The muon g-2 and dark matter in the MSSM at 100 TeV[1]

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[1] Kobakhidze, A., Talia, M., Wu, L., Phys. Rev. D **95** (2017)

Outline

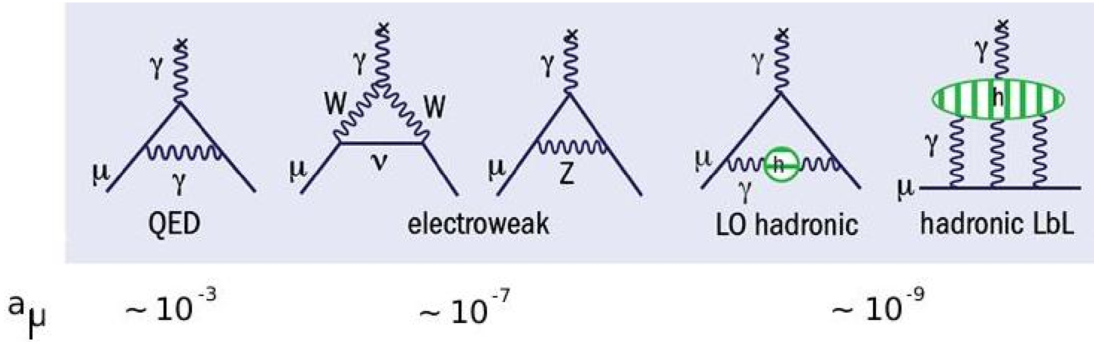
Introduction

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 $\sim m_Z$ - needs heavy stops/large mixing
- Predicts the existence of fermionic partners to the electroweak gauge bosons
- μ term predicts masses of higgsinos and is important for EWSB
- A light, stable neutralino - most studied WIMP DM candidate

The muon $g - 2$

Contributions to the SM:



- Main theoretical uncertainty comes from LO Hadronic loop contributions (quarks and gluons). The limits are within 2σ of Δa_μ:

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

where

$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{SM}, \quad a_\mu = \frac{g-2}{2}$$

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:

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

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

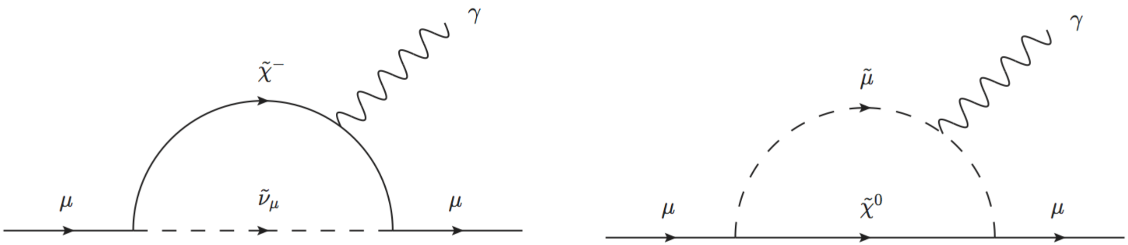
Significant contributions will typically require M_1, M_2, μ of same-sign, large $\tan\beta$, and a sizeable wino/higgsino contribution

Explaining the muon $g-2$ in the MSSM

- Important mass eigenstates in analyzing the $(g-2)_\mu$ in the MSSM:

$$\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm \tag{1}$$

One-loop diagrams:

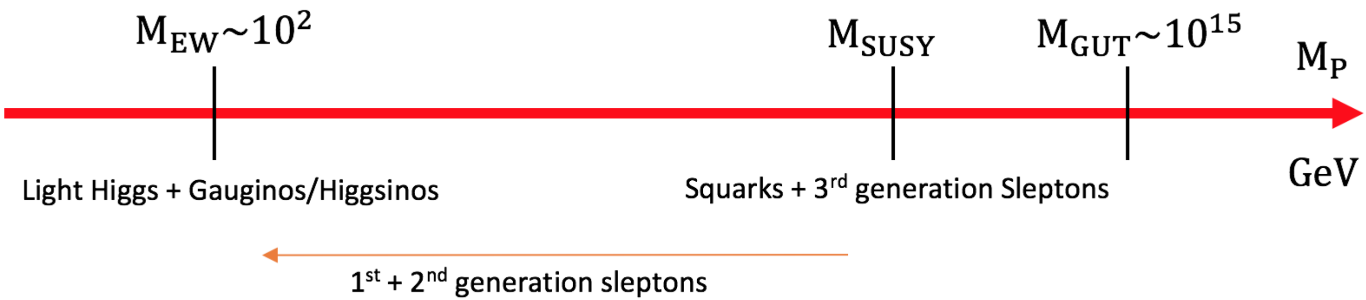


- Smuons should be kept light to increase contribution to the $(g-2)_\mu$
- Chargino-sneutrino diagram typically dominant, but bino-smuon loop can be dominant with light binos and large $\tilde{\mu}_{L,R}$ mixing (not favoured by DM constraints, naturalness, vacuum stability)
- Direct collider search constraints on neutralinos and charginos depend strongly on their kinematics (mass-splittings)

Minimal SUSY mass hierarchy

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

- Universal squark and 3rd gen slepton masses are heavy
- Gauginos + higgsinos at weak scale, protected by chiral symmetry
- Light 1st and 2nd generation sleptons degenerate ($\mu \to e\gamma$ FCNC constraints) $\to$ **muon g-2**



MSSM Parameter Scan

Parameter scan range:

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

- Squarks are allowed heavy at 5 TeV
- Stau sleptons $m_{\tilde{\tau}_L} = m_{\tilde{\tau}_R} = 5\,\text{TeV}$
- Gluino mass $M_3 = 3$ 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
- Light higgs very SM-like by setting $m_{A^0} = 2$ TeV (decoupling limit)

SUSY spectrum calculated in `FeynHiggs`, `MicrOmegas` to calculate DM relic density and SI WIMP-nucleon CS.

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:

