

The muon $g-2$ and dark matter in the MSSM at 100 TeV

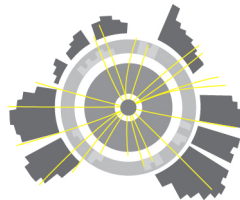
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ARC Centre of Excellence for
Particle Physics at the Terascale

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Introduction

The observation of a Higgs at 125 GeV at LHC has strengthened the need for SUSY to appear at the weak-scale.

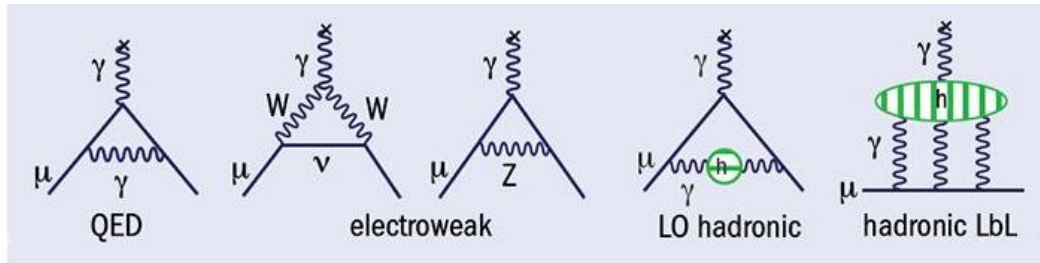
- Tree-level higgs mass prediction $\sim m_Z$
- Existence of electroweakinos (partners of EW gauge bosons)
- μ term predicts masses of higgsinos and must be $< O(\text{TeV})$ for EWSB
- Naturalness/fine-tuning

$$\Delta = \max \left\{ \left| \frac{a_i}{m_Z^2} \frac{\partial m_Z^2}{\partial a_i} \right| \right\} \quad (1)$$

- A light, stable neutralino - great for DM!

The muon $g - 2$

Contributions to the SM:



$$a_\mu \sim 10^{-3}$$

$$\sim 10^{-7}$$

$$\sim 10^{-9}$$

- Main theoretical uncertainty comes from LO Hadronic loop contributions (quarks and gluons)

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

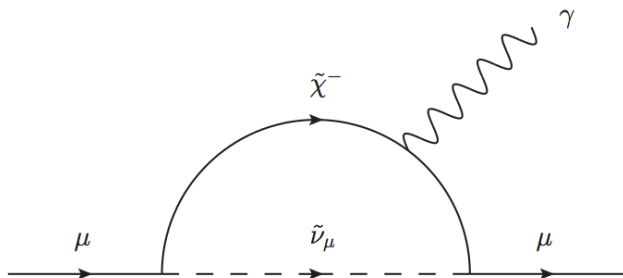
$$12.6 \times 10^{-10} < \Delta a_\mu < 44.6 \times 10^{-10} \quad (2\sigma)$$

where

$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$$

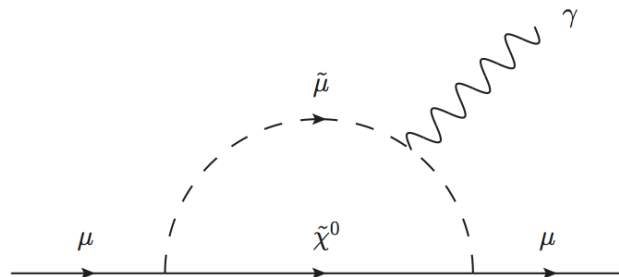
The muon $g - 2$ in SUSY

One-loop contributions come from the following diagrams:



Sneutrino-chargino diagram

- Typically dominant contribution
- Needs light charginos/sneutrinos



Smuon-neutralino diagram

- Bino-smuon loop can be dominant with light binos and large $\tilde{\mu}_{L,R}$ mixing (not favoured by DM constraints, naturalness, vacuum stability)

The muon $g - 2$ in SUSY

Contribution from the MSSM at one-loop:

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

f_χ and f_N are loop functions:

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

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

Explaining the muon $g - 2$ in the MSSM

- The following particles are important in analyzing the $(g - 2)_\mu$ in the MSSM:

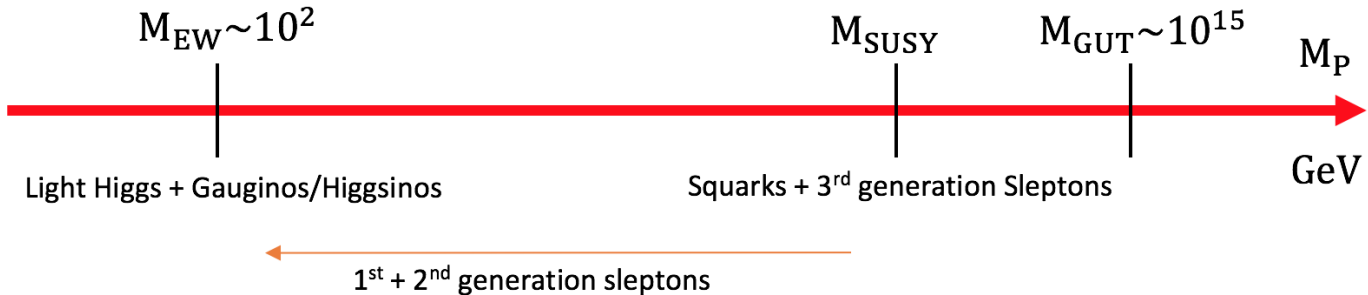
$$\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm \quad (2)$$

- Smuons should be kept light (less than around 500 GeV) to increase contribution to the $(g - 2)_\mu$
- Large $\tan \beta$ and positive μ
- Dark Matter (Direct/Indirect) searches can constrain neutralino LSPs in R-Parity conserving SUSY
- We can place bounds on the neutralino masses that satisfy the $(g - 2)_\mu$ through slepton and chargino searches at colliders

Minimal SUSY mass hierarchy

To explain the muon $g-2$, we separate the electroweakino and sfermion sectors:

- Universal squark and 3rd gen slepton masses decoupled
- Gauginos/higgsinos at weak scale, protected by chiral symmetry
- Light 1st and 2nd generation sleptons allowed by FCNC constraints
→ **muon $g-2$**



Constraints from Experiment

- LEP constraints on chargino and slepton masses:

$$\begin{aligned} m_{\tilde{l}_L}, m_{\tilde{l}_R} &> 100 \text{ GeV} \quad (l = e, \mu) \\ m_{\tilde{\chi}_1^\pm} &> 105 \text{ GeV} \end{aligned}$$

- Constraints on neutralino LSP as a DM candidate:

$$m_{\tilde{\chi}_1^0} > 30 \text{ GeV}$$

- Higgs mass from ATLAS/CMS:

$$123 < m_{h^0} < 127 \text{ GeV}$$

- Higgs precision constraints (LEP, Tevatron and LHC)
- Dark matter relic density (PLANCK 2013)

$$\Omega h^2 = 0.112 \pm 0.006 \quad (1\sigma)$$

- WIMP-nucleon Spin-Independent Cross Section (LUX 2016)

MSSM Parameter Scan

We calculate the $(g - 2)_\mu$ and mass spectrum in the MSSM using FeynHiggs-1.12.0:

- Decoupled Squarks at 5 TeV (Ignore B -Physics constraints)
- Stau sleptons $m_{\tilde{\tau}_L} = m_{\tilde{\tau}_R} = 5 \text{ TeV}$
- Gluino mass $M_3 \sim 3 \text{ TeV}$
- Trilinear coupling A_t in range $|A_t| < 5 \text{ TeV}$ (We keep $|X_t/M_S| < 2$ to avoid charge/colour-breaking minima)
- All other trilinear couplings set to zero
- Rest of higgs sector decoupled by setting $m_{A^0} = 2 \text{ TeV}$

MSSM Parameter Scan

Parameter scan range:

