MSSM dark matter and the muon g-2

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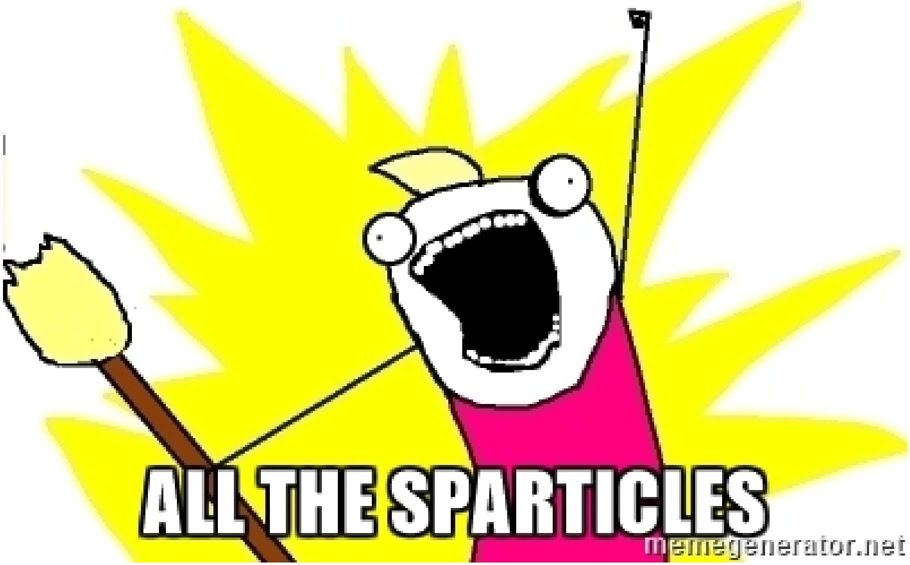
November 29th 2016

Outline

Introduction

The LHC has resumed its search for Supersymmetry (SUSY) in run 2, but direct evidence is still yet to be found. The search continues on!



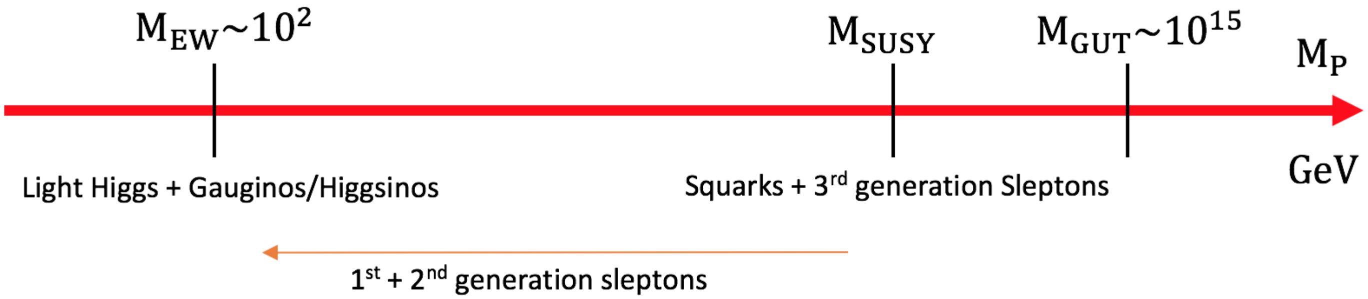
Introduction

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

- Tree-level higgs mass $\sim m_Z$.
- Existence of electroweakinos (partners of EW gauge bosons).
- A light neutralino - great for DM!
- Composition of DM is important (Wino, Bino, Higgsino).

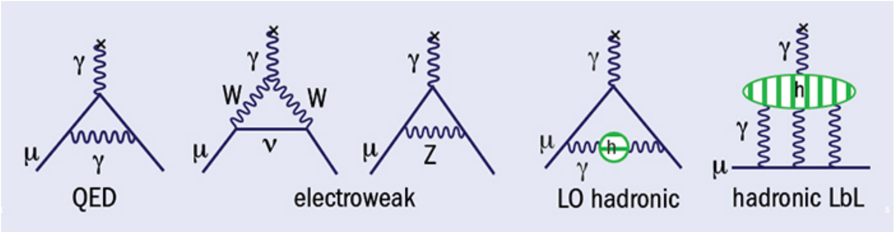
Minimal SUSY mass hierarchy

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



The muon $g - 2$

Contributions to the SM:



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

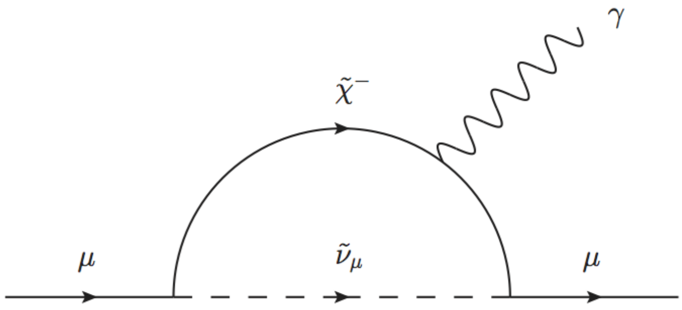
$$20.6 \times 10^{-10} < \Delta a_\mu < 36.6 \times 10^{-10} \quad (1\sigma)$$
$$12.6 \times 10^{-10} < \Delta a_\mu < 44.6 \times 10^{-10} \quad (2\sigma)$$

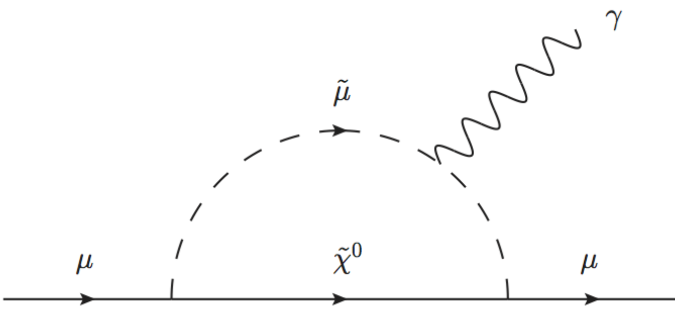
where

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

The muon $g-2$ in SUSY

Contributions come from sneutrino-chargino and smuon-neutralino loop diagrams





The muon $g-2$ in SUSY

Contribution from the MSSM:

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

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:
$$\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm \tag{1}$$
- We can heavily constrain the muon $g-2$ through slepton and chargino searches at colliders
- Smuons should be kept light (less than around 500 GeV) to increase contribution to the $(g-2)_\mu$
- Dark Matter (Direct/Indirect) searches can constrain neutralino LSPs in R-Parity conserving SUSY

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`:

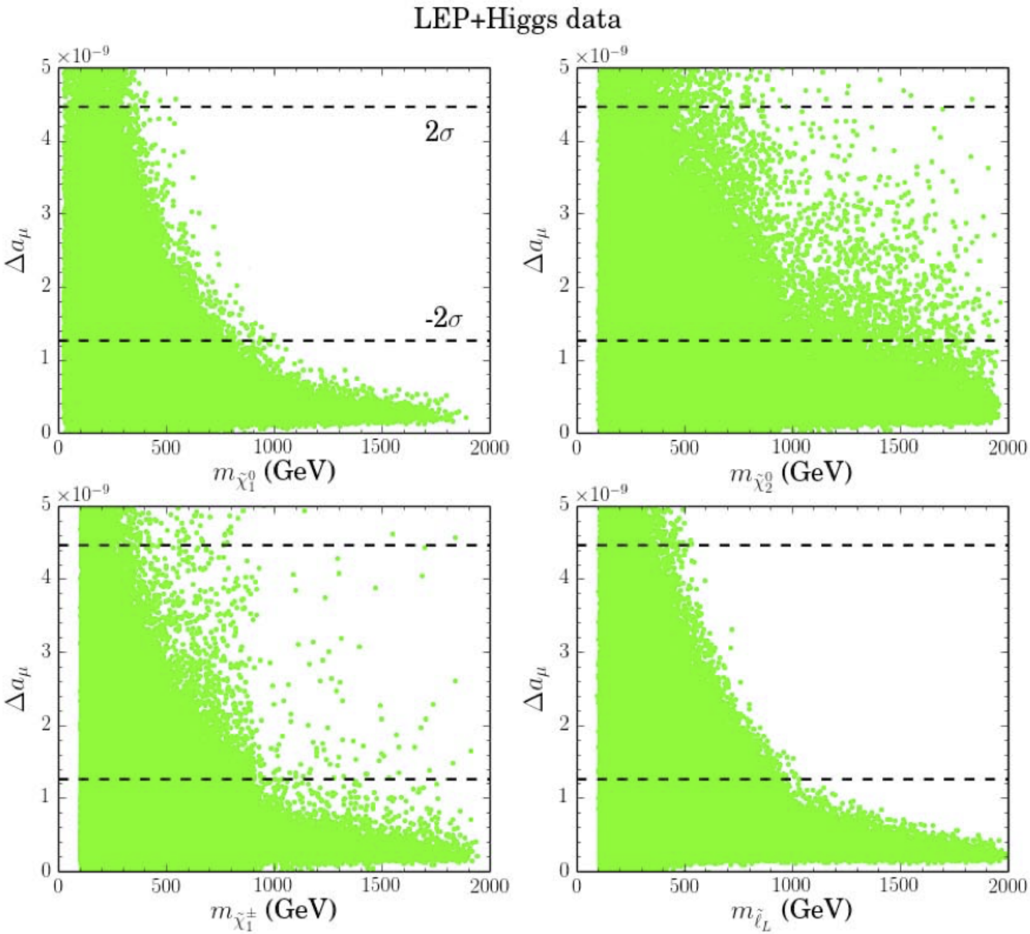
- Decoupled Squarks at 5 TeV (Ignore B-Physics constraints)
- Stau sleptons $m_{\tilde{\tau}_L} = m_{\tilde{\tau}_R} = 5\,\text{TeV}$
- Gluino mass $M_3 \sim 3$ TeV
- Trilinear coupling A_t in range $|A_t| < 5\,\text{TeV}$ (We keep $|X_t/M_S| < 2$ to avoid charge/colour-breaking minima)
- Rest of higgs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

