Dark Matter in the ESSM

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Contents

Dark Matter and Supersymmetry

- The present day dark matter relic density is measured to be

$$\Omega_{\mathrm{CDM}} h^2 = 0.105^{+0.007}_{-0.010}$$

- Many models of physics beyond the SM predict a new, stable dark matter candidate
- If this particle would have been in thermal and chemical equilibrium with SM matter in the past then the present day relic density of dark matter in the model can be calculated

- Supersymmetric models generally need to obey some kind of matter parity in order to suppress FCNCs and prevent proton decay
- This parity makes the lightest supersymmetric particle (LSP) stable, making it a potential dark matter (DM) candidate

Motivations for the ESSM

- The ESSM is a string theory inspired model where the GUT group E_6 is broken below a high energy scale
- The model has automatic anomaly cancellation
- A see-saw mechanism explains light neutrino masses

- Being a supersymmetric model, softly broken at the TeV scale, this model does not suffer from the hierarchy problem
- It also, as in the MSSM, leads to unification of running gauge coupling constants at some GUT scale

- The MSSM suffers from the μ problem - The dimensionful, supersymmetry preserving parameter μ should be around the weak scale to allow correct EWSB
- In the ESSM, like other singlet extended models, the μ term is generated radiatively when a SM-singlet acquires a VEV, naturally related to the soft breaking scale

The ESSM

- E_6 is broken below a high energy scale

$$\begin{aligned} E_6 &\rightarrow SO(10)\times U(1)_\psi \rightarrow SU(5)\times U(1)_\psi \times U(1)_\chi \\ E_6 &\rightarrow SU(3)\times SU(2)\times U(1)_Y \times U(1)_N \end{aligned}$$

- Anomaly cancellation ensured by three complete 27 representations of E_6 (three generations)

$$\begin{aligned} 27 \rightarrow\ & (10,1)+(\bar{5},2) \\ & +(\bar{5},-3)+(5,-2) \\ & +(1,5)+(1,0) \end{aligned}$$

$$\mathcal{W} = \lambda_{ijk}S_iH_{dj}H_{uk} + \kappa_{ijk}S_iD_j\bar{D}_k + \cdots$$

$$\mu = \lambda_{333}\langle S\rangle = \lambda s/\sqrt{2}$$

The ESSM continued

- A generalised version of matter parity is imposed, but which allows exotics to decay
- There are two options under which exotics are interpreted as either di-quarks or lepto-quarks

- However, an approximate symmetry Z_2^H is also imposed in order to prevent FCNCs
- Under Z_2^H only S_3, H_{d3} and H_{h3} are even
- The first and second generations of Higgs doublets and singlets then have suppressed couplings to ordinary matter
- This then explains why the first and second generations are inert

The ESSM Neutralinos and Charginos

- In the USSM neutralino interaction basis $\tilde{\chi}^0_{\text{int}} =$

$$\left(\begin{array}{cccc|cc} \tilde{B} & \tilde{W}^3 & \tilde{H}^0_d & \tilde{H}^0_u & \tilde{S} & \tilde{B}' \end{array} \right)^{\mathrm{T}}$$

the USSM neutralino mass matrix $M^n_{\text{USSM}} =$

$$\left(\begin{array}{cccc|cc} M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta & 0 & 0 \\ 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta & 0 & 0 \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -\mu & -\mu_s s_\beta & g_1' v c_\beta Q^N_d \\ m_Z s_W s_\beta & -m_Z c_W s_\beta & -\mu & 0 & -\mu_s c_\beta & g_1' v s_\beta Q^N_u \\ \hline 0 & 0 & -\mu_s s_\beta & -\mu_s c_\beta & 0 & g_1' s Q^N_s \\ 0 & 0 & g_1' v c_\beta Q^N_d & g_1' v s_\beta Q^N_u & g_1' s Q^N_s & M_1' \end{array} \right)$$

where

  - $\mu_s = \lambda v/\sqrt{2}$,
  - $\langle H_d \rangle = v\cos(\beta)/\sqrt{2}$ and
  - $\langle H_u \rangle = v\sin(\beta)/\sqrt{2}$

