Dark Matter in the Exceptional Supersymmetric Standard Model

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Motivations for the E_6SSM

S. F. King, S. Moretti and R. Nevzorov [arXiv:hep-ph/0510419]

- The E_6SSM is a string theory inspired model with an E_6 grand unification group
- The model is anomaly free since the low energy matter forms complete 27 representations of E_6
- A type-I 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 does not suffer from the μ problem of the MSSM
- In the E_6SSM, like in other singlet extended models, the μ term is generated radiatively when a SM-singlet field acquires a VEV naturally related to the soft breaking scale
- the lightest (SM-like) Higgs mass is not required to be less than $m_Z|\cos(2\beta)|$ at tree-level, as it is in the MSSM, leading the less fine-tuning and allowing smaller values of $\tan(\beta)$

The E_6SSM

S. F. King, S. Moretti and R. Nevzorov [arXiv:hep-ph/0510419]

- E_6 can be broken into the following subgroups

$$E_6 \quad \rightarrow \quad SO(10) \times U(1)_\psi \rightarrow SU(5) \times U(1)_\psi \times U(1)_\chi$$

- In the E_6SSM E_6 is broken directly to $SU(3) \times SU(2) \times U(1)_Y \times U(1)_N$, where

$$U(1)_N = \cos(\vartheta) U(1)_\chi + \sin(\vartheta) U(1)_\psi, \qquad \tan(\vartheta) = \sqrt{15}$$

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

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

The E_6SSM Superpotential

S. F. King, S. Moretti and R. Nevzorov [arXiv:hep-ph/0510419]

- The low energy gauge invariant superpotential can be written as follows

$$\begin{aligned}
\mathcal{W} &= \mathcal{W}_0 + \mathcal{W}_1 + \mathcal{W}_2, \quad \text{where} \\
\mathcal{W}_0 &= \lambda_{ijk} S_i H_{dj} H_{uk} + \kappa_{ijk} S_i D_j \bar{D}_k + h^N_{ijk} N^c_i H_{uj} L_k \\
&\quad + h^U_{ijk} u^c_i H_{uj} Q_k + h^D_{ijk} d^c_i H_{dj} Q_k + h^E_{ijk} e^c_i H_{dj} L_k, \\
\mathcal{W}_1 &= g^Q_{ijk} D_i Q_j Q_k + g^q_{ijk} \bar{D}_i d^c_j u^c_k, \\
\mathcal{W}_2 &= g^N_{ijk} N^c_i D_j d^c_k + g^E_{ijk} e^c_i D_j u^c_k + g^D_{ijk} Q_i L_j \bar{D}_k
\end{aligned}$$

- The terms that R-parity is invoked to remove in the MSSM are already not present since they break E_6

$\mathbb{Z}_2$ Symmetries of the E_6SSM Superpotential

- An approximate flavour symmetry $\mathbb{Z}_2^H$ suppresses FCNCs originating from the Higgs sector
- Under $\mathbb{Z}_2^H$ only S_3, H_{d3} and H_{h3} are even
- The first and second ("inert") generations of Higgs doublets and SM-singlets then have suppressed couplings to ordinary matter
- This then explains why the first and second generations are inert (do not radiatively acquire VEVs)

- An additional exact $\mathbb{Z}_2$ symmetry is imposed to prevent rapid proton decay, but still allow the coloured exotic D-particles to decay
- There are two options for this symmetry under which the invariant superpotential is either $\mathcal{W}_0 + \mathcal{W}_1$ or $\mathcal{W}_0 + \mathcal{W}_2$
- The exotic D-particles are interpreted as either diquark or leptoquark superfields respectively

- The active SM-singlet's VEV gives a mass to the Z' and generates the effective μ term

$$\mu \quad = \quad \lambda_{333}\langle S_3 \rangle \equiv \lambda_{333} s/\sqrt{2}$$

