Muon g-2, Neutralino Dark Matter and the LHC

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Motivation

LHC Run-2

FNAL *g-2* Ring

Fermi-LAT

Outline

- What is muon *g-2* ?
- BNL observed g-2 excess
- Explanation by MSSM
- Upper bound on SUSY particle masses
- Lower bound on the LSP mass from dwarf galaxies
- Search for relevant SUSY particles at the LHC
- Conclusion

Based on: M. Adeel Ajaib, Bhaskar Dutta, T.G,
Ilia Gogoladze, Qaisar Shafi (Upcoming)

Muon *g*-2 and BNL Excess

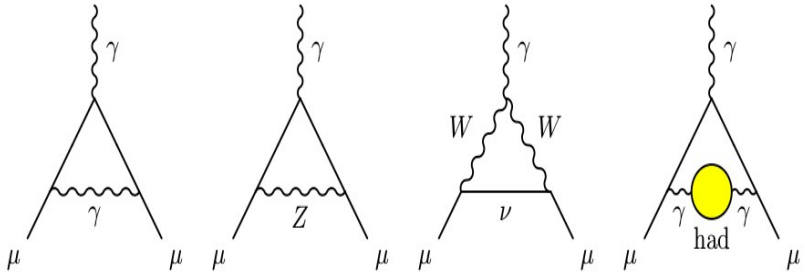
$$\vec{M} = g_\mu \frac{e}{2m_\mu}\vec{S}, \quad g_\mu = 2$$

Quantum Correction

$$a_\mu \equiv \frac{g_\mu - 2}{2}$$

SM

$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{Had}}$$



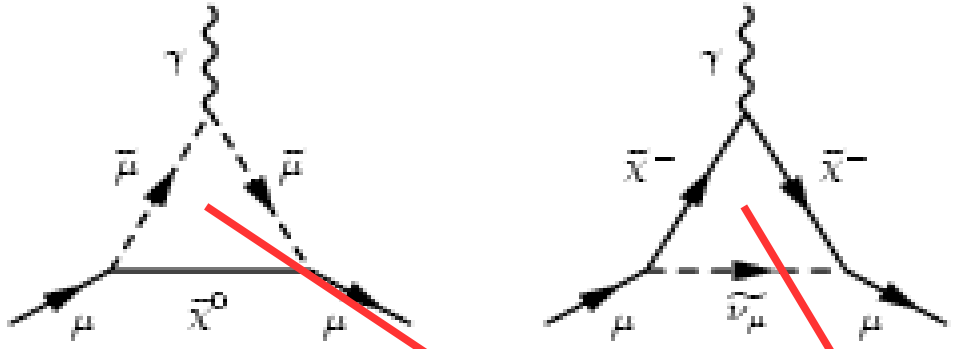
BNL

$$\Delta a_\mu \equiv a_\mu(\mathrm{exp}) - a_\mu(\mathrm{SM}) = (28.6 \pm 8.0) \times 10^{-10}$$

3.6 σ Excess

arXiv: 1302.1907 [M. Davier]

g-2 and MSSM



$$\Delta a_\mu = \frac{\alpha\, m_\mu^2\, \mu\, \tan\beta}{4\pi} \left\{ \frac{M_2}{\sin^2\theta_W\, m^2_{\tilde{\mu}_L}} \left[\frac{f_\chi(M_2^2/m^2_{\tilde{\mu}_L}) - f_\chi(\mu^2/m^2_{\tilde{\mu}_L})}{M_2^2 - \mu^2} \right] \right.$$
$$\left. + \frac{M_1}{\cos^2\theta_W\, (m^2_{\tilde{\mu}_R} - m^2_{\tilde{\mu}_L})} \left[\frac{f_N(M_1^2/m^2_{\tilde{\mu}_R})}{m^2_{\tilde{\mu}_R}} - \frac{f_N(M_1^2/m^2_{\tilde{\mu}_L})}{m^2_{\tilde{\mu}_L}} \right] \right\},$$

$$f_\chi(x) = \frac{x^2 - 4x + 3 + 2\ln x}{(1-x)^3}, \qquad f_\chi(1) = -2/3,$$

$$f_N(x) = \frac{x^2 - 1 - 2x\ln x}{(1-x)^3}, \qquad f_N(1) = -1/3\,.$$

$M_1,\ M_2,\ \mu,\ \tan\beta, m_{\tilde{\mu}_L},\ m_{\tilde{\mu}_R}$

MSSM parameter scan

$$12.6 \times 10^{-10} < \Delta a_\mu < 44.6 \times 10^{-10} \quad (2\sigma)$$
$$20.6 \times 10^{-10} < \Delta a_\mu < 36.6 \times 10^{-10} \quad (1\sigma)$$