Parameter scan range:

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

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

Limits on neutralinos, charginos and smuons



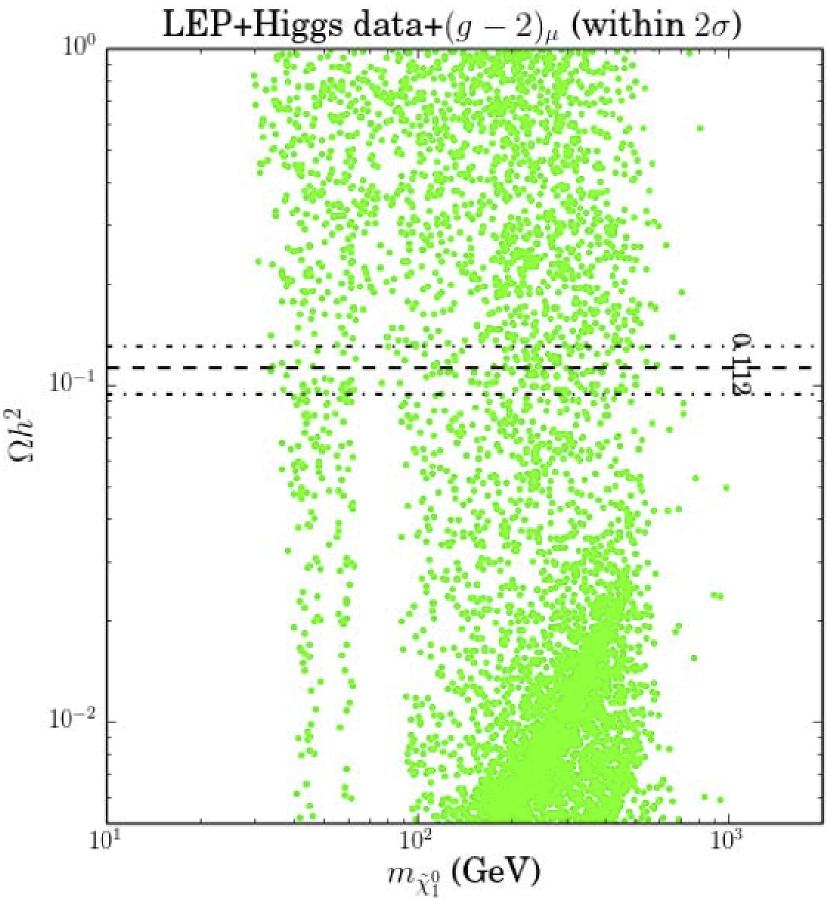
(N)LSP component

Parameters	**LSP**	**NLSP**
$M_1 > M_2 > \mu$	Higgsino	Wino
$M_1 > \mu > M_2$	Wino	Higgsino
$M_2 > \mu > M_1$	Bino	Higgsino
$\mu > M_2 > M_1$	Bino	Wino