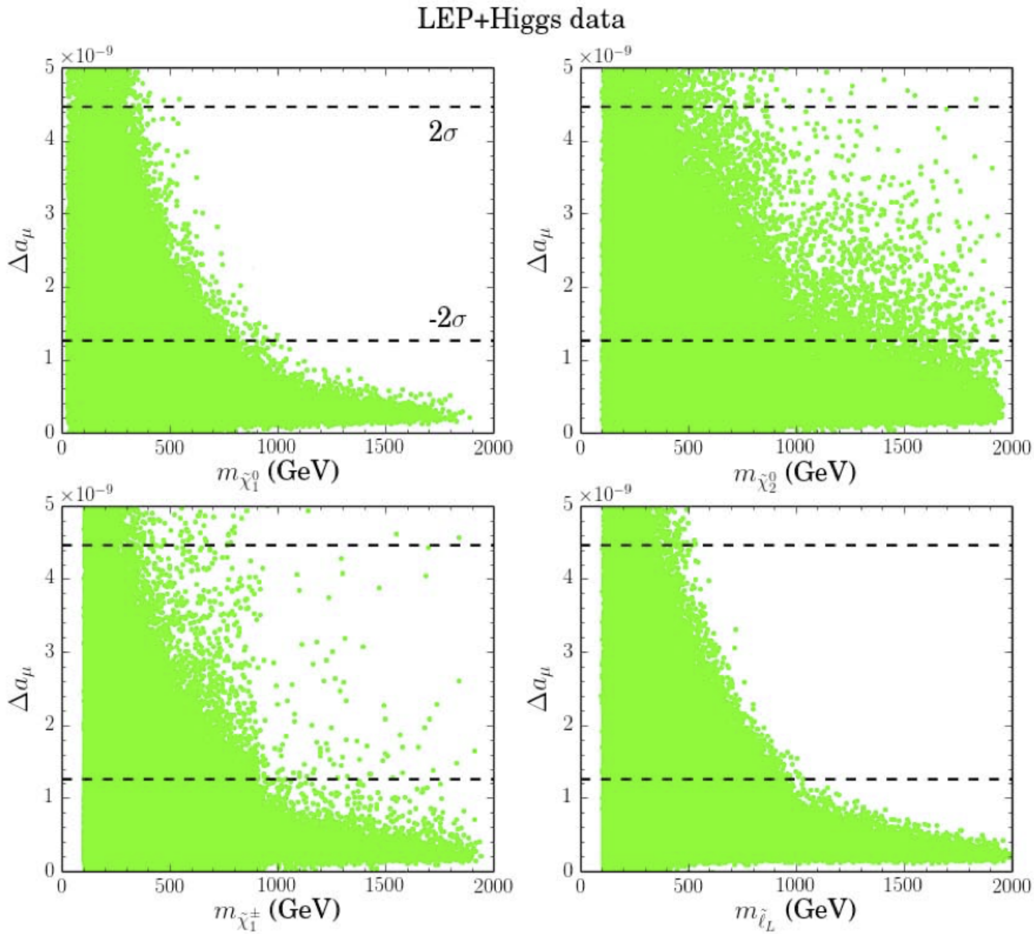
$$123 < m_{h^0} < 127\,\text{GeV}$$

- Higgs precision constraints (LEP, Tevatron and LHC)
- B-Physics constraints, namely $BR(B \to X_S\gamma)$ and $BR(B_S \to \mu^+\mu^-)$
- 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)
- LHC direct searches in multi-lepton + MET channel

Limits on neutralinos, charginos and smuons



Neutralino components and Dark Matter

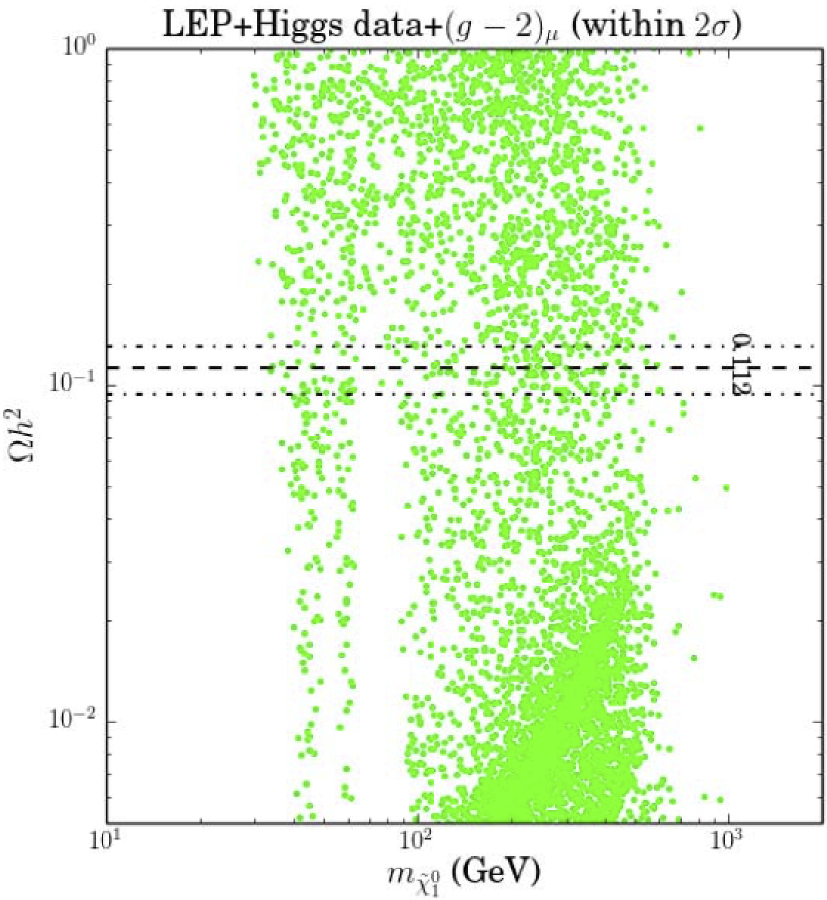
Dominant LSP components:

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

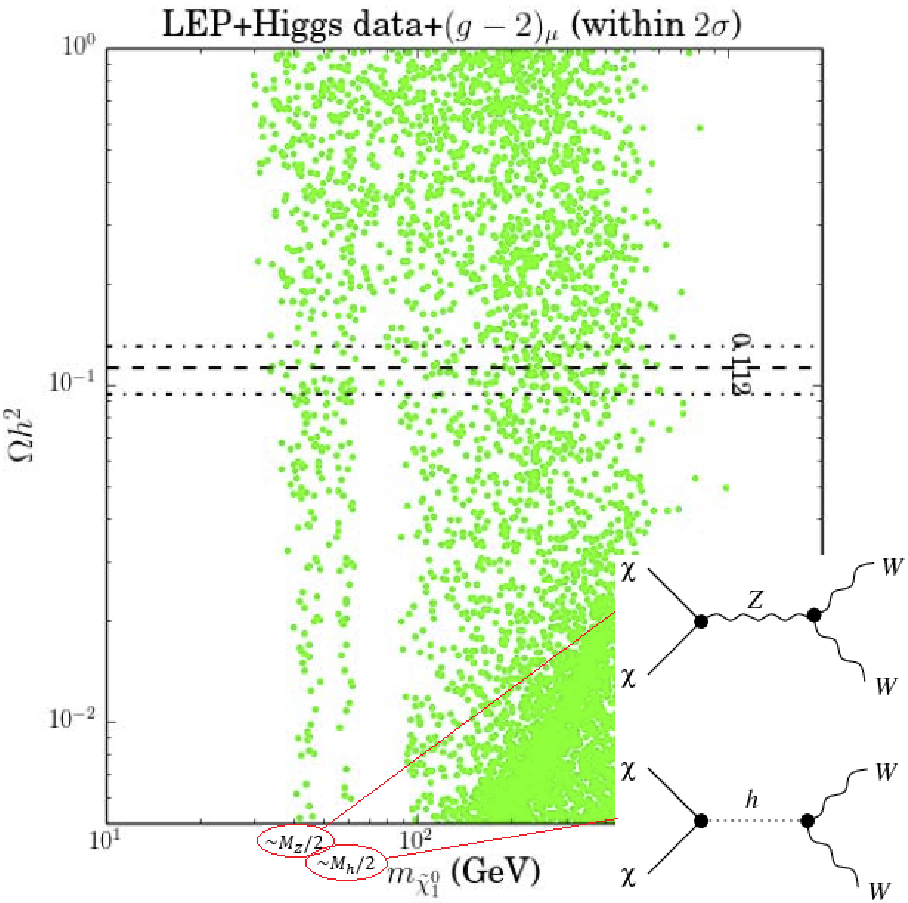
Dark Matter constraints on χ_1^0 vary for different compositions of Bino, Wino and Higgsinos:

- 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 (almost degenerate)
- The annihilation rate is significant with a wino or higgsino component, which can be difficult to reconcile with the correct relic density and constraints from direct-detection
- To avoid significant constraint, for any LSP abundance less than the relic density, we assume additional DM component (possibly non-WIMP axion-like DM)

Relic Density, Ωh^2



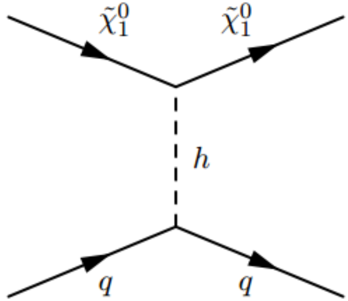
Relic Density, Ωh^2

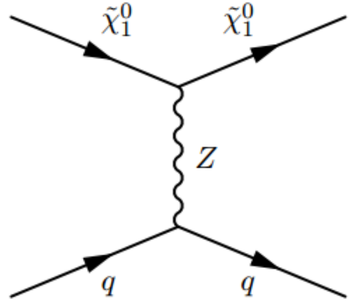


Direct detection of neutralino DM

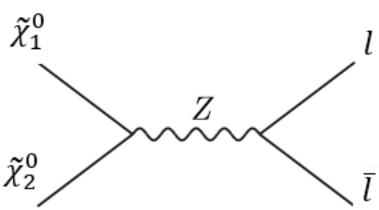
How can we avoid direct detection constraints and simultaneously satisfy Ωh^2?

