Exceptional Supersymmetric Standard Model

- USSM neutralino dark matter
- $E_6$SSM and inert higgsino/neutralino dark matter
- ME$_6$SSM

Steve King, University of Southampton
Singlet SUSY Models

To solve the $\mu$ problem of the MSSM and reduce fine tuning led to consider: $W = \lambda S H_u H_d$ where singlet $<S> \sim \mu$

But leads to weak scale axion due to global $U(1)$ PQ symmetry

Need to remove axion somehow

In NMSSM we add $S^3$ to break $U(1)$ PQ to $Z_3$ – talks by Ellwanger, Gunion

In USSM we gauge the $U(1)$ PQ symmetry to eat the axion resulting in a massive $Z'$ gauge boson – but not anomaly free

In $E_6$SSM the anomalies of the USSM are cancelled by three complete 27’s of $E_6$ at the TeV scale with $U(1)$ PQ $\in E_6$
Higgs mass bounds

\[ W = \lambda S H_u H_d \]

\[ m_h^2 \leq M_Z^2 \cos^2 2\beta + \frac{\lambda^2}{2} v^2 \sin^2 2\beta + \Delta \]

\( \lambda \) can be larger in E\(_6\) SSM than NMSSM

Larger tree-level Higgs mass = less tuning
USSM Neutralino Dark Matter

$$\lambda SH_u H_d + U(1)'_{\text{gauge}} \rightarrow \text{MSSM states} + S + Z'$$

Solves $\mu$ problem of MSSM anomaly cancellation - see later

How can a singlino LSP annihilate? Via $\lambda$SHH and $Z'$ couplings

$$\chi_1 = N_1 \tilde{B} + N_2 \tilde{W} + N_3 \tilde{H}_d + N_4 \tilde{H}_u + N_5 \tilde{S} + N_6 \tilde{B}'$$

New

mini-see-saw gives singlino LSP as $M_1' \rightarrow \infty$
**Scenario A: \( M'_1 \neq M_1 \)**

**Neutralino masses**

- \( M_1 = M_2/2 = 750 \text{ GeV} \)
- \( \mu = 300 \text{ GeV}, \tan \beta = 5 \)

**Dark matter abundance**

- CP-even Higgs
- CP-odd Higgs
- \( \Omega_{\text{CDM}} h^2 \)
- WMAP

**Spin-independent proton cross-section**

- MSSM
- \( M_1 = M_2/2 = 750 \text{ GeV} \)
- \( \mu = 300 \text{ GeV}, \tan \beta = 5 \)

**Spin-dependent proton cross-section**

- MSSM
- \( M_1 = M_2/2 = 750 \text{ GeV} \)
- \( \mu = 300 \text{ GeV}, \tan \beta = 5 \)
Scenario B: $M'_1 = M_1$

Neutralino masses

$M'_1 = M_1 = M_2/2$
$\mu = 600$ GeV, $\tan \beta = 5$

Kalinowski, SFK, Roberts

Dark matter abundance

CP-odd Higgs

CP-even Higgs

Z

WMAP

Spin-independent proton cross-section (atto-barn)

Spin-dependent proton cross-section (atto-barn)
**$E_6SSM$**

$E_6 \rightarrow SO(10) \times U(1)_\psi$

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

$E_6$ broken via SU(5) chain

Right handed neutrinos are neutral under:

$$U(1)_N = \frac{\sqrt{15}}{4} U(1)_\psi + \frac{1}{4} U(1)_\chi \rightarrow Z'(N)$$

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**$E_6$ broken via SU(5) chain**

**$E_6 \rightarrow SU(5) \times U(1)_N \rightarrow SM \times U(1)_N$**

$27_i \rightarrow (10, 1)_i + (5^*, 2)_i + (5^*, -3)_i + (5, -2)_i + (1, 5)_i + (1, 0)_i$

$27', 27'$

**RH $\nu$ masses**

- $M_3$
- $M_2$
- $M_1$

**$M_{GUT}$**

**$M_W$**

- Quarks, leptons
- Triplets and Higgs
- Singlets and RH $\nu$ s
- L', L'-bar

To achieve GUT scale unification we add extra vector leptons

$U(1)_N$ broken, $Z'(N)$ & triplets get mass, $\mu$ term generated

$SU(2)_L \times U(1)_Y$ broken
Matter content of E$_6$SSM at TeV

- **Quarks and Leptons**
  - $27_i$
  - Three families of Higgs
    - one active family
    - 2 inert families (no VEV)
  - Right-handed neutrinos (superheavy)

