Phenomenological aspects of the UMSSM

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G. Bélanger, JDS, U. Laa and A. Pukhov, in preparation
Outline

1 Motivations

2 The model

3 Results: Higgs and squark sectors

4 Low energy observables

5 Dark Matter constraints

6 LHC constraints on sparticles

7 Conclusions
Motivations

1. Motivations

2. The model

3. Results: Higgs and squark sectors

4. Low energy observables

5. Dark Matter constraints

6. LHC constraints on sparticles

7. Conclusions
**Drawbacks of the MSSM**

125 GeV Standard Model (SM)-like Higgs boson discovery by ATLAS and CMS collaborations + no other new particles found at LHC Run 1 → narrow window for new physics at the TeV scale

The Higgs couplings in the Minimal Supersymmetric Standard Model (MSSM) are to a large extent SM-like especially when other new particle masses \( \gg \) electroweak scale

Challenges of the MSSM:

\[
\begin{align*}
M_h &= 114 \text{ GeV} \\
M_h &= 120 \text{ GeV} \\
M_h &= 123 \text{ GeV} \\
M_h &= 126 \text{ GeV} \\
M_h &= 129 \text{ GeV} \\
M_h &= 132 \text{ GeV}
\end{align*}
\]
125 GeV Standard Model (SM)-like Higgs boson discovery by ATLAS and CMS collaborations + no other new particles found at LHC Run 1 → narrow window for new physics at the TeV scale

The Higgs couplings in the Minimal Supersymmetric Standard Model (MSSM) are to a large extent SM-like especially when other new particle masses ≫ electroweak scale

Challenges of the MSSM:

- Explain Higgs boson mass at 125 GeV → large contributions from 1-loop diagrams involving stops
- → Constrain stop sector
- Very small tan β, i.e. ≈ 1 ⇒ tricky:
  
  TeV-scale SUSY-breaking parameter $M_S +$ SM-like Higgs boson ≈ 125 GeV

  → Higgs boson mass of 125 GeV requires large $\tan \beta$

$\Rightarrow$ Going beyond the MSSM

A. Djouadi, J. Quevillon, JHEP 10 (2013) 028
The model

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E$_6$ inspired model

- Models with **extended gauge symmetries** are well motivated within the context of Beyond the Standard model (GUT scale models, extra-dimension motivations, superstring models, strong dynamics models, little Higgs models,...)


E$_6$ → SU(3)$_c$ × SU(2)$_L$ × U(1)$_Y$ × U(1)$_X$ × U(1)$_\psi$
E₆ inspired model

- Models with **extended gauge symmetries** are well motivated within the context of Beyond the Standard model (GUT scale models, extra-dimension motivations, superstring models, strong dynamics models, little Higgs models,...)


  \[
  E₆ \rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_χ \times U(1)_ψ
  \]

- Low energy gauge symmetry considered : \( SU(3)_c \times SU(2)_L \times U(1)_Y \times U'(1) \)

  Coupling constants : \( g_3, g_2, g_Y \) and \( g_1' = \sqrt{\frac{5}{3}} g_Y \)

- **U'(1) charge :**

  \[
  Q' = \cos \theta_{E₆} Q'_χ + \sin \theta_{E₆} Q'_ψ, \quad \theta_{E₆} \in [-\pi/2, \pi/2]
  \]

- **MSSM fields + RH (s)neutrinos + new gauge boson (gaugino) + new singlet (singlino) + \( \mathcal{O}(\text{TeV}s) = \text{UMSSM} \)**

