MSSM: muon g-2, dark matter and cosmology

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Outline

Introduction to Supersymmetry

Supersymmetry (SUSY) is a symmetry between bosons (forces) and fermions (matter).

Its generators transform as the *spinor representation* of the Lorentz group:

$$\{Q_\alpha, Q^\dagger_{\dot{\beta}}\} = 2(\sigma^\mu)_{\alpha\dot{\beta}} P_\mu \tag{1}$$

The minimal set of fields required to realize supersymmetry in the Standard Model is the *Minimal Supersymmetric Standard Model (MSSM)*.

Phenomenologically, thus far unobserved supersymmetric partner particles means that SUSY cannot be an exact symmetry of nature - and must be broken at some scale.

Why SUSY?

General Supersymmetric models can have a number of important consequences for low-energy observables and even cosmology:

- Only possible space-time symmetry extension to the SM (Coleman-Mandula Theorem)
- Stabilizes electroweak scale by removing quadratically divergent corrections
- An attractive thermal dark matter candidate - neutralino LSP (in R-Parity conserving models)
- Extra loop-level contributions to the muon $g - 2$ anomaly
- Gauge coupling unification at high-scale

We focus on model-independent SUSY studies which are particularly favorable for addressing a wide array of phenomena.

The Higgs mass in SUSY

The tree-level MSSM higgs mass at $\sim m_Z$ would require substantial radiative corrections to obtain the observed 125 GeV.

This would require either large stops, large stop sector mixing or both - spoiling the fine-tuning reduction (but only logarithmically).

$$m_{h^0}^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2} \frac{m_t^4}{v^2} \left(\log \frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2} \left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2} \right) \right) \tag{2}$$

where $X_t = A_t - \mu \cot \beta$ and $m_{\tilde{t}}^2 = \sqrt{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}$.

SUSY breaking

Our studies focus on the MSSM without any assumption of the mechanism of SUSY breaking - ie. a model-independent study.

The exact details of EWSB are still unknown - hence we can consider a number of parameterizations - this is important since electroweak and soft SUSY breaking are intricately connected in supersymmetry.

We studied a model-independent framework for parameterizing the higgs sector allowing for extra contributions to the tree-level higgs mass without introducing extra degrees of freedom (called EffMSSM[1]).

[1] Kobakhidze, A., Talia, M. *The Effective MSSM*, Phys. Lett. B **251-255** (2015)

Non-linear higgs sector

We introduce a non-linear chiral superfield describing the electroweak broken phase with residual $U(1)_{EM}$ symmetry:

$$U = e^{\frac{i}{2}\xi_i\sigma_i}, \quad \det \mathrm{U} = 1 \tag{3}$$

where $\xi_i (i = 1, 2, 3)$ are superfields whose scalar parts parameterize the coset space $SU(2)_L \times U(1)_Y / U(1)_{EM}$ and $\sigma_i (i = 1, 2, 3)$ are the pauli matrices. It transforms under this group as:

$$U \to e^{\frac{i}{2}\Lambda_i\sigma_i} U e^{-\frac{i}{2}\Sigma\sigma_3} \tag{4}$$

The neutral higgs are contained within a complex-valued singlet S under this gauge group. We can then identify the higgs fields through the **bidoublet** representation:

$$\Phi \equiv SU = \begin{pmatrix} H_u^0 & H_d^- \\ H_u^+ & H_d^0 \end{pmatrix}, \qquad \det\Phi = S^2 = H_u H_d \tag{5}$$

where H_u and H_d are the standard higgs doublets in the MSSM.

Non-linear higgs sector

The most general renormalizable Lagrangian for the gauged-higgs sector consists of the D-terms:

$$\begin{aligned}\mathcal{L}_{\mathrm{HG}} &= \left[Tr\left(\Phi^\dagger e^W \Phi e^B\right)\right]_D + \kappa^2\left[Tr\left(U^\dagger e^W U e^B\right)\right]_D \\ &\quad + \left[\alpha\, Tr\left(\Phi^\dagger e^W U e^B\right) + \alpha^* Tr\left(U^\dagger e^W \Phi e^B\right)\right]_D + \beta\left[\bar{S}S\right]_D \end{aligned} \tag{6}$$

where $W = gW_i\sigma_i$ and $B = g'Y\sigma_3$ are the respective $SU(2)$ and $U(1)_Y$ gauge superfields in the adjoint representation.

Higgs-Yukawa superpotential[2]:

$$W_{HY} = \bar{u}\left(\mathbf{y_u}\Phi + \mathbf{y'_u}U\right)\chi_u Q - \bar{d}\left(\mathbf{y_d}\Phi + \mathbf{y'_d}U\right)\chi_d Q - \bar{e}\left(\mathbf{y_e}\Phi + \mathbf{y'_e}U\right)\chi_d L \tag{7}$$

Higgs potential:

$$W_{\mathrm{H}} = \frac{\lambda}{3}S^3 + \frac{\mu}{2}S^2 - \tau S \tag{8}$$

[2]We have defined the quantities with doublet structure $\chi_u = (1\ 0)^{\mathrm{T}}$ and $\chi_d = (0\ 1)^{\mathrm{T}}$

Non-linear higgs potential

Tree-level scalar potential has extra contributions:

$$V_{\mathrm{H}} = \left|\lambda S^2 + \mu S - \tau\right|^2 + \left(S\bar{S} + \alpha\bar{S} + \alpha^* S + \kappa^2\right)^2 V_D + V_{\mathrm{soft}} \tag{9}$$

$$V_{\mathrm{soft}} = \left(\frac{1}{2} m_S^2 S^2 + \mathrm{h.c.}\right) + \frac{A}{2}\mathrm{Tr}\left(\Phi^\dagger \Phi\right) + \frac{B}{2}\mathrm{Tr}\left(\Phi^\dagger \Phi \sigma_3\right) \tag{10}$$

MSSM: $A = m_{H_u}^2 + m_{H_d}^2,\ B = m_{H_u}^2 - m_{H_d}^2,\ m_S^2 = 4B_\mu$.

We can even achieve EWSB in the supersymmetric limit ($A = B = m_S = 0$), where the S field develops a vev[3]:

$$\xi = 0\ ,\quad \lambda S^2 + \mu S - \tau = 0 \tag{11}$$

with the standard MSSM relation:

$$e^{\langle \xi \rangle} \equiv \tan\beta, \quad \langle S \rangle^2 = v_u v_d \tag{12}$$

Since S is complex, it can even be source of spontaneous CP violation.

[3]The charged fields ξ^+ and ξ^- minimize the potential, so here we define $\xi \equiv \mathrm{Im}(\xi_3)$

Spontaneous CP-violation

For this minima we identify $\langle S \rangle^2 = v^2/2$. If λ, μ, and τ are real then when $\lambda\tau < 0$ and $|\mu| < 2\sqrt{-\lambda\tau}$ then the singlet vev is written as:

$$\cos\theta = -\frac{\mu}{2\sqrt{-\lambda\tau}}, \quad |v| = \sqrt{-\frac{2\tau}{\lambda}} \tag{13}$$

If $\lambda\tau > 0$, v is real with 2 degenerate solutions:

$$v = -\frac{\mu}{2\sqrt{2}\lambda}\left(1 \pm \sqrt{1 + \frac{16\lambda\tau}{\mu^2}}\right), \quad (\theta = 0) \tag{14}$$

For $\theta = \pi$, $v \to -v$ and the equations are just swapped. We only focus on CP-conserving solutions.