The E_6SSM Neutralinos and Charginos

J. P. Hall and S. F. King [arXiv:0905.2696 [hep-ph]]

- In the E_6SSM chargino interaction basis $\tilde{\chi}^{\pm}_{\rm int} =$

$$\left(\tilde{W}^{+} \quad \tilde{H}^{+}_{u3} \quad \tilde{H}^{+}_{u2} \quad \tilde{H}^{+}_{u1} \,\middle|\, \tilde{W}^{-} \quad \tilde{H}^{-}_{d3} \quad \tilde{H}^{-}_{d2} \quad \tilde{H}^{-}_{d1} \right)^{\rm T}$$

the E_6SSM chargino mass matrix $M^{\rm C} =$

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

where

$$C = \begin{pmatrix} M_2 & \sqrt{2} m_W \sin(\beta) & 0 & 0 \\ \sqrt{2} m_W \cos(\beta) & \mu & \frac{1}{\sqrt{2}}\lambda_{332} s & \frac{1}{\sqrt{2}}\lambda_{331} s \\ 0 & \frac{1}{\sqrt{2}}\lambda_{323} s & \frac{1}{\sqrt{2}}\lambda_{322} s & \frac{1}{\sqrt{2}}\lambda_{321} s \\ 0 & \frac{1}{\sqrt{2}}\lambda_{313} s & \frac{1}{\sqrt{2}}\lambda_{312} s & \frac{1}{\sqrt{2}}\lambda_{311} s \end{pmatrix}$$

The E_6SSM Neutralinos and Charginos continued

S. F. King, S. Moretti and R. Nevzorov [arXiv:hep-ph/0510419]

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

$$\left(\begin{array}{cccc|cc} \tilde{B} & \tilde{W}^3 & \tilde{H}^0_{d3} & \tilde{H}^0_{u3} & \tilde{S}_3 & \tilde{B}' \end{array} \right)^{\mathrm{T}}$$

the USSM neutralino mass matrix $M^{\mathrm{N}}_{\mathrm{USSM}} =$

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

where

- $\mu_s = \lambda_{333} v/\sqrt{2}$,
- $\langle H^0_{d3} \rangle = v \cos(\beta)/\sqrt{2}$, and
- $\langle H^0_{u3} \rangle = v \sin(\beta)/\sqrt{2}$

- In the full E_6SSM neutralino interaction basis $\tilde{\chi}^0_{\text{int}} =$

$$\left(\tilde{B} \quad \tilde{W}^3 \quad \tilde{H}^0_{d3} \quad \tilde{H}^0_{u3} \;\middle|\; \tilde{S} \quad \tilde{B}' \;\middle|\; \tilde{H}^0_{d2} \quad \tilde{H}^0_{u2} \quad \tilde{S}_2 \;\middle|\; \tilde{H}^0_{d1} \quad \tilde{H}^0_{u1} \quad \tilde{S}_1 \right)^{\text{T}}$$

the E_6SSM neutralino mass matrix $M^{\text{N}} =$

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

where

$$A_{\alpha\beta} = -\frac{1}{\sqrt{2}} \begin{pmatrix} 0 & \lambda_{3\alpha\beta} s & \lambda_{\beta\alpha 3} v \sin(\beta) \\ \lambda_{3\beta\alpha} s & 0 & \lambda_{\beta 3\alpha} v \cos(\beta) \\ \lambda_{\alpha\beta 3} v \sin(\beta) & \lambda_{\alpha 3\beta} v \cos(\beta) & 0 \end{pmatrix}$$

An Analytic Study of One Inert Generation

J. P. Hall and S. F. King [arXiv:0905.2696 [hep-ph]]

- For illustration purposes consider just the first inert generation independently
- In the basis $\tilde{\chi}^0_{\text{int}} =$

$$\begin{pmatrix} \tilde{H}^0_{d1} & \tilde{H}^0_{u1} & \tilde{S}_1 \end{pmatrix}^{\mathrm{T}}$$

the mass matrix is $A_{11} =$

$$-\frac{1}{\sqrt{2}} \begin{pmatrix} 0 & \lambda' s & f_u v \sin(\beta) \\ \lambda' s & 0 & f_d v \cos(\beta) \\ f_u v \sin(\beta) & f_d v \cos(\beta) & 0 \end{pmatrix}$$

where

- $\lambda' \equiv \lambda_{311}$,
- $f_d \equiv \lambda_{131}$, and
- $f_u \equiv \lambda_{113}$

