Health-check of supersymmetric E(6) models into the new decade

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Talk based on M. Frank, Y. Hiçyılmaz, S. Moretti and Ö. Özdal

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Outline

1. Introduction
   - Supersymmetry
   - Cons of MSSM

2. $E_6$ Motivated UMSSM
   - Model
   - Scanning Procedure and Experimental Constraints

3. Results

4. Conclusion
Supersymmetry (SUSY) is one of the most studied NP theories at LHC, since it has remarkable advantages.
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- Natural light Higgs boson.
- Unification of the gauge couplings.
- WIMP candidate in order to solve the DM puzzle.
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Minimal Supersymmetric Standard Model (MSSM) is the simplest SUSY extension of the SM.

\[ W_{\text{MSSM}} = \mu H_u H_d + Y_u \hat{Q} H_u \hat{U} + Y_d \hat{Q} H_d \hat{D} + Y_e \hat{L} H_d \hat{E} \]
Little Hierarchy Problem!!!

\[(m_h^{\text{pole}})^2 \approx m_Z^2 \cos^2 2\beta + \Delta m_h^2\]

- \[m_h^{\text{pole}} \approx 125\text{GeV}\]
- \[m_Z \approx 91\text{GeV}\]
- \[\Delta m_h \gtrsim 87\text{GeV}\]
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One of them is the scenario which can be realised by breaking the exceptional group $E_6$, so called $E_6$ motivated UMSSM.

- The fundamental 27-dimensional representations.
- Cancellation of gauge anomalies.
- See-saw mechanisms for neutrino mass and mixing generation.
$E_6 \rightarrow SO(10) \times U(1)_\psi \rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi \rightarrow G_{MSSM} \times U(1)'$

$U(1)' = \cos \theta_{E_6} \ U(1)_\chi - \sin \theta_{E_6} \ U(1)_\psi$
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$U(1)' = \cos \theta_{E_6} U(1)_\chi - \sin \theta_{E_6} U(1)_\psi$

Superpotential:

$$W_{\text{UMSSM}} = Y_u \hat{Q} H_u \hat{U} + Y_d \hat{Q} H_d \hat{D} + Y_e \hat{L} H_d \hat{E} + h_s \langle S \rangle$$

$$\mu = h_s \langle S \rangle$$
\[ E_6 \rightarrow SO(10) \times U(1)_\psi \rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi \rightarrow G_{\text{MSSM}} \times U(1)' \]

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\[ \mu = h_s \langle S \rangle \]

U(1)' Charges:

<table>
<thead>
<tr>
<th>Model</th>
<th>( \hat{Q} )</th>
<th>( \hat{U}^c )</th>
<th>( \hat{D}^c )</th>
<th>( \hat{L} )</th>
<th>( \hat{E}^c )</th>
<th>( \hat{H}_d )</th>
<th>( \hat{H}_u )</th>
<th>( \hat{S} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 2\sqrt{6} \ U(1)_\psi )</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-2</td>
<td>-2</td>
<td>4</td>
</tr>
<tr>
<td>( 2\sqrt{10} \ U(1)_\chi )</td>
<td>-1</td>
<td>-1</td>
<td>3</td>
<td>3</td>
<td>-1</td>
<td>-2</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

\[ Q^i = Q^i_\chi \cos \theta_{E_6} - Q^i_\psi \sin \theta_{E_6} \]
Higgs Potential:

\[ V_{Higgs}^{UMSSM} = V_{Higgs}^{MSSM} |_{\mu = h_S s} + m_S^2 |S|^2 \]

\[ + \frac{g'^2}{2} \left( Q_{H_u} |H_u|^2 + Q_{H_d} |H_d|^2 + Q_S |S|^2 \right) \]
Higgs Potential:

\[
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\]

\[Z-Z'\text{ Mass Mixing:}\]

\[
M_Z^2 = \begin{pmatrix}
M_{ZZ}^2 & M_{ZZ'}^2 \\
M_{ZZ'}^2 & M_{Z'Z'}^2
\end{pmatrix}
\]