- **EXOTIC D,D-bar**

- **Singlets**

- **EXOTIC Vector leptons**
  - mass $\mu'$

- **Plus a TeV scale Z'(N)**

- **Plus all their SUSY superpartners**

**Message:** E$_6$SSM predicts SUSY+ 3(5+5*+1) + Z' at LHC
**E\textsubscript{6} SSM couplings**

\[ S \subset S_i, \quad D \subset D_i, \bar{D}_i, \]
\[ H \subset H_i^u, H_i^d, \quad F \subset Q_i, L_i, U_i^c, D_i^c, E_i^c, N_i^c \]

\[ W = SHH + SDD + HFF + DFF \]

- Singlet-Higgs-Higgs couplings includes effective $\mu$ term
- Singlet-D-D couplings includes effective D mass terms
- Yukawa couplings but extra Higgs give FCNCs
- DQQ, DQL allows D decay but also proton decay. Need to:
  - either forbid one of DQQ or DQL
  - or allow both with Yukawas $\sim 10^{-12}$
Two potential problems: rapid proton decay + FCNCs

- FCNC problem may be tamed by introducing a $Z_2^H$ under which third family Higgs and singlet are even all else odd → only allows Yukawa couplings involving third family Higgs and singlet $H_u, H_d, S$

- $Z_2^H$ also forbids all DFF and hence forbids D decay (and p decay) → $Z_2^H$ cannot be an exact symmetry!

How do we reconcile D decay with p decay?

In $E_6$SSM can have extra discrete symmetries:

$Z_2^L$ under which L are odd → forbids DQL, allows DQQ → exotic D are diquarks

$Z_2^B$ with L & D odd → forbids DQQ, allows DQL → exotic D are leptoquarks

Or:-- small DFF couplings $\sim 10^{-12}$ will suppress p decay sufficiently while couplings $\sim 10^{-12}$ will allow D decay with lifetime $<0.1$ s

(nucleosynth) N.B. $\Gamma_D \propto g^2$, $\Gamma_p \propto g^4$ (Howl, SFK)
Unification in E\textsubscript{6}SSM

2 loop, $\alpha_3(M_Z)=0.118$

SFK, Moretti, Nevzorov

$2 \log \left[ \frac{q}{M_X} \right] = 2 \times 10^{16} \text{ GeV}$
The Constrained E$_6$SSM

\[ W \approx \lambda_i S H_{u,i} H_{d,i} + \kappa_i S D_i \bar{D}_i \]

Low Mass Benchmark Points

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<tr>
<th>Parameter</th>
<th>Benchmark</th>
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<td>10</td>
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<td>$m_0$ [GeV]</td>
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<td>$A_0$ [GeV]</td>
<td>798</td>
<td>711</td>
<td>645</td>
<td>757</td>
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</table>
cE\textsubscript{6} SSM Low Mass Benchmarks

Athron, SFK, Miller, Moretti, Nevzorov
cE$_6$SSM predicts light gauginos

\[ M_3 \sim 0.7 \ M_{1/2} \quad \tilde{g} \quad \text{Gluino} \]

\[ M_2 \sim 0.25M_{1/2} \quad \chi^0_2, \chi^\pm_1 \sim \text{Wino} \]

\[ M_1 \sim 0.15M_{1/2} \quad \chi^0_1 \sim \text{Bino} \rightarrow \text{LSP?} \]

What about inert Higgsinos and singlinos?

Since \( M_i = \frac{\alpha_i}{\alpha_{GUT}} M_{1/2} \) with \( \alpha_3 \sim 0.7 \alpha_{GUT} \) in E$_6$SSM

c.f. MSSM \( M_3 \sim 2.7M_{1/2}, \ M_2 \sim 0.8M_{1/2}, \ M_1 \sim 0.4M_{1/2} \)
Dark Matter from Inert Higgsinos/singlino

3 families of Higgs = 1 MSSM family $H_u, H_d$ + 2 inert families $H_{u1}, H_{d1}, H_{u2}, H_{d2}$

3 families of Singlets = 1 NMSSM singlet $S$ + 2 inert singlets $S_1, S_2$

The full neutralino mass matrix

$$\tilde{\chi}_0^{\text{int}} = \begin{pmatrix} \tilde{B} & \tilde{W}^3 & \tilde{H}_d^0 & \tilde{H}_u^0 & \tilde{S} & \tilde{B}' \\
\tilde{H}_{d2}^0 & \tilde{H}_{d1}^0 & \tilde{H}_{u2}^0 & \tilde{S}_2 & \tilde{H}_{d1}^0 & \tilde{H}_{u1}^0 & \tilde{S}_1 \end{pmatrix}^T$$