An Analytic Study of One Inert Generation continued

J. P. Hall and S. F. King [arXiv:0905.2696 [hep-ph]]

- Expanding in terms of $fv/\lambda' s$

$$
\begin{aligned}
m_1 &= \frac{1}{\sqrt{2}} \frac{f_d f_u}{\lambda'} \frac{v^2}{s} \sin(2\beta) \;+\; \cdots \\
m_2 &= \frac{\lambda' s}{\sqrt{2}} - \frac{m_1}{2} \;+\; \cdots \\
m_3 &= -\frac{\lambda' s}{\sqrt{2}} - \frac{m_1}{2} \;+\; \cdots
\end{aligned}
$$

- The composition of the light state is given by

$$
N_1 = \begin{pmatrix} -\frac{f_d v}{\lambda' s} \cos(\beta) \;+\; \cdots \\ -\frac{f_u v}{\lambda' s} \sin(\beta) \;+\; \cdots \\ 1 \;-\; \frac{1}{2} \left(\frac{v}{\lambda' s} \right)^2 \left[f_d^2 \cos^2(\beta) + f_u^2 \sin^2(\beta) \right] \;+\; \cdots \end{pmatrix}
$$

An Analytic Study of One Inert Generation continued

J. P. Hall, S. F. King, R. Nevzorov, S. Pakvasa and M. Sher [arXiv:1012.5114 [hep-ph]]

- We again expand in terms of $fv/\lambda' s$
- The coupling of the lightest state to the Z-boson, normalised to that of a neutrino, is given by

$$R_{Z11} = \left(\frac{v}{\lambda' s}\right)^2 (f_d^2 \cos^2(\beta) - f_u^2 \sin^2(\beta)) \; + \; \cdots$$

- In this limit the coupling of the lightest state to the SM-like Higgs-boson is in fact given by

$$X_{11}^{h_1} = m_1/v \; + \; \cdots$$

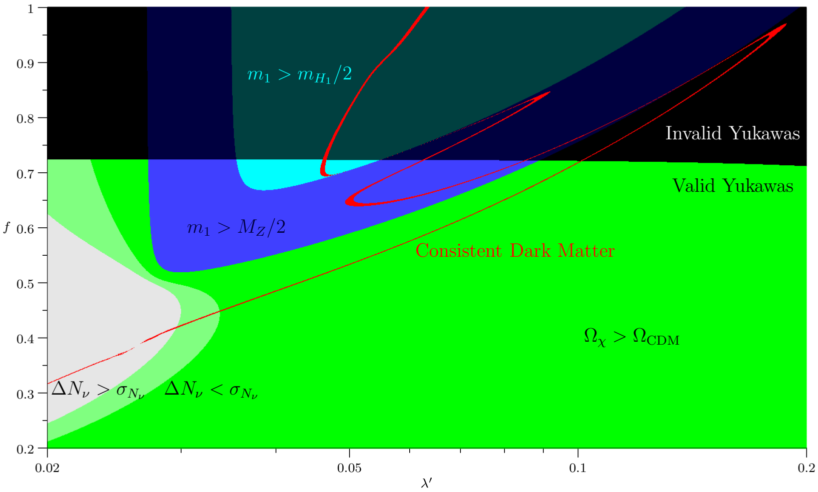
Numerical Analysis of DM in the E_6SSM

J. P. Hall, S. F. King, R. Nevzorov, S. Pakvasa and M. Sher [arXiv:1012.5114 [hep-ph]]

- With both inert generations considered there are two light neutralino states
- It turns out that if perturbation theory is required to be valid up to the grand unification scale then the two lightest states cannot be made heavier than about $60\ \mathrm{GeV}$
- At the same time the LSP is required not to be too light in order not to lead to too high a relic density of dark matter
- In practice this means that the two lightest states are always quite close in mass