\[
= \begin{pmatrix}
2g_1^2 \sum_i t_{3i}^2 |\langle \phi_i \rangle|^2 & 2g_1g' \sum_i t_{3i} Q_i |\langle \phi_i \rangle|^2 \\
g_1g' \sum_i t_{3i} Q_i |\langle \phi_i \rangle|^2 & 2g'^2 \sum_i Q_i^2 |\langle \phi_i \rangle|^2
\end{pmatrix}
\]

\[
\tan 2\alpha_{ZZ'} = \frac{2M_{ZZ'}^2}{M_{Z'Z'}^2 - M_{ZZ}^2}.
\]

\[
M_{Z,Z'}^2 = \frac{1}{2} \left[ M_{ZZ}^2 + M_{Z'Z'}^2 \mp \sqrt{(M_{ZZ}^2 - M_{Z'Z'}^2)^2 + 4M_{ZZ'}^4} \right].
\]
Kinetic Mixing:

\[ \mathcal{L}_{\text{kin}} \supset -\frac{\kappa}{2} \hat{B}^{\mu\nu} \hat{Z}'_{\mu\nu} \]

\[
\begin{pmatrix}
\hat{B}_\mu \\
\hat{Z}'_\mu
\end{pmatrix} =
\begin{pmatrix}
1 & -\frac{\kappa}{\sqrt{1-\kappa^2}} \\
0 & \frac{1}{\sqrt{1-\kappa^2}}
\end{pmatrix}
\begin{pmatrix}
B_\mu \\
Z'_\mu
\end{pmatrix}
\]

\[
g_y = \frac{g_{YY} g_{EE} - g_{YE} g_{EY}}{\sqrt{g_{EE}^2 + g_{EY}^2}} = g_1,
\]

\[
g_{yp} = \frac{g_{YY} g_{EY} + g_{YE} g_{EE}}{\sqrt{g_{EE}^2 + g_{EY}^2}} = -\kappa g_1 \frac{1}{\sqrt{1-\kappa^2}},
\]

\[
g_p = \sqrt{g_{EE}^2 + g_{EY}^2} = g' \frac{1}{\sqrt{1-\kappa^2}}
\]

\[ G = \begin{pmatrix} g_{YY} & g_{YE} \\ g_{EY} & g_{EE} \end{pmatrix} \]
Kinetic Mixing:

\[ \mathcal{L}_{\text{int}} = -\bar{\psi}_i \gamma^\mu \left[ g_y Y_i B_\mu + (g_p Q_i + g_{yp} Y_i) Z'_\mu \right] \psi_i \]

\[ Q_{i}^{\text{eff}} = Q_i - \kappa \frac{g_1}{g'} Y_i \]
### Parameter Space

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scanned range</th>
<th>Parameter</th>
<th>Scanned range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_0$</td>
<td>$[0., 3.]$ TeV</td>
<td>$h_s$</td>
<td>$[0., 0.7]$</td>
</tr>
<tr>
<td>$M_{1,4}/M_3$</td>
<td>$[-15., 15.]$</td>
<td>$\nu_S$</td>
<td>$[1., 15.]$ TeV</td>
</tr>
<tr>
<td>$M_3$</td>
<td>$[0., 3.]$ TeV</td>
<td>$A_s$</td>
<td>$[-5., 5.]$ TeV</td>
</tr>
<tr>
<td>$M_2/M_3$</td>
<td>$[-5., 5.]$</td>
<td>$\theta_{E_6}$</td>
<td>$[-\pi/2, \pi/2]$</td>
</tr>
<tr>
<td>$\tan \beta$</td>
<td>$[1., 50.]$</td>
<td>$\kappa$</td>
<td>$[-0.5, 0.5]$</td>
</tr>
<tr>
<td>$A_0$</td>
<td>$[-5., -5.]$ TeV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Constraints