<table>
<thead>
<tr>
<th>( Q'_Q )</th>
<th>( Q'_u )</th>
<th>( Q'_d )</th>
<th>( Q'_L )</th>
<th>( Q'_ν )</th>
<th>( Q'_e )</th>
<th>( Q'_{H_u} )</th>
<th>( Q'_{H_d} )</th>
<th>( Q'_S )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sqrt{40} Q'_χ )</td>
<td>-1</td>
<td>-1</td>
<td>3</td>
<td>3</td>
<td>-5</td>
<td>-1</td>
<td>2</td>
<td>-2</td>
</tr>
<tr>
<td>( \sqrt{24} Q'_ψ )</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-2</td>
<td>-2</td>
</tr>
</tbody>
</table>
**Superpotential :**

\[ \mathcal{W}_{\text{UMSSM}} = \mathcal{W}_{\text{MSSM}}|_{\mu=0} + \lambda S H_u H_d + \tilde{\nu}_R^* y_\nu \tilde{L} H_u + \mathcal{O}(\text{TeV}) \]

**As the NMSSM, this model solves the \(\mu\)-problem :** \(\mu = \lambda \frac{v_s}{\sqrt{2}}\)

**Gauge sector :** Physical abelian gauge bosons : \(Z_1\) and \(Z_2\), mixing between the \(Z^0\) of the SM and the \(Z'\), \(\alpha_Z\) is the mixing angle \(\Rightarrow \tan \beta\) constrained

\[
Z_1 = \cos \alpha_Z Z^0 + \sin \alpha_Z Z' \\
Z_2 = - \sin \alpha_Z Z^0 + \cos \alpha_Z Z'
\]

\[
\cos^2 \beta = \frac{1}{Q'_{H_d} + Q'_{H_u}} \left( \sin 2\alpha_Z (M_{Z_1}^2 - M_{Z_2}^2) \frac{v^2 g_1'}{\sqrt{g_Y^2 + g_Z^2}} + Q'_{H_u} \right)
\]
Superpotential:

\[ W_{\text{UMSSM}} = W_{\text{MSSM}}|_{\mu=0} + \lambda S H_u H_d + \tilde{\nu}_R^* y_\nu \tilde{L} H_u + O(\text{TeV}) \]

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\cos^2 \beta = \frac{1}{Q'_{H_d} + Q'_{H_u}} \left( \frac{\sin 2\alpha_Z (M_{Z_1}^2 - M_{Z_2}^2)}{v^2 g_1' \sqrt{g_Y^2 + g_2^2} + Q'_{H_u}} \right)
\]

Gauginos sector: 6 neutralinos in the basis \((\tilde{B}, \tilde{W}_3, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}, \tilde{B}')\)

Sfermion sector: New D-terms \(\Delta_F = \frac{1}{2} g_1'^2 Q'_F \left( Q'_{H_d} v_d^2 + Q'_{H_u} v_u^2 + Q'_{S} v_s^2 \right)\), where \(F \in \{Q, u, d, L, e, \nu\}\)

- Light d-squark and LH slepton for \(-\tan^{-1}(3\sqrt{3/5}) < \theta_{E_6} < 0\)
- Light u-squark and RH slepton for \(0 < \theta_{E_6} < \tan^{-1}(\sqrt{3/5})\)
- Light LH smuon for for \(\theta_{E_6} = -\tan^{-1}(3\sqrt{3/5}) \approx -1.16\) → significant contribution to the anomalous magnetic moment of the muon
Higgs properties

- MSSM fields + 1 singlet \( \Rightarrow \) 3 CP-even Higgs bosons \( h_i, i \in \{1, 2, 3\} \)

- New D-terms for the SM-like Higgs boson mostly \( h_1 \):

\[
m_{h_1}^2 \text{(tree)} \simeq M_{Z_0}^2 \cos^2 2\beta + \frac{1}{2} \lambda^2 v^2 \sin^2 2\beta + g_1' v^2 \left( Q'_{H_d} \cos^2 \beta + Q'_{H_u} \sin^2 \beta \right)^2

- \frac{\lambda^4 v^2}{g_1'^2 Q'_S^2} \left( 1 - \frac{A \sin^2 2\beta}{\sqrt{2} \lambda v_s} \right) + \frac{g_1'^2}{\lambda^2} \left( Q'_{H_d} \cos^2 \beta + Q'_{H_u} \sin^2 \beta \right) Q'_S \right)^2