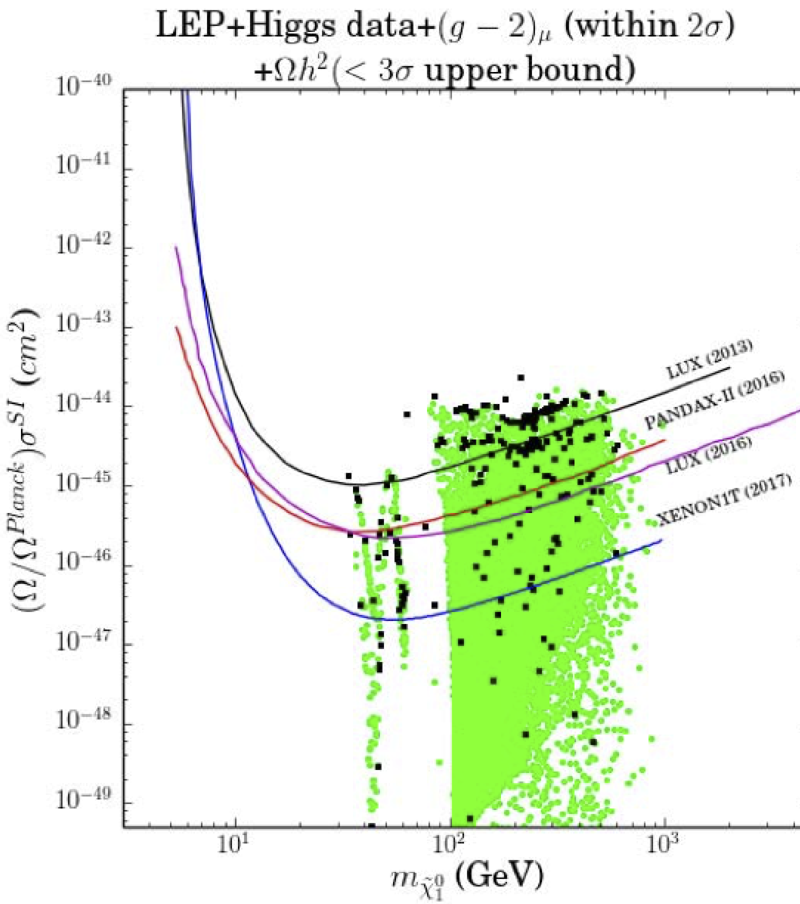
Constraints on χ_1^0 vary for different compositions of Bino, Wino and Higgsinos

- It is well known that pure Bino-like DM relics are typically overabundant (suppressed annihilation cross section), 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



WIMP-nucleon SI Cross Section



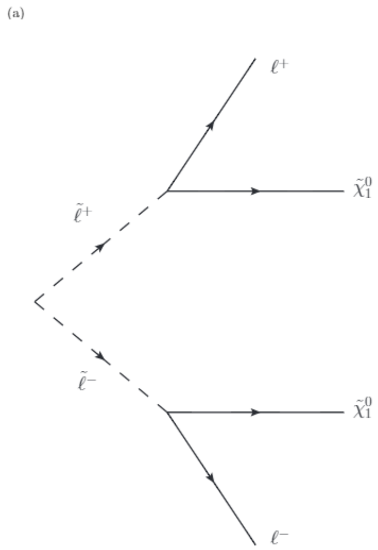
Collider Simulation

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

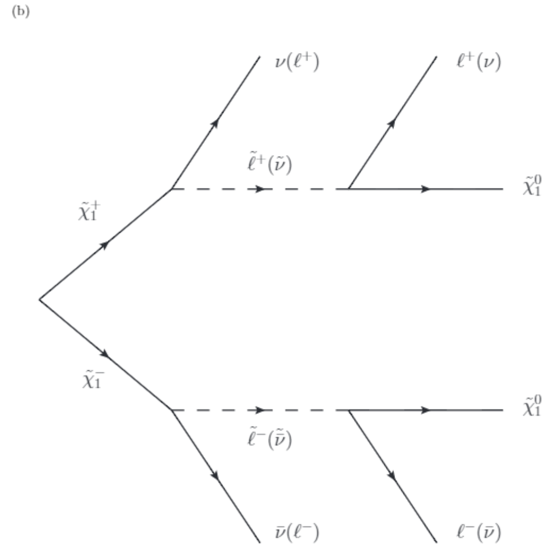
- We study electroweakinos at $\sqrt{s} = 8$ TeV LHC from slepton/sneutrino and W/Z decays
- Parameter sets that pass the previous collider and direct/indirect dark matter searches are considered
- Points are considered within the 2σ limit of Δa_μ
- We also present the prospects for electroweakino searches 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

