GUT-inspired SUSY and the muon *g-2* anomaly: prospects for LHC 14 TeV

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Based on

K.Kowalska, L.Roszkowski, E.Sessolo, and AJW
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Outline

- Muon g-2: discrepancy w/ SM and p.s. in the MSSM
- If real, **meaningful consequences for the LHC?**

  – In constrained vs phenomenological models

  – In gravity mediation with non-universal gauginos (NUGM) and GUT symmetries (Full p.s. within LHC 14 TeV!)
- Conclusions

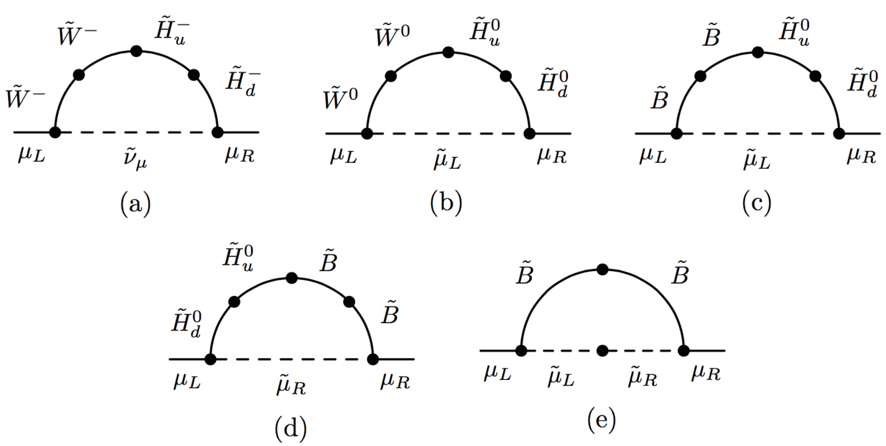
Muon g-2 anomaly

> 3σ discrepancy with the SM:

$$\delta\,(g-2)_\mu = (28.7 \pm 8.0) \times 10^{-10}$$

Can be indication of new physics

e.g. MSSM 1 loop: (T.Moroi, hep-ph/9512393)



$$(a)\ \Delta_{\chi_1^\pm \tilde{\nu}_\mu} = \frac{g^2}{(4\pi)^2} \frac{m_\mu^2 \tan\beta}{\mu M_2} \mathcal{F}_{[\chi_1^\pm \tilde{\nu}_\mu]} \left(\frac{\mu^2}{m_{\tilde{\nu}_\mu}^2}, \frac{M_2^2}{m_{\tilde{\nu}_\mu}^2} \right)$$

$$(b)\ \Delta^{(1)}_{\chi\tilde{\mu}} = -\frac{1}{2} \frac{g^2}{(4\pi)^2} \frac{m_\mu^2 \tan\beta}{\mu M_2} \mathcal{F}_{[\chi\tilde{\mu}]} \left(\frac{\mu^2}{m_{\tilde{\mu}_L}^2}, \frac{M_2^2}{m_{\tilde{\mu}_L}^2} \right)$$

$$(c)\ \Delta^{(2)}_{\chi\tilde{\mu}} = \frac{1}{2} \frac{g'^2}{(4\pi)^2} \frac{m_\mu^2 \tan\beta}{\mu M_1} \mathcal{F}_{[\chi\tilde{\mu}]} \left(\frac{\mu^2}{m_{\tilde{\mu}_L}^2}, \frac{M_1^2}{m_{\tilde{\mu}_L}^2} \right)$$

$$(d)\ \Delta^{(3)}_{\chi\tilde{\mu}} = -\frac{g'^2}{(4\pi)^2} \frac{m_\mu^2 \tan\beta}{\mu M_1} \mathcal{F}_{[\chi\tilde{\mu}]} \left(\frac{\mu^2}{m_{\tilde{\mu}_R}^2}, \frac{M_1^2}{m_{\tilde{\mu}_R}^2} \right)$$

$$(e)\ \Delta^{(4)}_{\chi\tilde{\mu}} = \frac{g'^2}{(4\pi)^2} \frac{m_\mu^2 M_1 \mu}{m_{\tilde{\mu}_L}^2 m_{\tilde{\mu}_R}^2} \tan\beta\, \mathcal{F}_{[\chi\tilde{\mu}]} \left(\frac{m_{\tilde{\mu}_R}^2}{M_1^2}, \frac{m_{\tilde{\mu}_L}^2}{M_1^2} \right)$$

(a) Loop $\chi_1^\pm \tilde{\nu}_\mu$:

Requires "light" winos, higgsino, sneutrinos (< 1TeV)

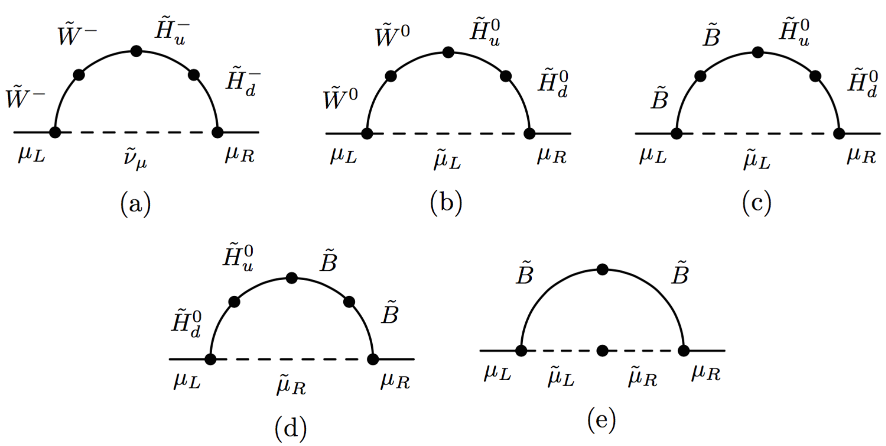
Muon g-2 anomaly

> 3σ discrepancy with the SM:

$$\delta\,(g-2)_\mu = (28.7 \pm 8.0) \times 10^{-10}$$

Can be indication of new physics

e.g. MSSM 1 loop: (T.Moroi, hep-ph/9512393)



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(b)-(e) Loops $\chi_1^0 \tilde{\mu}^\pm$:

Requires "light" smuons and light bino or wino, higgsinos can be heavy

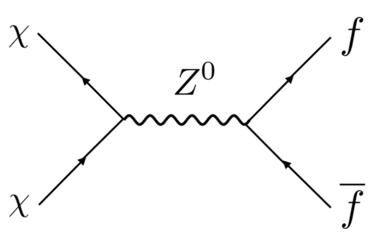
MSSM: Other constraints

A solution to the muon g-2 anomaly in the MSSM should be in agreement with other experimental constraints and expectations for DM:

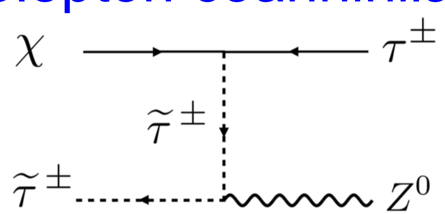
Key Constraints

- The Higgs mass at 125 GeV
- LHC direct bounds on sparticles
- The lightest neutralino as (part of) dark matter (limited # of mechanisms make this possible):