- To sum up:

\[
\begin{array}{cccc}
\text{u} & \text{c} & \text{t} \\
\text{d} & \text{s} & \text{b} \\
\nu_{eL} & \nu_{\mu L} & \nu_{\tau L} \\
\text{e} & \mu & \tau
\end{array}
\quad
\begin{array}{cccc}
\text{g} & A^0 \\
h_{1,2} \\
W^\pm & h_{\pm}
\end{array}
\quad
\begin{array}{cccc}
\tilde{\chi}_1^0 & \tilde{\chi}_1^\pm \\
\tilde{\chi}_2^0 & \tilde{\chi}_2^\pm \\
\tilde{\chi}_3^0 & \tilde{\chi}_3^\pm \\
\tilde{\chi}_4^0 & \tilde{\chi}_4^\pm
\end{array}
\quad
\begin{array}{cccc}
\tilde{u} & \tilde{c} & \tilde{t} \\
\tilde{d} & \tilde{s} & \tilde{b} \\
\tilde{\nu}_{eL} & \tilde{\nu}_{\mu L} & \tilde{\nu}_{\tau L} \\
\tilde{e} & \tilde{\mu} & \tilde{\tau}
\end{array}
\]
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Scan and first constraints

Scanning the UMSSM parameter space with the micrOMEGAs code:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\tilde{\nu}}^{\tau R}$</td>
<td>$[0, 2]$ TeV</td>
<td>$\mu, M_1$</td>
<td>$[-2, 2]$ TeV</td>
</tr>
<tr>
<td>$M'_1$</td>
<td>$[-20, 20]$ TeV</td>
<td>$M_3$</td>
<td>$[0.4, 12]$ TeV</td>
</tr>
<tr>
<td>$\theta_{E_6}$</td>
<td>$[-\pi/2, \pi/2]$ rad</td>
<td>$m_{\bar{\nu}_i, \nu_j}$</td>
<td>$[0, 4]$ TeV</td>
</tr>
<tr>
<td>$\alpha_Z$</td>
<td>$[-10^{-3}, 10^{-3}]$ rad</td>
<td>$m_t$</td>
<td>$173.34 \pm 1$ GeV Tevatron+LHC</td>
</tr>
</tbody>
</table>

$F \in \{Q, u, d, L, e\}$, $i \in \{1, 2, 3\}$, $j \in \{1, 2\}$ and where $m_{\bar{\nu}_2} = m_{\bar{\nu}_1}, m_{\nu_2} = m_{\nu_1}$

Constraints:

- $\tilde{\nu}_{\tau R}$ or $\chi_1^0$ is the Lightest Supersymmetric Particle (LSP)
- LEP constraints on neutralinos, charginos, sleptons and squarks
- $Z'$: ATLAS + CMS: $M_{Z_2} > 2.57$ TeV for $\theta_{E_6} = \theta_\psi$ assuming only SM decay modes → limits weakened in the UMSSM but still important so that heavy singlet-like Higgs boson → $h_2$ mostly doublet-like
- Higgs: $m_{h_1} = 125.1 \pm 3$ GeV, HiggsBounds-4.1.3 and HiggsSignals-1.2.0
- Higgs search in the $\tau^+\tau^-$ mode and other Higgs constraints through a modification of the NMSSMTools code: UMSSMTools
**Higgs sector**

- Maximum tree-level mass for $h_1$ reaches $\approx 107$ GeV and above the $Z^0$ mass for mixing angles $\alpha_Z > 2 \times 10^{-5}$ rad
Higgs sector

- Maximum tree-level mass for $h_1$ reaches $\approx 107$ GeV and above the $Z^0$ mass for mixing angles $\alpha_Z > 2 \times 10^{-5}$
- $\tan \beta \approx 1$ gives expected $m_{h_1}$ if $\lambda$ sufficiently large and $Z_2$ not too heavy
Squarks