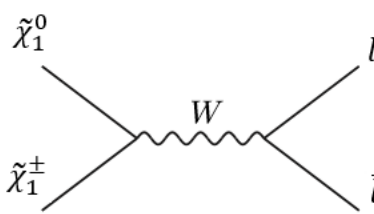
- SI MSSM "Blind Spots" (vanishing $h\chi_1^0\chi_1^0$ coupling through accidental cancellation)

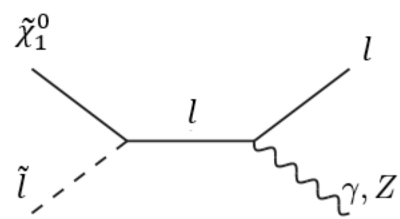




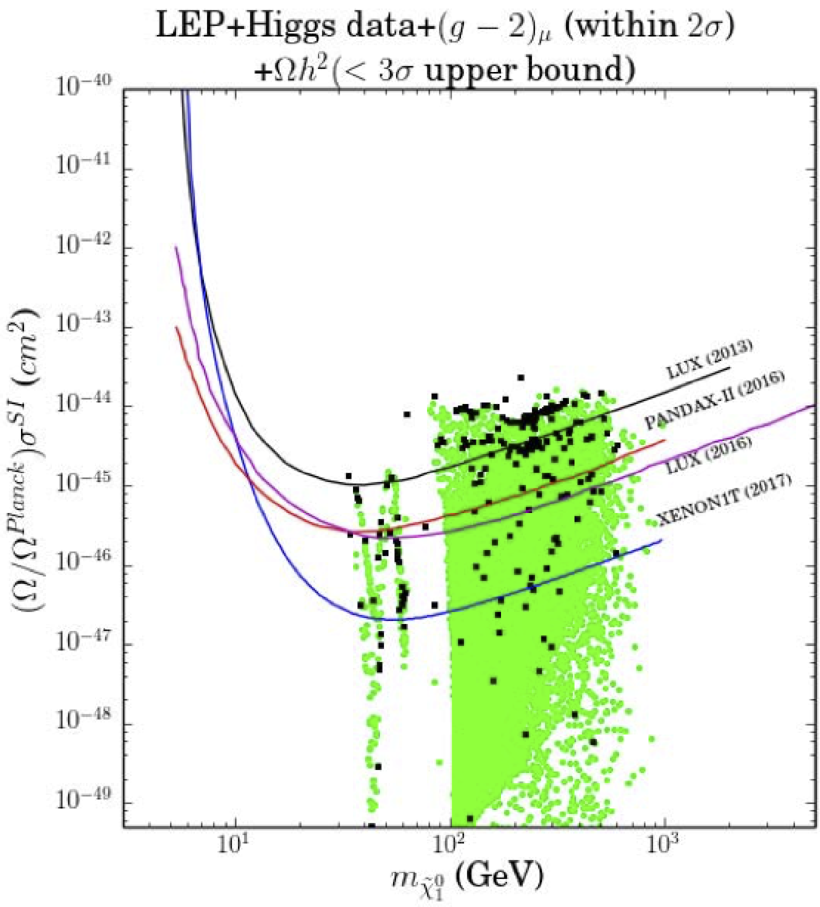
- Co-annihilation with other sparticles (Squarks, staus, other higgs too heavy - through NLSP or 1st & 2nd gen sfermions)