Z/h resonance



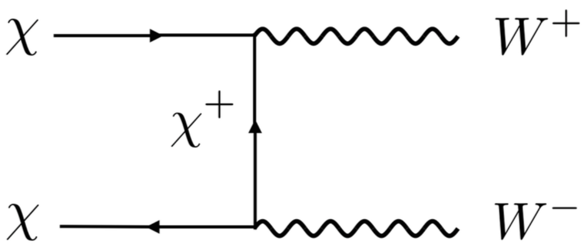
Slepton coannihilation



Mixed bino/higgsino

Pure higgsino

Pure wino $\Omega_\chi h^2 < 0.12$



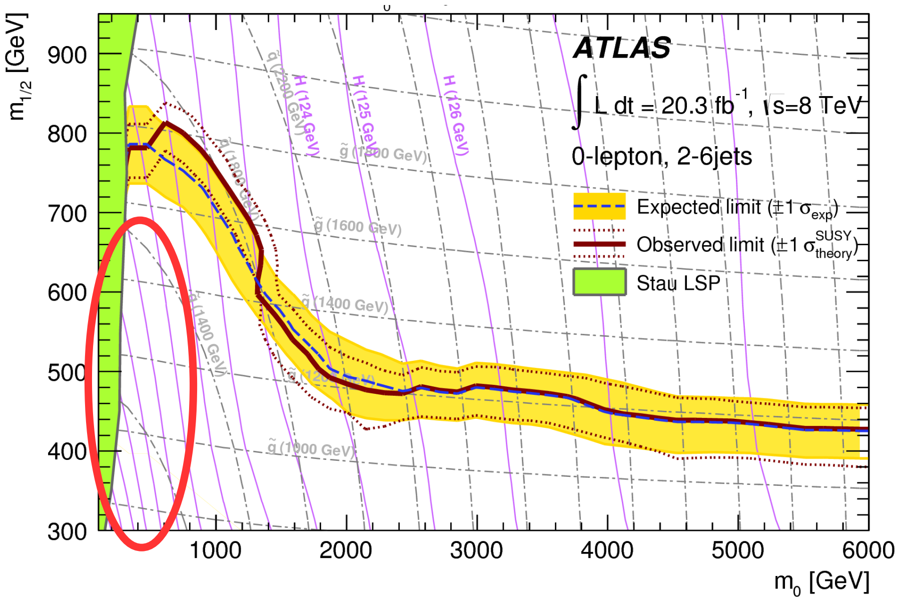
Scenarios consistent with *g-2* tested / testable at the LHC?

Extreme cases: from "no solution" to "too much freedom"

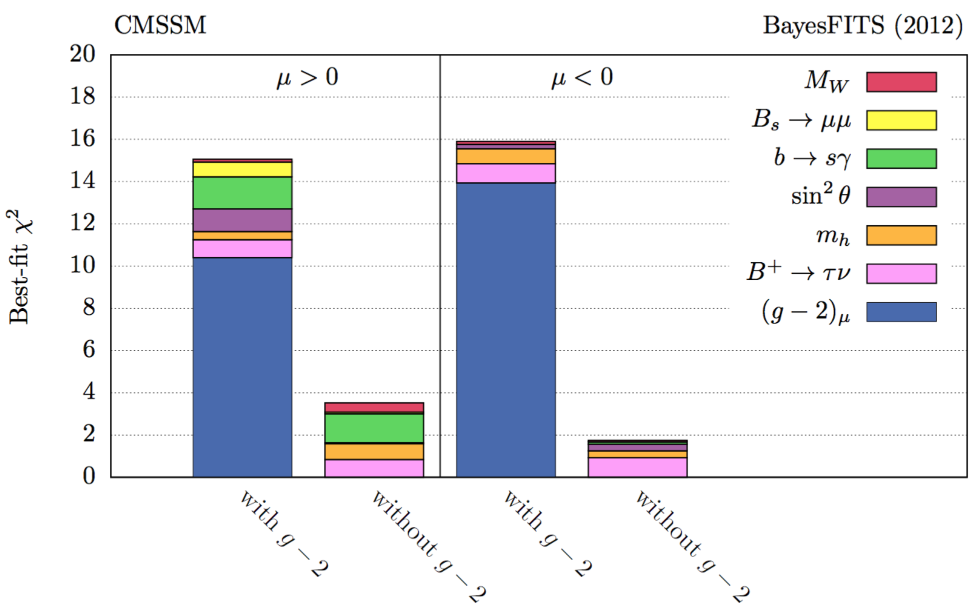
- CMSSM / NUHM

$m_0, m_{1/2}, A_0, \tan\beta, \mathrm{sgn}(\mu)$

Combination of Higgs mass value and LHC direct squark/gluino bounds => No solution left for g-2



g-2 region



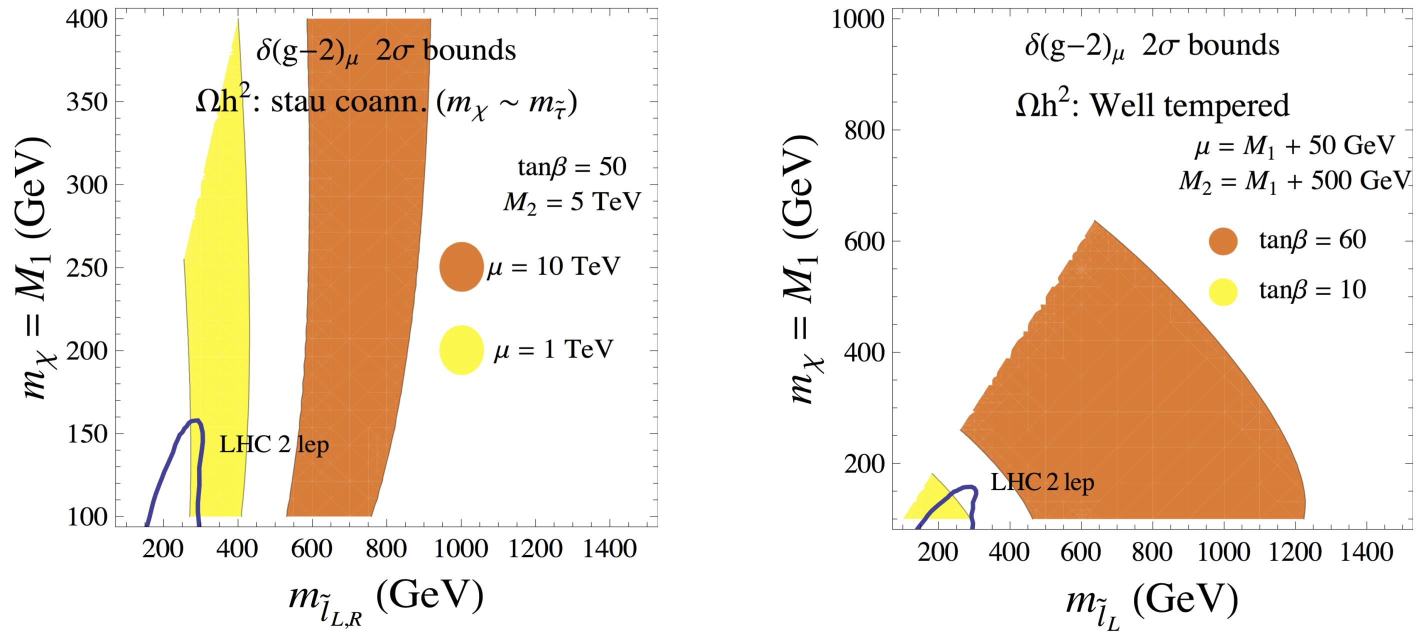
Extreme cases: from “no solution” to “too much freedom”