Mass Spectrum in EffMSSM

The mass eigenstates for the neutral CP-even higgs states, in the limit of the extra D-terms vanishing are:

$$m_{H_1^0}^2 = 2\mu^2 + 2\lambda\left(3\mu v + 3\lambda v^2 - 2\tau\right) + 2m_S^2 + A \quad (15)$$

and

$$m_{H_2^0}^2 = m_Z^2 + 4A \quad (16)$$

Any of these states can be identified with the light 125 GeV higgs (though H_1^0 would be more natural since it resembles the SM-like higgs in the MSSM limit)

The other higgs states are also modified:

$$\begin{aligned} m_{A^0}^2 &= 2\mu^2 + \lambda(\lambda v^2 + 2\mu v + 2\tau) + A - 2m_S^2 \quad (17) \\ m_{H^\pm}^2 &= m_W^2 + 4A \quad (18) \end{aligned}$$

Mass Spectrum in EffMSSM

Neutralinos:

$$m^2_{\tilde{N}_1} \approx \frac{m_Z^4 \Delta^2}{M^2 v^4} \quad (19)$$

$$m^2_{\tilde{N}_2} = |\mu + \sqrt{2}\lambda v|^2 \quad (20)$$

$$m^2_{\tilde{N}_3} \approx M^2 - \frac{m_Z^4 \Delta^2}{M^2 v^4} \quad (21)$$

$$m^2_{\tilde{N}_4} \approx M^2 \quad (22)$$

Charginos:

$$m^2_{\tilde{C}_1} \approx \frac{64 m_W^4 \Delta^2}{M_2^2 v^4} \quad (23)$$

$$m^2_{\tilde{C}_2} \approx M_2^2 + \frac{64 m_W^4 \Delta^2}{M_2^2 v^4} \quad (24)$$

where $\kappa = \alpha = \beta = 0$ (vanishing extra D-terms), $\Delta = 174$ GeV, $M_1 = M_2 \equiv M$.

SUSY breaking in general

The mechanism that transmits SUSY breaking to the MSSM is unknown - it is broken explicitly with a set of all possible soft-breaking terms.

This suggests that to explain spontaneous SUSY breaking, we must have some UV completion to the MSSM - ie. the MSSM is only a low-energy limit of some higher theory.

Moreover, this means we remain agnostic to this breaking scale, and in particular the fundamental parameters describing the theory.

Fine-Tuning and RGE

In the MSSM, SUSY breaking and the electroweak scale are intimately tied through the minimization of the higgs potential.

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2 \simeq -m_{H_u}^2 - \mu^2 \tag{25}$$

We can characterize the amount to which the fundamental parameters a_i of the theory must be "tuned" in order to obtain correct electroweak observables using the 'traditional' Barbieri-Guidice measure:

$$\Delta = \max\left\{ \left| \frac{a_i}{m_Z^2} \frac{\partial m_Z^2}{\partial a_i} \right| \right\} \tag{26}$$

One-loop RGEs in FT

Suppose the MSSM is valid up to some scale Λ in which we input these parameters. We must evolve these down to the SUSY scale to compute the spectrum and FT.

The μ parameter is easy to keep small at the SUSY scale:

$$\frac{d}{dt}\mu = \frac{\mu}{16\pi^2}\left[3y_t^* y_t + 3y_b^* y_b + y_\tau^* y_\tau - 3g_2^2 - \frac{3}{5}g_1^2\right] \tag{27}$$

However, the $m_{H_u}^2$ term depends on the gauginos + 3rd gen. scalar masses.

$$\frac{d}{dt}m_{H_u}^2 = \frac{1}{16\pi^2}\left[3|y_t|^2 X_t - 6g_2^2|M_2|^2 - \frac{6}{5}g_1^2|M_1|^2 + \frac{3}{5}g_1^2 S\right] \tag{28}$$

where:

$$S \equiv m_{H_u}^2 - m_{H_d}^2 + Tr[m_Q^2 - m_L^2 - 2m_{\bar{u}}^2 + m_{\bar{d}}^2 + m_{\bar{e}}^2] \tag{29}$$

$$X_t = 2(m_{H_u}^2 + m_{Q_3}^2 + m_{\bar{u}_3}^2) + 2|a_t|^2 \tag{30}$$

MSSM Fine-Tuning Scan

The MSSM 20 parameter space we choose includes non-universal gaugino M_1, M_2, M_3, scalar sfermion masses $m_Q^2, m_u^2, m_d^2, m_L^2, m_e^2$ (degenerate 1st + 2nd gen), higgs masses $m_{H_u}^2, m_{H_d}^2$, trilinear terms A_e, A_b, A_t, the higgsino mass-term $sgn(\mu)$ and $\tan\beta$. We additionally choose a low, medium and high scale for the UV cutoff of the MSSM:

$$\Lambda \in \left[10^5, 10^{10}, 10^{16}\right] \text{ GeV} \tag{31}$$

We compute the fine-tuning measure using the full MSSM two-loop RGEs in `SPHENO-3.3.8` combined with `SARAH`.

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:

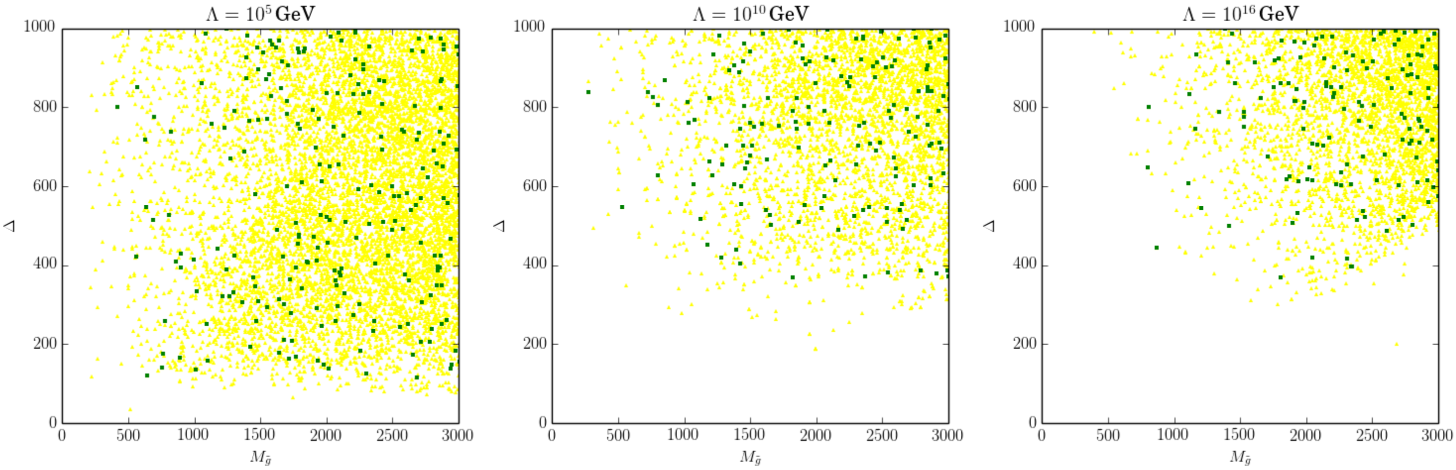
$$
123 < m_{h^0} < 127\,\text{GeV}
$$

- 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)

Fine-Tuning in the MSSM



Infrared Quasi-Fixed points in the MSSM

One technique we can use to find points of low fine-tuning for large scale Λ is exploiting the IRQFP of the MSSM.