WIMP-nucleon SI Cross Section



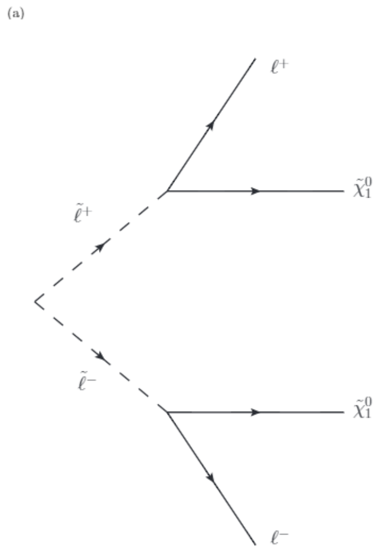
Collider Simulation

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

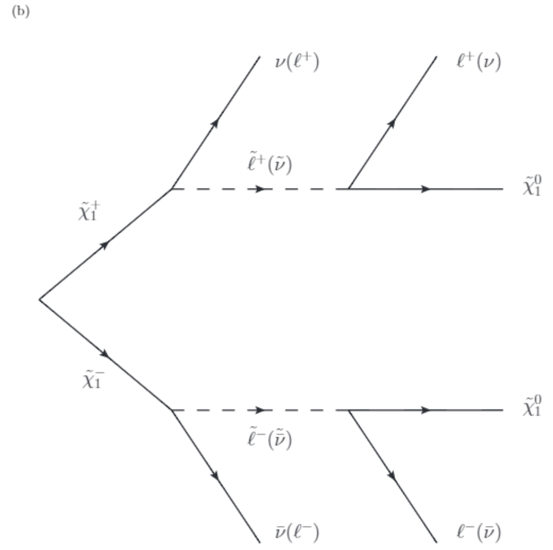
- We study electroweakinos at $\sqrt{s} = 8$ TeV LHC using 2ℓ +MET and 3ℓ + MET analyses
- Staus are heavy and do not contribute to the analysis
- Parameter sets that pass the previous Δa_μ, collider and direct/indirect dark matter searches are considered, which were typically bino-like with large coannihilation cross-section, 'blind-spot' region candidates, and also wino/higgsino-like that are usually underabundant.
- NLO events are simulated using `MadGraph 5` interfaced with `Pythia 6` and 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]