- pMSSM

19 free parameters

Plenty of parameter space still available =>
Limited predictivity at the LHC 14 TeV

Dark matter from Slepton, sneutrino coannihilations:
Chargino mass, slepton mass outside LHC reach



Dark matter from Well tempered, pure winos, pure higgsinos:
Compressed spectra, outside 14 TeV reach...

$$m_{\chi_1^\pm} \approx m_\chi$$

Intermediate possibility

- Gravity mediation with **gaugino non-universality** interesting possibility

$$\mathcal{L} \sim \frac{F_{ab}}{M_{Pl}} \lambda_a \lambda_b \qquad \lambda_a \lambda_b \sim (\mathbf{24} \times \mathbf{24})_{\text{sym}} = \mathbf{1} + \mathbf{24} + \mathbf{75} + \mathbf{200}$$

At the GUT scale:

$$M_3 \gg M_1, M_2$$

At the SUSY scale:

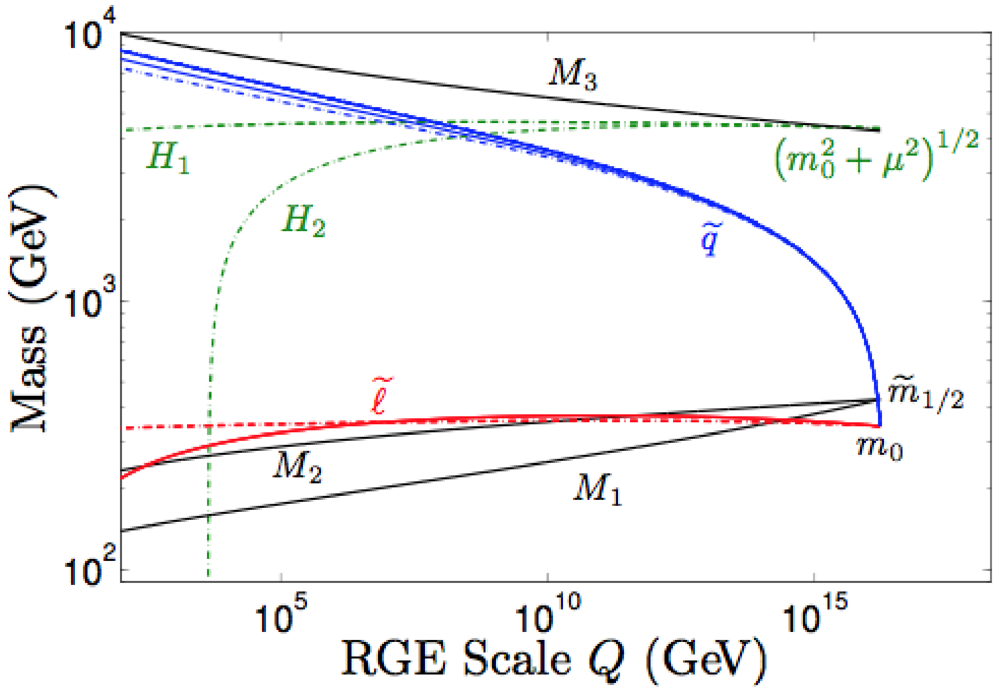
Color sector becomes heavy

- Fits the Higgs
- Evades LHC sq/gluino bounds

Noncolor sector remains light

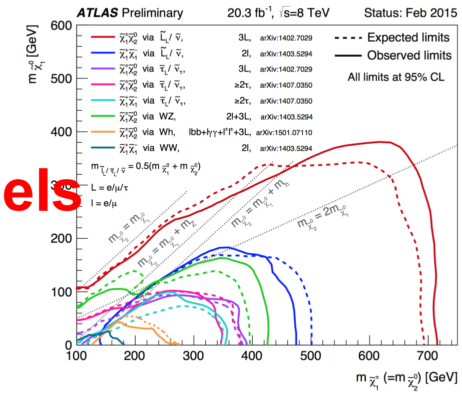
- Fits g-2

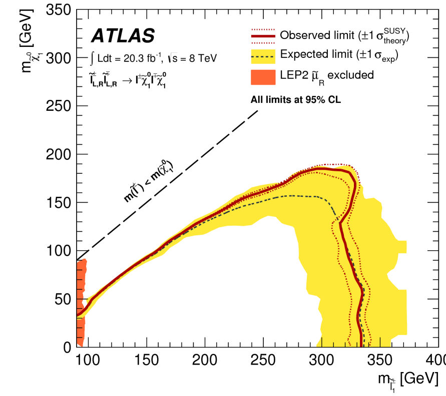
(see, e.g., Akula and Nath, 1304.5526)