$0 < M_1 < 1\,\text{TeV}$
$0 < M_2 < 1\,\text{TeV}$
$0 < M_{2SL} < 1\,\text{TeV}$
$0 < M_{2SE} < 1\,\text{TeV}$
$0 < \mu < 1\,\text{TeV}$

$\tan\beta = 10$
$\tan\beta = 50$

Parameter Space Decomposition

$M_2/\mu \geq 2,$
$M_2/\mu \leq 0.2,$
$0.2 < M_2/\mu < 2,$

Parameters Scanned

$m_{\tilde{\mu}_{1,2}} > 100\,\text{GeV}$
$M_{\tilde{\chi}_1^\pm} > 105\,\text{GeV}$

LEP bound

FeynHiggs

MSSM parameter scan

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$$\tan\beta = 50$$

Parameter Space Decomposition

Neutralino2 Composition :
Higgsino
Wino
Wino-Higgsino

$$M_2/\mu \geq 2,$$
$$M_2/\mu \leq 0.2,$$
$$0.2 < M_2/\mu < 2,$$

$$m_{\tilde{\mu}_{1,2}} > 100\,\text{GeV}$$
$$M_{\tilde{\chi}_1^\pm} > 105\,\text{GeV}$$

FeynHiggs

Results - I

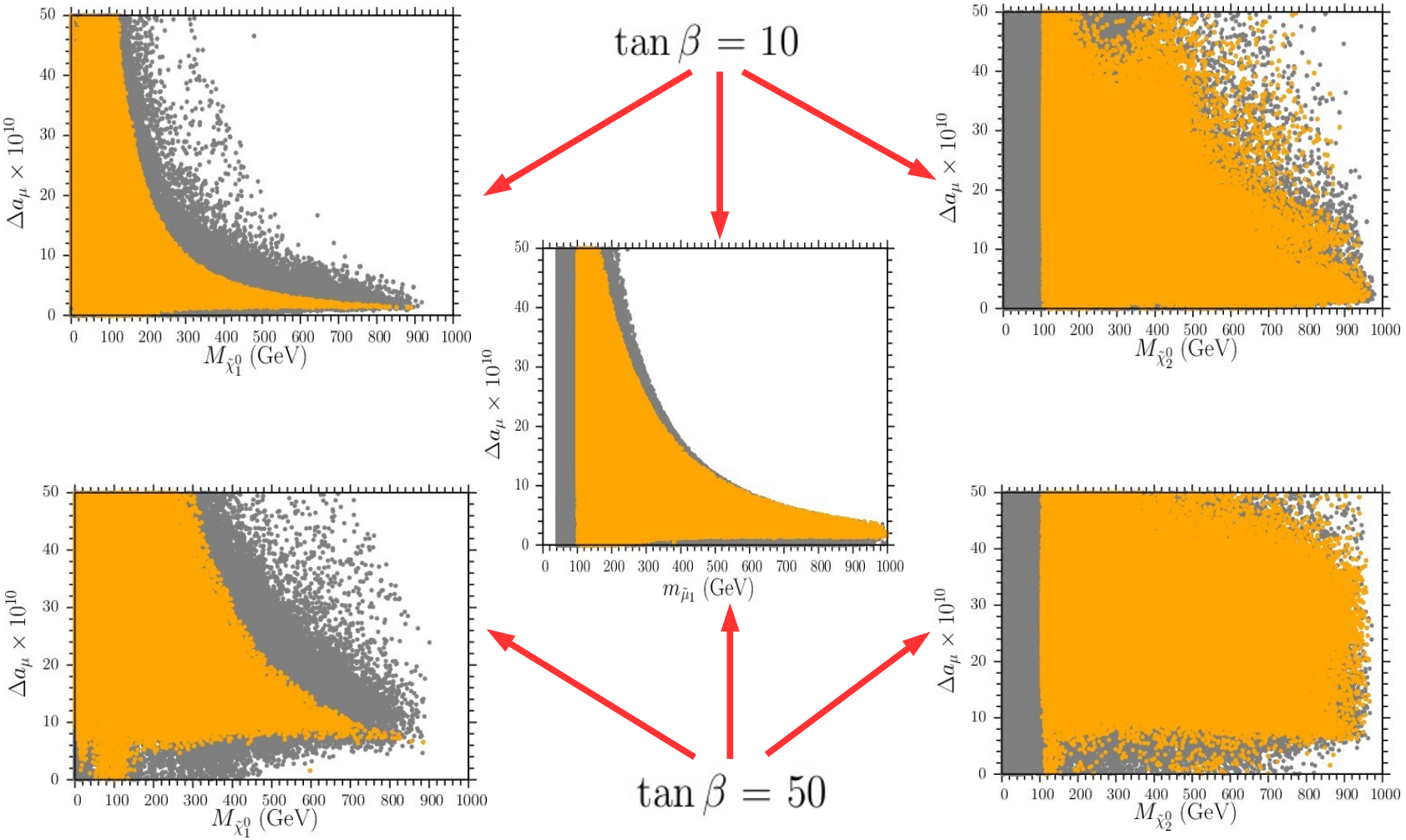
$\tan\beta = 10$

	Region-I	Region-II	Region-III
$m_{\tilde{\mu}_1}$	298.63 (426.84)	227.97 (306.81)	338.01 (470.12)
$m_{\tilde{\mu}_2}$	1000.67 (1000.79)	999.40 (999.61)	1000.58 (1000.73)
$m_{\tilde{\chi}_1^0}$	163.94 (218.31)	178.63 (192.12)	198.03 (259.97)
$m_{\tilde{\chi}_2^0}$	488.30 (488.30)	687.26 (907.32)	886.93 (886.93)
$m_{\tilde{\chi}_1^\pm}$	487.54 (487.54)	196.22 (196.22)	886.94 (886.94)
$m_{\tilde{\chi}_2^\pm}$	1008.63 (1008.63)	1006.75 (1006.75)	1029.14 (1029.14)

