Prospects for SUSY discovery after the LHC Run 1

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On behalf of the Mastercode collaboration


European Physical Society Conference on High Energy Physics
23 July 2015
Vienna
### The Minimal Supersymmetric Standard Model

#### Chiral supermultiplets

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>spin 0</th>
<th>spin 1/2</th>
<th>((SU(3)_C, SU(2)_L, U(1)_Y))</th>
</tr>
</thead>
<tbody>
<tr>
<td>squarks, quarks</td>
<td>Q</td>
<td>(\tilde{u}_L, \tilde{d}_L)</td>
<td>((u_L, d_L))</td>
<td>((3, 2, \frac{1}{6}))</td>
</tr>
<tr>
<td></td>
<td>(\tilde{u})</td>
<td>(\tilde{u}_R^*)</td>
<td>(u_R^\dagger)</td>
<td>((3, 1, -\frac{2}{3}))</td>
</tr>
<tr>
<td></td>
<td>(\tilde{d})</td>
<td>(\tilde{d}_R^*)</td>
<td>(d_R^\dagger)</td>
<td>((\bar{3}, 1, \frac{1}{3}))</td>
</tr>
<tr>
<td>sleptons, leptons</td>
<td>L</td>
<td>(\tilde{\nu}, \tilde{e}_L)</td>
<td>((\nu, e_L))</td>
<td>((1, 2, -\frac{1}{2}))</td>
</tr>
<tr>
<td></td>
<td>(\tilde{e})</td>
<td>(\tilde{e}_R^*)</td>
<td>(e_R^\dagger)</td>
<td>((1, 1, 1))</td>
</tr>
<tr>
<td>Higgses, Higgsinos</td>
<td>(H_u)</td>
<td>((H_u^+, H_u^0))</td>
<td>((\tilde{H}_u^+, \tilde{H}_u^0))</td>
<td>((1, 2, \frac{1}{2}))</td>
</tr>
<tr>
<td></td>
<td>(H_d)</td>
<td>((H_d^0, H_d^-))</td>
<td>((\tilde{H}_d^0, \tilde{H}_d^-))</td>
<td>((1, 2, -\frac{1}{2}))</td>
</tr>
</tbody>
</table>

#### Gauge supermultiplets

<table>
<thead>
<tr>
<th>Name</th>
<th>spin 1/2</th>
<th>spin 1</th>
<th>((SU(3)_C, SU(2)_L, U(1)_Y))</th>
</tr>
</thead>
<tbody>
<tr>
<td>gluino, gluon</td>
<td>(\tilde{g})</td>
<td>(g)</td>
<td>((8, 1, 0))</td>
</tr>
<tr>
<td>winos, W bosons</td>
<td>(\tilde{W}^\pm, \tilde{W}^0)</td>
<td>(W^\pm, W^0)</td>
<td>((1, 3, 0))</td>
</tr>
<tr>
<td>bino, B boson</td>
<td>(\tilde{B}^0)</td>
<td>(B^0)</td>
<td>((1, 1, 0))</td>
</tr>
</tbody>
</table>
Physical motivations

Global fits

- In the unconstrained MSSM 105 new free parameters (masses, mixing angles and phases). Impossible/uninteresting to probe.
- Define a simplified model based on reasonable assumptions and a minor number of free parameters.
- Use of the available collider data, electro-weak precision observables and DM constraint to fit the best value and the likelihood profile of the model parameters.
- Effectively implement interplay between different searches (e.g. collider vs direct detection for DM).
The models

<table>
<thead>
<tr>
<th>GUT Models</th>
<th>pMSSM10</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CMSSM</strong></td>
<td>$M_1, M_2, M_3$</td>
</tr>
<tr>
<td>$m_0, m_{1/2}, A_0, \tan \beta$</td>
<td>$m_{\tilde{q}<em>1, 2}, m</em>{\tilde{q}<em>3}, m</em>{\tilde{t}}$</td>
</tr>
<tr>
<td><strong>NUHM1</strong></td>
<td>$A$</td>
</tr>
<tr>
<td>$m_0, m_{1/2}, A_0, \tan \beta, m_H$</td>
<td>$M_A, \tan \beta, \mu$</td>
</tr>
<tr>
<td><strong>NUHM2</strong></td>
<td></td>
</tr>
<tr>
<td>$m_0, m_{1/2}, A_0, \tan \beta, m_{H_u}, m_{H_d}$</td>
<td></td>
</tr>
</tbody>
</table>

- Based on unifications assumptions for the soft-SUSY breaking mass terms.
- Introduce correlation between the colored and uncolored sectors.
- Phenomenological model with 10 low-energy input parameters.
- We assume all left and right soft-SUSY mass breaking terms to be equal.
- We assume that the first two generations of squarks have the same soft-SUSY breaking term.
- All the trilinear coupling are the same.
The framework