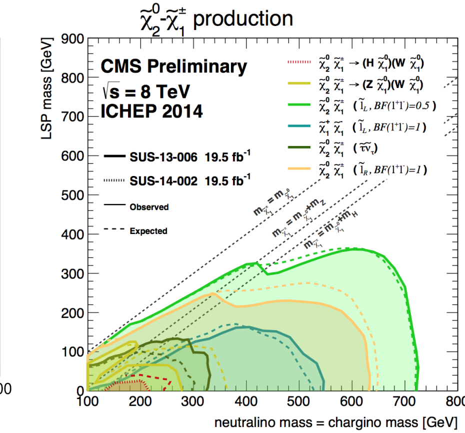


Simulation of LHC bounds and projections

8 TeV LHC bounds:
Recast existing searches for new models







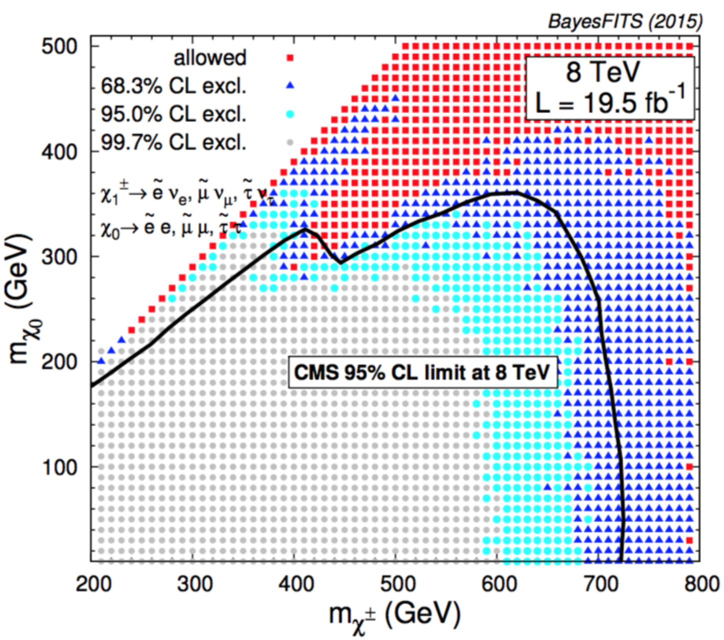
- ATLAS 3 lepton
- ATLAS 2 lepton

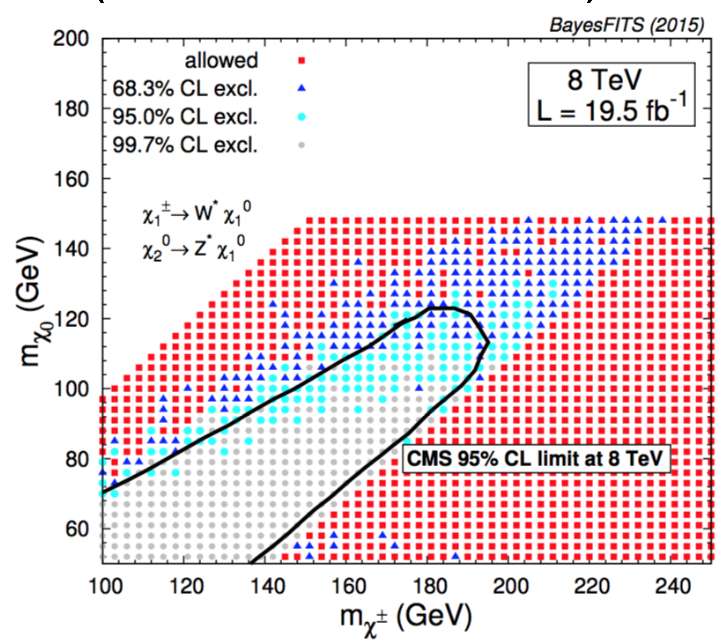
We use CheckMATE

Drees, Dreiner, Schmeier, Tattersall, Kim (1312.2591)

- CMS 3 lepton

We use our own code, **produces point by point likelihood function** (validated down here)





Simulation of LHC bounds and projections

14 TeV LHC 300/fb:

Simulate SM backgrounds to 3 lepton and 2 lepton searches
Compare to signal point by point

3 lepton: 3×10^5 rare SM

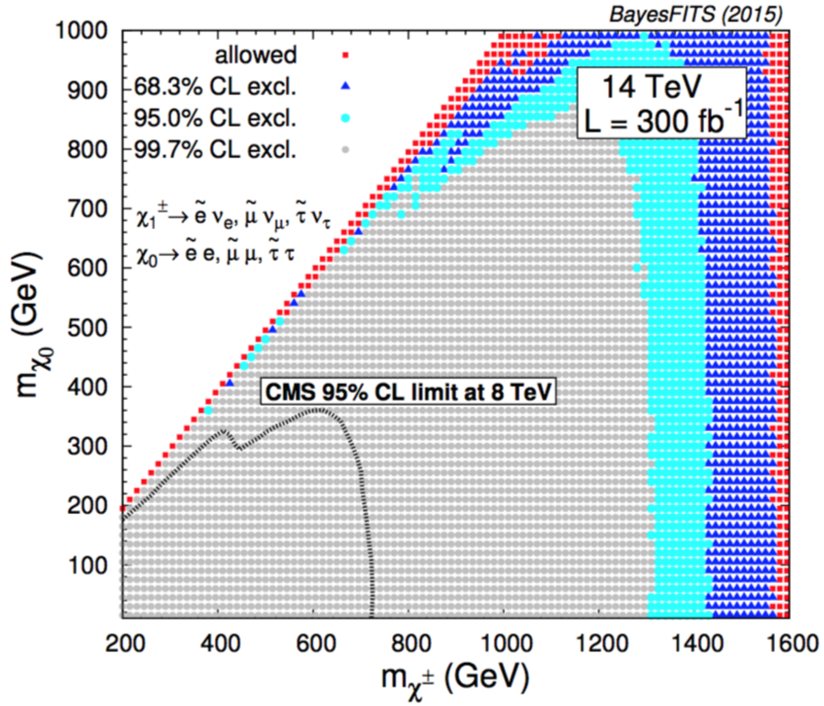
$1.5 \times 10^6 \; t\bar{t} \quad 2 \times 10^5 \; WZ$

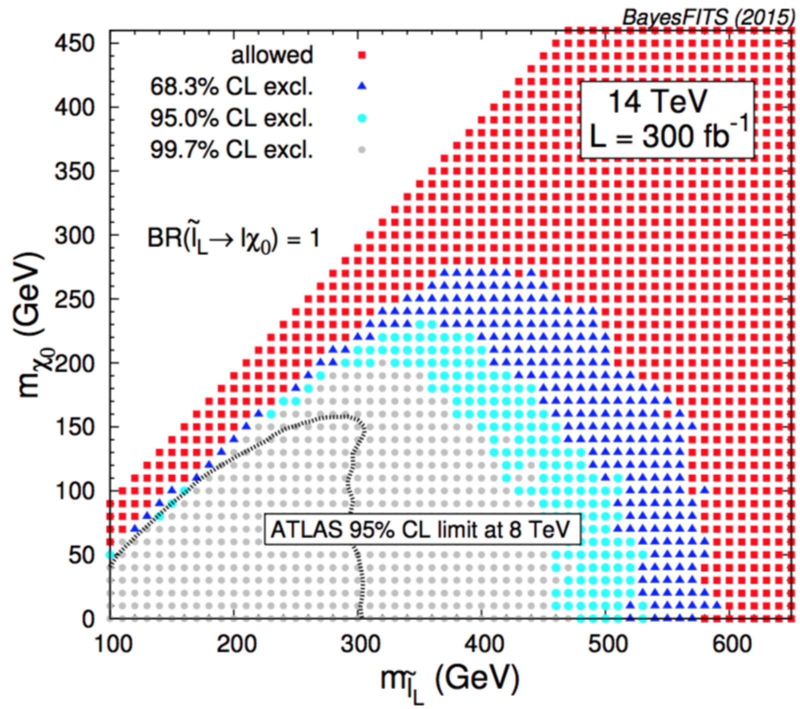
2 lepton: $10^6 \; W^+W^-$

$1.5 \times 10^6 \; t\bar{t} \quad 10^6 \; ZZ$

MadGraph5_aMC@NLO → PYTHIA8 → DELPHES 3

Example: apply to simplified models to get a sense of reach:





Scans: GUT NUGM models

Model 1
Extension of the CMSSM

$$m_0, m_{1/2}, M_3, A_0, \tan\beta, \mathrm{sgn}(\mu)$$

Model 2
Full gaugino nonuniversality

$$m_0, M_1, M_2, M_3,$$
$$A_0, \tan\beta, \mathrm{sgn}(\mu)$$

Model 3
SO(10)-like GUT scale b.c.