\[ m_h = 123 - 127 \text{ GeV (and SM - like couplings)}, \]
\[ m_{\tilde{g}} \geq 1.8 \text{ TeV}, \]
\[ 0.8 \times 10^{-9} \leq \text{BR}(B_s \rightarrow \mu^+\mu^-) \leq 6.2 \times 10^{-9} \ (2\sigma \text{ tolerance}), \]
\[ m_{\tilde{\chi}^0_1} \geq 103.5 \text{ GeV}, \]
\[ m_{\tilde{\tau}} \geq 105 \text{ GeV}, \]
\[ 2.99 \times 10^{-4} \leq \text{BR}(B \rightarrow X_s\gamma) \leq 3.87 \times 10^{-4} \ (2\sigma \text{ tolerance}), \]
\[ 0.15 \leq \frac{\text{BR}(B_u \rightarrow \tau\nu_{\tau})_{\text{UMSSM}}}{\text{BR}(B_u \rightarrow \tau\nu_{\tau})_{\text{SM}}} \leq 2.41 \ (3\sigma \text{ tolerance}), \]
\[ 0.0913 \leq \Omega_{\text{CDM}} h^2 \leq 0.1363 \ (5\sigma \text{ tolerance}). \]

(1)
Grey: Radiative EWSB (REWSB) and neutralino LSP.
Red: The subset of grey plus Higgs boson mass and coupling constraints, SUSY particle mass bounds and EWPT requirements.
Green: The subset of red plus $B$-physics constraints.
Blue: The subset of green plus WMAP constraints on the relic abundance of the neutralino LSP (within $5\sigma$).
Black: The subset of blue plus exclusion limits at the LHC from $Z'$ direct searches via $pp \rightarrow Z' \rightarrow ll$ and $pp \rightarrow Z' \rightarrow WW$. 
$\Gamma(Z' \rightarrow WW)$ is proportional to $M_{Z'}^5/M_W^4$ as well as $\sin^2 \alpha_{ZZ'}$. 

\[ \Gamma(Z' \rightarrow WW) \propto \frac{M_{Z'}^5}{M_W^4} \cdot \sin^2 \alpha_{ZZ'} \]
Parameter Space and $Z'$ Decay Width
Effective U(1)’ Charges and Z’ Decays
Neutralino Masses
Introduction

E6 Motivated UMSSM

Results

Conclusion

Dark Matter-Relic Density
Dark Matter-Direct Detection

Motivated UMSSM

Results

Conclusion

Introduction
We have explored the low scale and DM implications of an $E_6$ based UMSSM, with generic mixing between the two ensuing Abelian groups under current experimental and Dark Matter bounds.
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We have studied on the gauge kinetic mixing between the $Z$ and $Z'$ states which in turn onsets a significant $Z'WW$ coupling. We have found that the $Z' \rightarrow WW$ decay channel overwhelm the $Z' \rightarrow ll$ one, thus producing a wide (yet, still perturbative) $Z'$ state and so that it is the former and not the latter search channel that sets the limit on $M_{Z'}$, at 4 TeV,
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The fundamental parameters, i.e., the gauge kinetic mixing coefficient and the $E_6$ mixing angle, are found to be $0.2 \lesssim \kappa \lesssim 0.4$ and $-1 \lesssim \theta_{E6} \lesssim -0.8$ radians.
We have found two specific Dark Matter LSP compositions which are consistent with all current experimental bounds coming from relic density and direct detection experiments: a higgsino-like LSP neutralino with $0.9 \text{ TeV} \lesssim m_{\chi_1^0} \lesssim 1.2 \text{ TeV}$ and a singlino-like LSP neutralino with $0.9 \text{ TeV} \lesssim m_{\chi_1^0} \lesssim 1.6 \text{ TeV}$. 
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Our solutions which are compatible with experimental bounds include heavy sparticle spectrum for third generation sfermions ($m_{\tilde{t}, \tilde{b}} \gtrsim 4 \, \text{TeV}$ and $m_{\tilde{\tau}} \gtrsim 5 \, \text{TeV}$) as well as the gluino ($m_{\tilde{g}} \gtrsim 4 \, \text{TeV}$).
Thank You for Your Attention!!!