MSSM dark matter and the muon g-2

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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!
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 → **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

\[
\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}}
\]
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:

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

$$+ \frac{M_1}{\cos^2 \theta_W (m_\mu^2_R - m_\mu^2_L)} \left( \frac{f_N(M_1^2/m_\mu^2_R) - f_N(M_1^2/m_\mu^2_L)}{m_\mu^2_R - m_\mu^2_L} \right)$$

$f_\chi$ and $f_N$ are loop functions:

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

$$f_N(x) = \frac{x^2 - 1 - 2x \ln(x)}{(1 - x)^3}, \quad f_N(1) = -1/3$$
The following particles are important in analyzing the $(g - 2)_\mu$ in the MSSM:

$$\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm$$

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:
  \[ m_{\tilde{\chi}_L}, m_{\tilde{\chi}_R} > 100 \text{ GeV} \quad (l = e, \mu) \]
  \[ m_{\tilde{\chi}_1^\pm} > 105 \text{ GeV} \]

- 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 \(m_{\tilde{\tau}_L} = m_{\tilde{\tau}_R} = 5\) TeV
- Gluino mass \(M_3 \sim 3\) TeV
- Trilinear coupling \(A_t\) in range \(|A_t| < 5\) 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:

\[
10 < \tan(\beta) < 50, \\
|M_1|, |M_2|, |\mu| < 2\) TeV, \\
0.1 < m_{\tilde{l}_L}^{\tilde{\tau}}, m_{\tilde{l}_R}^{\tilde{\tau}} < 2\) TeV, \quad (l = e, \mu)
\]

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

LEP+Higgs data

\[ \Delta a_\mu \]

\[ m_{\tilde{\chi}_1^0} \text{ (GeV)} \]

\[ m_{\tilde{\chi}^\pm_1} \text{ (GeV)} \]

\[ m_{\tilde{\mu}_L} \text{ (GeV)} \]
(N)LSP component

<table>
<thead>
<tr>
<th>Parameters</th>
<th>LSP</th>
<th>NLSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_1 &gt; M_2 &gt; \mu$</td>
<td>Higgsino</td>
<td>Wino</td>
</tr>
<tr>
<td>$M_1 &gt; \mu &gt; M_2$</td>
<td>Wino</td>
<td>Higgsino</td>
</tr>
<tr>
<td>$M_2 &gt; \mu &gt; M_1$</td>
<td>Bino</td>
<td>Higgsino</td>
</tr>
<tr>
<td>$\mu &gt; M_2 &gt; M_1$</td>
<td>Bino</td>
<td>Wino</td>
</tr>
</tbody>
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Constraints on $\chi^0_1$ 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 $\chi^0_1$.
- To avoid significant constraint, for any LSP abundance less than the relic density, we assume additional DM component (possibly axion-like DM).
Relic Density, $\Omega h^2$

LEP+Higgs data+$g - 2)_\mu$ (within 2$\sigma$)
WIMP-nucleon SI Cross Section

LEP+Higgs data + \((g - 2)\mu\) (within 2\(\sigma\))
+ \(\Omega h^2\) (< 3\(\sigma\) upper bound)
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 $2\sigma$ limit of $\Delta a_\mu$
- 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
$2\ell + E_T$ (2 leptons + missing energy) \(^1\)

(a) via direct slepton decays  
(b) via sleptons/sneutrinos

\(^1\)atlas_conf_2013_049
Electroweakinos and sleptons at colliders

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

(a) via sleptons/sneutrinos

(b) via gauge bosons

\(^2\)atlas_1402_7029

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

LEP+Higgs data+$\left(g - 2\right)_{\mu}$ (within 2σ)
+$\Omega h^2 (< 3\sigma$ upper bound)$+$LUX (2016)
Large $\mu$ 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 $\mu$ case

We scan the extended region:

\[ 10 < \tan(\beta) < 50, \]
\[ |M_1|, |M_2| < 3 \text{ TeV}, \]
\[ 10 < \mu < 100 \text{ TeV}, \]
\[ 10 < \mu < 100 \text{ TeV}, \]
\[ 0.1 < m_{\tilde{l}_L}, m_{\tilde{l}_R} < 2 \text{ TeV}, \quad (l = e, \mu) \]

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 \(2\sigma\), we find upper limits of \( m_{\tilde{\chi}_1}\) < 2.4 TeV and \( m_{\tilde{l}_1} < 1.1 \text{ TeV} \).

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

\[
N^{100 \text{ TeV}} = \left( \frac{\sigma^{100 \text{ TeV}}}{\sigma^{8 \text{ TeV}}} \right) (3000 \text{ fb}^{-1} / 20.3 \text{ fb}^{-1}) N^{8 \text{ TeV}}
\]

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 \(\beta_{sys}\) parameterizes the systematic uncertainty.
Results for 100 TeV Analysis

$\sqrt{s} = 100$ TeV
$L = 3000 \; fb^{-1}$

- Allowed
- $3l+MET$
- $3l+MET (\, -3\sigma < \Omega h^2 < +3\sigma)$
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).