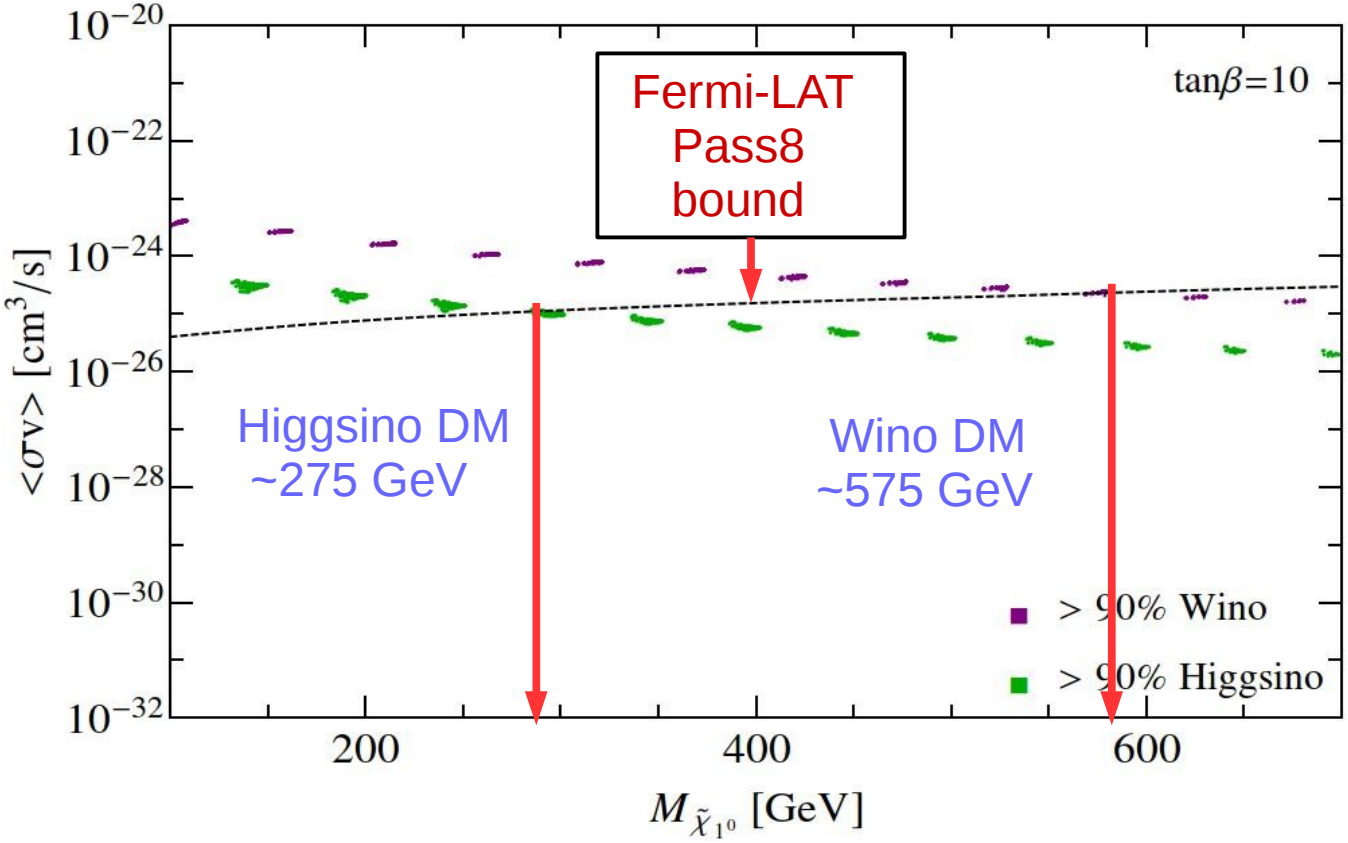
$\tan\beta = 50$

	Region-I	Region-II	Region-III
$m_{\tilde{\mu}_1}$	911.78 (992.38)	715.16 (904.52)	957.74 (996.20)
$m_{\tilde{\mu}_2}$	1000.88 (1000.88)	1000.92 (1000.92)	1000.86 (1000.93)
$m_{\tilde{\chi}_1^0}$	390.05 (478.42)	197.71 (197.71)	482.08 (637.11)
$m_{\tilde{\chi}_2^0}$	477.76 (491.96)	963.56 (963.56)	947.02 (966.17)
$m_{\tilde{\chi}_1^\pm}$	477.19 (487.97)	197.95 (197.95)	910.37 (939.92)
$m_{\tilde{\chi}_2^\pm}$	1007.69 (1007.89)	1006.65 (1006.65)	1033.37 (1055.87)

Results - II

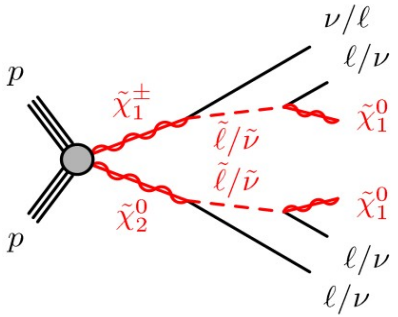

$\tan\beta = 10$
$\tan\beta = 50$