$$m_{1/2}, M_3, A_0, \tan\beta, \mathrm{sgn}(\mu)$$

$$m_Q^2 = m_U^2 = m_E^2 \equiv m_{16}^2 + M_D^2$$
$$m_D^2 = m_L^2 \equiv m_{16}^2 - 3M_D^2$$
$$m_{H_{u,d}}^2 \equiv m_{10}^2 \mp 2M_D^2$$

Model 4
SU(5)-like / Pati-Salam b.c.

$$m_{1/2}, M_3, m_{H_d}^2, m_{H_u}^2,$$
$$A_0, \tan\beta, \mathrm{sgn}(\mu)$$
$$m_Q^2 = m_U^2 = m_E^2 \equiv m_{10}^2$$
$$m_D^2 = m_L^2 \equiv m_5^2\,,$$

Prior ranges and constraints

Model 1	CMSSM-like M_3 floating	
Parameter	Description	Range
m_0	Universal scalar mass	100, 4000
$m_{1/2}$	Bino/wino soft mass	100, 4000
M_3	Gluino soft mass	700, 10000
A_0	Universal trilinear coupling	-8000, 8000
$\tan\beta$	Ratio of the Higgs vevs	2, 62
$\mathrm{sgn}\,\mu$	Sign of the Higgs/higgsino mass parameter	$+1$
Model 2	**Non-universal gaugino masses**	
M_1	Bino soft mass	-4000, 4000
M_2	Wino soft mass	-4000, 4000
m_0, M_3, A_0, $\tan\beta$, $\mathrm{sgn}\,\mu$	Same as Model 1	Same as Model 1
Model 3	**$SO(10)$-like sfermions**	
m_{16}	Universal scalar mass **16** repr.	100, 4000
m_{10}^2	Universal scalar mass **10** repr.	-10000^2, 10000^2
$3\,M_D^2$	D-term extra $U(1)$	0, $m_{16}^2 - (100\,\mathrm{GeV})^2$
$m_{1/2}$	Bino/wino soft mass	100, 2000
M_3	Gluino soft mass	800, 5000
A_0, $\tan\beta$, $\mathrm{sgn}\,\mu$	Same as Model 1	Same as Model 1
Model 4	**$SU(5)$-like sfermions**	
m_{10}	Universal scalar mass **10** repr.	100, 4000
m_5	Universal scalar mass $\bar{\mathbf{5}}$ repr.	100, 2000
$m_{H_d}^2$	Down Higgs doublet soft mass	-10000^2, 10000^2
$m_{H_u}^2$	Up Higgs doublet soft mass	-10000^2, 10000^2
$m_{1/2}$, M_3, A_0, $\tan\beta$ $\mathrm{sgn}\,\mu$	Same as Model 3	Same as Model 3
Model 4-zoom	**$SU(5)$ μ, m_A parameterization**	
μ	EW-scale higgsino mass parameter	10, 2000
m_A	Pseudoscalar pole mass	100, 4000
M_3	Gluino soft mass	500, 2000
m_{10}, m_5, $m_{1/2}$, A_0, $\tan\beta$	Same as Model 3	Same as Model 3

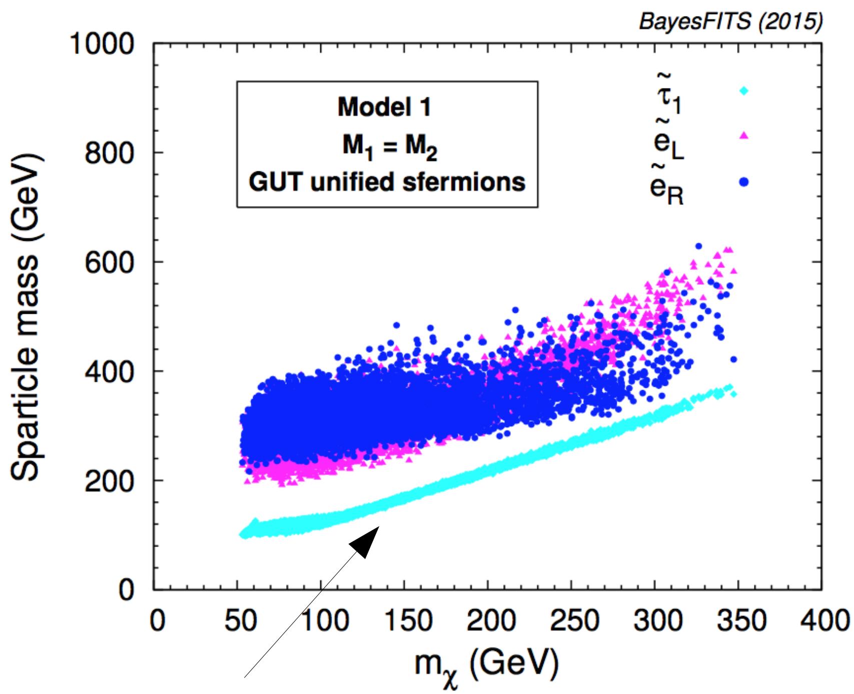
Constraint	Mean	Exp. Error	Th. Error	Ref.
Higgs sector	See text.	See text.	See text.	[86–89]
LUX	See [77, 92].	See [77, 92].	See [77, 92].	[93]
$\Omega_\chi h^2$	0.1199	0.0027	10%	[44]
$\delta\,(g-2)_\mu \times 10^{10}$	28.7	8.0	3.0	[1, 94]
$\sin^2\theta_{\mathrm{eff}}$	0.23155	0.00015	0.00015	[95]
$\mathrm{BR}\,(\overline{\mathrm{B}} \to \mathrm{X_s}\gamma) \times 10^4$	3.43	0.22	0.21	[96]
$\mathrm{BR}\,(\mathrm{B_u} \to \tau\nu) \times 10^4$	0.72	0.27	0.38	[97]
ΔM_{B_s}	17.719 ps^{-1}	0.043 ps^{-1}	2.400 ps^{-1}	[95]
M_W	80.385 GeV	0.015 GeV	0.015 GeV	[95]
$\mathrm{BR}\,(\mathrm{B_s} \to \mu^+\mu^-) \times 10^9$	2.9	0.7	10%	[98, 99]
$\Gamma(Z \to \chi\chi)$	≤ 1.7 MeV	0.3	–	[100]