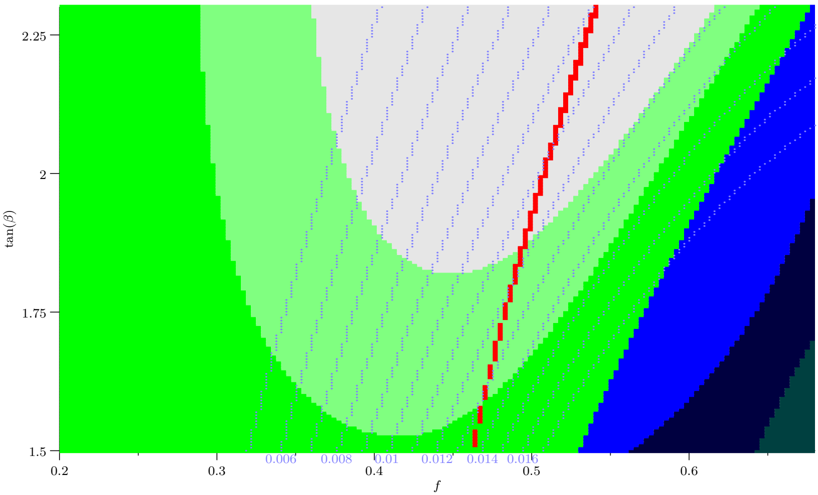
Numerical Analysis of DM in the E_6SSM continued

$s = 2400$ GeV, $\tan(\beta) = 1.7$ $\qquad$ $N_\nu = 2.9840 \pm 0.0082$

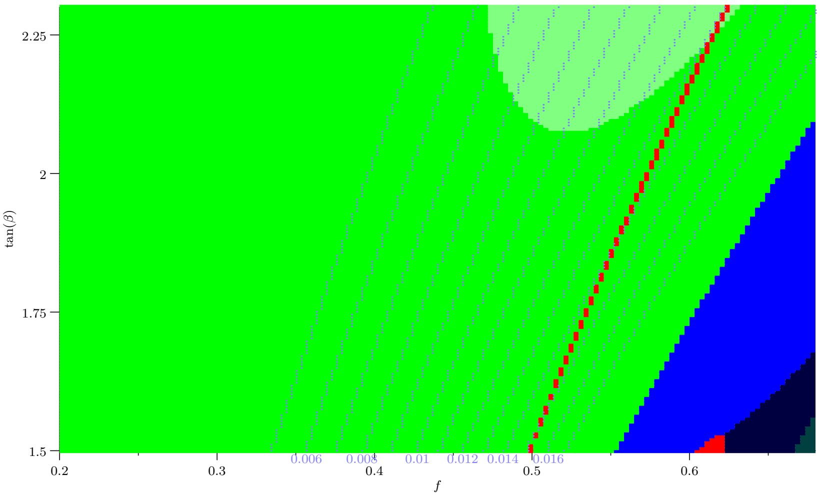


The LSP–Higgs Coupling

J. P. Hall, S. F. King, R. Nevzorov, S. Pakvasa and M. Sher [arXiv:1012.5114 [hep-ph]]



J. P. Hall, S. F. King, R. Nevzorov, S. Pakvasa and M. Sher [arXiv:1012.5114 [hep-ph]]



The LSP–Higgs Coupling continued

- If the two lightest inert neutralinos are lighter than half of the Higgs mass they typically dominate its width
- In regions that predict the observed relic density of dark matter the total Higgs branching ratio into SM particles is between about 2% and 4%

- The XENON100 Collaboration now claims a 90% confidence level limit on the spin independent WIMP-nucleon cross-section of $7.0 \times 10^{-45}\ \mathrm{cm}^2$ for a $50\ \mathrm{GeV}$ WIMP
- In our model this cross-section would be dominated by t-channel Higgs exchange
- Even allowing for the theoretical uncertainties in its calculation the cross-section in the E_6SSM for regions where the correct DM relic density is predicted cannot be less than about $17 \times 10^{-45}\ \mathrm{cm}^2$
- This model of dark matter therefore looks to be ruled out now by the recent XENON100 analysis of 100.9 days of data

The LSP–Higgs Coupling continued

J. P. Hall, S. F. King, R. Nevzorov, S. Pakvasa and M. Sher [arXiv:1012.5114 [hep-ph]]

- Since the LSP must contain a certain amount of inert Higgsino component the LSP-Higgs coupling cannot be suppressed
- The Higgs mass can be made larger by having a larger λ_{333}, but this leads to tighter constraints on the other Yukawa couplings
- The approximate minimum cross-section quoted has Higgs mass of $133\ \mathrm{GeV}$ with $\lambda_{333} = 0.6$