$\Delta a_\mu \times 10^{10}$
$M_{\tilde{\chi}_1^0}$ (GeV)
$M_{\tilde{\chi}_2^0}$ (GeV)
$m_{\tilde{\mu}_1}$ (GeV)

Dwarf Galaxies constraint on the LSP Mass



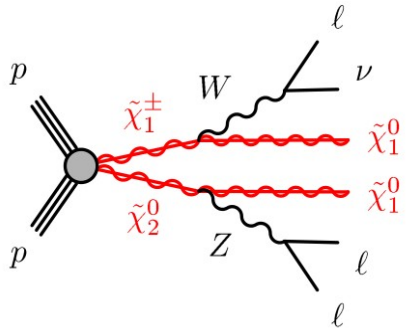
Search for Long-Lived Charged Particle at the LHC
Wino-type Chargino bound ~ 620 GeV
[arXiv:1411.6795]

Electroweakino and Smuon production and current bounds at the LHC



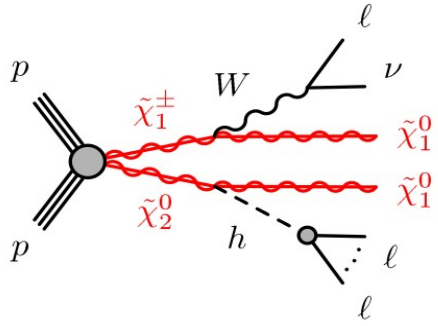
(a) $\tilde{\ell}_L$-mediated

$$m_{\tilde{l}} = (M_{\tilde{\chi}_1^0} + M_{\tilde{\chi}_2^0})/2$$
$$M_{\tilde{\chi}_2^0} \sim 730 \text{ GeV}$$
$$M_{\tilde{\chi}_1^0} \sim 0 - 350 \text{ GeV}$$