▶ Frequentist fitting framework written in Python/Cython and C++.
▶ We use SLHA standard as an interface between the external codes that are used to compute the spectrum and the observables.
▶ The Multinest algorithm is used to sample the parameter space.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Number of segments</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_1 )</td>
<td>((-1, 1) \text{ TeV})\</td>
<td>2</td>
</tr>
<tr>
<td>( M_2 )</td>
<td>((0, 4) \text{ TeV})\</td>
<td>2</td>
</tr>
<tr>
<td>( M_3 )</td>
<td>((-4, 4) \text{ TeV})\</td>
<td>4</td>
</tr>
<tr>
<td>( m_{\tilde{q}} )</td>
<td>((0, 4) \text{ TeV})\</td>
<td>2</td>
</tr>
<tr>
<td>( m_{\tilde{q}_3} )</td>
<td>((0, 4) \text{ TeV})\</td>
<td>2</td>
</tr>
<tr>
<td>( m_{\tilde{\ell}} )</td>
<td>((0, 2) \text{ TeV})\</td>
<td>1</td>
</tr>
<tr>
<td>( M_A )</td>
<td>((0, 4) \text{ TeV})\</td>
<td>2</td>
</tr>
<tr>
<td>( A )</td>
<td>((-5, 5) \text{ TeV})\</td>
<td>1</td>
</tr>
<tr>
<td>( \mu )</td>
<td>((-5, 5) \text{ TeV})\</td>
<td>1</td>
</tr>
<tr>
<td>( \tan \beta )</td>
<td>((1, 60))</td>
<td>1</td>
</tr>
</tbody>
</table>

Total number of boxes: 128

Codes

**Spectrum generation**
- SoftSUSY

**Higgs sector and \((g-2)_\mu\)**
- FeynHiggs, Higgssignals, Higgsbounds

**B-Physics**
- SuFla, SuperIso

**EW precision observables**
- FeynWZ

**Dark matter**
- MicroOMEGAs, SSARD
The constraints

Indirect measurements

- $(g-2)_\mu$. $3.4\sigma$ discrepancy may be explained with $\mathcal{O}(100)$ GeV smuons.
- $M_W, M_Z, M_h$ and EWPO.
- Flavor observables ($B_s \to \mu\mu$, $b \to s\gamma$).

Dark matter

- Relic density and direct detection.

Collider – GUT models

- Limits are independent of $A_0, \tan \beta, m^2_{H_u}$ and $m^2_{H_d}$.
- Due to unification, limits on squarks and gluinos are relevant also for sleptons and electroweakinos.
The constraints – collider pMSSM10

Three classes of constraints

Colored sparticle production
We have combined the following CMS searches (8 TeV, 20 fb\(^{-1}\)):

- 0-lepton \(M_{T2}\)
- 1-lepton \(M_{T2}^W\)
- 2-lepton OS/SS
- \(\geq 3\) leptons.

Compressed stop region
This region is separately. The stop cross-section is set to zero in the other constraints.

Electroweakinos production

- Simplified ModelS (SMS) approach. Limited mass hierarchies.
- Slepton production.
- \(\tilde{\chi}^\pm_1 \tilde{\chi}^0_2\) via sleptons.
- \(\tilde{\chi}^\pm_1 \tilde{\chi}^0_2\) via WZ.
pMSSM10 best fit point

- Heavy Higgses, squarks, gluinos are relatively unconstrained.
- Left-handed fermion decay chains evolve via $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$.
- Sleptons are at less than 1 TeV.
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pMSSM10 mass spectrum

- Poor determination of the mass of colored sparticles (only lower bound from LHC searches).
- Larger freedom allow to fullfill the \((g - 2)\) constraint without being in tension with the LHC searches.
- Improved fit with respect to the GUT models.
The $(g-2)_\mu$ constraint

<table>
<thead>
<tr>
<th>Model</th>
<th>$\chi^2/n_{dof}$</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMSSM</td>
<td>32.8/24</td>
<td>11 %</td>
</tr>
<tr>
<td>NUHM1</td>
<td>31.1/23</td>
<td>12 %</td>
</tr>
<tr>
<td>NUHM2</td>
<td>30.3/22</td>
<td>11 %</td>
</tr>
<tr>
<td>pMSSM10</td>
<td>20.5/18</td>
<td>31 %</td>
</tr>
</tbody>
</table>

- 3.5σ discrepancy between the SM $(g-2)_\mu$ value and the measured one.
- In CMSSM, NUHM1 and NUHM2 there is a tension between the $(g-2)_\mu$ and LHC constraints from direct searches, due to the universality relations.
- In the pMSSM10 we are able to fit perfectly the $(g-2)_\mu$.
- Impact of LHC8 EWK constraint limited.
Higgs physics

- pMSSM10 likelihood is very similar to the experimental value smeared by the theoretical uncertainty as given by FeynHiggs.
- Lower value of tan β are disfavored at the 68% CL by LHC8\(_{EWK}\), \((g-2)_{\mu}\) and DM constraints
- The constraints interplay with the choice of a single soft SUSY-breaking mass-parameter for the sleptons.
Physical mass planes for the colored sparticles

- $m_{\tilde{g}}$ vs. $m_{\tilde{q}}$
- $m_{\tilde{g}}$ vs. $m_{\tilde{t}_1}$
- $m_{\tilde{g}}$ vs. $m_{\tilde{b}_1}$

Legend:
- $\ast$ pMSSM10 w LHC8: best fit, 1σ, 2σ
- $\ast$ pMSSM10 w/o LHC8: best fit, 1σ, 2σ
Perspectives for discovery at LHC run 2
Perspectives for discovery at $e^+e^-$ colliders
Conclusions

- We performed the first global likelihood analysis of the pMSSM using a frequentist approach including LHC8 constraints.
- Some model parameter, like the squark or the gluino mass, are poorly constrained by the fit.
- Others, like the $\tilde{\chi}_1^0$ and the slepton masses are effectively constrained, mainly defined by the $(g-2)_\mu$ and DM constraints.
- LHC14 searches have a good prospect of exploring the preferred regions of $m_{\tilde{q}}$ and $m_{\tilde{g}}$, as well as light $\tilde{t}_1$, $\tilde{e}$ and $\tilde{\mu}$.
- Production threshold for various particles in the preferred fit region accessible with a 500-1000 GeV collider.
Backup slides