Eg. consider the one-loop RGE for the top-Yukawa coupling:

$$\frac{dg_3}{dt} = -3\frac{g_3^3}{16\pi^2} \tag{32}$$

$$\frac{dy_t}{dt} = \frac{y_t}{16\pi^2}\left(6y_t^2 - \frac{16}{3}g_3^2\right) \tag{33}$$

At a certain energy scale, the RGE vanishes at the critical value $y_t^2/g_3^2 = 7/18$ - so this quantity is stabilized in the infrared.

We can search for the same behavior in the RGE for $m_{H_u}^2$ in order to keep it small and negative at the SUSY scale from a high-scale input.

Infrared Quasi-Fixed points in the MSSM

For $\Lambda = 10^{16}$ GeV, we take a rather large input top-yukawa coupling $y_t \sim 3$ and $m^2_{H_u}/m^2_0 \sim 10$ where m_0 are all other scalar masses in the theory (including $m^2_{H_d}$). This enhances the $3|y_t|^2 X_t$ term compared to the others in the RGE for $m^2_{H_u}$.

The stop mass parameters m^2_{Q3} and m^2_{u3} are driven large and positive towards the infrared and can destabilize $m^2_{H_u}$ - high-scale **negative stop mass-squared parameters** can prevent this.

Although tachyonic scalar masses are not excluded cosmologically, we cannot make the stop mass-squared parameter arbitrarily large with negative sign at high-scale.[4]

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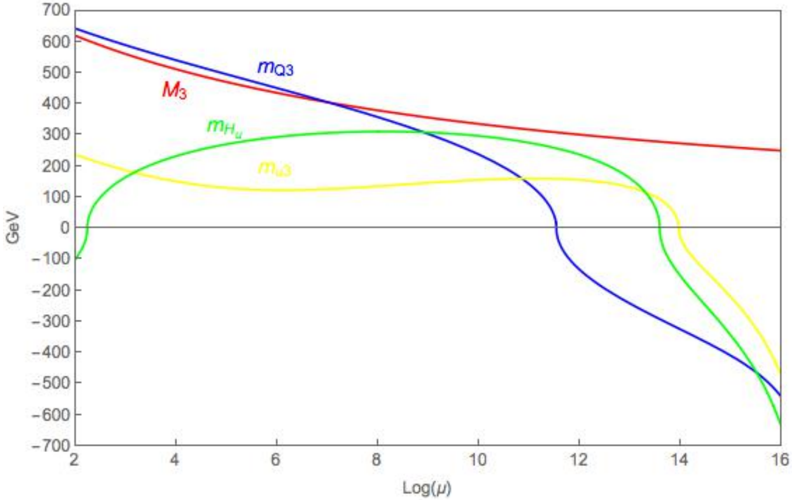
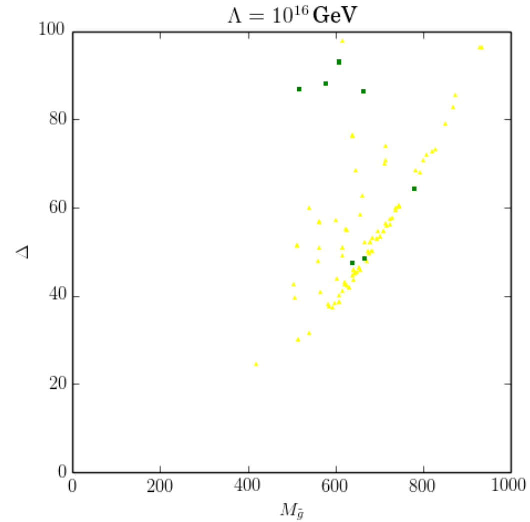
[4] Dermisek, R., Do Kim, H. *Radiatively Generated Maximal Mixing Scenario for the Higgs Mass and the Least Fine Tuned Minimal Supersymmetric Standard Model*, Phys. Rev. Lett. **96**, 211803

Infrared Quasi-Fixed points in the MSSM





Definition: $m_{H_u} \equiv m^2_{H_u}/\sqrt{|m^2_{H_u}|}$ & $m_{Q3} \equiv m^2_{Q3}/\sqrt{|m^2_{Q3}|}$

SUSY as an effective theory

Naturalness arguments clearly favour as small a Λ as possible - hence suggesting that SUSY can remain a natural theory so long as it is considered an effective theory valid up to some UV scale $Q < \Lambda$ - where Λ in this case is an arbitrary NP scale.

What may look like 'fine-tuning' in the low-energy MSSM may actually be correlations among parameters in the (unknown) UV-complete theory.

Clearly, the naturalness criteria as it stands is in conflict with squark and gluino searches which are favoured at sub-TeV scale ($m_{\tilde{g}} \gtrsim 1.5$ TeV when $m_{\tilde{g}} \sim m_{\tilde{q}}$).

Weak-scale SUSY

There are several more motivations for SUSY to appear at the weak-scale:

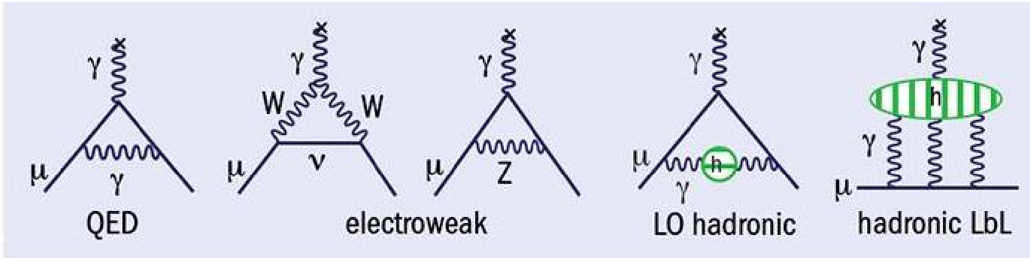
- Tree-level higgs mass around m_Z
- Existence of electroweakinos (partners of EW gauge bosons)
- μ term predicts masses of higgsinos and must be $< O(\text{TeV})$ for EWSB
- SUSY DM candidates fits the WIMP paradigm

Weak-scale SUSY is important for its contribution to low-energy observables, namely the muon $g-2$ anomaly - this is being measured to even higher precision at Fermilab.

We explored the potential for the MSSM to explain the anomaly but also remain consistent with the previously discussed constraints on the higgs and DM.

