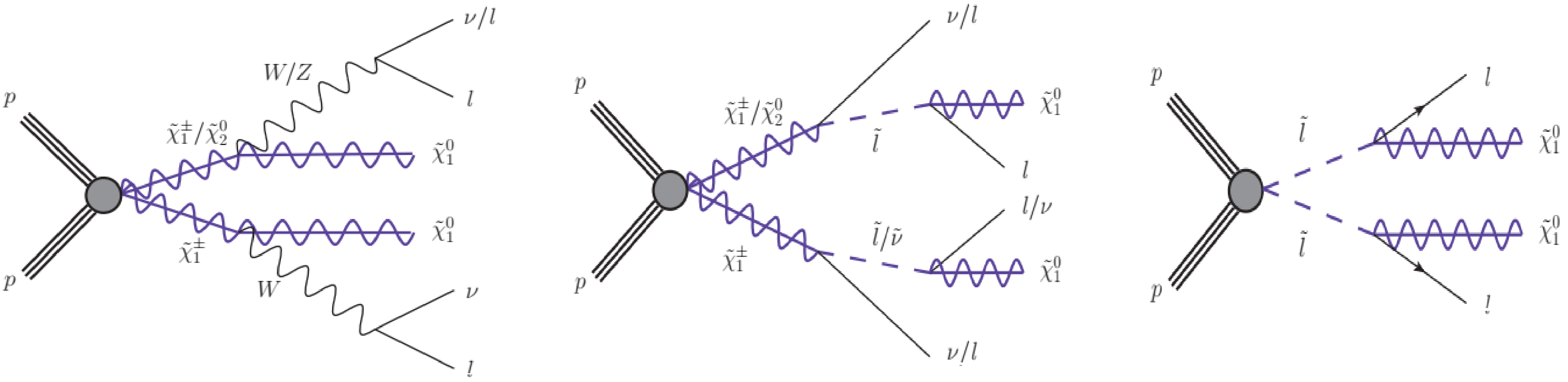
$$a_l^{\tilde{\chi}^\pm} = \frac{m_l}{16\pi^2}\sum_{k=1}^{2}\left[\frac{m_l}{12m_{\tilde{\nu}_l}^2}\left(|c_k^L|^2+|c_k^R|^2\right)F_1^C(y_k^l)\right.$$
$$\left.+\frac{2m_{\tilde{\chi}_k^\pm}}{3m_{\tilde{\nu}_l}^2}\mathrm{Real}\left(c_k^L c_k^R\right)F_2^C(y_k^l)\right]$$

$$\mathcal{L}_{int} = \sum_{i,j}\bar{l}(n_{ij}^L P_L + n_{ij}^R P_R)\tilde{\chi}_j^0\tilde{l}_i + \sum_k \bar{l}(c_k^L P_L + c_k^R P_R)\tilde{\chi}_k^\pm\tilde{\nu}_l + \mathrm{h.c.}$$

T. Moroi, Phys. Rev. D 53, 6565 (1996)
S. P. Martin and J. D. Wells, Phys. Rev. D 64, 035003 (2001)

Is it possible?

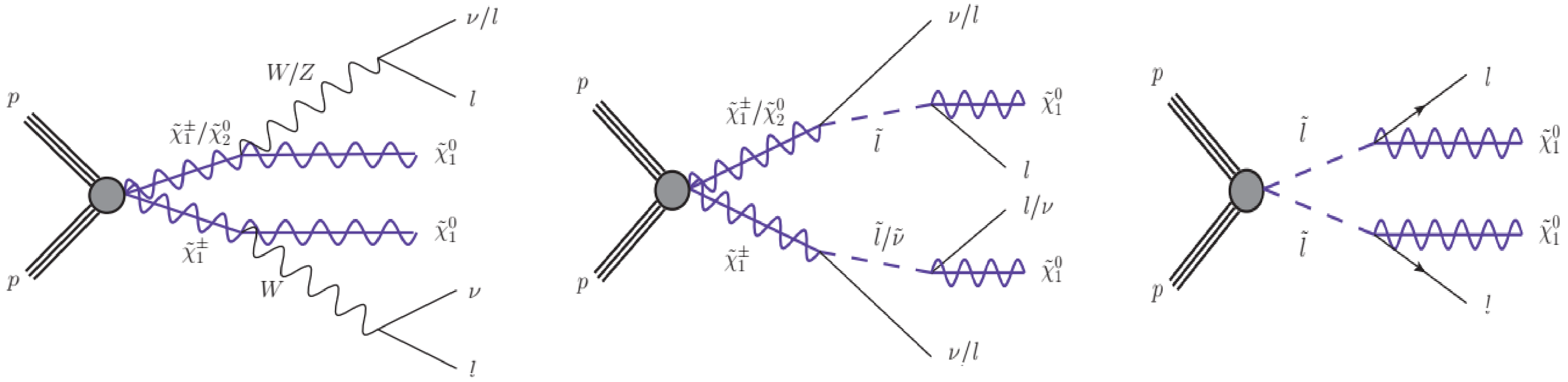
LHC Constraints:



- Constraints are weaker for SM gauge boson mediated decays of the lightest chargino and associated neutralino. Higgsinos decay with near 100% branching ratio into these modes.
- Constraints are weaker on heavier charginos/neutralinos: smaller branching ratios into specific decay modes.

Is it possible?

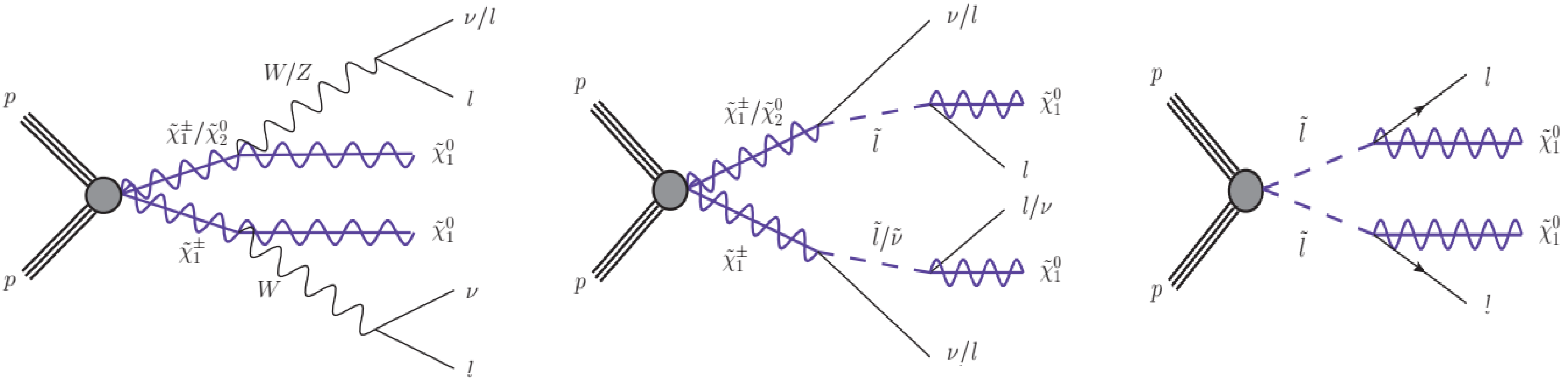
LHC Constraints:



- Constraints on slepton masses from their direct pair production.
- Selectron and e-sneutrino masses are required to be low to explain electron (g-2)
- Smuon and the corresponding sneutrino masses are required to be high enough to suppress their negative contribution to muon (g-2).

Is it possible?

LHC Constraints:



- MSSM-like lightest neutralino is stable within collider scales even if they are not the LSP.
- Mass of B` gaugino dominated neutralino is inconsequential.
- LSP is B`ino dominated: decay of NLSP into a photon and LSP may affect BBN/CMB. Decay time constrained to be less than a second.

LHC results used:

- M. Aaboud *et al.* [ATLAS], JHEP **06**, 022 (2018)
- M. Aaboud *et al.* [ATLAS], Eur. Phys. J. C **78**, no.12, 995 (2018)
- M. Aaboud *et al.* [ATLAS], Phys. Rev. D **98**, no.9, 092012 (2018)
- G. Aad *et al.* [ATLAS], Eur. Phys. J. C **80**, no.2, 123 (2020)
- G. Aad *et al.* [ATLAS], Phys. Rev. D **101**, no.5, 052005 (2020)

Application of constraints

$$\sigma^X = \sigma^{\mathrm{ATLAS}} \times \mathrm{F_M}(parameters) \times (\prod \mathrm{B_R}(parameters))$$