Electroweakinos and sleptons at colliders

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



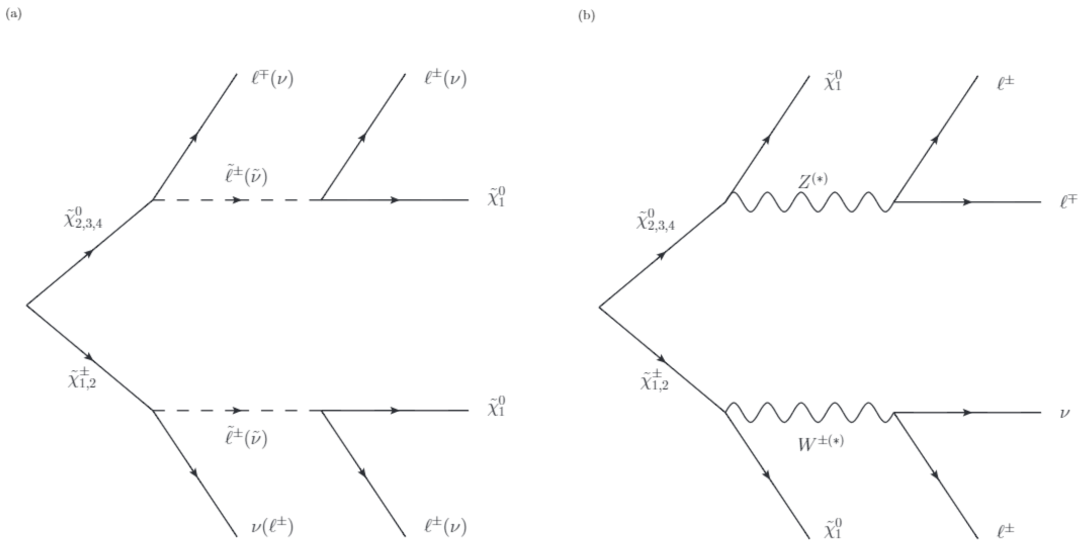
(a) via direct slepton decays



(b) via sleptons/sneutrinos

[1] atlas_conf_2013_049

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

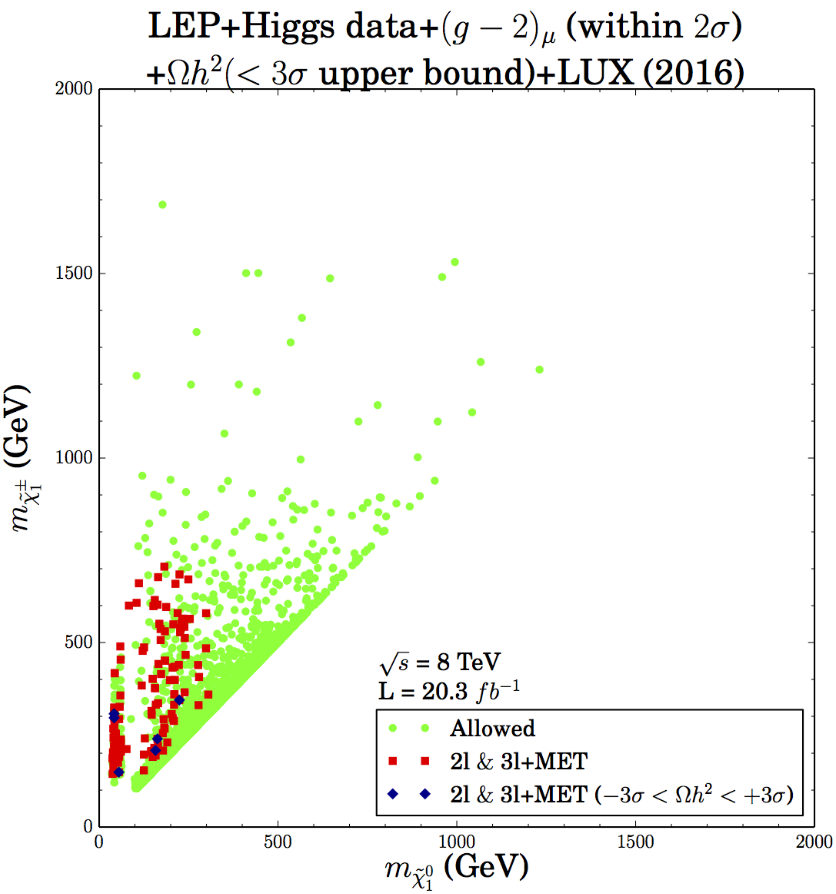


(a) via sleptons/sneutrinos

(b) via gauge bosons

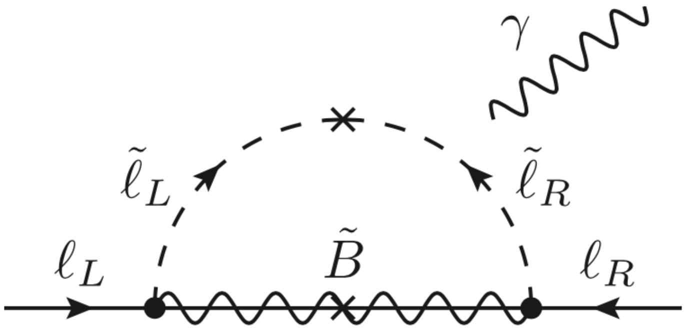
[2] atlas_1402_7029

Results in $m_{\chi_1^0} - m_{\chi_1^\pm}$ plane