$$10 < \tan(\beta) < 50,$$

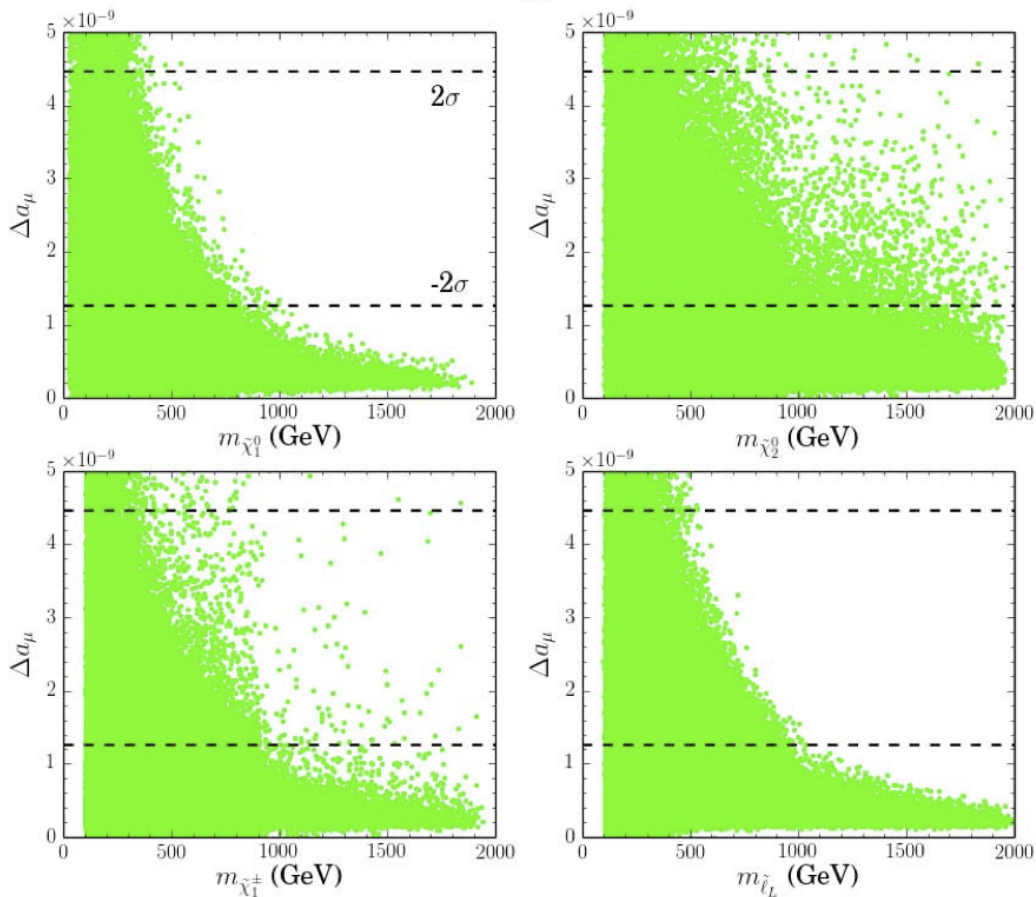
$$|M_1|, |M_2|, |\mu| < 2 \text{ TeV},$$

$$0.1 < m_{\tilde{l}_L}, m_{\tilde{l}_R} < 2 \text{ TeV}, \quad (l = e, \mu)$$

SUSY spectrum calculated in FeynHiggs, precision constraints in HiggsBounds-4.2.1. MicrOmegas to calculate DM relic density and SI WIMP-nucleon CS.

Limits on neutralinos, charginos and smuons

LEP+Higgs data



Neutralino mass mixing

Every neutralino is a very important combination of the gauge eigenstates:

$$\mathcal{L}_{neutralino} = -\frac{1}{2} \begin{pmatrix} \tilde{B} \\ \tilde{W} \\ \tilde{H}_d \\ \tilde{H}_u \end{pmatrix} \mathcal{M}_{\chi^0} \begin{pmatrix} \tilde{B} & \tilde{W} & \tilde{H}_d & \tilde{H}_u \end{pmatrix} + c.c.$$

MSSM neutralino mass mixing matrix:

$$\mathcal{M}_{\chi^0} = \begin{pmatrix} M_1 & 0 & -g'v_d/\sqrt{2} & g'v_u/\sqrt{2} \\ 0 & M_2 & gv_d/\sqrt{2} & -gv_u/\sqrt{2} \\ -g'v_d/\sqrt{2} & -gv_d/\sqrt{2} & 0 & -\mu \\ g'v_u/\sqrt{2} & -gv_u/\sqrt{2} & -\mu & 0 \end{pmatrix}$$

If R-parity is conserved, the lightest neutralino χ_1^0 is a good dark matter candidate!

