MSSM dark matter and the muon g-2

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THE UNIVERSITY OF SYDNEY

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

Outline

Everybody has been talking about LHC run 2...

Donald J. Trump
@realDonaldTrump

Scientists working at the LHC, collide protons at high energy, claim it is safe to do so - MICRO BLACK HOLES. Many such cases!

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802 16K 5K

Kellyanne Conway
@KellyannePolls

Supersymmetry was discovered at Fermilab decades before the LHC #AlternativeFacts

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Sean Spicer
@seanspicer

You nailed it. Period!

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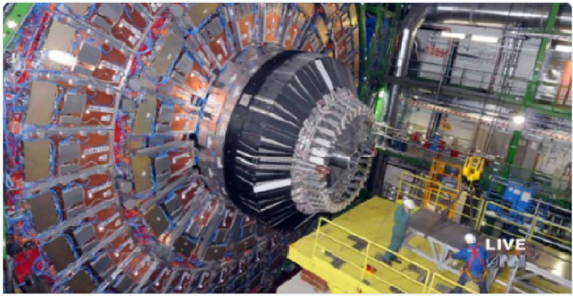
Bored Scientists Now Just Sticking Random Things Into Large Hadron Collider theonion.com/video/bored-sc... via @the-onion



Bored Scientists Now Just Sticking Random Things Into Large Hadr...
One year after confirming the existence of the Higgs Boson, or "God Particle," scientists at CERN say they are struggling to find other uses fo...
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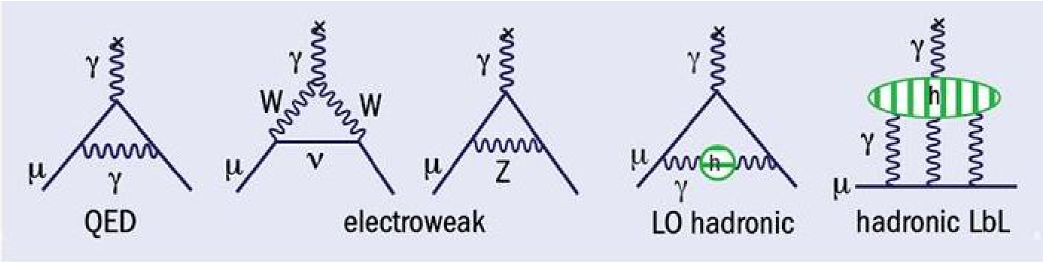
Introduction

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
- A light neutralino - great for DM!

The muon $g-2$

Contributions to the SM:



a_μ $\sim 10^{-3}$ $\sim 10^{-7}$ $\sim 10^{-9}$

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

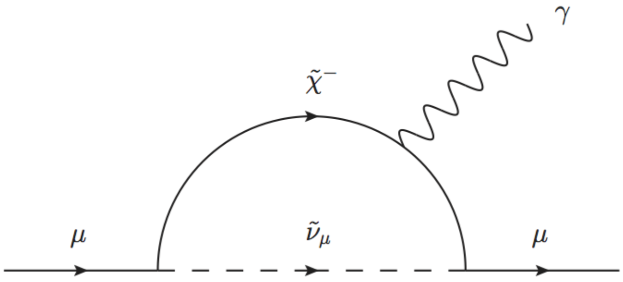
$$20.6 \times 10^{-10} < \Delta a_\mu < 36.6 \times 10^{-10} \quad (1\sigma)$$
$$12.6 \times 10^{-10} < \Delta a_\mu < 44.6 \times 10^{-10} \quad (2\sigma)$$

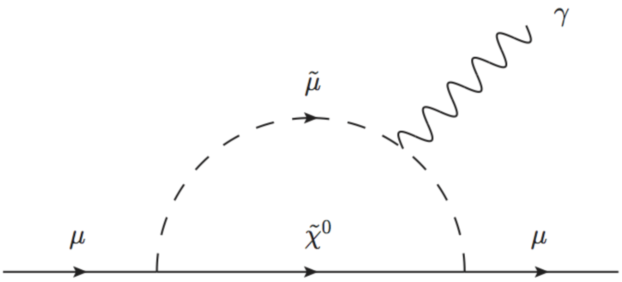
where

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

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:

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

f_χ and f_N are loop functions:

