The Constrained $E_6$SSM

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Based on:

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The $E_6$SSM

“Inspired” by the gauge group $E_6$, breaking to the SM via

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

$$\downarrow$$

$$SU(5) \times U(1)_\chi$$

$$\downarrow$$

$$SU(3)_C \times SU(2)_W \times U(1)_Y$$

where only one linear superposition of the extra $U(1)$ symmetries survives to low energies:

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

This combination is required in order to keep the right handed neutrinos sterile.

So the $E_6$SSM is really a $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_N$ gauge theory.
All the SM matter fields are contained in one 27-plet of $E_6$ per generation.

$$i \rightarrow \begin{pmatrix} 10, 1 \end{pmatrix}_i^+ + \begin{pmatrix} 5^*, 2 \end{pmatrix}_i^+ + \begin{pmatrix} 5^*, -3 \end{pmatrix}_i^+ + \begin{pmatrix} 5, -2 \end{pmatrix}_i^+ + \begin{pmatrix} 1, 5 \end{pmatrix}_i^+ + \begin{pmatrix} 1, 0 \end{pmatrix}_i^+$$

$Q_i, u^c_i, e^c_i$

3 generations of “Higgs”

$H_{1i} = \begin{pmatrix} H_{11}^0 & \bar{D}_i \\ H_{1i}^- & \bar{D}_i \end{pmatrix}$

$H_{2i} = \begin{pmatrix} H_{21}^+ & D_i \\ H_{21}^0 & D_i \end{pmatrix}$

$S_i$ 

$N^c_i$ 

SU(5) reps. 

$U(1)_N$ charge $\times \sqrt{40}$

exotic quarks

singlets

right handed neutrino
New exotic states

Placing each generation in a 27-plet forces us to have new particle states:

- Now have 3 generations of Higgs bosons. Only the third generation Higgs boson gains a VEV. The others are neutral and charged scalars - we call them "inert Higgs".

- Three generations of singlets, $S_i$ with $\langle S_3 \rangle \neq 0$

- New coloured triplets of “exotic quarks” $D_i$ and $\bar{D}_i$ with charge $\pm 1/3$.

New gauge group structure, with unification:

- Extra $U(1) \rightarrow$ extra gauge boson, $Z'$
  After ewsb this will become massive (after eating the imaginary part of $S_3$)

- Additional $SU(2)$ doublets $H'$ and $\bar{H}'$, relics of an additional 27' and 27' which survive down to low energies, and are required for gauge unification.

[+ right handed neutrinos]
**Discrete Symmetries**

- $Z_2^B$ or $Z_2^L$ Symmetries
  
  To prevent proton decay, we need a baryon or lepton symmetry. This is analogous to R-parity in the MSSM. Note that the exotic D is odd, so must decay to a susy particle.

  $Z_2^B \rightarrow$ D is a leptoquark  $Z_2^L \rightarrow$ D is a diquark

- Approximate $Z_2^H$ Symmetry
  
  To evade large Flavour Changing Neutral Currents, we need another $Z_2$.

  Make the $3^{rd}$ generation Higgs and singlet superfields even, all other fields odd.

  Must only be approximate to allow exotic particles to decay.

  For a Renormalisation Group analysis and mass spectra, $Z_2^H$ violating couplings can be neglected.
To simplify the model a little:

- Impose $Z_2^{B/L}$ and (approximate) $Z_2^H$ symmetries,
- Integrate out heavy right-handed Majorana neutrinos,
- Assume a hierarchical structure of Yukawas, and keep only large ones.

$$W_{E_6SSM} \simeq \lambda S(H_d H_u) + \lambda_\alpha S(H_{1,\alpha} H_{2,\alpha}) + \kappa_i S(D_i \bar{D}_i) + h_t(H_u Q)t^c + h_b(H_d Q)b^c + h_\tau(H_d L)\tau^c + \mu'(H' \bar{H}')$$

**Note:** this is really an oversimplification – we have lots of very small $Z_2^H$ violating couplings such as $g_{ijk} D_i (Q_j Q_k)$ which are unimportant for production, but may be important for decays.

Also need lots of new SUSY breaking parameters.
The E$_6$SSM has 43 new parameters compared with the MSSM (14 are phases).

But if we apply constraints at the GUT scale, this is drastically reduced.

Set:

\[ g_1(M_X) = g_2(M_X) = g_3(M_X) = g_1'(M_X) \]

soft scalar masses \[ \rightarrow m_0 \]

soft gaugino masses \[ \rightarrow M_{1/2} \]

\[ A_{\lambda_i}(M_X) = A_{\kappa_i}(M_X) = A_{t,b,\tau}(M_X) = A(M_X) \]

Important parameters: \( \lambda_i, \kappa_i, h_t, h_b, h_\tau, m_0, M_{1/2}, A \)

- Gauge and Yukawa couplings (2 loop),
- Soft breaking gaugino and trilinear masses (2 loop),
- Soft scalar masses (1 loop).