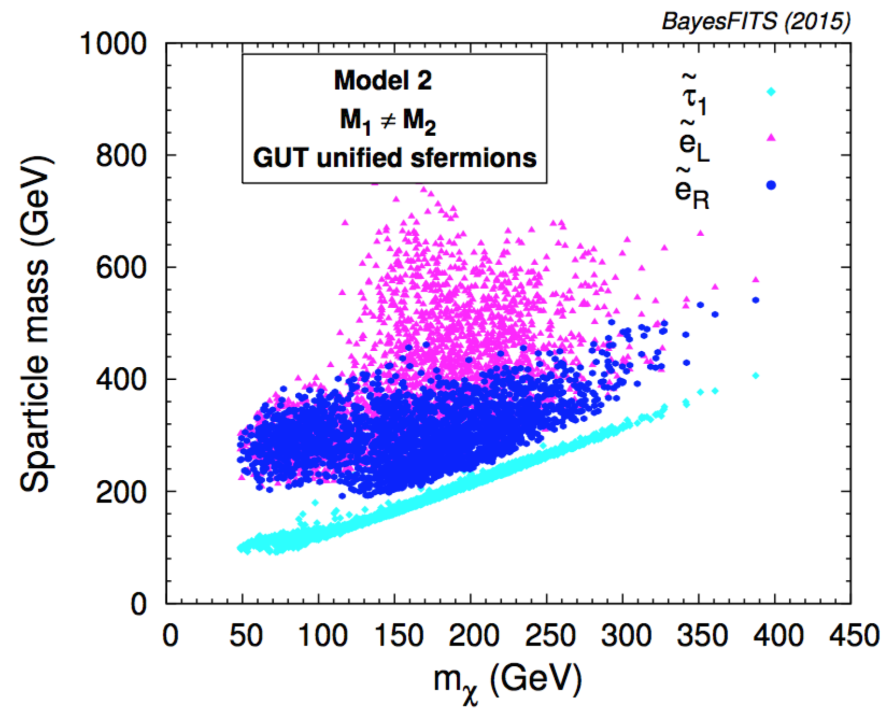
- Broad ranges scanned
- All relevant low energy constraints applied

(For *g*-2 `SuperISO v3.4`)

Models 1-2: Physical mass distribution

Relic density $\Omega_\chi h^2 \simeq 0.12$ affects EW-ino and sfermion sectors:





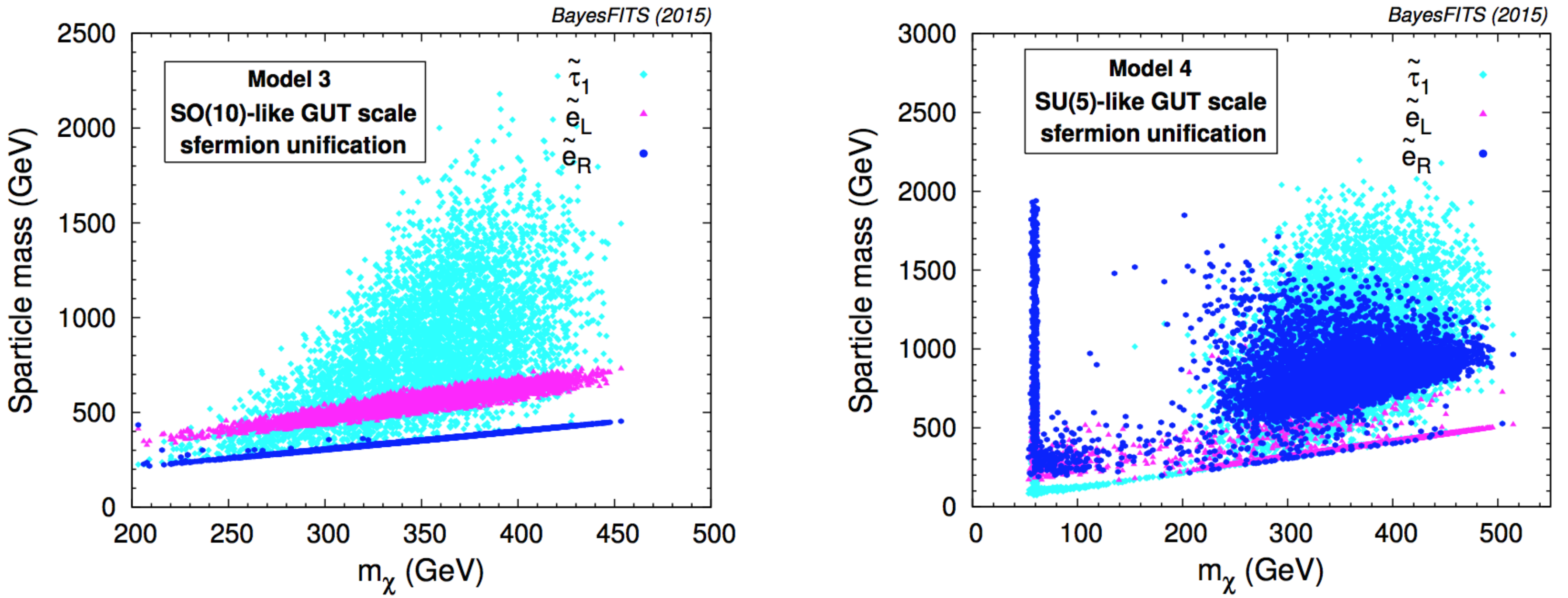
$m_{\tilde{\tau}_1} \gtrsim m_\chi$ (Bulk / stau-coannihilation)

Color sparticles are heavy (as expected):

$$m_{\tilde{t}_1} \simeq 1.5 - 7 \text{ TeV} \qquad m_{\tilde{g}} \simeq 2 - 10 \text{ TeV}$$

Models 3-4: Physical mass distribution

Relic density $\Omega_\chi h^2 \simeq 0.12$ affects EW-ino and sfermion sectors:



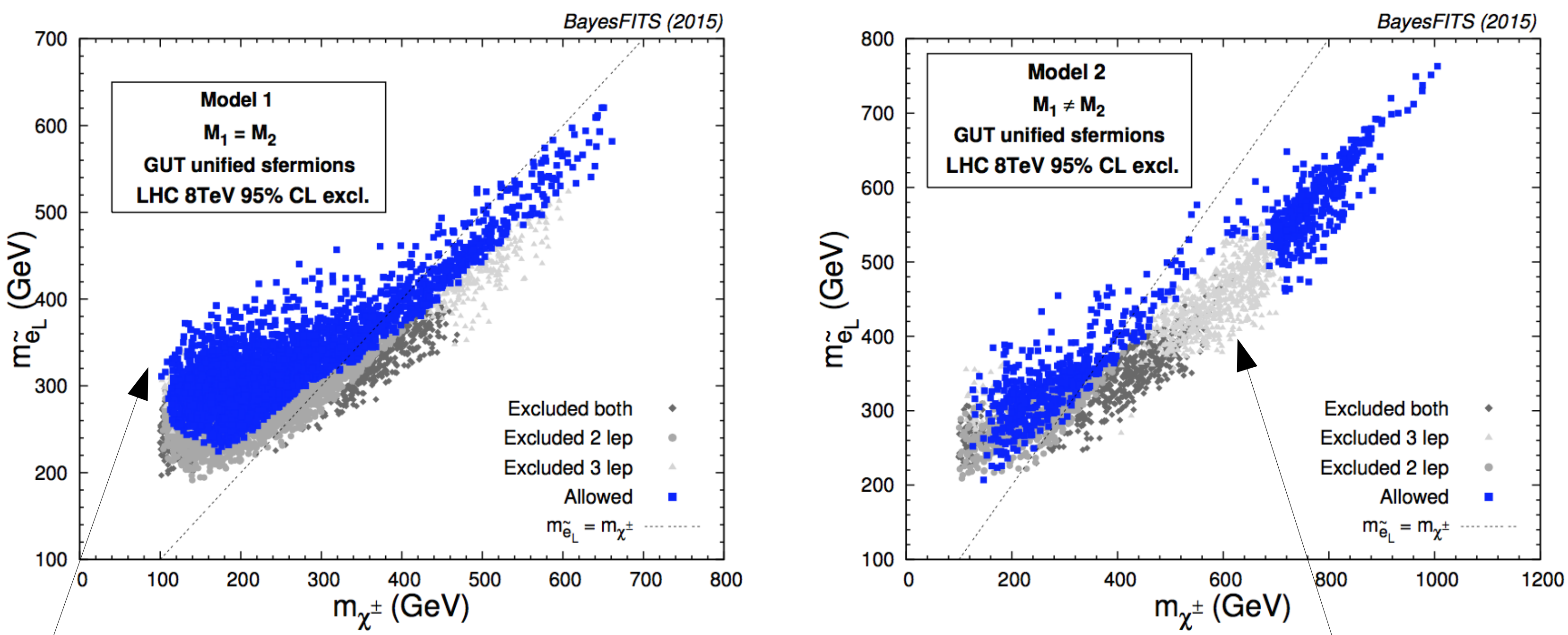
Additional mechanisms: L - R selectron/smuon, or sneutrino coannihilation