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

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

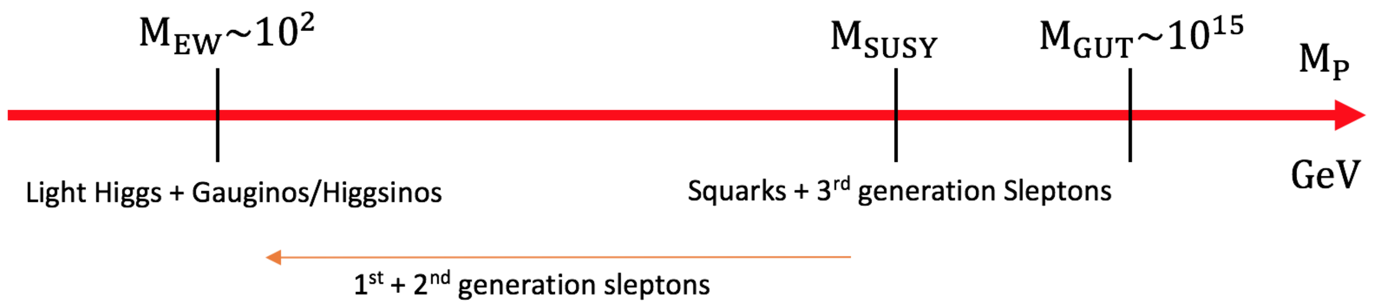
Explaining the muon $g-2$ in the MSSM

- The following particles are important in analyzing the $(g-2)_\mu$ in the MSSM:
$$\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm \tag{1}$$
- 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 $\rightarrow$ **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 $M_3 \sim 3$ 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 $m_{A^0} = 2$ TeV

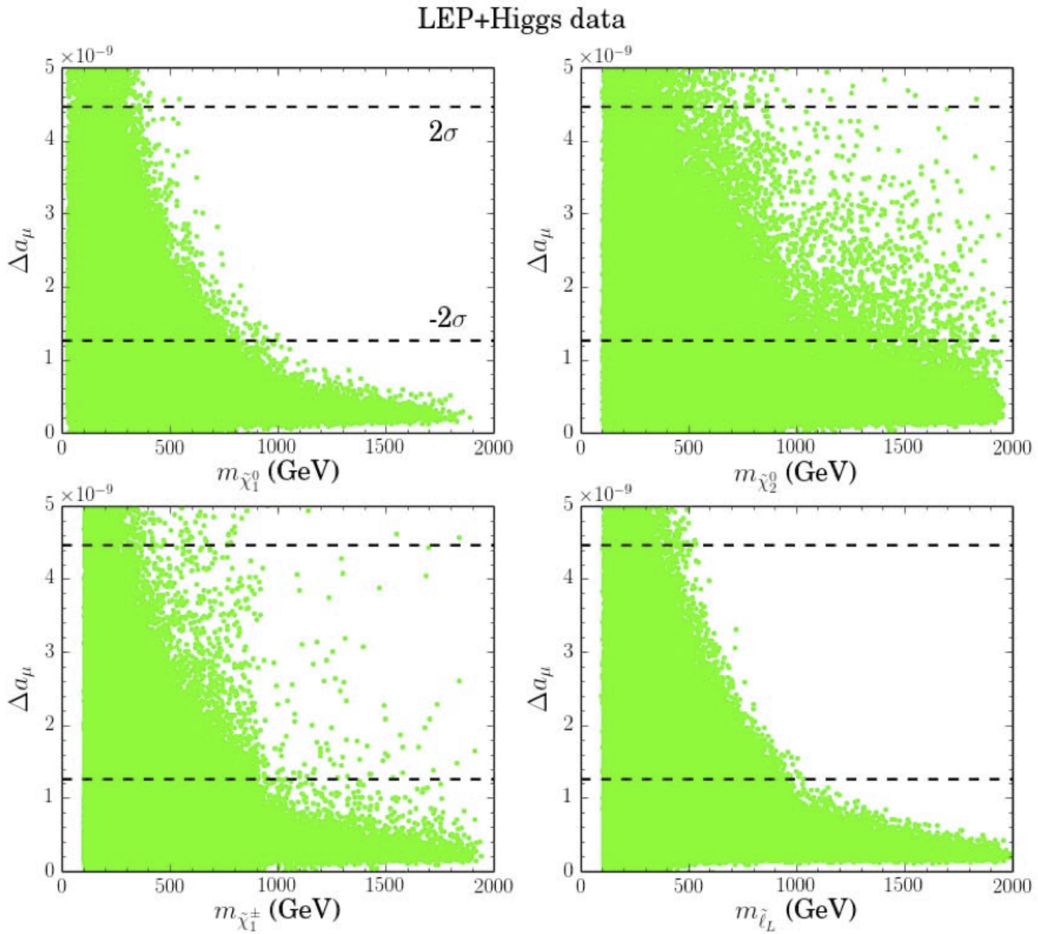
MSSM Parameter Scan

Parameter scan range:

$$
\begin{aligned}
&10 < \tan(\beta) < 50, \\
&|M_1|, |M_2|, |\mu| < 2\,\text{TeV}, \\
&0.1 < m_{\tilde{l}_L}, m_{\tilde{l}_R} < 2\,\text{TeV}, \qquad (l = e, \mu)
\end{aligned}
$$

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



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:

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

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

Neutralino components and Dark Matter

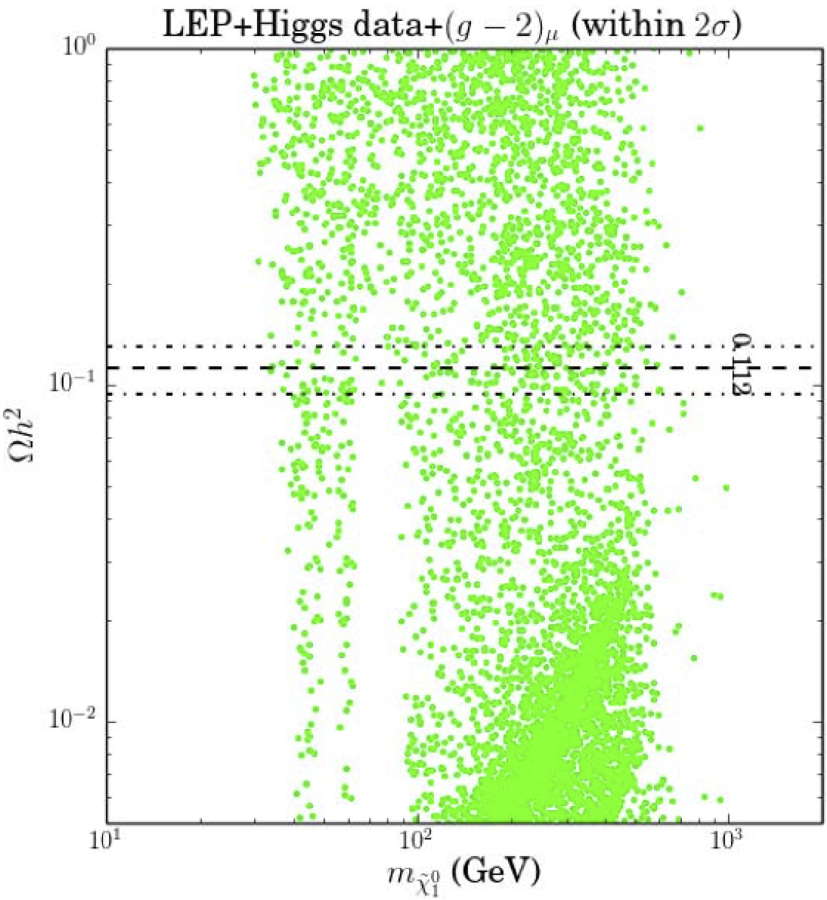
If the LSP component has...