(c) WZ-mediated

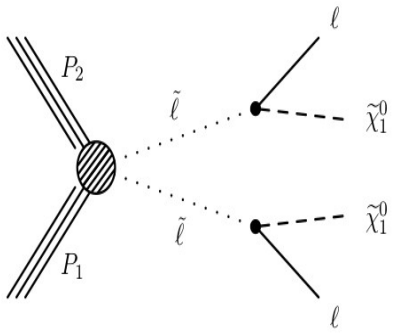
$$M_{\tilde{\chi}_2^0} \sim 425 \text{ GeV}$$
$$M_{\tilde{\chi}_1^0} = 0 \text{ GeV}$$



(d) Wh-mediated

$$M_{\tilde{\chi}_2^0} \sim 270 \text{ GeV}$$
$$M_{\tilde{\chi}_1^0} = 0 \text{ GeV}$$

$$m_{\tilde{l}_R} \sim 250 \text{ GeV}$$
$$M_{\tilde{\chi}_1^0} = 0 \text{ GeV}$$



$$m_{\tilde{l}_L} \sim 330 \text{ GeV}$$
$$M_{\tilde{\chi}_1^0} = 0 \text{ GeV}$$

Search strategy at 14 TeV LHC

- Case-I: M(slepton) > M(neutralino2)

S.Gori, SJung, L.T Wang [arXiv:1307.5952 [hep-ph]]

(i) 50 GeV < ΔM < M_Z : *3 leptons + MET+ 1 jet*

12 GeV < M_{ll}(OSSF) < 50 GeV

Boost

(ii) ΔM > M_Z : *3 leptons + MET, 2 leptons + 2 jets+MET*

MET > 200 GeV

Δφ(MET, 3rd lepton) > 1

40 GeV < M_T < 150 GeV

$$M_T = \sqrt{2\not{E}_T p_{T_l}(1-\cos(\Delta\phi_{l,\not{E}_T}))}$$

- Case-II: M(slepton) < M(neutralino2)

3 leptons + MET

MET > 200 GeV

p_T (l_1) > 30-100 GeV

- Sleptons : Extrapolated from Eckel, Ramsey-Musolf, Shepherd, Su [arXiv: 1408.2841 [hep-ph]]

Simulation: MadGraph + Pythia + PGS4

Results

Benchmark Points:
M(LSP) = 150 GeV (Case-I)
150 GeV, 250 GeV (Case-II)

95% CL exclusion limit @ $\sqrt{s} = 14$ TeV and 3000 fb^{-1} of luminosity

$M_{\tilde{\chi}_1^0}$	Region	M_2/μ		$M_{\tilde{\chi}_2^0}$ [GeV]		$m_{\tilde{l}}$ [GeV]	
				$(g-2)_\mu$	LHC	$(g-2)_\mu$	LHC
150	I	2	$m_{\tilde{l}} > M_{\tilde{\chi}_2^0}$	200 (550)	600	270 (520)	775 ($\tilde{l}_L$)
			$m_{\tilde{l}} < M_{\tilde{\chi}_2^0}$	1200 (720)	850		
	II	0.2	$m_{\tilde{l}} > M_{\tilde{\chi}_2^0}$	300 (550)	475	310 (670)	
			$m_{\tilde{l}} < M_{\tilde{\chi}_2^0}$	200 (1200)	1300		670 ($\tilde{l}_R$)
	III	0.75	$m_{\tilde{l}} > M_{\tilde{\chi}_2^0}$	300 (650)	600	300 (620)	
			$m_{\tilde{l}} < M_{\tilde{\chi}_2^0}$	900 (875)	1350		

$\tan\beta = 10$ $\tan\beta = 50$

- Similar conclusions for M(LSP) = 250 GeV (Case-II)
- For higher LSP masses → Compressed Spectra → Difficult to detect (soft leptons)
- Alternative Search Strategies → **VBF** [B.Dutta, T.G et al. [1210.0964, 1411.6043]];
  Monojet [H. Baer et al.[1409.7058], Z. Han et al.[1401.1235,1412.0618], P. Schwaller et al. [1312.7350]]
- Compressed Spectra exclusion limit ~ 250 GeV

Conclusions

Muon *g-2* excess @ 2σ is explaned by MSSM for:

- neutralino1 ~ 650 GeV
- smuon, neutralino2 ~ 1 TeV

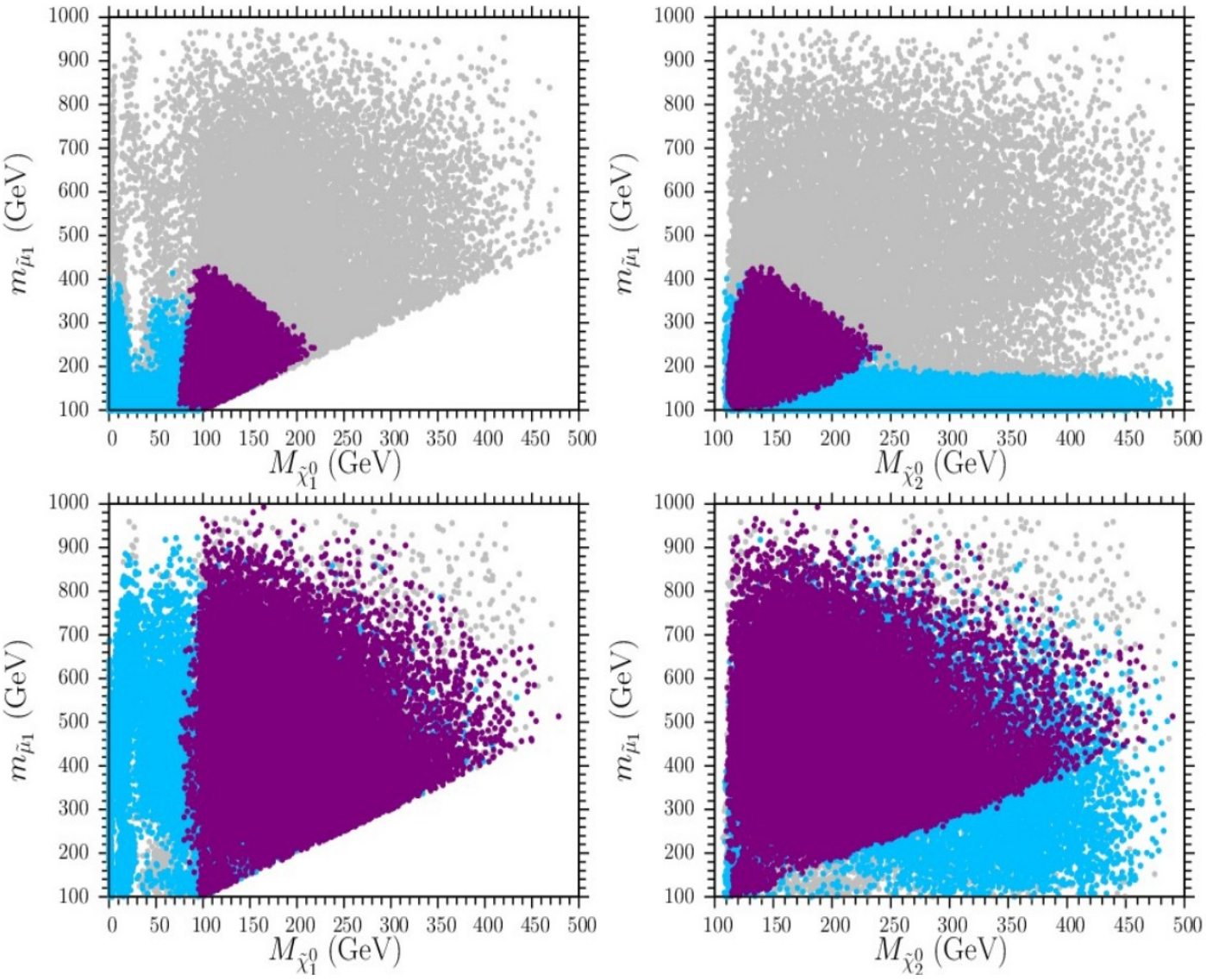
LHC 14 TeV 95% CL exclusion limit with 3000 fb^{-1}:

- neutralino2 ~ 850 GeV (higgsino) – 1300 GeV (wino) $m_{\tilde{l}} < M_{\tilde{\chi}_2^0}$
  450 GeV (wino) – 600 GeV (higgsino) $m_{\tilde{l}} > M_{\tilde{\chi}_2^0}$
- smuon ~ 670 GeV (right) – 775 GeV (left)