Neutralino components and Dark Matter

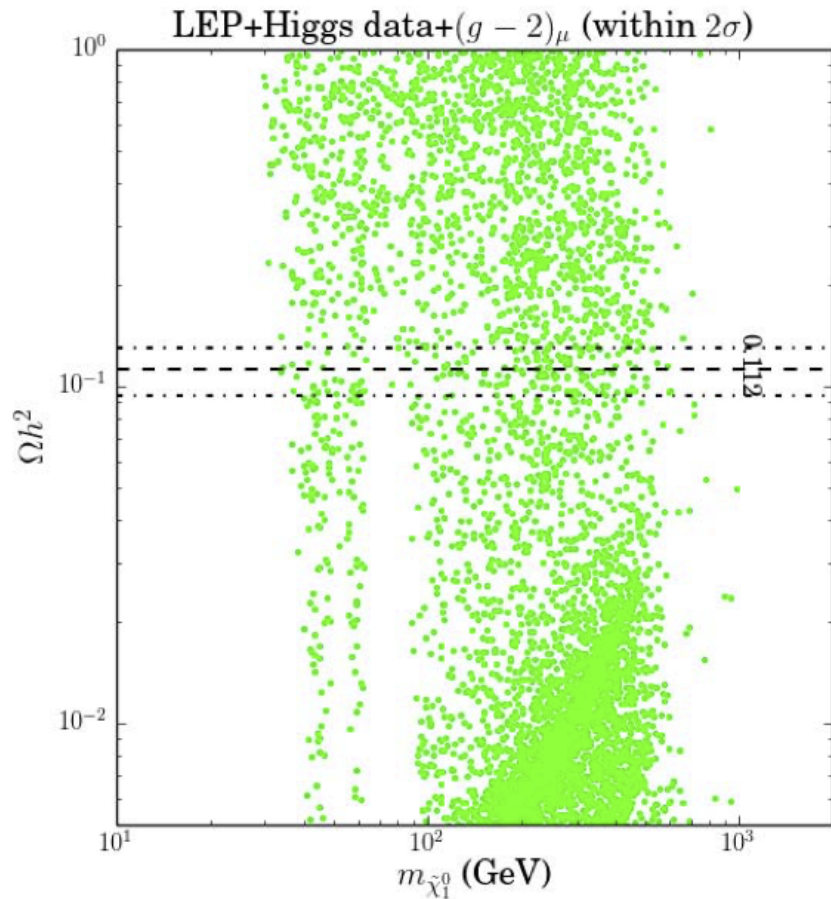
If the LSP component has...

- $M_1 \ll M_2, \mu$ then χ_1^0 is **Bino-like**
- $M_2 \ll M_1, \mu$ then χ_1^0 is **Wino-like**
- $\mu \ll M_1, M_2$ then χ_1^0 is **Higgsino-like**

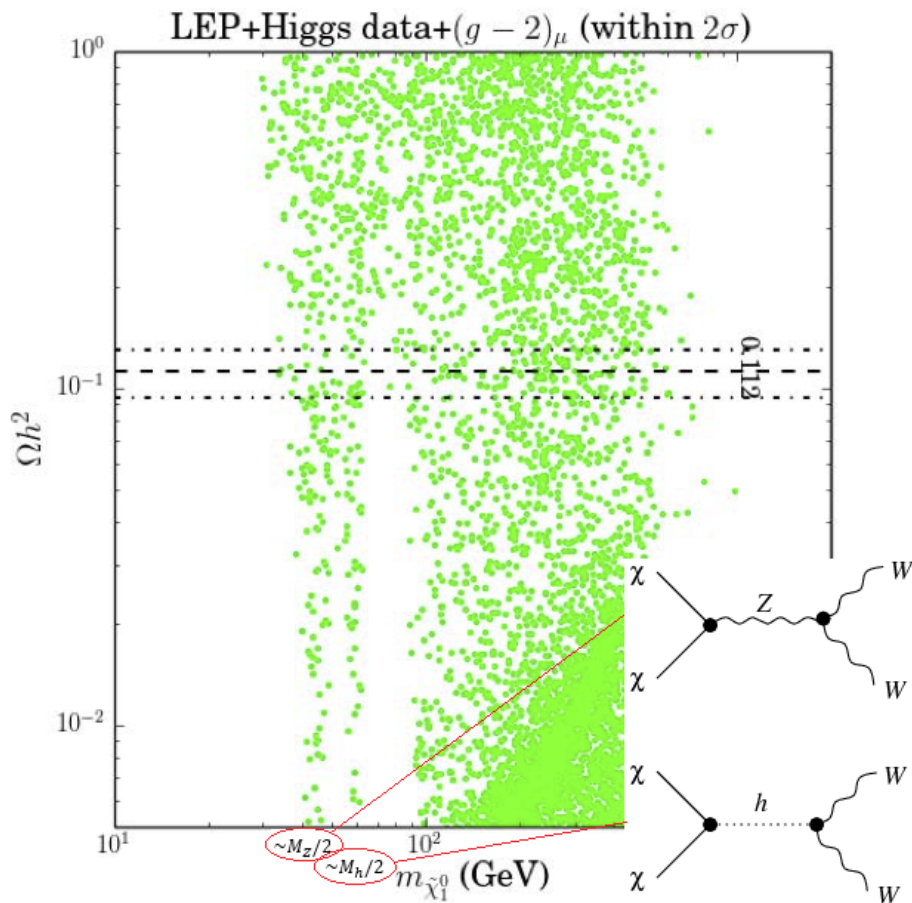
Dark Matter constraints on χ_1^0 vary for different compositions of Bino, Wino and Higgsinos:

- It is well known that pure Bino-like DM relics are typically overabundant, except in the case where the bino co-annihilates with other sparticles
- We can enhance the annihilation rate with a wino or higgsino component in χ_1^0
- To avoid significant constraint, for any LSP abundance less than the relic density, we assume additional DM component (possibly axion-like DM)

Relic Density, Ωh^2



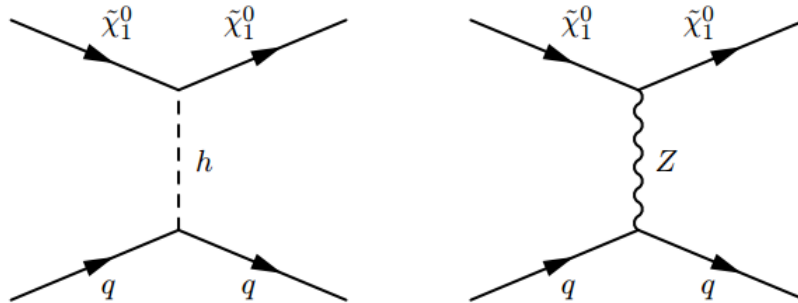
Relic Density, Ωh^2



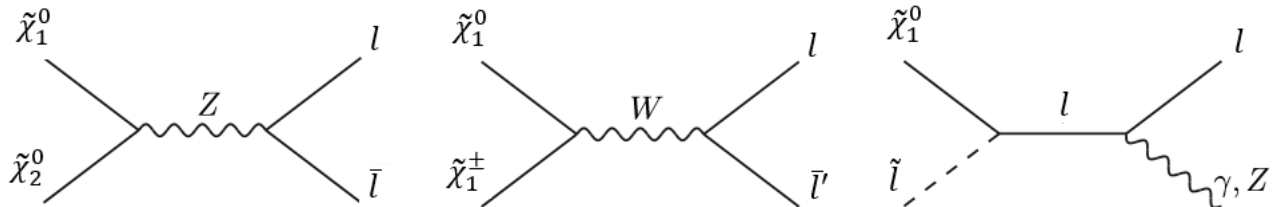
Direct detection of neutralino DM

How can we avoid direct detection constraints and simultaneously satisfy Ωh^2 ?

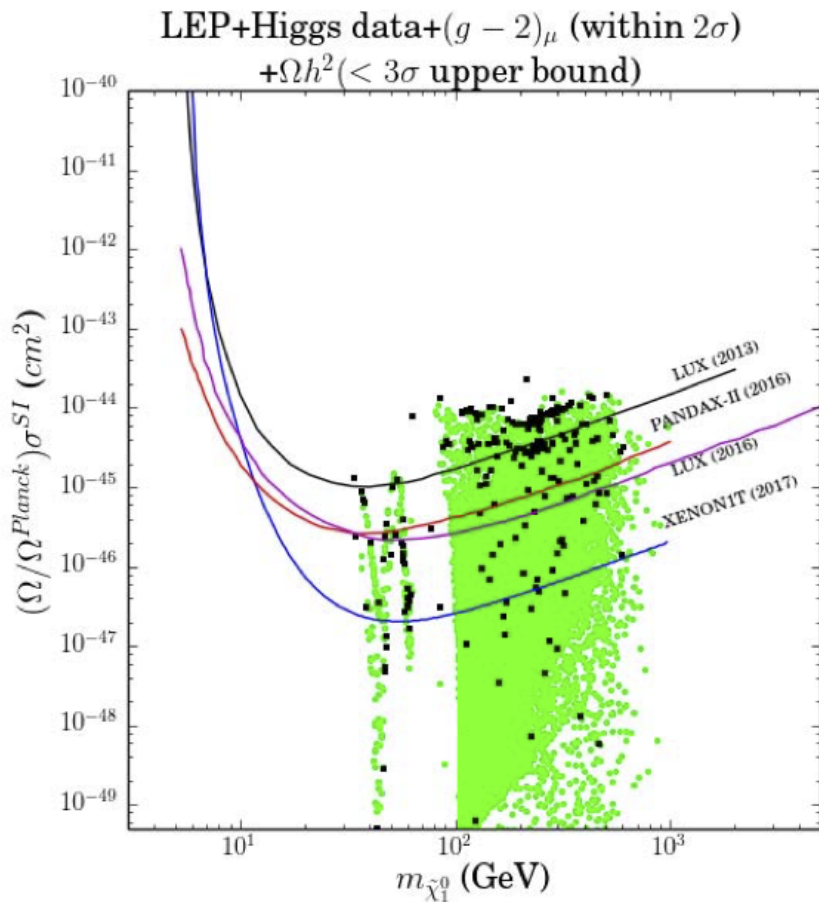
- SI MSSM "Blind Spots" (vanishing $h\tilde{\chi}_1^0\tilde{\chi}_1^0$ coupling through accidental cancellation)



