SUSY fits with full LHC Run I data

Kees Jan de Vries
on behalf of the MasterCode Collaboration


arXiv:1312.5250 and to appear
Global fit of SUSY

- **Mastercode today**
  - **supergravity**: CMSSM, NUHM1, NUHM2\(^{\text{NEW}}\)
  - \(m_0, m_{1/2}, A_0, \tan \beta, (m_{H_u}^2, m_{H_d}^2)\)
  - **phenomenological**: pMSSM10\(^{\text{NEW}}\)
    - \(m_{\tilde{q}_{12}}, m_{\tilde{q}_3}, m_{\tilde{\tau}}, M_1, M_2, M_3, A, M_A, \tan \beta, \mu\)

**Parameters**

**Compatibility**

**Predictions**

**Experimental constraints**

**SUSY model**

\[
\chi^2 = \sum_i^{N_{\text{meas}}} \left( \frac{P_i - \mu_i}{\sigma_i} \right)
\]

03/07/2014

Kees Jan de Vries; Mastercode; ICHEP 2014
Experimental constraints

<table>
<thead>
<tr>
<th>Dark matter</th>
<th>Indirect searches</th>
<th>Direct searches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>$M_W$, $\Gamma_Z$, $A_{f_b}(b)$, ...</td>
<td>$\chi^2 = \sum_i^{N_{\text{meas}}} \left( \frac{P_i - C_i}{\sigma_i} \right)^2$</td>
</tr>
<tr>
<td>Direct Detection</td>
<td>$(g - 2)_\mu$</td>
<td>Lightest Higgs</td>
</tr>
<tr>
<td>Flavour observables</td>
<td>$B_s \to \mu\mu$, $b \to s\gamma$, ...</td>
<td>SUSY particles</td>
</tr>
</tbody>
</table>

03/07/2014
Kees Jan de Vries; Mastercode; ICHEP 2014
parameter planes
Interplay of constraints

CMSSM (4 parameters)

best fit point has $m_0 = 5600$

LHC

$\mu\mu$

Bs $\to$ mumu

TENSION

$M_h$

DM

stau LSP

1σ

2σ

best fit
Lifting degeneracy

\[ m_{H_u}^2 = m_{H_d}^2 \neq m_0^2 \]  

NUHM1  
(5 parameters)

\[ m_{1/2}^2 \]  

\[ m_0 \]
Lifting degeneracy further

$$m_{H_u}^2 \neq m_{H_d}^2 \neq m_0^2$$

NUHM2
(6 parameters)
preliminary
$(g-2)_\mu$
Resolving tension (g-2) and LHC

Can adding extra parameters resolve the tension between (g-2) and LHC constraints?

<table>
<thead>
<tr>
<th>Model</th>
<th>$\chi^2/n_{\text{dof}}$</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMSSM</td>
<td>35.1/23</td>
<td>5.1 %</td>
</tr>
<tr>
<td>NUHM1</td>
<td>32.7/22</td>
<td>6.6 %</td>
</tr>
</tbody>
</table>
NUHM2 can get \((g-2)\) right but only at the cost of other constraints.
Resolving tension \((g-2)\) and LHC

<table>
<thead>
<tr>
<th>Model</th>
<th>(\chi^2/n_{dof})</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMSSM</td>
<td>35.1/23</td>
<td>5.1 %</td>
</tr>
<tr>
<td>NUHM1</td>
<td>32.7/22</td>
<td>6.6 %</td>
</tr>
<tr>
<td>NUHM2</td>
<td>32.5/21</td>
<td>5.2 %</td>
</tr>
<tr>
<td>pMSSM10</td>
<td>21.1/17</td>
<td>22 %</td>
</tr>
</tbody>
</table>

pMSSM10 resolves the tension between \((g-2)\) and LHC constraints. This significantly improves the fit.
LHC: discovery potential
The **CMSSM**, **NUHM1** and **NUHM2** give very comparable mass ranges. For the squark mass, the two-modal structure is quite visible in the CMSSM, and less so in the other models.

We currently apply 7TeV searches in the pMSSM10. The searches at 8TeV are work in progress.
A lot of the parameter space, including the current best fit point, lies outside the reach of 8 TeV searches. \textbf{Early Discovery?}
Direct detection: spin-independent scattering cross section
direct detection: past-present-future

Red circle is meant to represent predictions from SUSY. Let’s see what our models say.

arXiv:1310.8327
Future searches would significantly probe the CMSSM
Some of the parameter of the NUHM1 space lies beyond the intrinsic background from atmospheric neutrinos.

arXiv:1310.8327
direct detection: NUHM2

All these GUT-models are indeed within the red blob. So what about the pMSSM10?

arXiv:1310.8327
The pMSSM10 shows that there is a significant complementary parameter space at low neutralino mass which was for a long time thought to be disfavoured.

pMSSM10 preliminary

The pMSSM10 shows that there is a significant complementary parameter space at low neutralino mass which was for a long time thought to be disfavoured.

arXiv:1310.8327
Zooming out of this picture reveals that there is a large region where direct detection experiments do not have sensitivity due to the coherent neutrino scattering. An opportunity for colliders?
Comparison of our models