Z / *h* resonance

Color sparticles are heavy (as expected):

$$m_{\tilde{t}_1} \simeq 1.5 - 7 \text{ TeV} \qquad m_{\tilde{g}} \simeq 2 - 10 \text{ TeV}$$

Models 1-2: LHC 8 TeV bounds



A lot of available parameter space

~1/3 p.s. excluded already

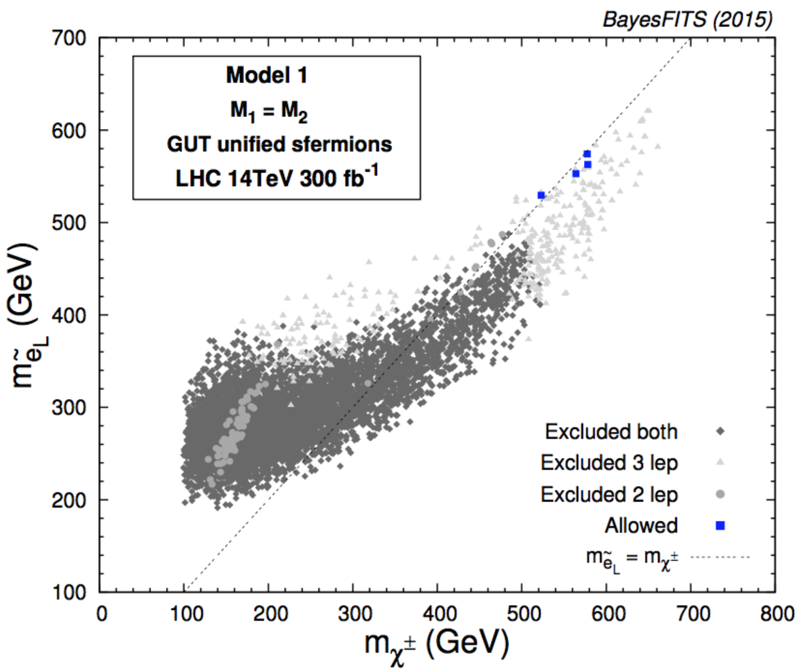
If $M_2 >> M_1$
3 lepton search becomes more effective

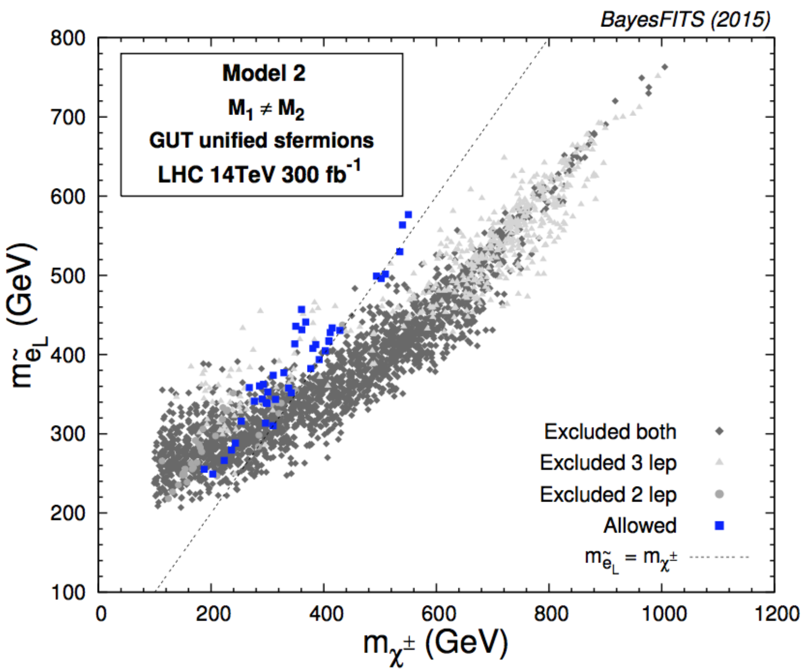
Since $m_{\tilde{l}} > m_{\chi_1^\pm}$

$\tilde{\nu}_l \rightarrow \chi_1^\pm l^\mp$ is most effective channel

(stau coannihilation constrains sleptons)

Models 1-2: 14 TeV 300/fb projection





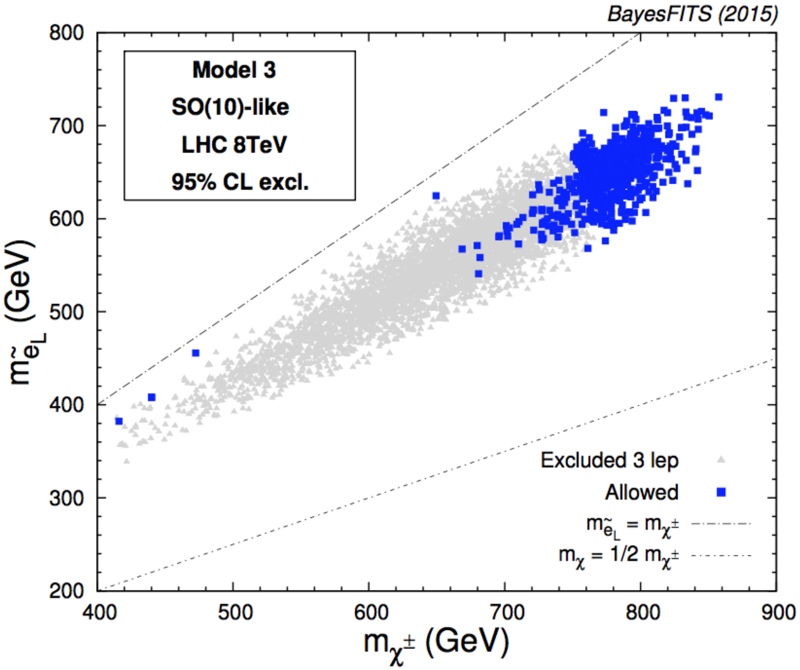
Parameter space almost fully covered!