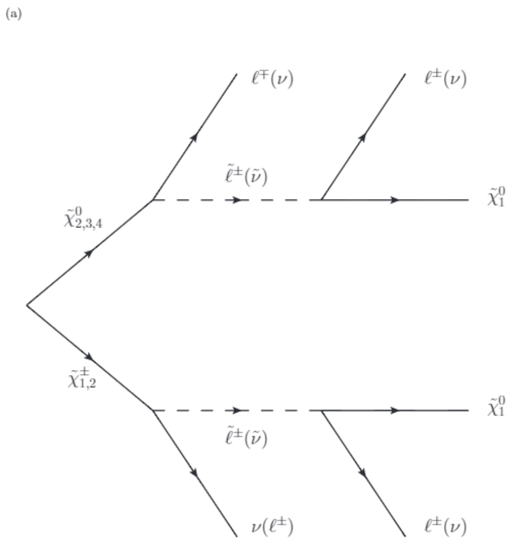
(a) via direct slepton decays



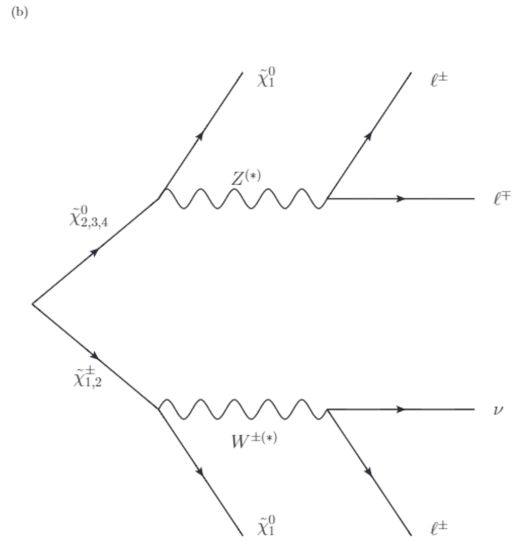
(b) via sleptons/sneutrinos

[1] atlas_conf_2013_049

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



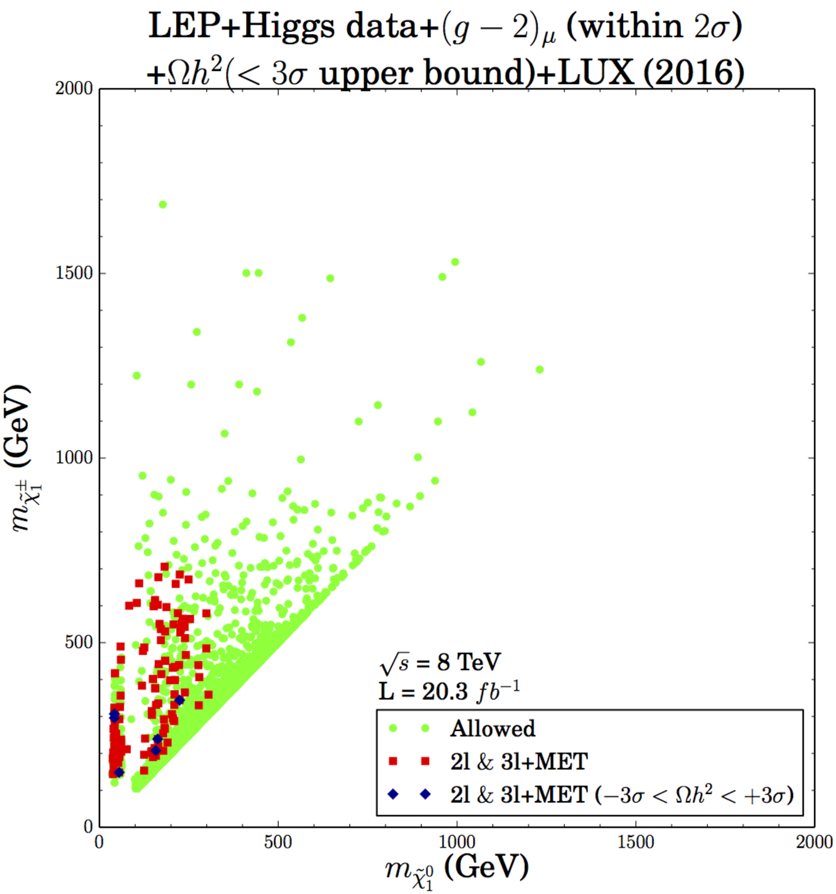
(a) via sleptons/sneutrinos



(b) via gauge bosons

[2] atlas_1402_7029

Results for 8 TeV collider search



100 TeV Analysis

A 100 TeV *pp* collider has been under discussion in recent times, hoping to probe new physics scales almost an order of magnitude higher than current LHC.

We scale the signal (S) and background (B) events for the 8 TeV $3\ell +$ MET analysis by the ratio:

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

Sources of background (B):