The $E_6\mathbb{Z}_2^S$SSM

J. P. Hall and S. F. King [arXiv:1104.2259 [hep-ph]]

- The $E_6\mathbb{Z}_2^S$SSM is a variation of the E_6SSM that supposes that there is a additional exact $\mathbb{Z}_2$ symmetry of the superpotential under which only the inert SM-singlet superfields $S_{1,2}$ are odd
- This forces to the the fermionic components of these superfields, the two inert singlinos, to be exactly massless
- Theses massless inert singlinos are exactly decoupled from the rest of the neutralino mass matrix

- The lightest neutralino mass state from the diagonalisation of the remaining neutralino mass matrix becomes absolutely stable

- The inert neutral Higgsinos become approximately degenerate with the inert charged Higgsinos *i.e.* they are pseudo-Dirac states with masses approximately given by the bi-unitary diagonalisation of $-\frac{1}{\sqrt{2}}\lambda_{3\alpha\beta}s$

DM in the c$E_6\mathbb{Z}_2^S$SSM

J. P. Hall and S. F. King [arXiv:1104.2259 [hep-ph]]

- The massless inert singlinos are not the DM candidate of the model
- They do however contribute to the effective number of neutrinos contributing to the expansion rate of the universe prior to BBN (next slide)

- The DM candidate of the model is typically the bino
- There is a successful DM scenario in which one pair of pseudo-Dirac inert Higgsino states are close to the bino in mass
- Frequent inelastic scattering off of SM particles allows the ratios of the number densities of binos and the inert Higgsinos to maintain their equilibrium values during the time of thermal freeze-out

- This scenario can be achieved within a grand-unification-scale-constrained version of the model, the c$E_6\mathbb{Z}_2^S$SSM

The Effective number of Neutrinos

J. P. Hall and S. F. King [arXiv:1104.2259 [hep-ph]]

- Neutrinos decouple from thermal equilibrium with the photon at a temperature between the electron mass and muon mass
- After the decoupling of the neutralinos the disappearance of the electrons heats the photons, but not the neutrinos
- The smaller a relativistic particle's temperature prior to nucleosynthesis, the less it would have contributed to the expansion rate prior to BBN
- The expansion rate is characterised by the "effective number neutrinos" N_{eff} (3 in the SM)

- The effective number of neutrinos prior to BBN strongly affects the ^{4}He relic abundance
- The analysis by Izotov *et al.* [arXiv:1001.4440 [astro-ph.CO]] gives $N_{\text{eff}} = 3.80^{+0.80}_{-0.70}$ at 2-sigma, implying a more-than-2-sigma tension
- Although Aver *et al.* [arXiv:1001.5218] suggest that these errors may be larger, similar results are also obtained for the effective number of neutrinos from fits to WMAP data *e.g.* Komatsu *et al.* [arXiv:1001.4538 [astro-ph.CO]]

The Effective number of Neutrinos continued

J. P. Hall and S. F. King [arXiv:1104.2259 [hep-ph]]

- The massless inert singlinos decouple at a still higher temperature, typically above the strange quark mass, but below the charm quark mass
- They are kept in equilibrium via an effective Fermi-like 4-point interaction term with a coupling suppressed the Z'-boson mass, experimentally constrained to be more than 892 GeV
- They would therefore contribute to N_{eff} less than 2

- With the inert singlinos decoupling in the above temperature range the prediction is $N_{\text{eff}} = 3.19$
- For all experimentally viable values of the Z' mass the prediction is closer to the measured central value than the SM prediction
- depending on the details of the colour transition it could be as high as 4.37 for a light Z'

Main Points

- The conventional E_6SSM inert DM scenario is very constrained and looks to be ruled out by direct detection

- The $E_6\mathbb{Z}_2^S$SSM DM scenario presented is not currently constrained by direct detection experiments
- The typical DM candidate is the bino and a successful DM relic density can be achieved in the constrained version of the model when at least one pair of pseudo-Dirac inert Higgsinos is close by in mass