SUSY Dark Matter in Light of LHC and LUX Results

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Introduction

- **After the discovery of the Higgs particle at the LHC:**

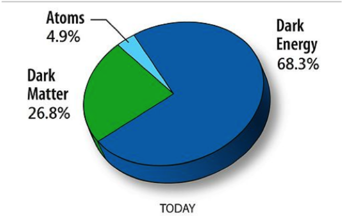
  Dark matter is the next important physics question

- **The search is complementary to other experimental techniques used:**

  Direct detection: e.g. Large Underground Xenon (LUX)
  Indirect detection: Alpha Magnetic Spectrometer (AMS-02)

- **Supersymmetry was not "invented" to solve the dark matter problem, but can provide a great solution.**

- **Lightest SUSY Particle (WIMP DM candidate) comes for free.**



MSSM Parameter Space

- **The particle content of the MSSM is three generations of (chiral) quark and lepton superfields, the (vector) superfields necessary to gauge the $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge of the SM, and two (chiral) $SU(2)$ doublet Higgs superfields.**

- **The interactions between Higgs and matter superfields are described by the superpotential**

$$W = Y_u Q_L U_L^c H_2 + Y_d Q_L D_L^c H_1 + Y_e L_L E_L^c H_1 + \mu H_1 H_2. \qquad (1)$$

- **Here Q_L contains $SU(2)$ (s)quark doublets and U_L^c, D_L^c are the corresponding singlets, (s)lepton doublets and singlets reside in L_L and E_L^c respectively. While H_1 and H_2 denote Higgs superfields with hypercharge $Y = \mp\frac{1}{2}$.**

MSSM Parameter Space

- Due to the fact that Higgs and lepton doublet superfields have the same $SU(3) \times SU(2)_L \times U(1)_Y$ quantum numbers, we have additional terms that can be written as

$$W' = \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} D_i^c D_j^c U_k^c + \mu_i L_i H_2. \qquad (2)$$

- These terms violate baryon and lepton number explicitly and lead to proton decay at unacceptable rates.

- To forbid these terms a new symmetry, called R-parity, is introduced, which is defined as $R_P = (-1)^{3B+L+2S}$, where B and L are baryon and lepton number and S is the spin.

- There are two remarkable implications of the presence of R-parity:

  i) SUSY particles are produced or destroyed only in pair.
  ii) The LSP is absolutely stable, a possible candidate for DM.

MSSM Parameter Space

- **The soft SUSY breaking Lagrangian is given by**

$$\begin{aligned}\mathcal{L}_{\rm soft} &= -\frac{1}{2}M_a\lambda^a\lambda^a - m^2_{\tilde{q}_{ij}}\tilde{q}^*_i\tilde{q}_j - m^2_{\tilde{u}_{ij}}\tilde{u}^*_i\tilde{u}_j - m^2_{\tilde{d}_{ij}}\tilde{d}^*_i\tilde{d}_j - m^2_{\tilde{l}_{ij}}\tilde{l}^*_i\tilde{l}_j \\ &- m^2_{\tilde{e}_{ij}}\tilde{e}^*_i\tilde{e}_j - m^2_{H_2}|H_2|^2 - m^2_{H_1}|H_1|^2 - \Big[A^{ij}_u Y^{ij}_u\tilde{q}_i\tilde{u}_j H_2 \\ &+ A^{ij}_d Y^{ij}_d\tilde{q}_i\tilde{d}_j H_1 + A^{ij}_e Y^{ij}_e\tilde{\ell}_i\tilde{e}_j H_1 - B\mu H_2 H_1 + h.c\Big]. \qquad (3)\end{aligned}$$

- **In the MSSM, a certain universality of soft SUSY breaking terms at grand unification scale $M_X = 3\times 10^{16}$ GeV is assumed. These terms are defined as m_0, the universal scalar soft mass, $m_{1/2}$, the universal gaugino mass, A_0, the universal trilinear coupling, B, the bilinear coupling (the soft mixing between the Higgs scalars).**
- **In addition, the MSSM contains another two free SUSY parameters: μ and $\tan\beta = \langle H_2\rangle/\langle H_1\rangle$. Two of these free parameters, μ and B, can be determined by the electroweak breaking conditions:**

$$\mu^2 = \frac{m^2_{H_1} - m^2_{H_2}\tan^2\beta}{\tan^2\beta - 1} - M_Z^2/2, \quad \sin 2\beta = \frac{-2m_3^2}{m_1^2 + m_2^2}. \qquad (4)$$

Thus, the MSSM has only four independent free parameters: $m_0, m_{1/2}, A_0, \tan\beta$, besides to the sign of μ, that determine the whole spectrum.