- Co-annihilation with other sparticles (Squarks, staus, other higgs too heavy - through NLSP or 1st & 2nd gen sfermions)



WIMP-nucleon SI Cross Section



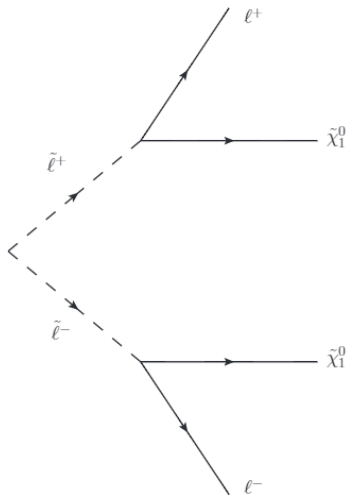
We study constraints from multilepton + MET searches at the LHC.

- We study electroweakinos at $\sqrt{s} = 8$ TeV LHC from slepton/sneutrino and W/Z decays
- Parameter sets that pass the previous collider and direct/indirect dark matter searches are considered
- Points are considered within the 2σ limit of Δa_μ
- We also present the prospects for electroweakino searches with a 100 TeV collider
- NLO events are simulated using MadGraph 5 interfaced with Pythia 6
- These are passed to CheckMATE-1.2.2 to check exclusion limits at 95% CL

Electroweakinos and sleptons at colliders

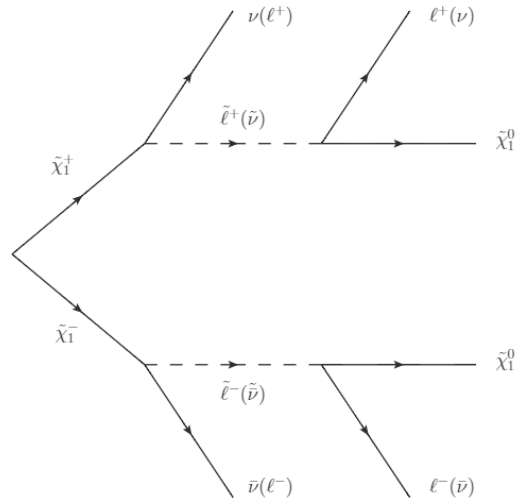
$2\ell + \cancel{E}_T$ (2 leptons + missing energy) ¹

(a)



(a) via direct slepton decays

(b)



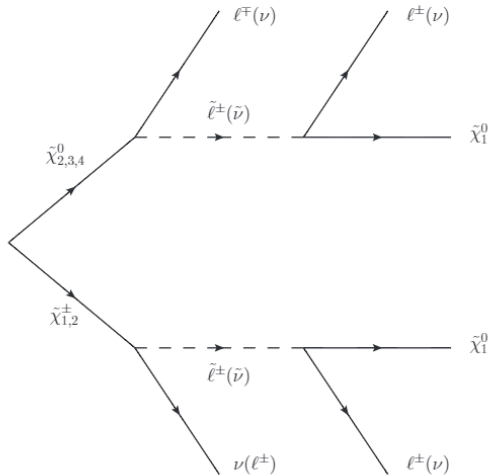
(b) via sleptons/sneutrinos

¹atlas_conf_2013_049

Electroweakinos and sleptons at colliders

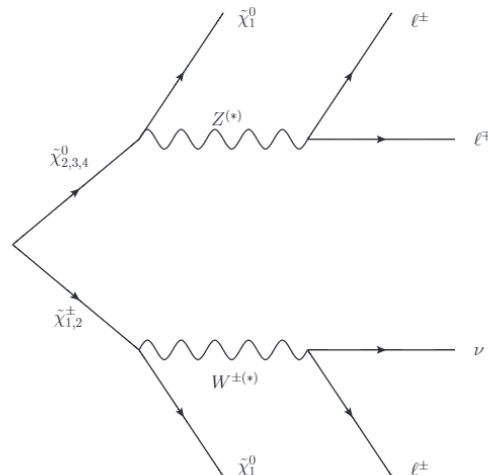
$3\ell + \cancel{E}_T$ (3 leptons + missing energy)²

(a)