- $M_1 \ll M_2, \mu$ 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**

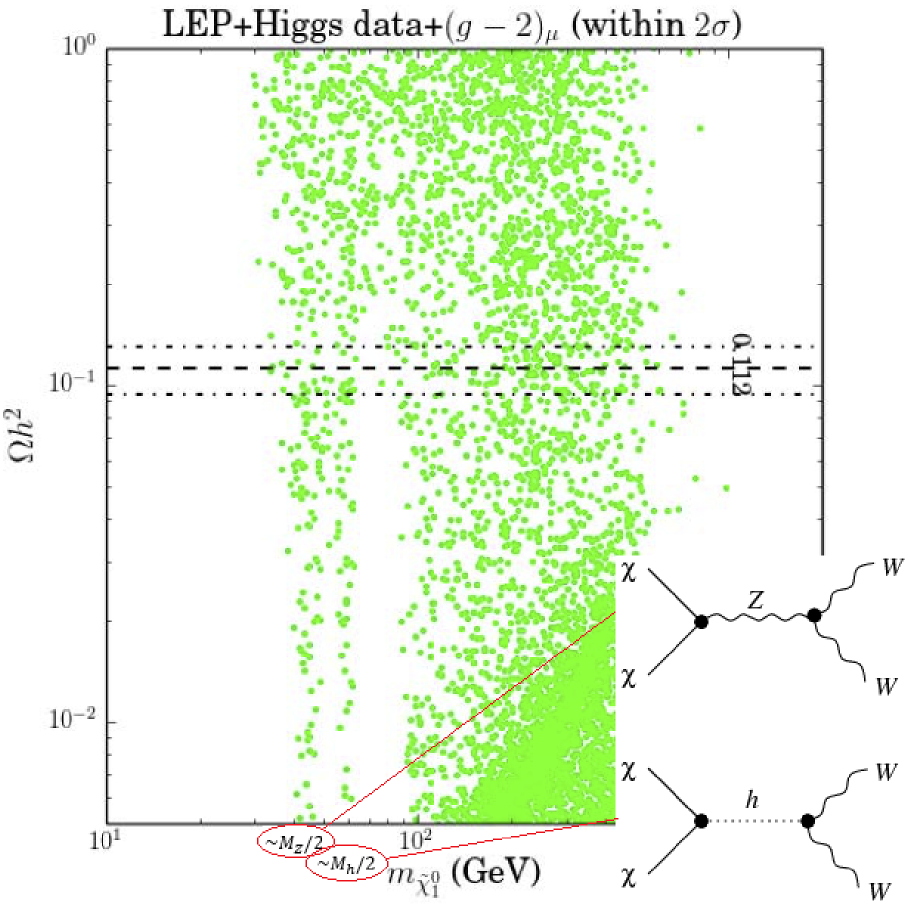
Dark Matter constraints on χ_1^0 vary for different compositions of Bino, Wino and Higgsinos:

- 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



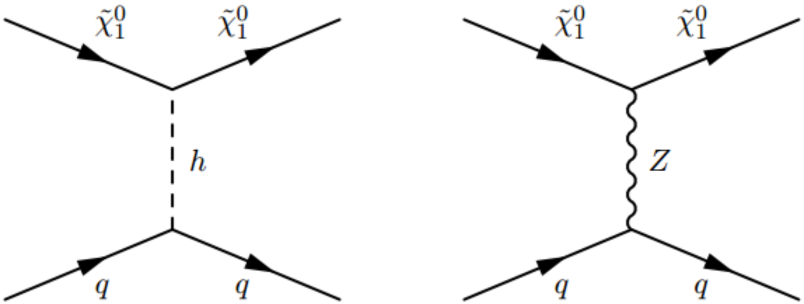
Relic Density, Ωh^2



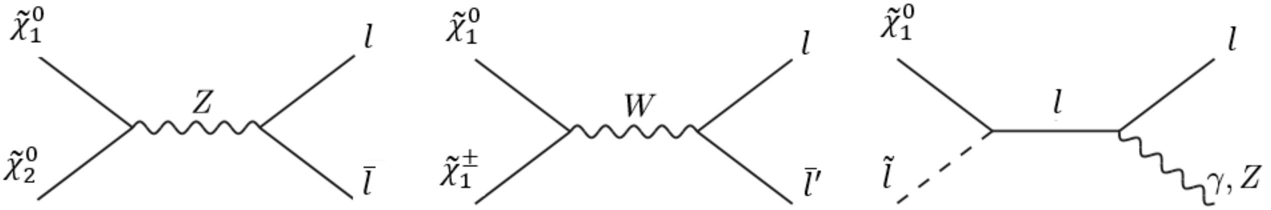
Direct detection of neutralino DM

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

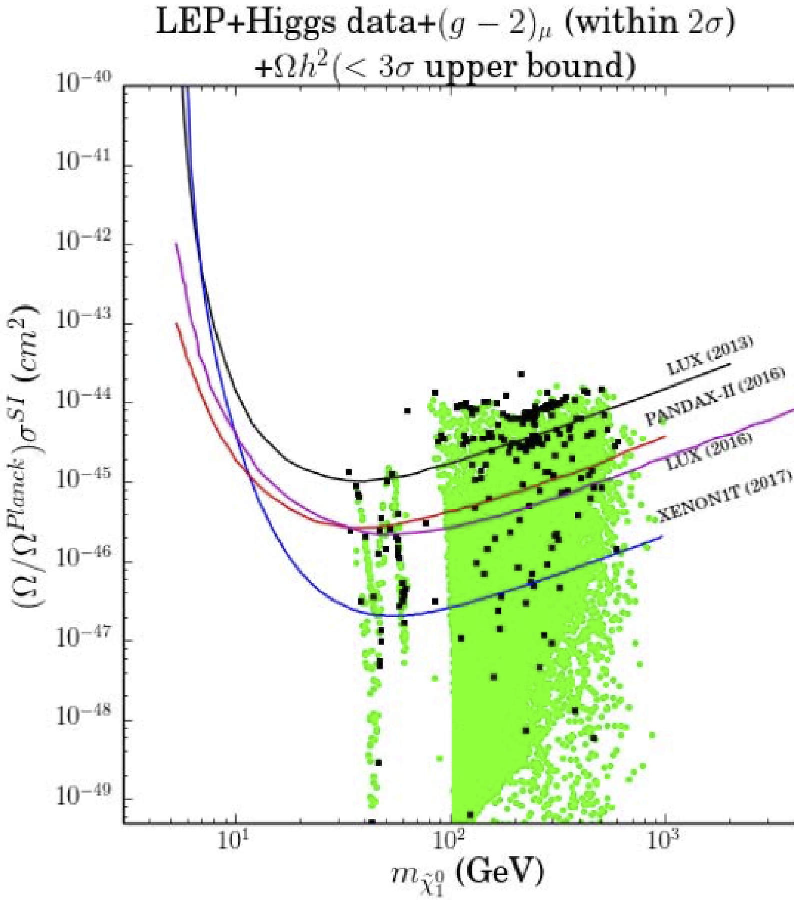
- SI MSSM "Blind Spots" (vanishing $h\chi_1^0\chi_1^0$ coupling through accidental cancellation)



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



WIMP-nucleon SI Cross Section

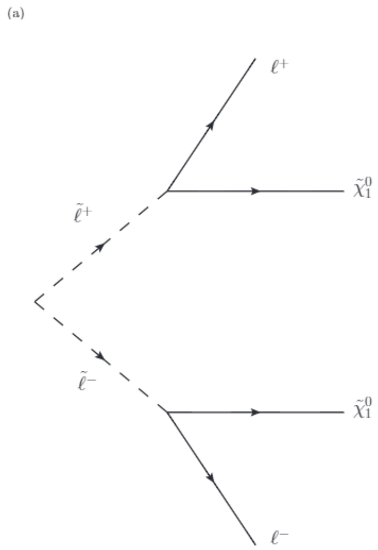


Collider Simulation

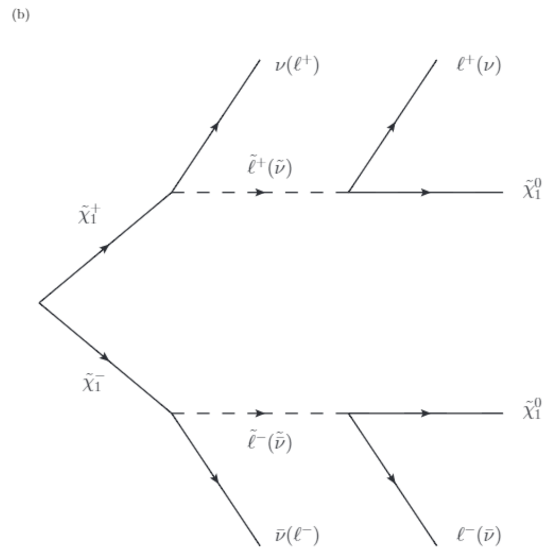
We study constraints from multilepton + MET searches at the LHC.