- **CMSSM, NUHM1** and **NUHM2** show **tension** between the searches at the **LHC** and **(g-2)**
- **pMSSM10** seems to **resolve** this **tension** and provides a significantly **better fit**

Discovery potential at the LHC

- In the **pMSSM10** there is a huge parameter space “just around the corner” at low neutralino masses. **Early discovery?**

Direct detection experiments

- Future direct detection experiments will have access to a significant part of the parameter space of the **CMSSM, NUHM1** and **NUHM2**
- The **pMSSM10** reveals a complimentary region with a large fraction below the neutrino floor. **An opportunity for colliders?**

Outlook

- Finish implementation of **LHC** searches for coloured and electroweak sparticles at 8 TeV for **pMSSM10** and update our results
thank you for you attention!
backup
Mastercode: global fits of SUSY

- **Models**
  - *supergravity*: CMSSM, NUHM1, NUHM2 \(^{NEW}\)
  - *phenomenological*: pMSSM10 \(^{NEW}\)

- **Experimental constraints**
  - *cosmology*: Dark Matter density, direct detection
  - *indirect searches*: Flavour and Electroweak Precision observables
  - *direct searches*: Higgs, coloured sparticles, electroweakinos

- **Predictor codes**
  - *public*: SoftSUSY, FeynHiggs, Micromegas, SuperIso
  - *private*: SuFla, FeynWZ, SSARD

- **Sampling algorithm**
  - Multinest

The implementation of the experimental constraints follows arXiv:1312.5250. Some details can be found in the backup slides.
### Parameter Ranges

<table>
<thead>
<tr>
<th></th>
<th>CMSSM</th>
<th>NUHM1</th>
<th>NUHM2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_0$</td>
<td>(0, 6000) GeV</td>
<td>(0, 4000) GeV</td>
<td>(-1000, 4000) GeV</td>
</tr>
<tr>
<td>$m_{H^2}$</td>
<td>-</td>
<td>(-5x10^7, 5x10^7) GeV^2</td>
<td>-</td>
</tr>
<tr>
<td>$m_{H_u}^2$</td>
<td>-</td>
<td>-</td>
<td>(-5x10^7, 5x10^7) GeV^2</td>
</tr>
<tr>
<td>$m_{H_d}^2$</td>
<td>-</td>
<td>-</td>
<td>(-5x10^7, 5x10^7) GeV^2</td>
</tr>
<tr>
<td>$m_{1/2}$</td>
<td>(0, 4000) GeV</td>
<td>(0, 4000) GeV</td>
<td>(0, 4000) GeV</td>
</tr>
<tr>
<td>$A_0$</td>
<td>(-5000, 5000) GeV</td>
<td>(-5000, 5000) GeV</td>
<td>(-8000, 8000) GeV</td>
</tr>
<tr>
<td>$\tan\beta$</td>
<td>(2, 68)</td>
<td>(2, 68)</td>
<td>(2, 68)</td>
</tr>
<tr>
<td>$\text{sign}(\mu)$</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Note: these parameter ranges were chosen to examine relevant parameter space for the LHC. As we will see, the **1σ and 2σ contours do not always** close for this choice of ranges. This should be kept in mind when interpreting the results.
LHC limits on coloured production

challenge: establish level of exclusion for \( O(10^8) \) points

if one had infinite CPU time, one could run for each point in parameter space

- generate events
- detector simulation
- emulation of analyses
- calculate limit

but NOT computationally feasible (6 years on 1000 cores)

an alternative is to combine all SMS models but
1. not all relevant SMS limits are available (problem)
2. would need to evaluate for each point in parameter space (NOT computationally feasible)

In our approach we make use of the finding by OB and JM in 1304.2185 that if one combines sufficiently inclusive searches, then the exclusion is mainly driven by the masses of 1) neutralino; 2) gluino; 3) 1\textsuperscript{st} and 2\textsuperscript{nd} generation squark; 4) 3\textsuperscript{rd} generation squark
LHC limits on coloured production

How to do the hard work: Our Analysis Framework

SLHA file → PYTHIA v6 → DELPHES → Analysis → Limit Code → Results

Guarantees full coverage by definition of the generator i.e. no need to make SMS assumptions or depend on coverage of experiments

Note: we have implemented and validated the 7 TeV searches. The 8 TeV searches are work in progress.

We generate a 4-d grid using inclusive searches for:
- 0 leptons + MET
- 1 lepton + MET
- 2 leptons (OS & SS) + MET
- >=3 leptons + MET

We linearly interpolate MET based on this grid.

Preliminary

1000 points from pMSSM sample
\[ \chi^2 \text{ including } \Delta(\sigma^{SI}) \]
\[ \chi^2 \text{ and } \Delta(\sigma^{SI})/\sigma^{SI} \]
\[ \chi^2 \text{ excluding } \Delta(\sigma^{SI}) \]
\[ \chi^2 = 4.61 \text{ at 90\%CL} \]
A lot of the parameter space, including the current best fit point, lies outside the reach of 8 TeV searches. **Early Discovery?**