- Light squarks still allowed → add more constraints
Low energy observables

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## Low energy observables

<table>
<thead>
<tr>
<th>Observable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(B^\pm \to \tau^\pm \nu_\tau)$</td>
<td>$[0.70, 1.58] \times 10^{-4}$ HFAG</td>
</tr>
<tr>
<td>$\mathcal{B}(B^0 \to X_s \gamma)$</td>
<td>$[2.99, 3.87] \times 10^{-4}$ HFAG</td>
</tr>
<tr>
<td>$\mathcal{B}(B^0_s \to \mu^+ \mu^-)$</td>
<td>$[1.6, 4.2] \times 10^{-9}$ CMS+LHCb</td>
</tr>
<tr>
<td>$\Delta M_s$</td>
<td>$[17.805, 17.717]$ ps$^{-1}$ HFAG</td>
</tr>
<tr>
<td>$\Delta M_d$</td>
<td>$[0.504, 0.516]$ ps$^{-1}$ HFAG</td>
</tr>
<tr>
<td>$\delta a_\mu$</td>
<td>$[7.73, 42.14] \times 10^{-10}$ E821</td>
</tr>
</tbody>
</table>

Points allowed by $\delta a_\mu$ mostly around $\theta_{E_6} \approx -1.16$ as expected.
Dark Matter constraints
LSP abundance

- Dark Matter (DM) observables for either neutralino or RH sneutrino DM candidate:
  - $\Omega_{\rm LSP} h^2 < 0.1208$ (2$\sigma$ upper bound from Planck combination)
  - $\tilde{B}, \tilde{H}, \tilde{W}, \tilde{S}$ can satisfy relic abundance constraint
Dark Matter (DM) observables for either neutralino or RH sneutrino DM candidate :

- $\Omega_{LSP} h^2 < 0.1208$ (2$\sigma$ upper bound from Planck combination)
- WIMP-nucleon scattering cross section limits from LUX

DM direct detection experiments can probe entirely some regions, especially for $\tilde{\nu}_R$ LSP.
Dark Matter (DM) observables for either neutralino or RH sneutrino DM candidate:
- $\Omega_{LSP} h^2 < 0.1208$ ($2\sigma$ upper bound from Planck combination)
- WIMP-nucleon scattering cross section limits from LUX
- Limits on DM annihilation from the dwarf spheroidal satellite galaxies of the Milky Way from Fermi-LAT

→ $b\bar{b}$ channel complementary to direct detection for $\tilde{\nu}_R$ LSP
LHC constraints on sparticles

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Using SModelS for interpreting simplified-model results from the LHC

Some regions with light squarks remain unconstrained
Nature of the LSP

- Using SModelS for interpreting simplified-model results from the LHC
- Some regions with light squarks remain unconstrained
  → Mostly because of $\tilde{W}$ LSP
- Important signatures are not covered by existing SMS results
Conclusions

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Conclusions

- New D-terms in the UMSSM $\Rightarrow$ low $\tan \beta$ values still allowed for TeV-scale $M_S$ to get a 125 Higgs boson
  $\Rightarrow$ sfermion sector impacted

- $\delta a_\mu$ constraint can be easily satisfied for some regions of $\theta_{E_6}$

- $\chi_1^0$ or $\tilde{\nu}_R$ LSP that does not overclose the Universe exclude a large region of the parameter space

- Viable or excluded regions depend strongly on $\theta_{E_6}$

- Forthcoming direct detection experiments would probe entirely some scenarios

- Complementarity between direct and indirect detection of DM, especially for $\tilde{\nu}_R$ LSP

- Simplified-model results from the LHC can exclude scenarios but some interesting signatures obtained in this study are not yet covered in SMS results
BACKUP
Phenomenological aspects of the UMSSM

Jonathan Da Silva (U. Manchester)
$X_t - M_S$ plane:
Some missing topologies with highest cross section for $\tilde{H}$ LSP

- $[[b],[t]]$
- $[[b],[b],[jet,jet]]$
- $[[b],[b]],[[b],[t]]$
- $[[jet],[t,b]],[[t,b]]$

Other topologies