- 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

$2\ell + \not{E}_T$ (2 leptons + missing energy) [1]



(a) via direct slepton decays

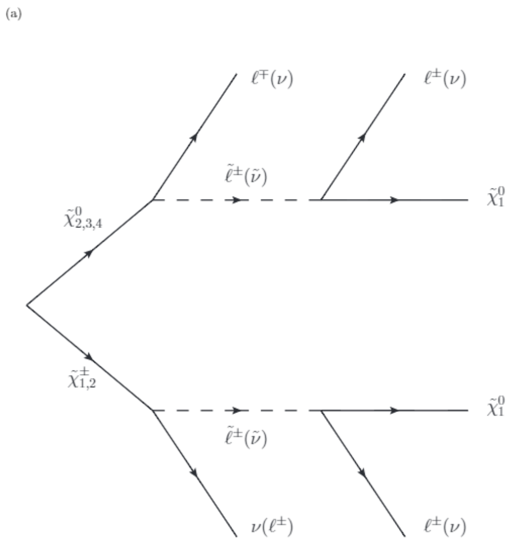


(b) via sleptons/sneutrinos

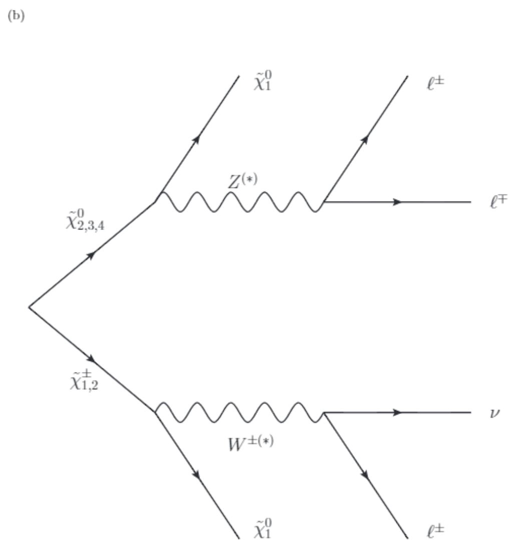
[1] atlas_conf_2013_049

Electroweakinos and sleptons at colliders

$3\ell + \not{E}_T$ (3 leptons + missing energy) [2]



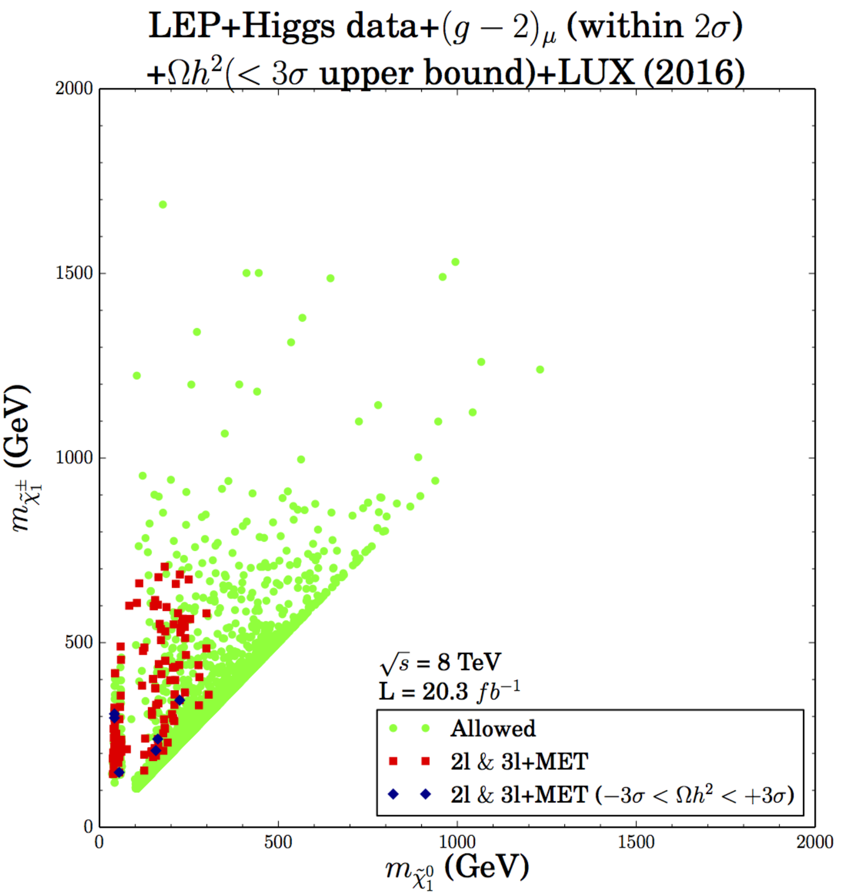
(a) via sleptons/sneutrinos



(b) via gauge bosons

[2] atlas_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):