LHC Constraints on MSSM Parameter Space

- **In the MSSM, the mass of the lightest Higgs state can be approximated, at the one-loop level, as**

$$m_h^2 \leq M_Z^2 + \frac{3g^2}{16\pi^2 M_W^2} \frac{m_t^4}{\sin^2\beta} \log\left(\frac{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}{m_t^4}\right). \tag{5}$$

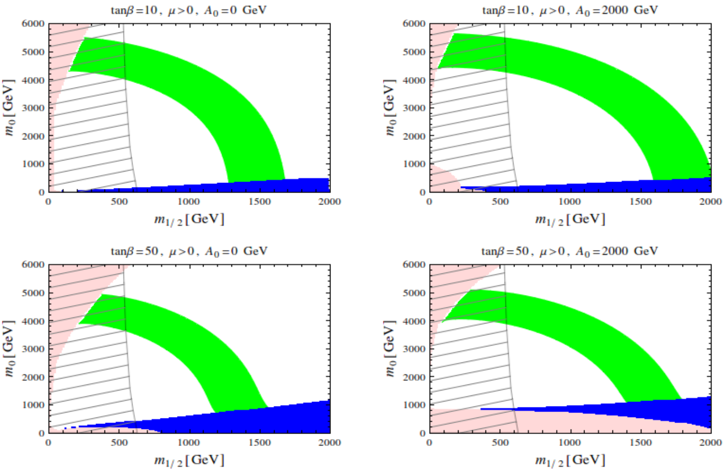
- **Therefore, if one assumes that the stop masses are of order TeV, then the one-loop effect leads to a correction of order $\mathcal{O}(100)$ GeV, which implies that**

$$m_h^{\mathrm{MSSM}} \lesssim \sqrt{(90\ \mathrm{GeV})^2 + (100\ \mathrm{GeV})^2} \simeq 130\ \mathrm{GeV}. \tag{6}$$

- **MSSM predicts an upper bound for the Higgs mass: $m_h \lesssim 130$ GeV, which was consistent with the measured value of Higgs mass (of order 125 GeV) at the LHC.**

- **This mass of lightest Higgs boson implies that the SUSY particles are quite heavy. This may justify the negative searches for SUSY at the LHC-run I**

LHC Constraints on MSSM Parameter Space



Green region indicates for $124 \lesssim m_h \lesssim 126$ GeV. Blue region is excluded because the lightest neutralino is not the LSP. Pink region is excluded due to absence of radiative electroweak symmetry breaking. Gray shadow lines denote the excluded area because of $m_{\tilde{g}} < 1.4$ TeV.

The Lightest Neutralino as the LSP

- The neutralinos χ_i (i=1,2,3,4) are the physical (mass) superpositions of two fermionic partners of the two neutral gauge bosons, called gaugino $\tilde{B}^0$ (bino) and $\tilde{W}_3^0$ (wino), and of the two neutral Higgs bosons, called Higgsinos $\tilde{H}_1^0$ and $\tilde{H}_2^0$. The neutralino mass matrix is given by

$$M_N = \begin{pmatrix} M_1 & 0 & -M_Z c_\beta s_\theta & M_Z s_\beta s_\theta \\ 0 & M_2 & M_Z c_\beta c_\theta & -M_Z s_\beta c_\theta \\ -M_Z c_\beta s_\theta & M_Z c_\beta c_\theta & 0 & -\mu \\ M_Z s_\beta s_\theta & -M_Z s_\beta c_\theta & -\mu & 0 \end{pmatrix}, \qquad (7)$$

  where M_1 and M_2 are related due to the universality of the gaugino masses at the grand unification scale, $M_1 = \frac{3g_1^2}{5g_2^2} M_2$, where g_1, g_2 are the gauge couplings of $U(1)_Y$ and $SU(2)_L$ respectively. This Hermitian matrix is diagonlaized by a unitary transformation of the neutralino fields, $M_N^{diag} = N^\dagger M_N N$.

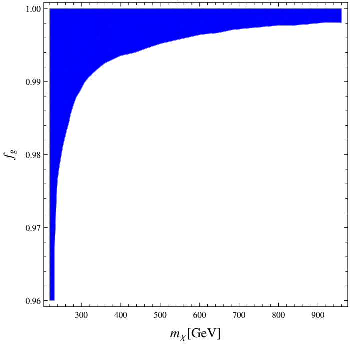
- The lightest eigenvalue of this matrix and the corresponding eigenstate say χ has good chance of being the LSP. The lightest neutralino will be a linear combination of the original fields:

$$\chi = N_{11}\tilde{B}^0 + N_{12}\tilde{W}^0 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0. \qquad (8)$$

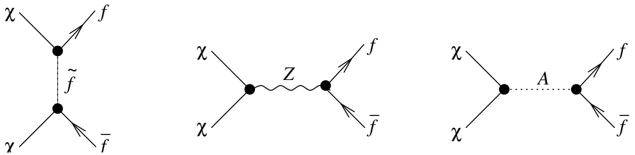
- A useful parameter for describing the neutralino composition is the gaugino "purity" function $f_g = |N_{11}|^2 + |N_{12}|^2$. If $f_g > 0.5$, then the neutralino is gaugino-like and if $f_g < 0.5$, then the neutralino is Higgsino-like. Actually if $|\mu| > |M_2| \geq M_Z$, the two lightest neutralino states will be determined by the gaugino components. While if $|\mu| < |M_2|$, the two lighter neutralinos are all mostly Higgsinos, with mass close to $|\mu|$. Finally if $|\mu| \simeq |M_2|$, the states will be strongly mixed.