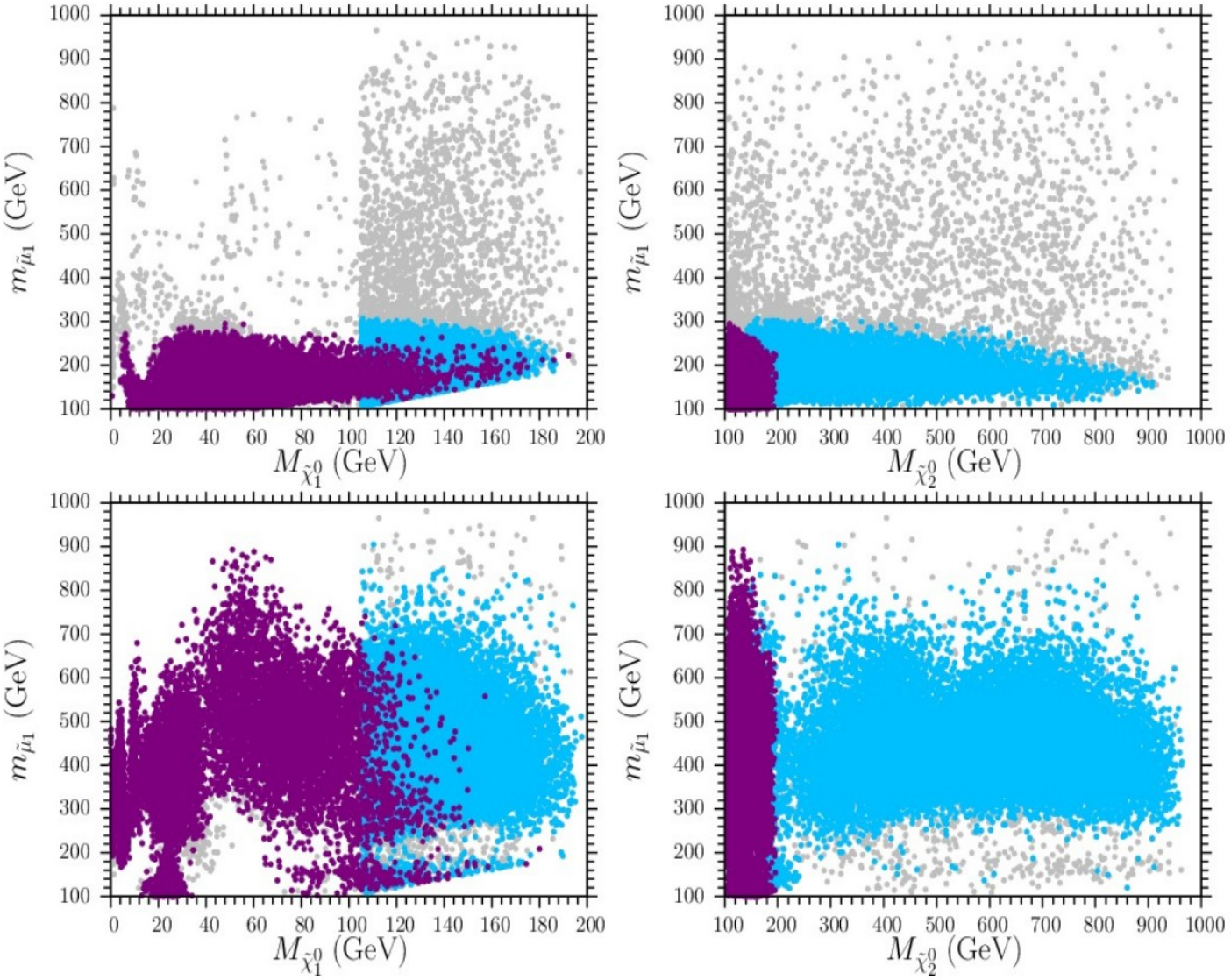
Compressed spectra may remain unprobed

Thank You!