Expect couplings of inert - active sector to be small $\sim 1\%$

Expect almost decoupled inert sector
Almost decoupled inert sector

\[ \tilde{\chi}^0_{\text{int}} = \begin{pmatrix} \tilde{H}^0_{d1} & \tilde{H}^0_{u1} & \tilde{S}_1 \end{pmatrix} \]

\[ A_{22} = A_{11} = -\frac{1}{\sqrt{2}} \begin{pmatrix} 0 & \lambda' s & f v \sin \beta \\ \lambda' s & 0 & f v \cos \beta \\ f v \sin \beta & f v \cos \beta & 0 \end{pmatrix} \]

\[ A_{21} = \epsilon A_{22}. \]

\[ \rightarrow m_{\text{LSP}} \approx \frac{f^2}{\lambda'} \frac{v^2}{s} \sin 2\beta \]

LSP is naturally light \( \sim v^2 /s \)

LSP is inert Higgsino/singlino

Following results assume the parameters:

\[ \epsilon = 0.1, \lambda = 0.2, s=3000 \text{ GeV} \rightarrow M_{Z'}=1100 \text{ GeV}, \]

\[ M_1=M_1'=M_2/2=250 \text{ GeV}, M_s = 800 \text{ GeV}, m_h \sim 115 \text{ GeV}, m_A=500 \text{ GeV} \]
Contours of $\Omega$ and LSP mass $f=1$

$\tan \beta$

$\Omega_x > \Omega_{CDM}$

$\Omega_x < \Omega_{CDM}$

Ruled out by LEP Z width

Successful regions

$m_{H_1}/2$

$m_W$ (≈ 80 GeV)

$m_Z$ (≈ 91 GeV)

$f=1$

50 GeV $m_Z/2$

40 GeV

30 GeV

60 GeV

0.05

0.1

0.2

$\lambda'$
Contours of $\Omega$ and LSP mass $\tan \beta=1.5$

Successful regions

Ruled out by LEP Z width

$\Omega_x > \Omega_{CDM}$

$\Omega_x < \Omega_{CDM}$

$\Omega_x > \Omega_{CDM}$
Spectrum of Charginos and Neutralinos

Composition of LSP

\[ \tan \beta = 1.5 \]

\[ f = 1 \]

F圣SFK, Hall

Inert Charginos

Inert Neutralinos

03/06/2009

Steve King, BSM-LHC'09, Boston
**D fermions vs inert Higgsinos at LHC**

D fermions are **coloured** and easier to produce at LHC

D fermions may be **diquarks** or **leptoquarks**

(unlike the usual case of scalar leptoquarks)

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**Inv. mass distribution**

\[ m_D = 300 \text{ GeV} \]

SFK, Moretti, Nevzorov

**Total cross section at LHC**

SFK, Moretti, Nevzorov

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Fermionic diquarks D→ \( \tilde{t}b, \, t\tilde{b}, \, \tilde{t}b, \, \tilde{b}b \)

Fermionic leptoquarks D→ \( \tilde{t}\tau, \, t\tilde{\tau}, \, \tilde{b}\nu, \, \nu\tilde{b} \)

\[
\begin{align*}
pp &\rightarrow t\bar{t}b\bar{b} + E_T^{\text{miss}} + X \\
pp &\rightarrow t\bar{t}\tau\bar{\tau} + E_T^{\text{miss}} + X \\
pp &\rightarrow b\bar{b} + E_T^{\text{miss}} + X
\end{align*}
\]
$Z'(N)$ at LHC

\[ M_{Z'(N)} > 861 \text{ GeV} \ (CDF \ 95\% \ C.L.) \]

Cross section for Drell-Yan production at the LHC

\[ M_Z' \approx g_i s \]
\[ s = <S> \]

solid: SM + $Z'$ + light D

dashed: SM + $Z'$ + light $\tilde{H}$

dotted: SM + $Z'$
Minimal $E_6$ SSM: Unification at $M_p$

$E_6 \rightarrow SO(10) \times U(1)_\psi$

$SO(10) \rightarrow SU(4)_{PS} \times SU(2)_L \times SU(2)_R$

$E_6$ broken via Pati-Salam chain

Howl, SFK

$M_{Planck}$

$M_{GUT}$

$M_3$

$M_2$

$M_1$

RH $\nu$ masses

Quarks, leptons

Triplets and Higgs

Singlet

$M_{Planck}$

$E_6 \rightarrow SU(4)_{PS} \times SU(2)_L \times SU(2)_R \times U(1)_\psi$

$SU(4)_{PS} \times SU(2)_L \times SU(2)_R \times U(1)_\psi \rightarrow SM \times U(1)_X$

$\{4,2,1\} + \{\overline{4},1,2\} + \{6,1,1\} + \{1,2,2\} + (1,1,1) = 27$

No vector leptons hence no $\mu$’ problem!