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**.

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):

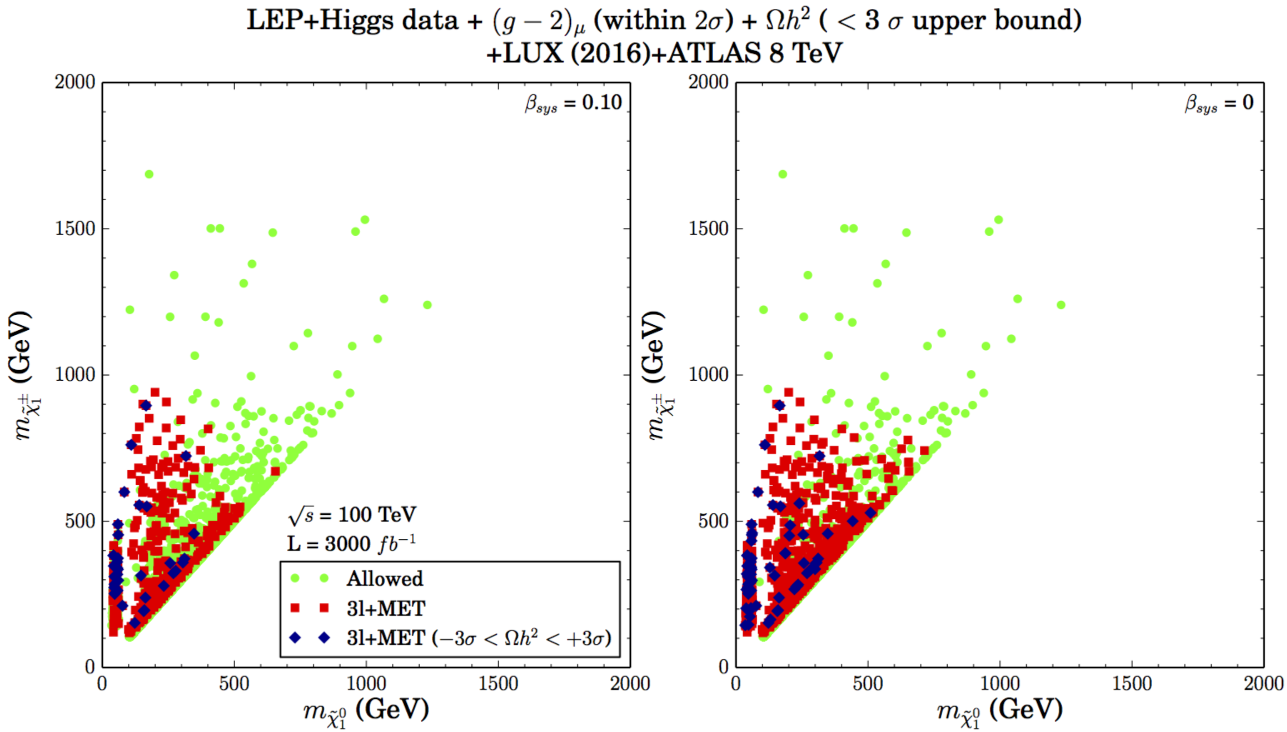
- WZ, ZZ, H
- $ttV + ttZ$
- VVV
- Reducible (t single/pair, WW, single W/Z with jets or photons)

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.
- One can further the analysis using monojet-like signals with greater sensitivity to the degenerate mass region.
- 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).