The ESSM Neutralinos and Charginos continued

- In the ESSM neutralino interaction basis $\tilde{\chi}^0_{\text{int}} =$

  $$\left(\ \tilde{B}\quad \tilde{W}^3\quad \tilde{H}^0_d\quad \tilde{H}^0_u \,\middle|\, \tilde{S}\quad \tilde{B}' \,\middle|\, \tilde{H}^0_{d2}\quad \tilde{H}^0_{u2}\quad \tilde{S}_2 \,\middle|\, \tilde{H}^0_{d1}\quad \tilde{H}^0_{u1}\quad \tilde{S}_1\ \right)^{\text{T}}$$

  the ESSM neutralino mass matrix $M^n =$

  $$\begin{pmatrix} M^n_{\text{USSM}} & B_2 & B_1 \\ B_2^{\text{T}} & A_{22} & A_{21} \\ B_1^{\text{T}} & A_{21}^{\text{T}} & A_{11} \end{pmatrix}$$

  where

  $$A_{\alpha\beta} = -\frac{1}{\sqrt{2}} \begin{pmatrix} 0 & \lambda_{\alpha\beta} s & f^u_{\beta\alpha} v \sin(\beta) \\ \lambda_{\beta\alpha} s & 0 & f^d_{\beta\alpha} v \cos(\beta) \\ f^u_{\alpha\beta} v \sin(\beta) & f^d_{\alpha\beta} v \cos(\beta) & 0 \end{pmatrix}$$

The ESSM Neutralinos and Charginos continued

- In the ESSM chargino interaction basis $\tilde{\chi}^{\pm}_{\text{int}} =$

  $$\left(\tilde{W}^{+} \quad \tilde{H}_u^{+} \quad \tilde{H}_{u2}^{+} \quad \tilde{H}_{u1}^{+} \,\middle|\, \tilde{W}^{-} \quad \tilde{H}_d^{-} \quad \tilde{H}_{d2}^{-} \quad \tilde{H}_{d1}^{-} \right)^{\mathrm{T}}$$

  the ESSM chargino mass matrix $M^c =$

  $$\begin{pmatrix} & C^{\mathrm{T}} \\ C & \end{pmatrix}$$

  where

  $$C = \begin{pmatrix} M_2 & \sqrt{2} m_W \sin(\beta) & 0 & 0 \\ \sqrt{2} m_W \cos(\beta) & \mu & \frac{1}{\sqrt{2}} x_2^d s & \frac{1}{\sqrt{2}} x_1^d s \\ 0 & \frac{1}{\sqrt{2}} x_2^u s & \frac{1}{\sqrt{2}} \lambda_{22} s & \frac{1}{\sqrt{2}} \lambda_{21} s \\ 0 & \frac{1}{\sqrt{2}} x_1^u s & \frac{1}{\sqrt{2}} \lambda_{12} s & \frac{1}{\sqrt{2}} \lambda_{11} s \end{pmatrix}$$

The Inert Neutralino LSP parametrisation

- The relevant physics for predicting dark matter can be seen with the following parametrisation

$$\lambda' = \lambda_{22} = \lambda_{11} \qquad f = f^d_{22} = f^u_{22} = f^d_{11} = f^u_{11}$$

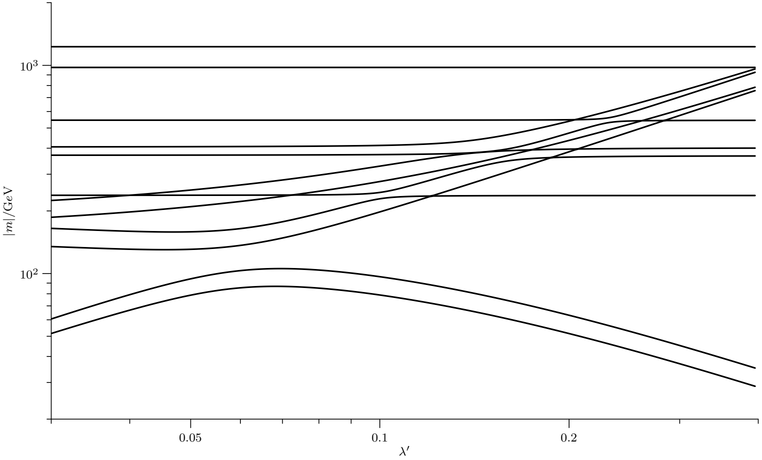
varying λ', f and $\tan(\beta)$

- The A matrices become

$$\begin{aligned} A_{22} &= A_{11} = -\frac{1}{\sqrt{2}} \begin{pmatrix} 0 & \lambda' s & f v \sin(\beta) \\ \lambda' s & 0 & f v \cos(\beta) \\ f v \sin(\beta) & f v \cos(\beta) & 0 \end{pmatrix} \\ A_{21} &= \epsilon A_{22} \end{aligned}$$