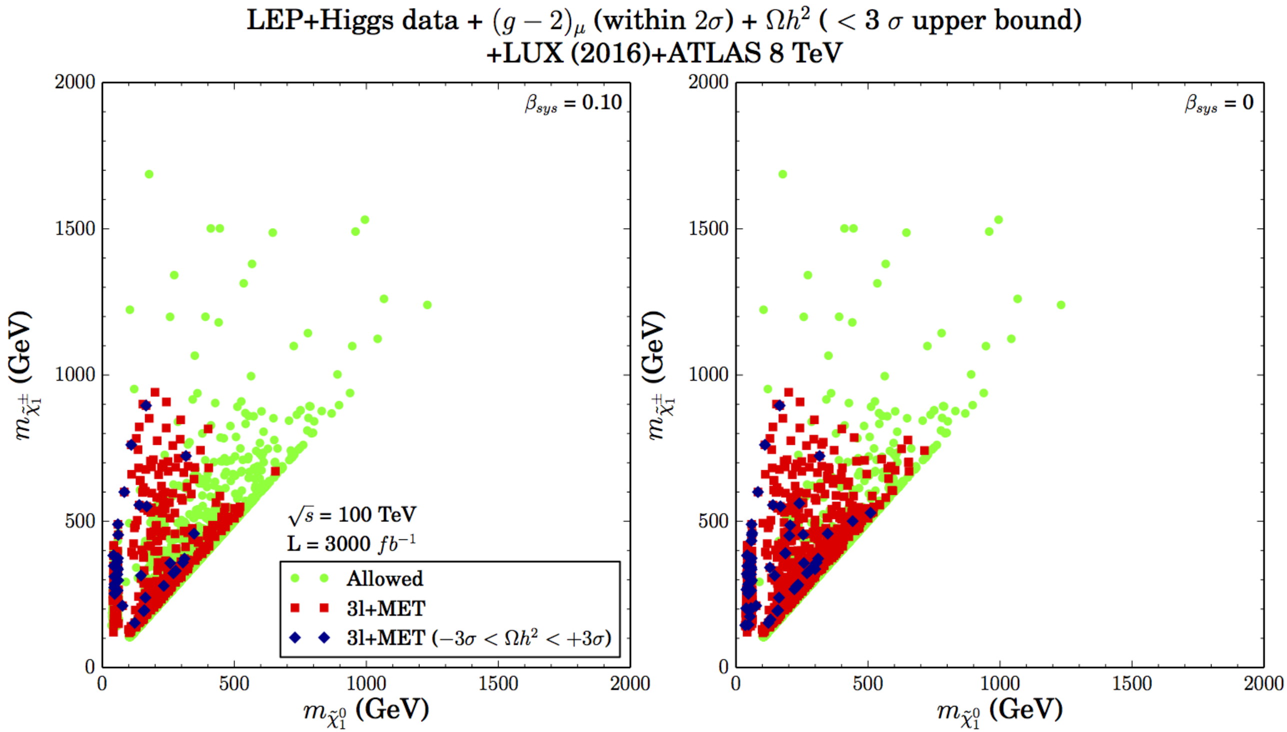
- WZ, ZZ, H
- $ttV + ttZ$
- VVV
- Reducible (t single/pair, WW, single W/Z with jets or photons)

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

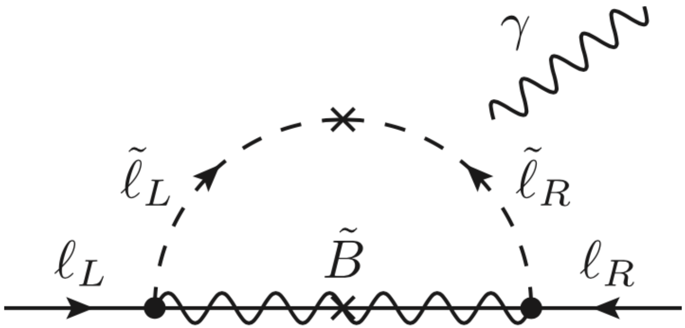


Conclusions

- We studied the potential for the MSSM to explain the muon $(g-2)_\mu$, which requires light sleptons + electroweakinos with some sizable higgsino/wino component.
- Points that satisfy the DM relic density (within 3σ) and the LUX constraints belong either to the MSSM 'blind-spot' region or are bino-like with a large slepton/wino coannihilation cross section.
- Points that survive the 100 TeV collider search correspond to wino/higgsino candidates in the compressed region and coannihilating bino-like samples with a smaller production cross-section.
- One can further the collider 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).
- Limits will be expected to become stronger as advances are made on the theoretical and experimental side for Δa_μ.

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**.