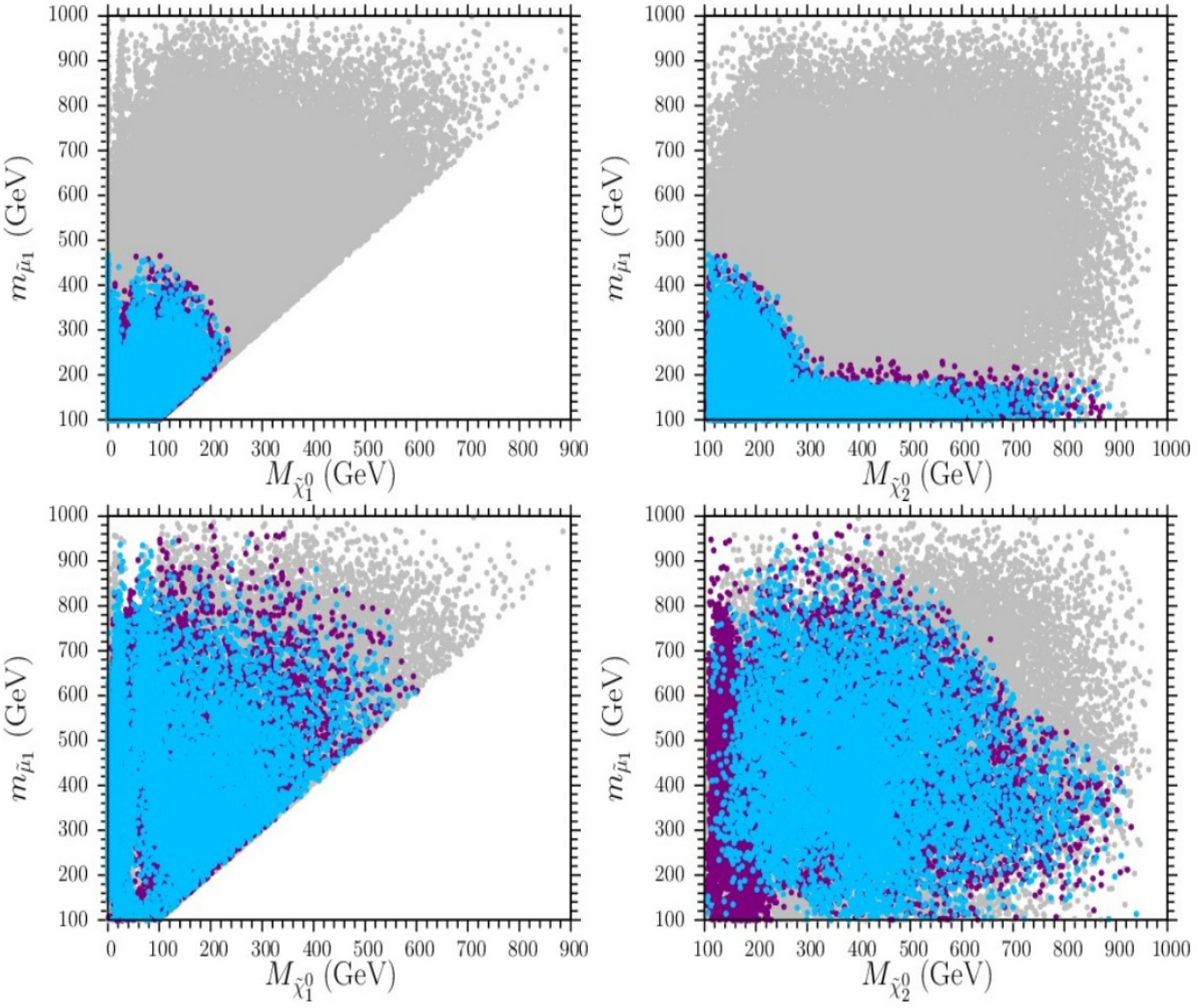
Backup - I



Backup - II



Backup - III



Backup - IV

Region	M_2/μ	$M_{\tilde{\chi}_1^0}$ [GeV]	$\tan\beta$	$M_{\tilde{\chi}_2^0}$ [GeV]	Significance(σ) $\frac{S}{\sqrt{(S+B)}}$
I	2	150	10	200	30.7
			50	300	10.5
				400	6.50
				500	3.67
II	0.2		10	200	124
				250	6.55
			50	300	2.48
				400	2.72
				500	1.78
III	0.75		10	200	53.4
				250	12.6
			50	350	7.14
				500	3.33
				600	1.94

Backup - V

Region	M_2/μ	$M_{\tilde{\chi}_1^0}$ [GeV]	$\tan\beta$	$M_{\tilde{\chi}_2^0}$ [GeV]	Significance(σ) $\frac{S}{\sqrt{(S+B)}}$
I	2	150	10	400	52.9
				500	31.1
				700	7.07
			50	-	-
		250	10	-	-
			50	300	66.4
				400	28.6
				500	23.6
				700	6.94
II	0.2	150	10	-	-
			50	-	-
		250	10	300	56.8
				400	60.7
				500	89.4
				700	56.3
				1000	17.7
			50	-	-
III	0.75	150	10	700	62.8
				900	16.4
			50	-	-
		250	10	300	74.6
			50	500	93.6
				600	78.8
				700	58.7
				800	41.9

Backup - IV

Region	M_2/μ	$M_{\tilde{\chi}_1^0}$ [GeV]	$\tan\beta$	$M_{\tilde{\chi}_2^0}$ [GeV]	Significance(σ) $\frac{S}{\sqrt{(S+B)}}$
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