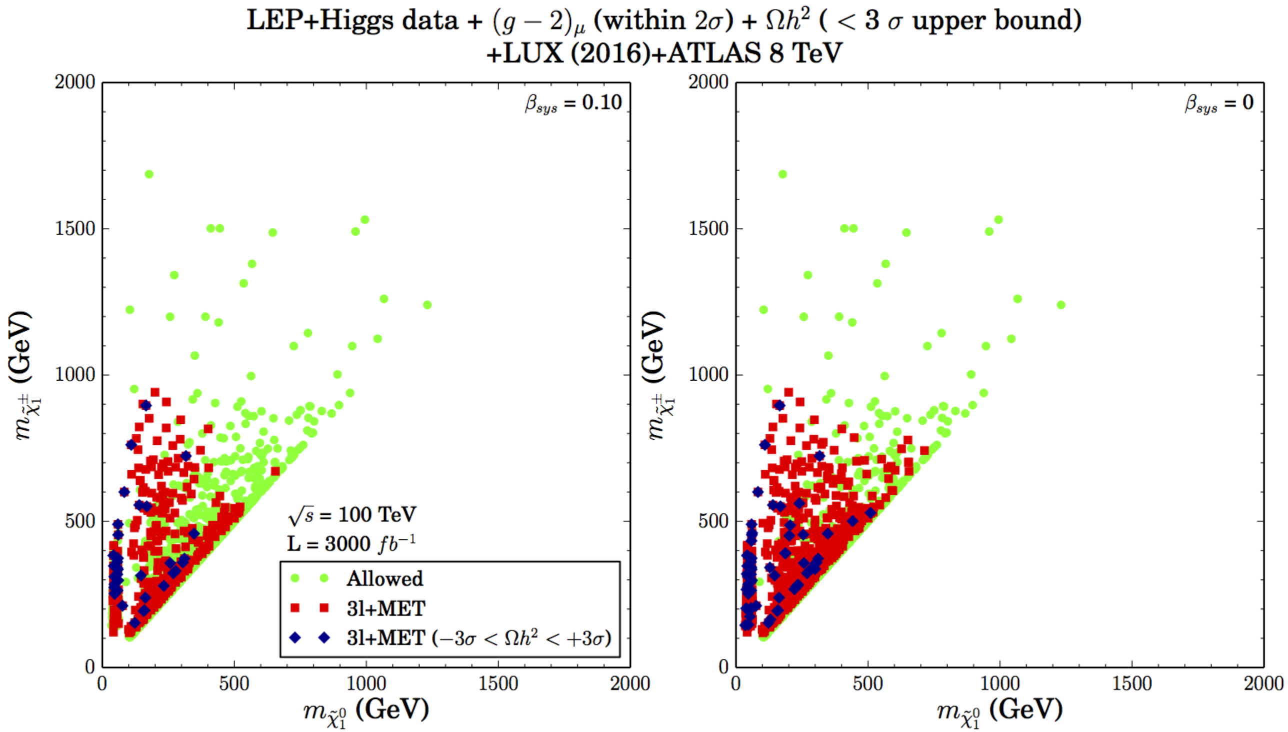
- WZ, ZZ, H
- $ttV + ttZ$
- VVV
- Reducible (t single/pair, WW, single W/Z with jets or photons)

We exclude events corresponding to:

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

where β_{sys} parameterizes the systematic uncertainty.

Results for 100 TeV analysis

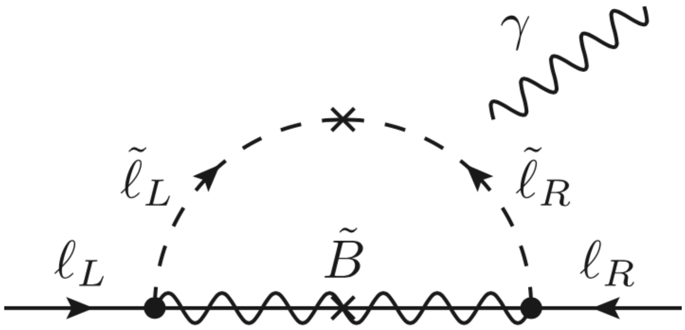


Conclusions

- 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:

$$
\begin{aligned}
&10 < \tan(\beta) < 50, \\
&|M_1|, |M_2| < 3\,\text{TeV}, \\
&10 < \mu < 100\,\text{TeV}, \\
&0.1 < m_{\tilde{l}_L}, m_{\tilde{l}_R} < 2\,\text{TeV}, \qquad (l = e, \mu)
\end{aligned}
$$

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**.