The evolution of Gauge and Yukawa couplings doesn’t depend on the soft SUSY breaking so they can be done separately and fed into the

- Sensitive to thresholds.
- At one-loop \( \beta_3 \approx 0 \), so need two loops.
Gauge and Yukawa couplings

\[ g_1 = g_2 = g_3 = g'_1 \]
\[ \lambda_i, \kappa_i \]

scenario inputs

unification constraint

iterate

\[ T_{E_6 SSM} \]

MSSM running

\[ T_{MSSM} \]

SM running

\[ M_X \]

E\(_6\) SSM running

\[ M_Z \]

iterate

\[ \langle S \rangle, \tan \beta \]
\[ g_1, g_2, g_3 \]
\[ h_t, h_b, h_{\tau} \]
\[ \lambda_i, \kappa_i \]

scenario inputs

experimental values

first guess

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Generically, we can write
\[
\begin{align*}
    m_i^2(Q) &= a_i(Q)M_{1/2}^2 + b_i(Q)A_0^2 + c_i(Q)A_0M_{1/2} + d_i(Q)m_0^2, \\
    A_i(Q) &= e_i(Q)A_0 + f_i(Q)M_{1/2}, \\
    M_i(Q) &= p_i(Q)A_0 + q_i(Q)M_{1/2}.
\end{align*}
\]

- Fix \( m_0^2, M_{1/2}, A_0 \) using ewsb constraints
- Calculate the mass spectrum
- Apply experimental constraints

\[
\begin{align*}
    \frac{\partial V}{\partial s} &= \frac{\partial V}{\partial v_1} = \frac{\partial V}{\partial v_2} = 0
\end{align*}
\]

including one-loop stop contributions.
To ensure phenomenologically acceptable solutions, we require

- squarks and gluinos \( \gtrsim 300 \text{ GeV} \)
- exotic quarks and squarks \( \gtrsim 300 \text{ GeV} \) [HERA]
- \( M_{Z'} \gtrsim 700 \text{ GeV} \)
- Insist on neutralino LSP (sort of)
- Keep Yukawa couplings \( \lesssim 3 \)
- Inert Higgs and Higgsinos \( \gtrsim 100 \text{ GeV} \)
Set $\tan \beta = 10$, $s = 3, 4, 5$ TeV, $\lambda_{1,2} = 0.1$, and vary $\lambda_3$ and $\kappa = \kappa_{1,2,3}$. 

$\chi_1^\pm < 100$ GeV

$m_{H_1} < 100$ GeV

(inert Higgs)

$m_h < 114$ GeV
Firstly, notice that for most allowed scenarios \( m_0 \gtrsim M_{1/2} \), so squarks tend to be heavier than the gluino.

**Neutralinos, charginos and gluino**

\[
\begin{align*}
    m_{\widetilde{\chi}_1^0} &\approx M_1 &
m_{\widetilde{g}} &\approx M_3 \\
    m_{\widetilde{\chi}_2^0} &\approx m_{\widetilde{\chi}_1^\pm} &\approx M_2 \\
    m_{\widetilde{\chi}_{3,4}^0} &\approx m_{\widetilde{\chi}_2^\pm} &\approx \mu = \lambda \langle S' \rangle \\
    m_{\widetilde{\chi}_{5,6}^0} &\approx M_{Z'} \\
\end{align*}
\]

**Higgs bosons**

\[
\begin{align*}
    m_{h_1} &\approx M_Z + \Delta \\
    m_{h_2} &\approx m_{H^\pm} \approx m_A \\
    m_{h_3} &\approx M_{Z'} \\
\end{align*}
\]

**Exotic quarks**

\[
\begin{align*}
    \approx \kappa_i \langle S \rangle \\
\end{align*}
\]

**Exotic squarks**

\[
\begin{align*}
    \approx m^2_{D_i} + \kappa^2_i \langle S \rangle^2 \\
    \approx m^2_{H_i} + \lambda^2_i \langle S \rangle^2 \\
    \approx \lambda_i \langle S' \rangle \\
\end{align*}
\]

+ mixing and auxiliary D-terms
+ auxiliary D-terms
\[
\begin{align*}
\tan \beta &= 3 \\
\lambda_3(M_X) &= -0.465 \\
\lambda_{1,2}(M_X) &= 0.1 \\
\kappa_3(M_X) &= 0.3 \\
\kappa_{1,2}(M_X) &= 0.3 \\
\sqrt{2 \langle S \rangle} &= 3.3 \text{ TeV} \\
M_{1/2} &= 365 \text{ GeV} \\
m_0 &= 640 \text{ GeV} \\
A_0 &= 798 \text{ GeV}
\end{align*}
\]

- gluino rather light
- light Higgs and Bino
- \( \kappa_1 = \kappa_2 = \kappa_3 \) so Ds are degenerate and rather heavy

\( m_{h_1} = 114 \text{ GeV} \) (approx. two loop)
Benchmark C

\[ \tan \beta = 10 \]
\[ \lambda_3 (M_X) = -0.378 \]
\[ \lambda_{1,2} (M_X) = 0.1 \]
\[ \kappa_3 (M_X) = 0.42 \]
\[ \kappa_{1,2} (M_X) = 0.06 \]
\[ \sqrt{2} \langle S \rangle = 2.7 \text{ TeV} \]
\[ M_{1/2} = 388 \text{ GeV} \]
\[ m_0 = 681 \text{ GeV} \]
\[ A_0 = 645 \text{ GeV} \]