- The Higgs mass limit and gluino mass lower bound imply that $m_\chi \gtrsim 240$ GeV. Moreover, an upper bound of order one TeV is also obtained (from Higgs mass constraint).

- In this region of allowed parameter space, the LSP is essentially pure bino. Because μ-parameter, determined by the radiative electroweak breaking condition, is typically of order m_0 and hence it is much heavies than the gaugino mass M_1.



The Lightest Neutralino as the LSP



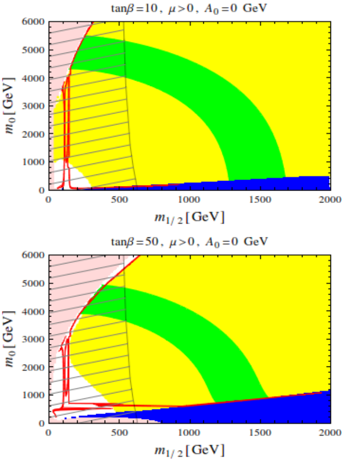
- **For a bino-like LSP,** *i.e.* $N_{11} \simeq 1$ **and** $N_{1i} \simeq 0$**,** $i = 2, 3, 4$**, the relevant annihilation channels are the fermion-antifermion ones.**

- **The t-channel annihilation is predominantly into leptons through the exchanges of the three slepton families** $(\tilde{l}_L, \tilde{l}_R)$**, with** $l = e, \mu, \tau$**. The squarks exchanges are suppressed due to their large masses.**

- **The annihilation process mediated by** Z **gauge boson is suppressed due to the small** $Z\chi\chi$ **coupling** $\propto N_{13}^2 - N_{14}^2$**, except at the resonance when** $m_\chi \sim m_Z/2$**, which is no longer possible due to the above mentioned constraints.**

Dark Matter Constraints on MSSM Parameter Space

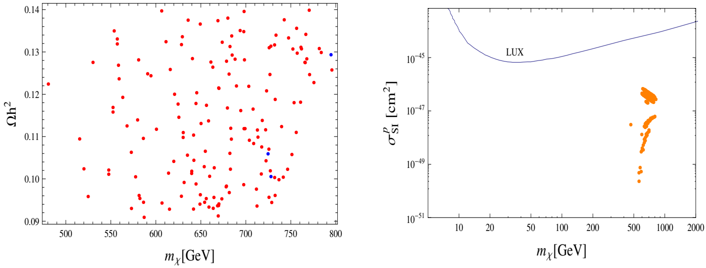
- **Combining the collider and astrophysics constraints almost rule out the MSSM.**



- **At low** $\tan\beta$**, a region of co-annihilation between LSP and lightest** $\tilde{\tau}$ **is excluded by the Higgs & gluino mass constraints.**
- **At large** $\tan\beta$**, a region with a possible resonance due to** $M_A \simeq 2m_\chi$ **is allowed.**

MSSM and LUX Results

- **Combined LHC and relic abundance constraints rule out most of the MSSM parameter space except a very narrow region with very large** $\tan\beta$ (~ 50)**.**



- **Red points indicate for** $40 \leq \tan\beta \leq 50$ **and blue points for** $30 \leq \tan\beta < 40$**.**

- **Spin-independent scattering cross section of the LSP with a proton versus the mass of the LSP within the region allowed by all constraints (from the LHC and relic abundance.)**

Summary

- **In the MSSM, according to the Higgs mass limit and the gluino lower bound $m_{1/2}$ will be within the mass range: $620\ \mathrm{GeV} \lesssim m_{1/2} \lesssim 2000$ GeV, while the other parameters (m_0, A_0, $\tan\beta$) are much less constrained.**

- **The effect of the measured DM relic density on the MSSM allowed parameter space. It turns out that most of the MSSM parameter space is ruled out except few points around $\tan\beta \sim 50$, $m_0 \sim 1$ TeV and $m_{1/2} \sim 1.5$ TeV.**

- **In the MSSM, the spin-independent scattering cross section of the LSP with a proton is less than the recent LUX bound by at least two order of magnitudes.**

Thank you