The muon $g - 2$

Contributions to the SM:



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

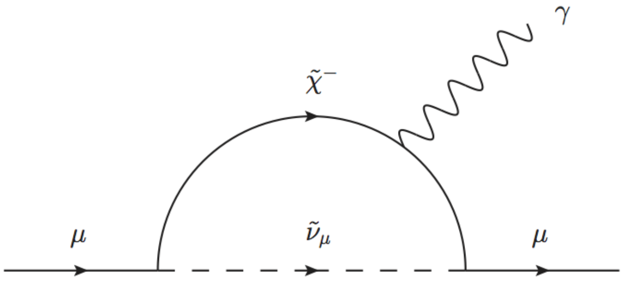
- Main theoretical uncertainty comes from LO Hadronic loop contributions (quarks and gluons)

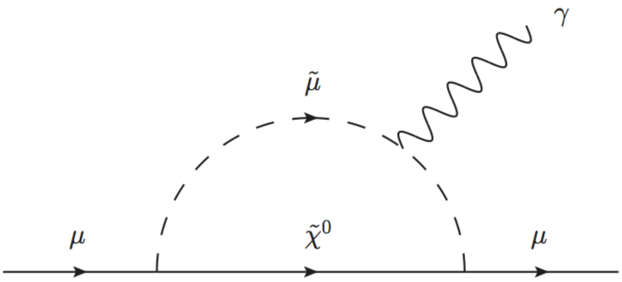
$$20.6 \times 10^{-10} < \Delta a_\mu < 36.6 \times 10^{-10} \quad (1\sigma)$$
$$12.6 \times 10^{-10} < \Delta a_\mu < 44.6 \times 10^{-10} \quad (2\sigma)$$

where

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

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:

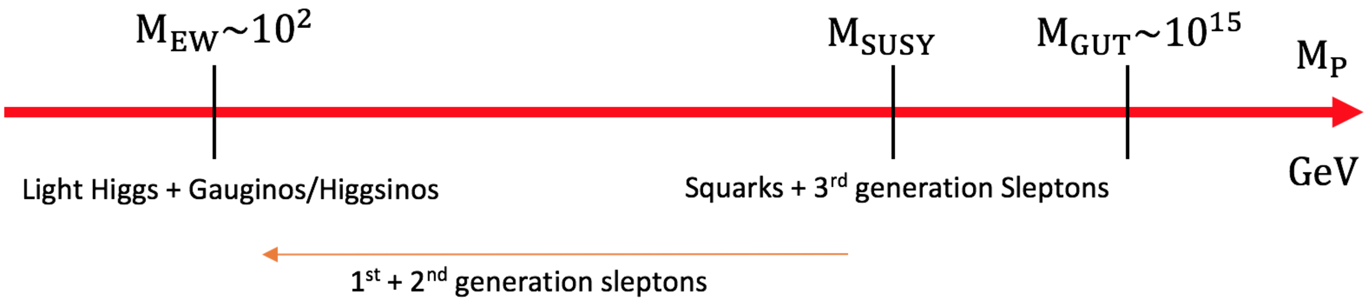
$$\tilde{\mu}, \tilde{\nu}_\mu, \tilde{\chi}^0, \tilde{\chi}^\pm \tag{34}$$

- 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**



MSSM Parameter Scan

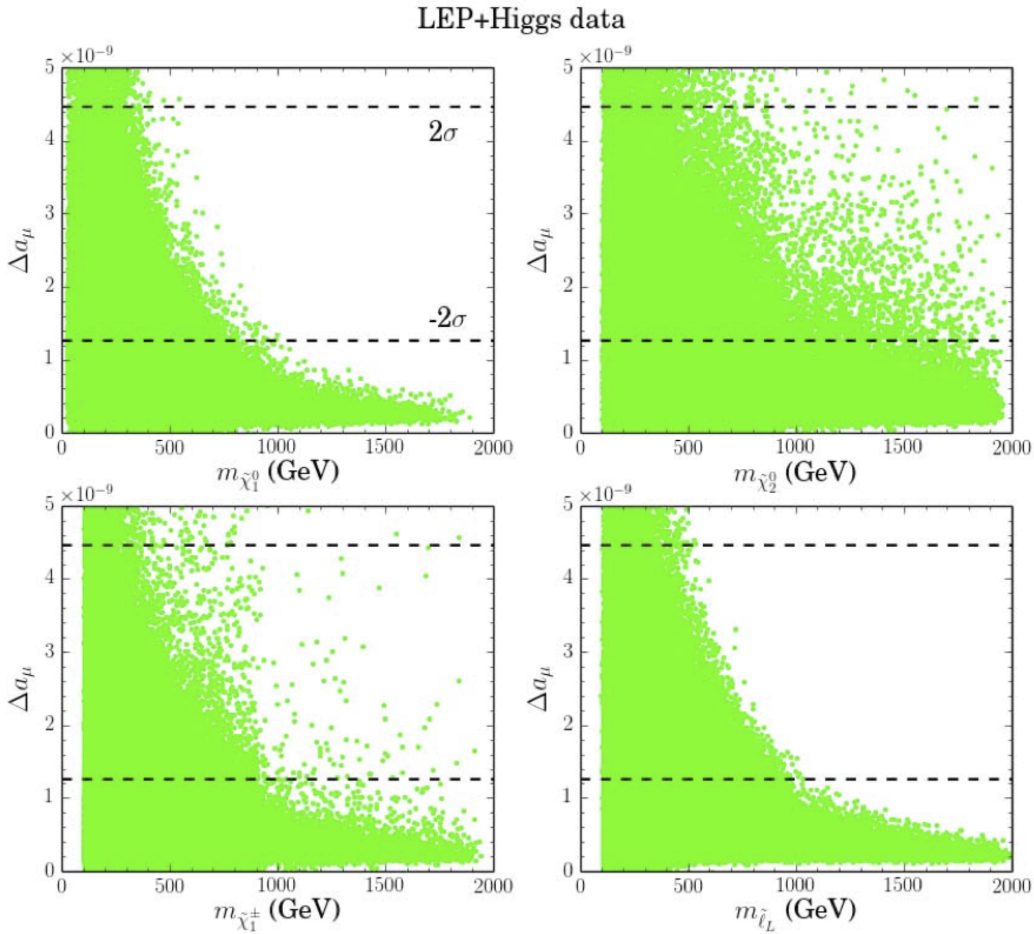
We calculate the $(g-2)_\mu$ and mass spectrum in the MSSM using `FeynHiggs-1.12.0`:

- 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

Parameter scan range:

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

Limits on neutralinos, charginos and smuons



Neutralino components and Dark Matter

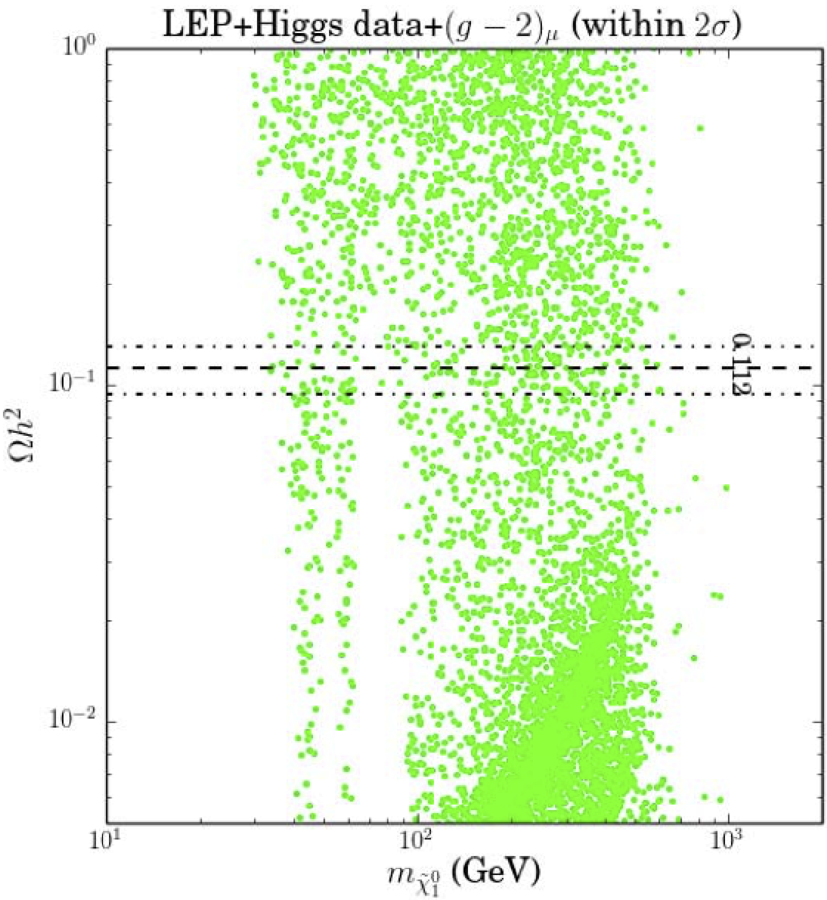
If the LSP component has...

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

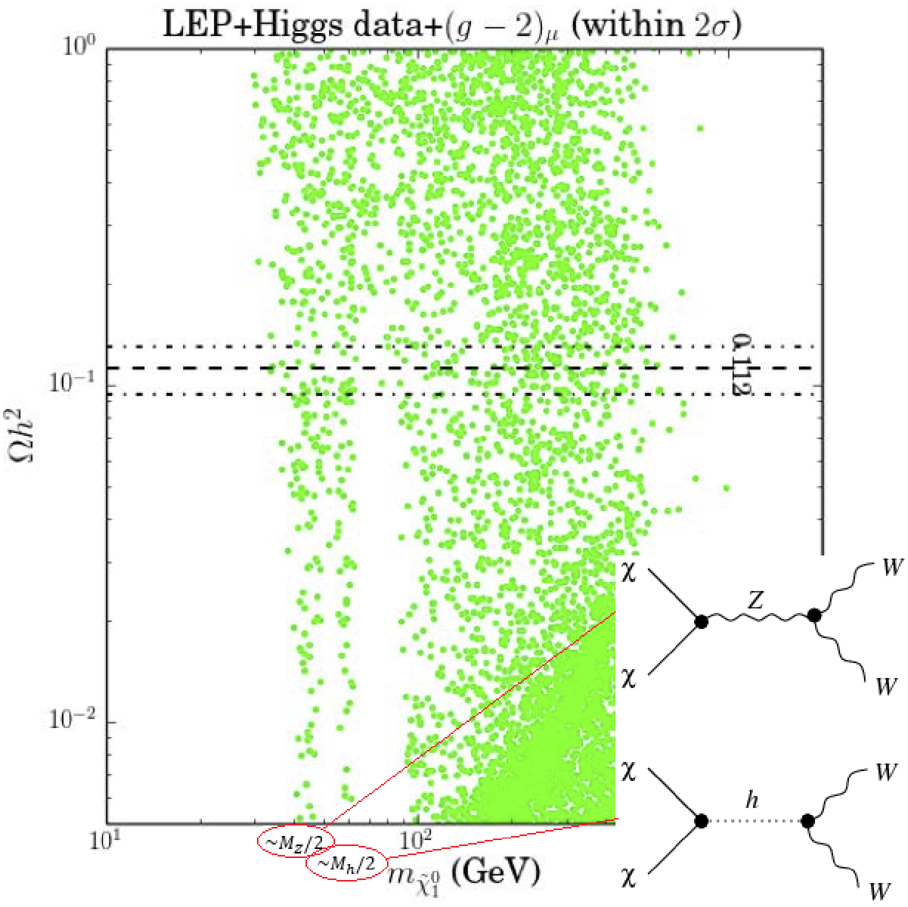
Dark Matter constraints on χ_1^0 vary for different compositions of Bino, Wino and Higgsinos:

- 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



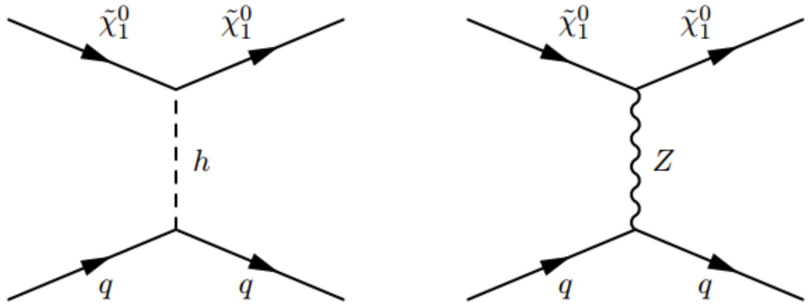
Relic Density, Ωh^2



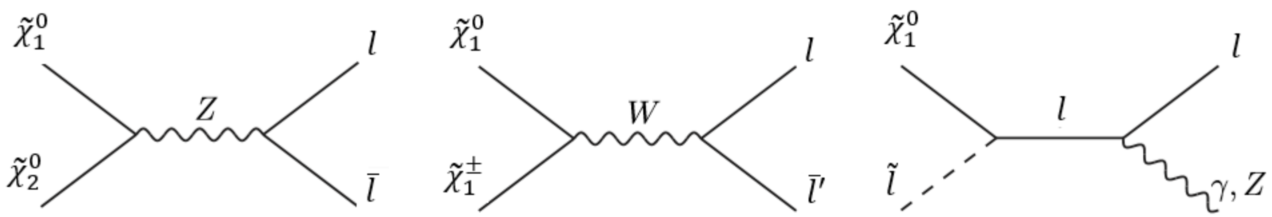
Direct detection of neutralino DM

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

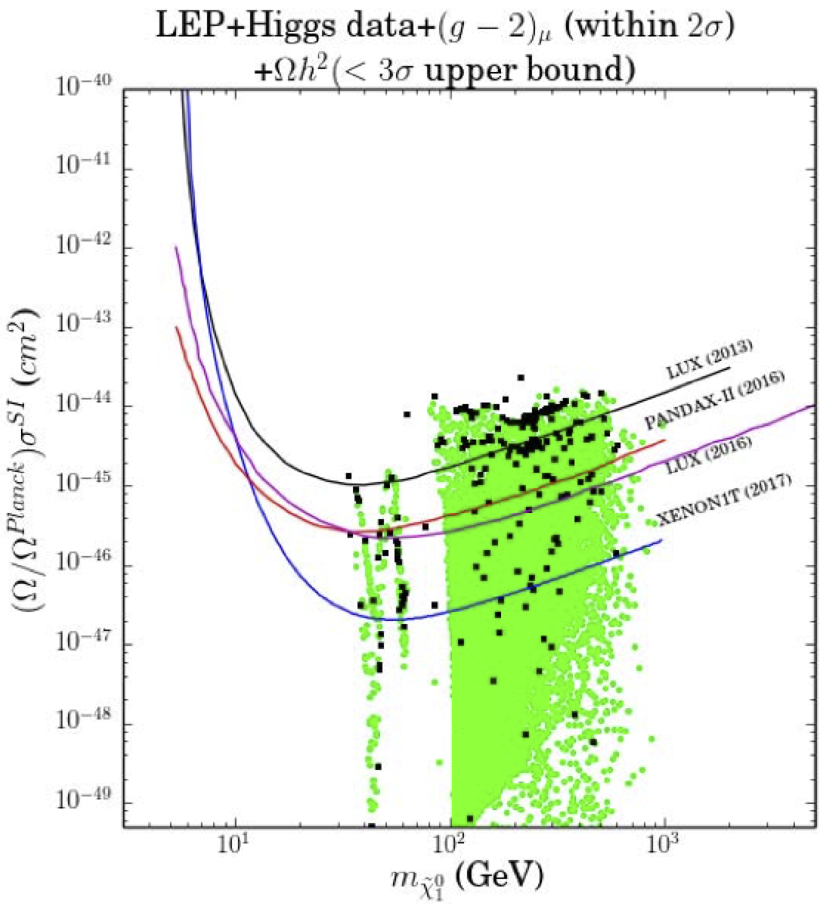
- SI MSSM "Blind Spots" (vanishing $h\chi_1^0\chi_1^0$ coupling through accidental cancellation)



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



WIMP-nucleon SI Cross Section



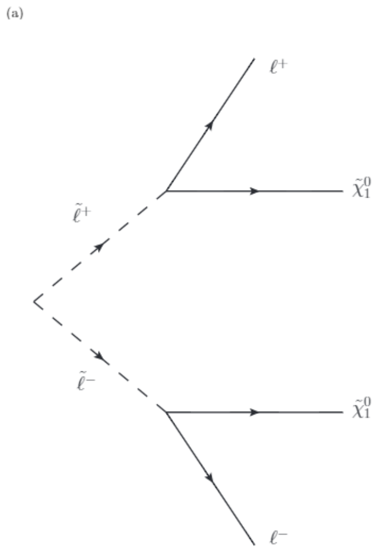
Collider Simulation

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

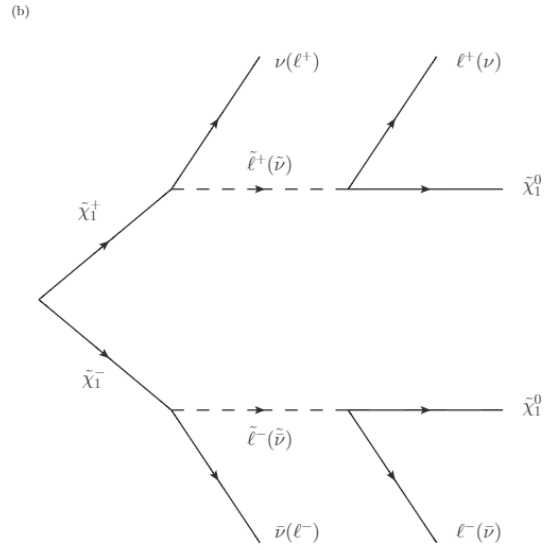
- We study electroweakinos at $\sqrt{s} = 8$ TeV LHC from slepton/sneutrino and W/Z decays
- Parameter sets that pass the previous collider and direct/indirect dark matter searches are considered
- Points are considered within the 2σ limit of Δa_μ
- We also present the prospects for electroweakino searches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

Electroweakinos and sleptons at colliders

$2\ell + \not{E}_T$ (2 leptons + missing energy) [5]



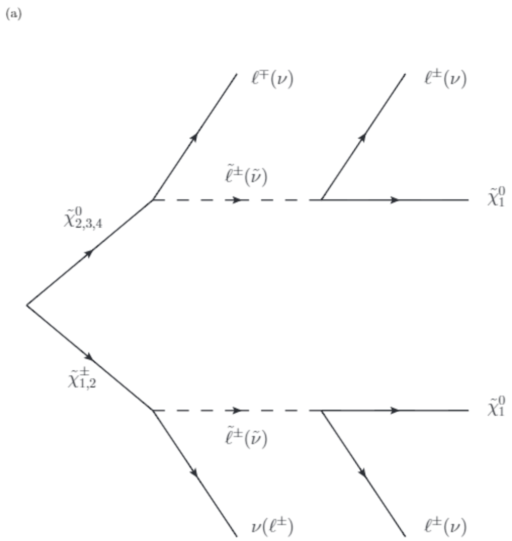
(a) via direct slepton decays



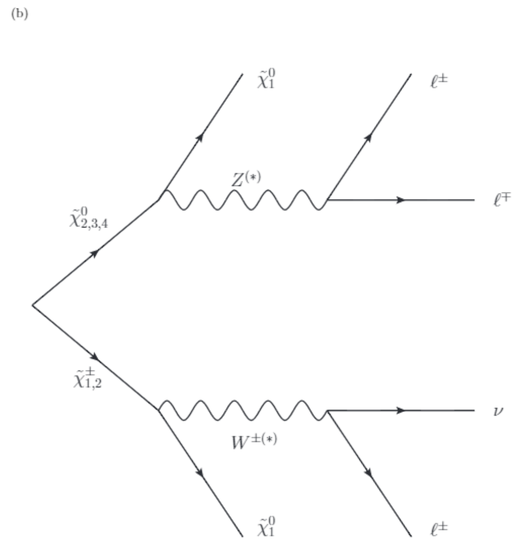
(b) via sleptons/sneutrinos

[5] atlas_conf_2013_049

$3\ell + \not{E}_T$ (3 leptons + missing energy) [6]