- \( \kappa_1 = \kappa_2 \neq \kappa_3 \) so degeneracy of Ds is lifted.
- lightest exotic quark is 300 GeV
Benchmark E

\[ \tan \beta = 30 \]
\[ \lambda_3 (M_X) = -0.38 \]
\[ \lambda_{1,2} (M_X) = 0.1 \]
\[ \kappa_3 (M_X) = 0.17 \]
\[ \kappa_{1,2} (M_X) = 0.17 \]
\[ \sqrt{2} \langle S \rangle = 3.1 \text{ TeV} \]
\[ M_{1/2} = 365 \text{ GeV} \]
\[ m_0 = 702 \text{ GeV} \]
\[ A_0 = 1148 \text{ GeV} \]

- mixing causes a rather light \( \tilde{D} \) (393 GeV)
\[
\begin{align*}
\tan \beta &= 10 \\
\lambda_3(M_X) &= -2.0 \\
\lambda_{1,2}(M_X) &= 2.6 \\
\kappa_3(M_X) &= 2.5 \\
\kappa_{1,2}(M_X) &= 2.5 \\
\sqrt{2\langle S \rangle} &= 4.0 \text{ TeV} \\
M_{1/2} &= 389 \text{ GeV} \\
m_0 &= 725 \text{ GeV} \\
A_0 &= -1528 \text{ GeV}
\end{align*}
\]

- it is possible to construct scenarios where all exotic particles are heavy
- gluino is still lighter than the squarks
If the exotic quarks are light, their discovery at the LHC should be rather straightforward.

Since the exotic quarks are colored, their production cross-sections are very large.
LHC signatures: Exotic quarks

Assuming Ds couple predominantly to the 3\textsuperscript{rd} generation:

- Diquarks decay to \( \tilde{t}b, \ t\tilde{b} \), so would give an enhancement to
  
  \[ pp \rightarrow t\bar{t}b\bar{b} + E_T^{miss} + X \]

- Leptoquarks decay to \( \tilde{t}\tau, \ t\tilde{\tau}, \ b\tilde{\nu}_\tau, \ b\nu_\tau \) so give enhancements to
  
  \[ pp \rightarrow t\bar{t}\tau^+\tau^- + E_T^{miss} + X \]

  \[ pp \rightarrow b\bar{b} + E_T^{miss} + X \]

Notice that SM production of \( t\bar{t}\tau^+\tau^- \) is suppressed by \( (\alpha_W/\pi)^2 \) in comparison.
If the $Z_2^H$ violating coupling, e.g. $g_{ijk}D_i(Q_j Q_k)$ is very small, D quarks may hadronize before they decay leading to spectacular signatures.

- The exotic squarks $\tilde{D}$ are $Z_2^{B/L}$ even, so don’t need to decay to the LSP.

They give an enhancement to, e.g. $pp \rightarrow t\bar{t}\tau\bar{\tau} + X$

Note that the Tevatron rules out the scalar diquarks lighter than about 630 GeV and scalar leptoquarks lighter than about 300 GeV.

- Inert Higgs decays are similar to their MSSM counterparts

\[
\begin{align*}
H^0_{1,i} & \rightarrow b\bar{b} & H^-_{1,i} & \rightarrow \tau\bar{\nu}_\tau \\
\tilde{H}^0_i & \rightarrow t\tilde{t}^* & \tilde{H}^0_i & \rightarrow \tau\tilde{\tau}^* & \tilde{H}^+_i & \rightarrow t\tilde{b}^* & \tilde{H}^-_i & \rightarrow \tau\tilde{\nu}^*_\tau
\end{align*}
\]
Even if all the exotic particles are heavy, the cE₆SSM still makes striking predictions.

- light gluino, much lighter than the squarks
- light neutralinos $\tilde{\chi}^0_1$ and $\tilde{\chi}^0_2$
- light chargino $\tilde{\chi}^\pm_1$

Gluino decays will provide an enhancement of

$$pp \rightarrow q\bar{q}q\bar{q} + E_T^{\text{miss}} + X$$
Conclusions and Summary

- The E₆SSM provides a credible example of a model which could arise from a GUT, where each generation forms a complete 27-plet of E₆.

- We have examined a constrained E₆SSM, using RGEs to construct realistic, phenomenologically reasonable scenarios at LHC energies.

- The model predicts a light gluino, much lighter than the squarks, light neutralinos, $\tilde{\chi}^0_1$ and $\tilde{\chi}^0_2$, and a light chargino $\tilde{\chi}^\pm_1$.

- It also predicts new exotic quarks and squarks, “inert” Higgs bosons, and a $Z'$.

- If the new exotic quarks are light, they will give striking signatures, such as a significant enhancement to $pp \rightarrow t\bar{t}bb + E_T^{miss} + X$ which should be easily observable at the LHC.