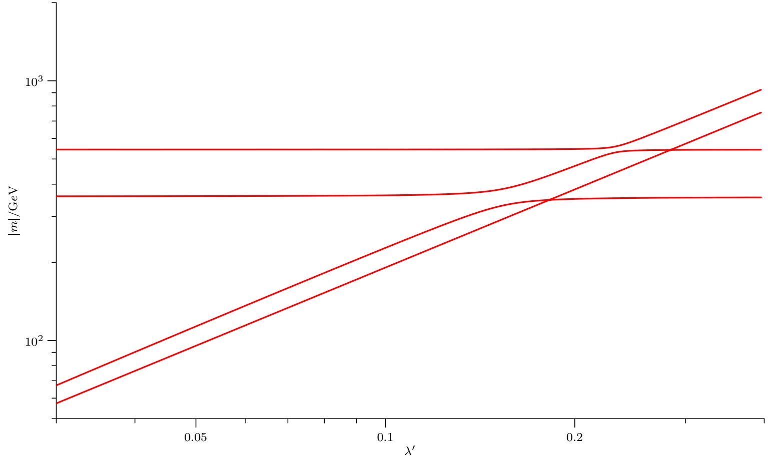
The Inert Neutralino LSP neutralino spectrum

- $s = 3000$ GeV, $\tan(\beta) = 1.5$, $f = 1$, $\epsilon = 0.1$



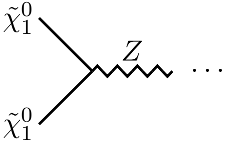
The Inert Neutralino LSP chargino spectrum

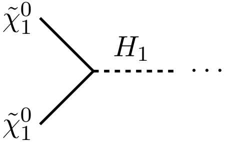
- $s = 3000$ GeV, $\tan(\beta) = 1.5$, $f = 1$, $\epsilon = 0.1$



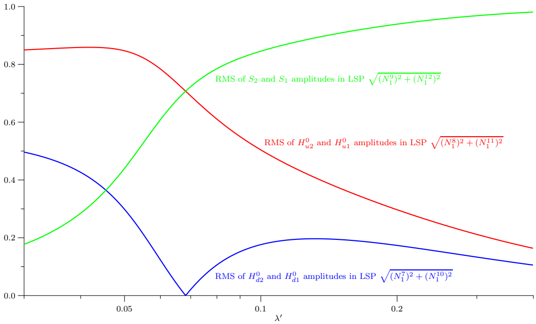
The Inert Neutralino LSP LSP composition

- The most important annihilation channels are



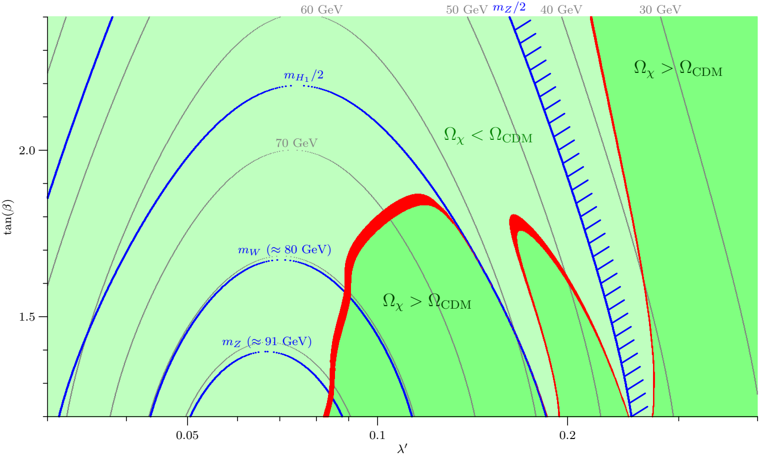


- $s = 3000$ GeV, $\tan(\beta) = 1.5$, $f = 1$, $\epsilon = 0.1$



Dark Matter Predictions (using `MicrOMEGAs`)

- $s = 3000$ GeV, $f = 1$, $\epsilon = 0.1$



Conclusions and Future Work

- The observed dark matter relic density can be accounted for in this model
- The only hard limit on the USSM parameter space from dark matter considerations is that $\tan(\beta)$ should be less than about 2, in fact the lightest USSM-like supersymmetric particle could even be a sfermion, not a neutralino
- The fact that this particular model has two of the approximately decoupled inert generations is not necessary for explaining dark matter

- Current and future work
  - Limits from requiring consistent Yukawa running to the GUT scale
  - Limits from precision Z measurements
  - Constrained version of the model
  - Phenomenological scenarios

References

- This work
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- Theory and Phenomenology of an Exceptional Supersymmetric Standard Model
  S. F. King, S. Moretti and R. Nevzorov, Phys. Rev. D **73** (2006) 035009 [arXiv:hep-ph/0510419]
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