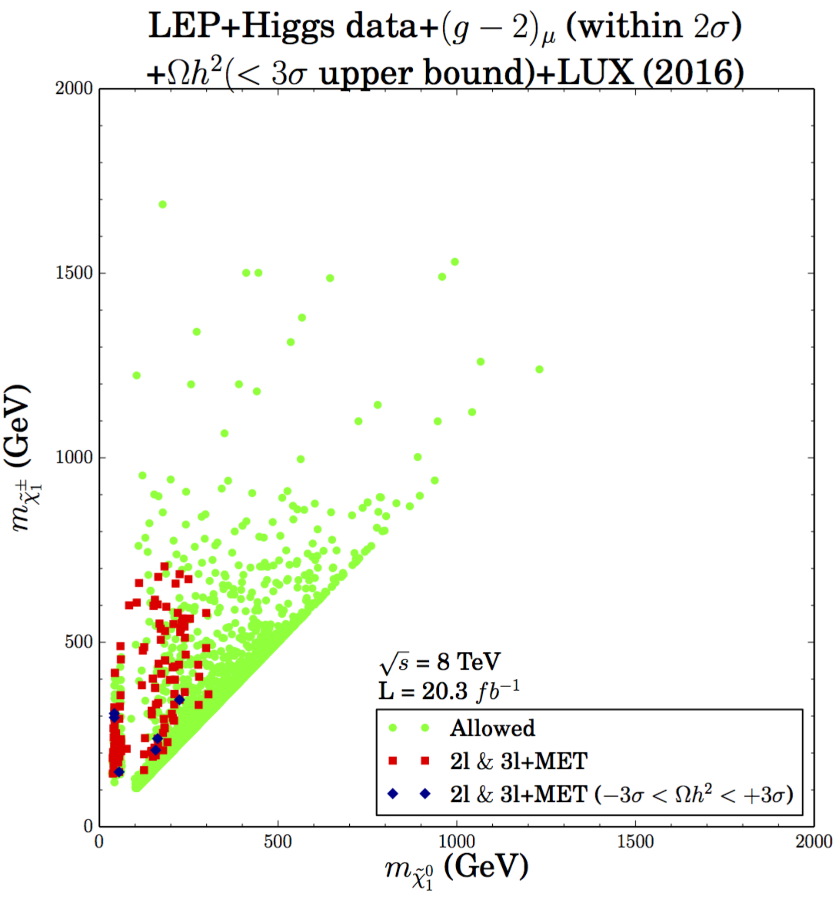
(a) via sleptons/sneutrinos



(b) via gauge bosons

[6] 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 perform a preliminary analysis by scaling the signal (S) and background (B) events for the 8 TeV 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):

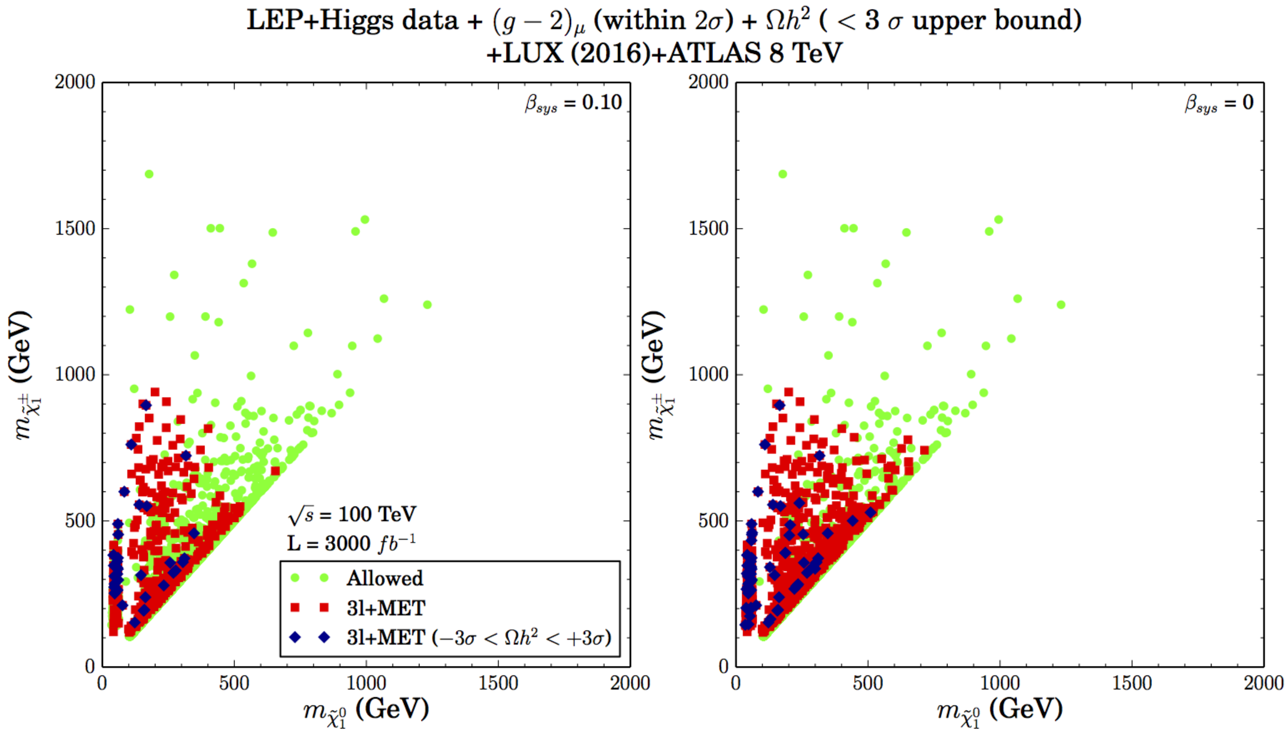
- WZ, ZZ, H
- $ttV + ttZ$
- VVV
- Reducible (t single/pair, WW, single W/Z with jets or photons)

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



MSSM Dark Matter overpopulation

It is clear that a neutralino DM candidate with a significant **bino fraction** has a small interaction rate - and these are typically excluded since they are overabundant at freeze-out.

The overabundance of thermally-produced LSP neutralino DM can be alleviated through neutral superpartner mixing (with winos or higgsinos), however one can even explore cosmological mechanisms.

We studied a mechanism for DM depopulation by temporarily violating (and then restoring) R-parity in the early universe through sneutrino condensation.

Finite Temperature potential w/ sneutrino

Consider the tree-level (zero temperature) potential for this light higgs and one light sneutrino field (assuming the heavier higgs are >TeV):

$$V_0 = -\frac{m_h^2}{4} h^2 + m_{\tilde{\nu}}^2 |\tilde{\nu}|^2 + \frac{m_Z^2}{8v^2} \left(\frac{m_h}{m_Z} h^2 + 2|\tilde{\nu}|^2 \right)^2 \tag{35}$$

Since the squared sneutrino mass must be positive, this leads to the constraint:

$$-\left(\frac{m_Z m_h}{2} + \text{rad. corr.} \right) < m_{\tilde{\nu}}^2 < 0 \tag{36}$$