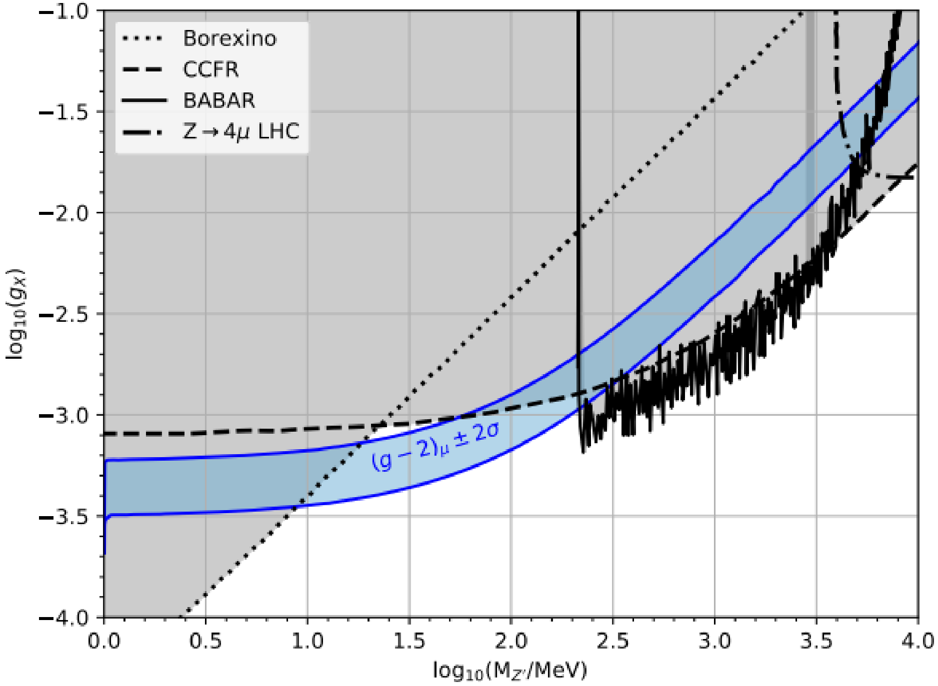
Point excluded if $\sigma^X > \sigma^{\mathrm{UL}}$ for the specific choice of parameters

Values of σ^{ATLAS} obtained for specific scenarios from
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections

Values of σ^{UL} obtained for specific scenarios from
https://www.hepdata.net/

Constraints on L_μ-L_τ parameter space

L_μ-L_τ parameter space:



- A very narrow slice of parameter space left to explain muon MDM. Now both electron and muon MDM can be explained in this region.

Electroweakino constraint scenarios

Five scenarios based on the mass ordering of the Bino, Wino and Higgsino mass parameters, M_1, M_2, μ

1) $M_2 \ll M_1, \mu$

   a) Constraints on long-lived Wino-like chargino.

   b) Constraints on heavier electroweakinos from pair production of Higgsino-like chargino/neutralinos.

2) $\mu \ll M_1, M_2$

   a) Weak constraint from pair production of light nearly-degenerate Higgsino-triplet.

   b) Constraints on heavier Wino-like electroweakinos significant.

Electroweakino constraint scenarios

Five scenarios based on the mass ordering of the Bino, Wino and Higgsino mass parameters, M_1, M_2, μ

3) $M_1 < M_2 < \mu$

   a) Constraints from pair production of light wino-like chargino and associated neutralino.

   b) Constraints on heavier Higgsino-like electroweakinos nearly non-existent.