(a) via sleptons/sneutrinos

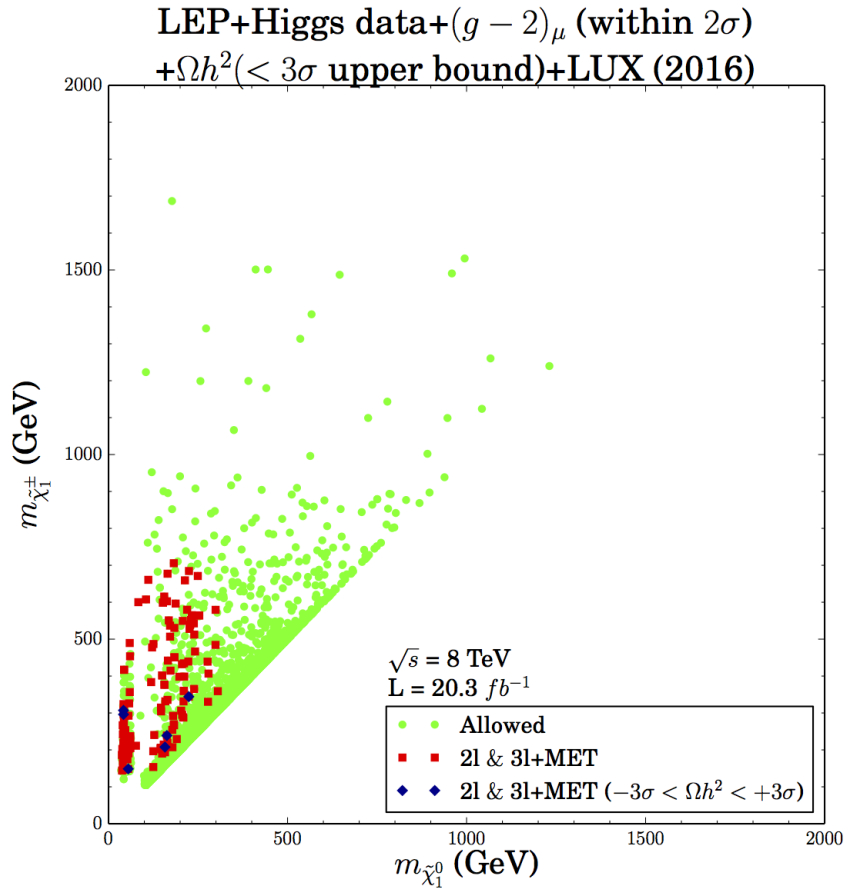
(b)



(b) via gauge bosons

²atlas_1402_7029

Results for 8 TeV collider search



100 TeV Analysis

The 3 lepton + MET events at 100 TeV are expected to have the largest reach over the MSSM parameter space.

We scale the signal (S) and background (B) events for the 8 TeV analysis by the ratio:

$$N^{100 \text{ TeV}} = (\sigma^{100 \text{ TeV}} / \sigma^{8 \text{ TeV}}) (3000 \text{ fb}^{-1} / 20.3 \text{ fb}^{-1}) N^{8 \text{ TeV}}$$

Sources of background (B):