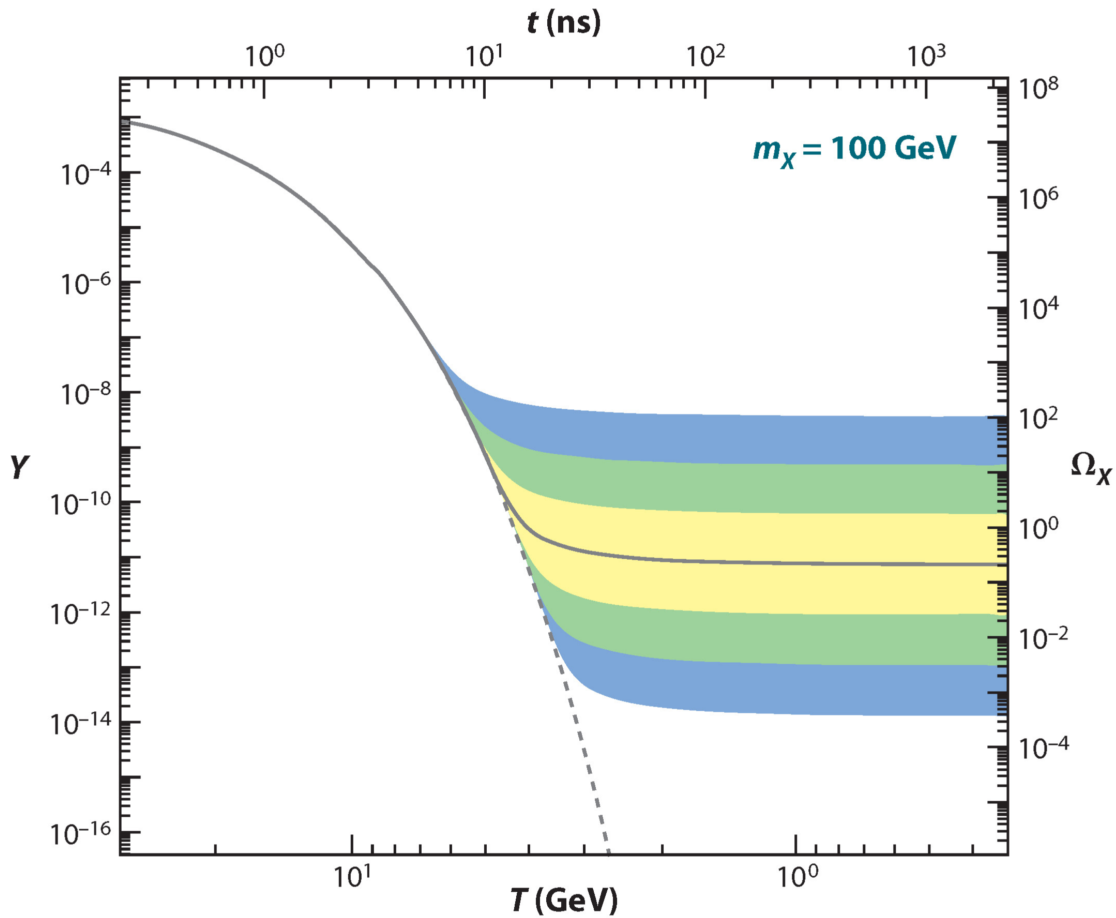
The finite temperature corrections to the potential are:

$$V_T = \frac{\alpha_h T^2}{2} h^2 + \alpha_{\tilde{\nu}} T^2 |\tilde{\nu}|^2 \ , \tag{37}$$

$$\alpha_h \approx 0.383 \tag{38}$$

$$\alpha_{\tilde{\nu}} \approx 0.129 \tag{39}$$

The standard thermal DM freeze-out scenario



Cosmological Sneutrino instability

At large T, $\langle h \rangle_T = \langle \tilde{\nu} \rangle_T = 0$ (R-parity, EW symmetry unbroken).

Consider a cosmological timeline where the sneutrino first condenses (breaking R-Parity) and then as the temperature of the universe cools, we break electroweak symmetry with higgs condensation. The positive contribution from the higgs in the sneutrino direction forces restoration of R-parity.

In this temperature range, the neutralino LSP is unstable:

$$T_c^h \approx 143 < T < T_c^{\tilde{\nu}} \approx 2.78 |m_{\tilde{\nu}}| \text{ GeV} \tag{40}$$

Depending on the DM freeze-out temperature T_f:

- $T_f \ll T_c^h$ - freeze-out occurs far after instability phase took place (probably not interesting since scatterings can force back to equilibrium)
- $T_f \gg T_c^{\tilde{\nu}}$ - freeze-out occurs far before instability phase
- $T_c^h < T_f < T_c^{\tilde{\nu}}$ - freeze–out occurs during or just after instability

Sneutrino mixing

During the instability, there is mixing between the one-flavour neutrino and gaugino eigenstates:

$$\hat{M}_{N\nu} = \begin{pmatrix} 0 & g\langle\tilde{\nu}\rangle_T & g'\langle\tilde{\nu}\rangle_T \\ g\langle\tilde{\nu}\rangle_T & M_2 & 0 \\ g'\langle\tilde{\nu}\rangle_T & 0 & M_1 \end{pmatrix} \tag{41}$$

where $\langle\tilde{\nu}\rangle_T \approx 2|m_{\tilde{\nu}}|/(g'^2 + g^2)^{1/2}$.

Assuming the soft mass hierarchy $|m_{\tilde{\nu}}| < M_1 < M_2$, the lightest neutralino is **bino-like**. It can then undergo the (dominant) 2-body decay $\chi \to Z\nu'$ with width:

$$\Gamma_\chi \simeq \frac{1}{2\pi} \frac{|m_{\tilde{\nu}}|^2 s_W^2}{M_1^2} \frac{m_{\chi_1^0}^3}{v^2} \left(1 - \frac{m_Z^2}{m_{\chi_1^0}^2}\right)^2 \tag{42}$$

where the only free parameter is $m_{\tilde{\nu}}$, apart from $m_{\chi_1^0} \sim M_1$.

Instability phase calculation

The Boltzmann equation for dark matter yield $Y_\chi(x = m_\chi/T) = n_\chi/s$ is modified with this decay process:

$$\frac{dY_\chi}{dx} = -\frac{2\Gamma_\chi x}{g_\chi H_\chi}\left(Y_\chi - Y_\chi^{(eq)}\right) + (2 \rightleftarrows 2) \tag{43}$$

where $g_\chi = 2$ for majorana DM and $H_\chi = (\pi^2 g_*/90)^{1/2}\frac{m_\chi^2}{M_P}$.
We can ignore the 2-body scattering term since it is suppressed by the factor $(m_\chi/m_{\tilde{l},\tilde{q}})^2$.

Abundance after neutralino decay

For the case $T_f \gg T_c^{\tilde{\nu}}$, the equilibrium abundance is negligible.

$$Y_{\chi,0} \simeq Y_\chi(x_h) \approx \frac{x_f}{\lambda} \exp\left[-\frac{\Gamma_\chi}{2H_\chi}(x_h^2 - x_{\tilde{\nu}}^2)\right] \tag{44}$$

Since $\frac{\Gamma_\chi}{H_\chi} \propto M_P/m_\chi$, this exponential suppression factor is very large. Hence, either the neutralino mass must be heavy or the instability phase extremely short as to not completely remove the DM after freeze-out.

For the case $T_f \sim T_c^{\tilde{\nu}}$, the abundance after freeze-out depends on the ratio between scatterings and decay rates. One would expect the decays to dominate over scatterings, and hence one should see a large suppression again.

Conclusions

- With a 100 TeV collider, we can potentially probe all of the parameter space satisfying the muon g-2, dark matter direct/indirect detection and higgs/electroweakino searches.
- Constraints on almost Bino-like neutralino DM are relieved through the temporary instability in the sneutrino direction - particular when it follows after freeze-out - this expands the allowed parameter space to support weak-scale observables.
- As the collider center-of-mass energies increase over time, we have the potential to study weak-scale supersymmetry in great detail - particularly we present a strong case for probing the muon g-2.