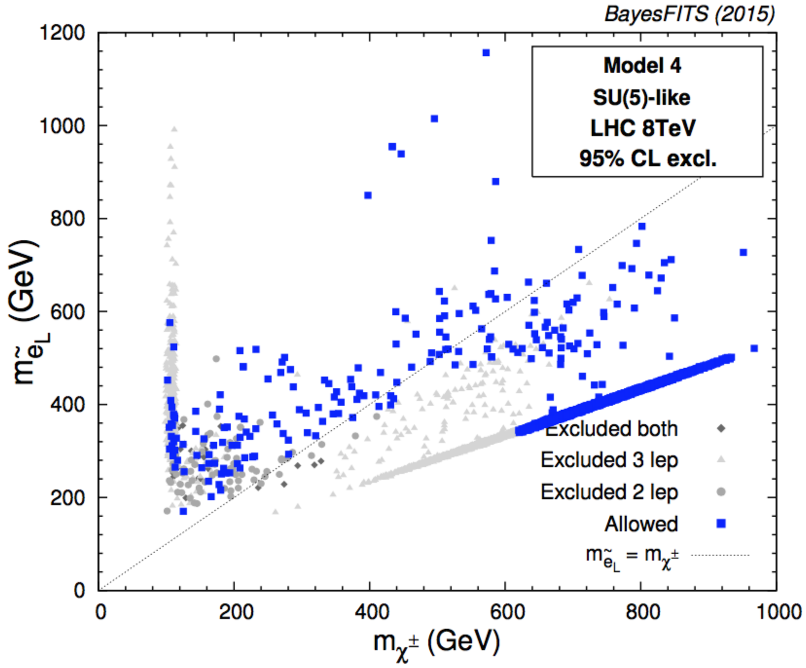
(interplay of different production and decay channels)

A few blind spots (compressed) might escape detection:

$$m_{\tilde{l}_L} \approx m_{\chi_1^\pm} \simeq 500 - 600\,\mathrm{GeV} \qquad m_{\chi_1^\pm} \approx m_{\tilde{l}_L} \approx m_\chi$$

Models 3-4: LHC 8 TeV bounds





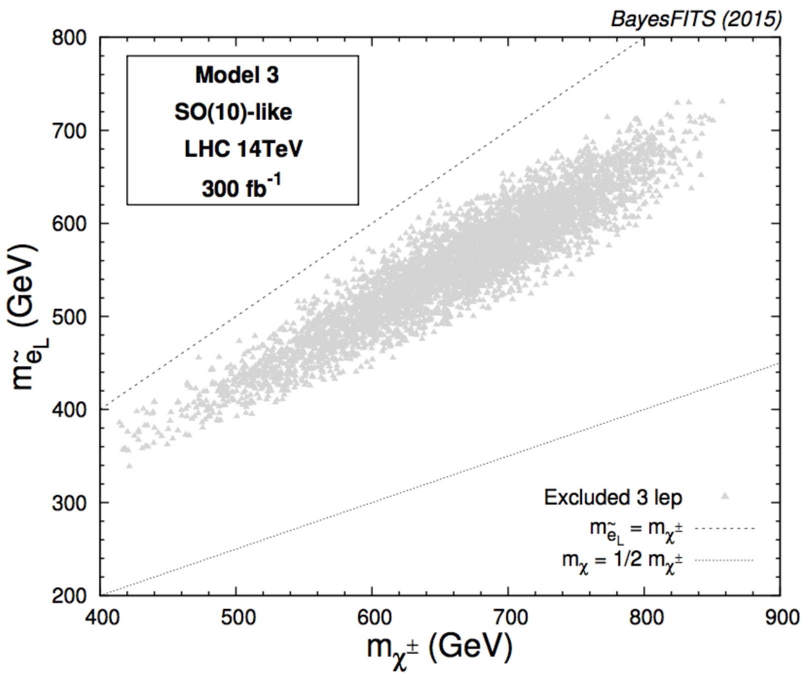
3-lepton search quite effective in placing bounds if $M_2 \sim M_1$

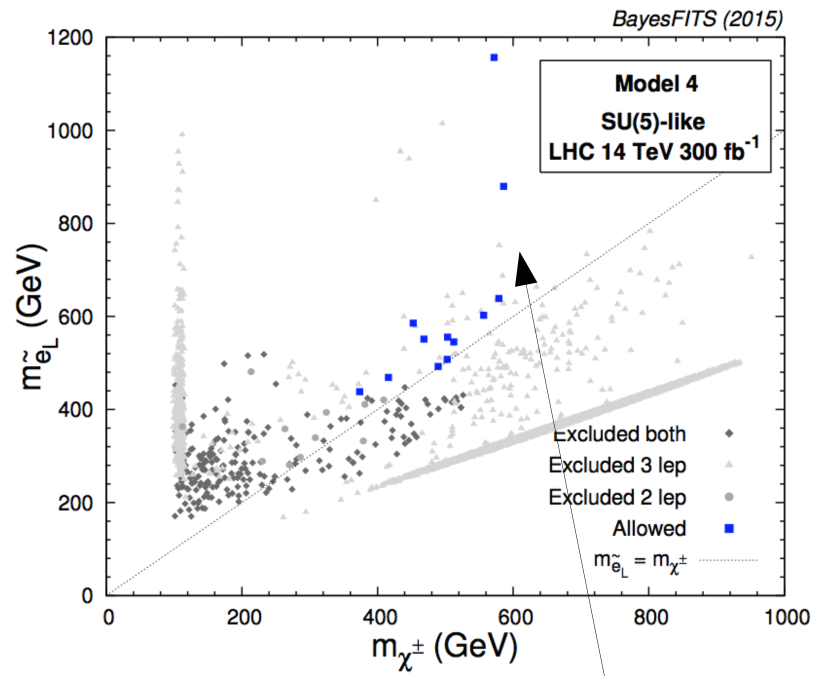
(Sleptons are kept light by requirement of coannihilation)

Channels presently unconstrained:

$$\tilde{\chi}_2^0 \chi_1^\pm \rightarrow \tilde{\tau}_1 \tau \, \tilde{\tau}_1 \nu_\tau \qquad \tilde{\chi}_2^0 \chi_1^\pm \rightarrow \tilde{\nu}_\tau \nu_\tau \, \tilde{\nu}_\tau \tau$$

Models 3-4: 14 TeV 300/fb projection





Parameter space almost fully covered!

(Actually the full p.s. of *SO(10)* is testable with 100-110/fb!)

Some *SU(5)* might remain beyond reach...

...As 3-lepton not very sensitive to decays through Higgs

$$\tilde{\chi}_2^0 \chi_1^\pm \rightarrow h \tilde{\chi}_1^0 \, W^\pm \tilde{\chi}_1^0$$

3000/fb will be enough!

Summary

- Muon g-2 anomaly: easy fit in the MSSM, but one needs more specific theoretical framework for predictable scenarios.
- GUT scale b.c. $M_3 >> M_1$, M_2 fit all constraints well.
- These scenarios only partially constrained at the LHC 8 TeV.
- Almost fully tested at LHC 14 TeV.
- Possible blind spots: Charginos degenerate with left selectrons; no light selectrons, decay involves Higgs; large BR to staus...