Three families of 27’s survive to low energy (minus the RH $\nu$’s)

Extra $U(1)_X$ survives to TeV scale

$U(1)_X$ broken, $Z'$ and triplets get mass, $\mu$ term generated

$SU(2)_L \times U(1)_Y$ broken

RH $\nu$ masses

$M_3$

$M_2$

$M_1$

$M_{Planck}$

$M_{GUT}$

$M_{W}$

03/06/2009

Steve King, BSM-LHC’09, Boston
**String scale unification in ME\textsubscript{6}SSM**

Low energy (below $M_{\text{GUT}}$)
three complete families of 27’s of $E\textsubscript{6}$

High energy (above $M_{\text{GUT}} \sim 10^{16}$ GeV) this is embedded into a Pati-Salam model and additional heavy Higgs are added.
### ME₆SSM with $\Delta_{27}$ family sym

<table>
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<tr>
<th>Field</th>
<th>$\Delta_{27}$</th>
<th>SU(4)$_{PS} \times$ SU(2)$_L \times$ SU(2)$<em>R \times$ U(1)$</em>\psi$</th>
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<th>U(1)</th>
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\[ \frac{1}{M^2_R} F^i F^{c j} h_3 \bar{\phi}_{3 i} \bar{\phi}_{3 j} \]
\[ \frac{1}{M^3_R} F^i F^{c j} h_3 H_{45} \bar{\phi}_{23 i} \bar{\phi}_{23 j} \]
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\[ \frac{1}{M^5_R} F^i F^{c j} h_3 H_{45} (\bar{\phi}_{3 i} \bar{\phi}_{123 j} + \bar{\phi}_{3 j} \bar{\phi}_{123 i}) (\bar{\phi}_{123 k} \phi^k_1) \]
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\[ \frac{1}{M_R} F^{c i} F^{c j} H_{R i} H_{R j} \]
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\[ \frac{1}{M^5_R} F^{c i} F^{c j} \bar{\phi}_{123 i} \bar{\phi}_{123 j} H_{R k} H_{R l} (\phi^k_{123} \phi^l_{123}) \]
\[ \frac{1}{M_S M^9_d} \sum D_{1,2,3} F^i F^j \bar{\phi}_{123 i} \bar{\phi}_{23 j} (\phi^k_{123} \phi^l_{3 k}) (\phi^l_{3 i} \phi^s_{3 l}) + (F^{i,j} \rightarrow F^{c i,j}) \]
\[ \frac{1}{M_S M^9_d} \sum D_{1,2,3} (\epsilon_{i j k} F^{c i} \phi^j_{123} \phi^k_3)(\epsilon_{l m n} F^{c l} \phi^m_1 \phi^n_3)(\phi^l_{1} \phi^s_{123 l}) + (F^{i,j} \rightarrow F^{c i,j}) \]

Dirac type Yukawa couplings

Majorana type Yukawa couplings

Suppressed proton decay long lived D
Long Lived D hadrons

In ME$_6$SSM the DFF couplings are highly suppressed giving rise to long lived D quarks giving jets containing heavy long lived D-hadrons.

D-hadrons resemble protons or neutrons but with mass >300 GeV:

$$D_p = \bar{D}u, \; D_n = \bar{D}d$$

Clean events with two D-jets containing a pair of stable D-hadrons.
Conclusion

- MSSM FT/$\mu$ problem motivates singlet SUSY models
- USSM containing an extra singlet and Z-prime can give neutralino dark matter with LSP being singlino-Higgsino dramatically affecting the spin independent and spin dependent cross-sections
- $E_6$SSM is an anomaly free version of USSM which predicts 3(5+5*+1) at TeV $\rightarrow$ rich phenomenology at LHC
- $E_6$SSM includes inert Higgsinos/singlinos which may be almost decoupled from the usual MSSM neutralinos and naturally lighter $\rightarrow$ good dark matter candidates
- ME$_6$SSM without vector leptons to avoid $\mu'$ problem:
  - allows string scale unification via Pati-Salam
  - Yukawa couplings controlled by discrete family sym
  - predicts long lived D-hadrons at the LHC