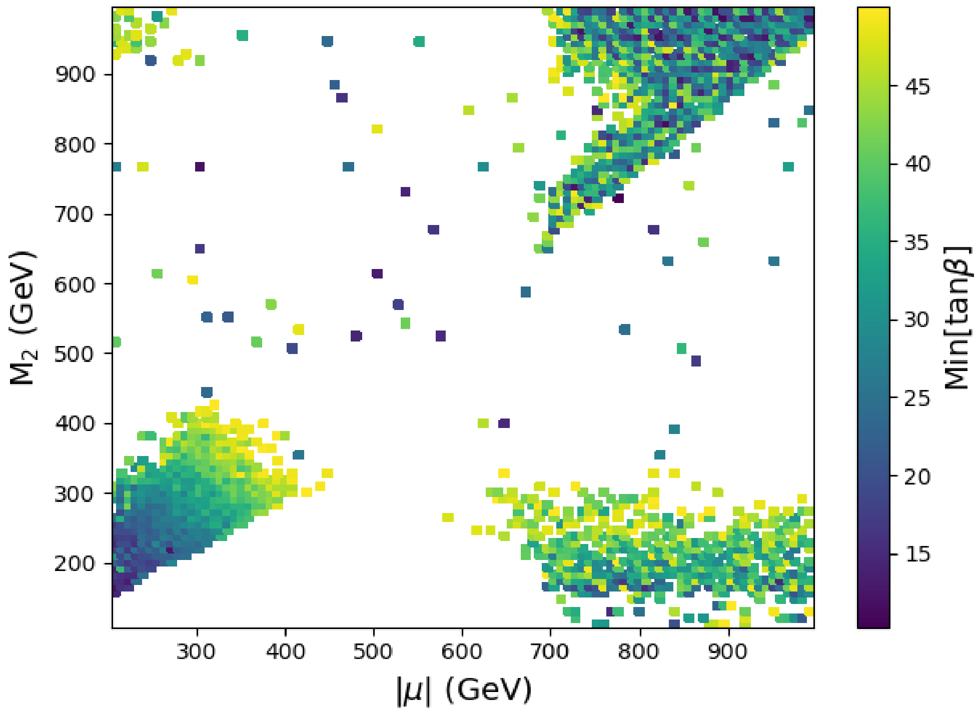
4) $M_1 < \mu < M_2$

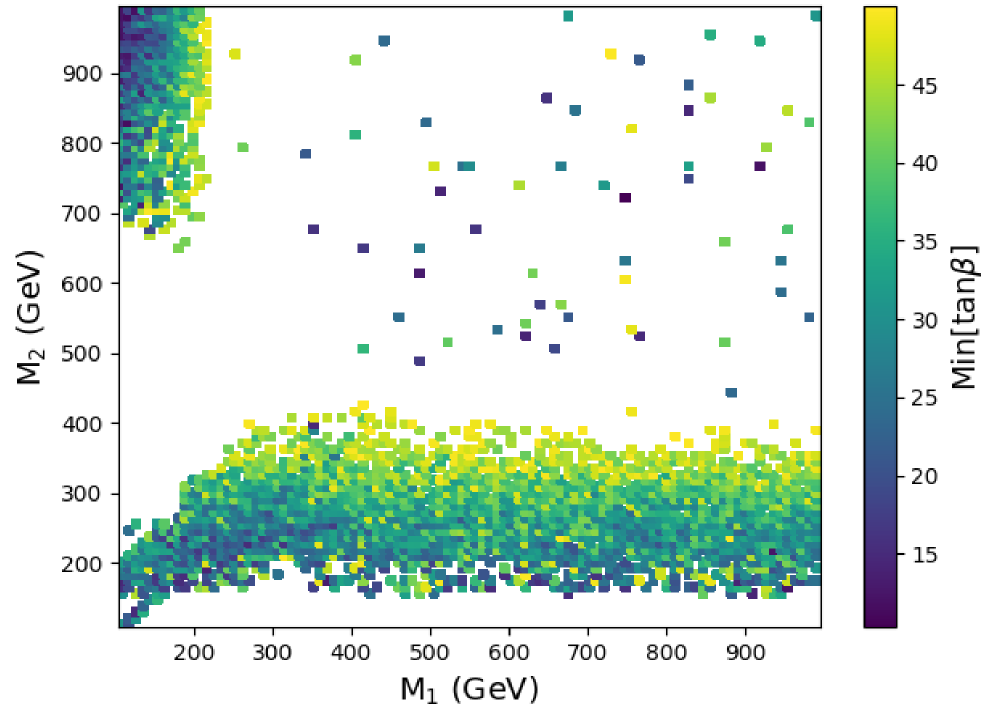
   a) Same set of constraints, but this time constraints on heavier WINO-like electroweakinos are significant.

5) When LSP is B` gaugino dominated, radiative decays of neutral NLSP into a photon and the LSP may affect BBN/CMB. This decay time constrained to be less than 1 second.

Results of the scan

Heavy Winos: Bino needs to be light. Tight constraints from pair production of chargino neutralino.





Light Winos: Unless compressed, Bino heavier than Wino. Long-lived charge Wino constrained. Constraint from pair production of Higgsinos.