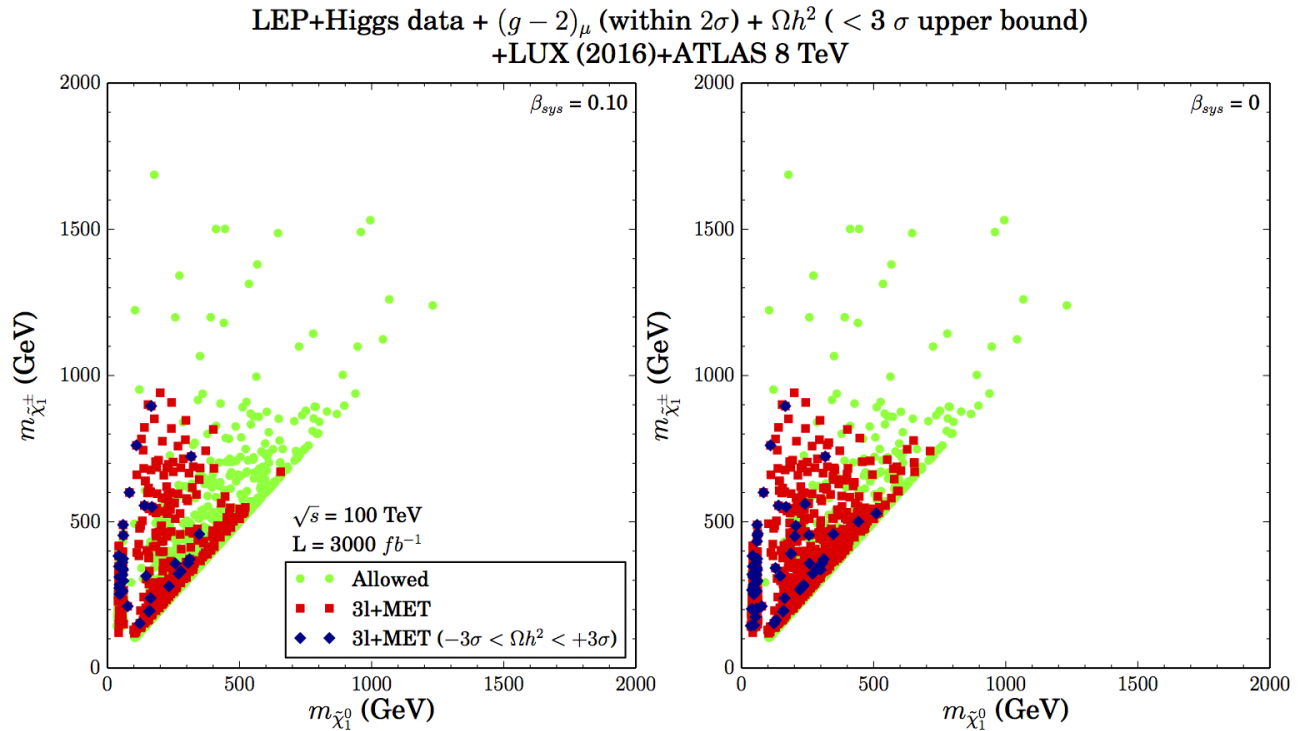
- WZ, ZZ, H
- $ttV + ttZ$
- VVV
- Reducible (t single/pair, WW , single W/Z with jets or photons)

We exclude events corresponding to:

$$\frac{S}{\sqrt{B + (\beta_{\text{sys}} B)^2}} \geq 2$$

where β_{sys} parameterizes the systematic uncertainty.

Results for 100 TeV analysis

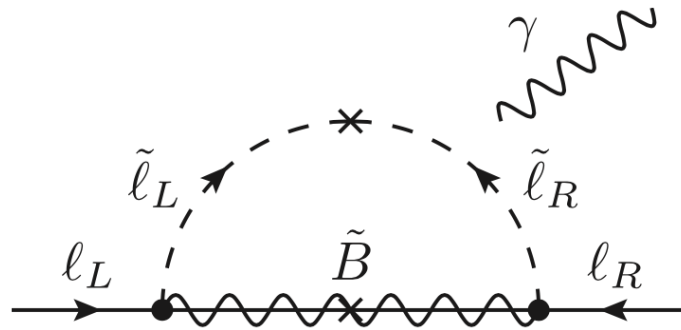


Conclusions

- We studied constraints from direct/indirect measurements on the MSSM with heavy squarks and light sleptons.
- A 100 TeV collider could potentially probe almost the entire mass range for electroweakinos in this model as an explanation for the muon $(g - 2)_\mu$ and dark matter.
- We find points that satisfy the DM relic density (within 3σ) and the LUX 2016 constraints belong either to the MSSM 'blind-spot' region or are bino-like with a large slepton/wino coannihilation cross section.
- One can further the collider analysis using monojet-like signals with greater sensitivity to the degenerate mass region in which the samples are predominantly wino/higgsino-like.
- Our 100 TeV analysis can be considered a preliminary one, that can be improved once the collider environment details are known (and/or a public code is released).

Large μ case

It has been noted that one can explain the $(g - 2)_\mu$ can be explained with a dominant bino-smuon loop contribution.



This is enhanced with a large **smuon left-right mixing**.

Too large, and this can spoil the electroweak vacuum stability.

Large μ case

We scan the extended region:

$$10 < \tan(\beta) < 50,$$

$$|M_1|, |M_2| < 3 \text{ TeV},$$

$$10 < \mu < 100 \text{ TeV},$$

$$0.1 < m_{\tilde{l}_L}, m_{\tilde{l}_R} < 2 \text{ TeV}, \quad (l = e, \mu)$$

with staus decoupled at $m_{\tilde{\tau}_L} = m_{\tilde{\tau}_R} = 10 \text{ TeV}$ and $A_\tau = 0$.

To explain $(g - 2)_\mu$ within 2σ , we find upper limits of $m_{\tilde{\chi}_1^0} < 2.4 \text{ TeV}$ and $m_{\tilde{\ell}_1} < 1.1 \text{ TeV}$.

The previous DM constraints severely limit this case, and so is **not the preferred scenario**.