What if the LHC does not find Supersymmetry
(here: mSUGRA)
by the end of 2011/2012?

Philip Bechtle,
K. Desch, H. Dreiner, M. Krämer, B. O’Leary, C. Robens, B. Sarrazin, P. Wienemann

March 15th 2011
Rencontres de Moriond
1 Introduction and Methods

2 Fit Results

3 Model Independent Data from LHC, Model Dependent Fits
1 Introduction and Methods

2 Fit Results

3 Model Independent Data from LHC, Model Dependent Fits
An Incomplete Overview of the Current Situation

Does the non-observation of SUSY in the 2010 LHC searches agree with mSUGRA?
If mSUGRA-like SUSY is realized, can we expect to discover SUSY in 2011/2012?
If not, what are the implications for mSUGRA/SUSY and for Collider Physics?

e.g. arXiv:0907.2589 [hep-ph]


P. Bechtle: mSUGRA Fits with LHC Moriond EW 15.03.2011
Confronting LHC Searches with Precision Data


See e.g. also

Many activities converging in LPCC meetings (e.g. http://indico.cern.ch/categoryDisplay.py?categId=2689) and many interesting discussions in the Terascale Alliance http://www.terascale.de/research_topics/rt1_physics_analysis/susy__bsm_fit_working_group/
Confronting LHC Searches with Precision Data

- **Multi-Messenger**: Combine Information about SUSY from different sources
- For LHC: Do not only use the 95% CL as a brick wall, but calculate \( \Delta \chi^2 \)

Processes sensitive to SUSY

Combining \( \chi^2 \) of LE and LHC
Implementation of an LHC Limit Projection

\[
M_{\text{eff}} = \sum_i p_{T,i} + E_{T\text{miss}}
\]

- Using the open parametrized detector simulation tool DELPHES
  \texttt{arXiv:0903.2225 [hep-ph]}
- Careful tuning against public ATLAS full simulation
- Implement the 4jet+MET cuts from \texttt{atl-pub-phys-2010-010} and generate a grid in \((\Delta M_{1/2} = 25 \text{ GeV}, \Delta M_0 = 50 \text{ GeV})\)
- Use a bilinear interpolation to obtain the resulting \(M_{\text{eff}}\) spectrum
Systematic Check of the MSUGRA Parameter Grid

- Variations of the signal shape for different $\tan \beta$ and $A_0$ covered by systematic uncertainty
- This is specific for the $0\ell$ search – more complicated grids would be necessary for other searches
- Based on the full $M_{\text{eff}}$ distribution, calculate $CL_{s+b}$ for the median background hypothesis
- Transfer $CL_{s+b}$ into $\chi^2 = 2[\text{erf}^{-1}(1 - 2 CL_{s+b})]^2$
1 Introduction and Methods

2 Fit Results

3 Model Independent Data from LHC, Model Dependent Fits
# Pre-LHC knowledge about mSUGRA/CMSSM

## mSUGRA fit to LE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best fit value ± Unc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_t$</td>
<td>172.4 ± 1.2</td>
</tr>
<tr>
<td>$m_b$</td>
<td>4.2 ± 0.17</td>
</tr>
<tr>
<td>$m_Z$</td>
<td>91.1875 ± 0.0021</td>
</tr>
<tr>
<td>$\alpha_s$</td>
<td>0.1176 ± 0.0020</td>
</tr>
<tr>
<td>$G_F$</td>
<td>$1.16637 \times 10^{-5}$ ± 10^{-10}</td>
</tr>
<tr>
<td>$G_{em}$</td>
<td>127.925 ± 0.016</td>
</tr>
<tr>
<td>$m_{\chi}^0$</td>
<td>114.4</td>
</tr>
<tr>
<td>$\sigma_{oo}^0$</td>
<td>41.54 ± 0.04</td>
</tr>
<tr>
<td>$A_t$</td>
<td>0.1465 ± 0.0032</td>
</tr>
<tr>
<td>$A_e$</td>
<td>0.1513 ± 0.0021</td>
</tr>
<tr>
<td>$A_c$</td>
<td>0.67 ± 0.027</td>
</tr>
<tr>
<td>$A_b$</td>
<td>0.923 ± 0.02</td>
</tr>
<tr>
<td>$A_{tb}$</td>
<td>0.0707 ± 0.0035</td>
</tr>
<tr>
<td>$A_{ts}$</td>
<td>0.0992 ± 0.0016</td>
</tr>
<tr>
<td>$R_e$</td>
<td>0.1721 ± 0.003</td>
</tr>
<tr>
<td>$R_b$</td>
<td>0.21629 ± 0.00066</td>
</tr>
<tr>
<td>$R_l$</td>
<td>20.767 ± 0.025</td>
</tr>
<tr>
<td>$\Gamma_Z$</td>
<td>2495.2 ± 2.51</td>
</tr>
<tr>
<td>$\sin\theta_{eff}$</td>
<td>0.2324 ± 0.0012</td>
</tr>
<tr>
<td>$m_W$</td>
<td>80.399 ± 0.027</td>
</tr>
<tr>
<td>$\Omega_{DM}$</td>
<td>0.1099 ± 0.0013</td>
</tr>
<tr>
<td>$(g-2)_\mu$</td>
<td>3.02 $10^9$ ± 9.0 $10^{-10}$</td>
</tr>
<tr>
<td>$BR(b \to s\gamma)$</td>
<td>1.117 ± 0.122</td>
</tr>
<tr>
<td>$BR(b \to s\nu)$</td>
<td>1.15 ± 0.4</td>
</tr>
<tr>
<td>$BR(B_s \to X_{sll})$</td>
<td>0.99 ± 0.32</td>
</tr>
<tr>
<td>$BR(K \to \nu)$</td>
<td>1.008 ± 0.014</td>
</tr>
<tr>
<td>$\Delta m_e$</td>
<td>0.92 ± 0.14</td>
</tr>
<tr>
<td>$\Delta(m_{\chi}^0)$</td>
<td>1.11 ± 0.32</td>
</tr>
<tr>
<td>$\Delta m_t/\Delta m_{\chi}^0$</td>
<td>1.09 ± 0.16</td>
</tr>
</tbody>
</table>

## mSUGRA Fit to measured observables

- $\tan \beta$: $12.8 \pm 9.7$
- $M_{12}$: $332.8 \pm 88.6$
- $M_0$: $77.1^{+113.4}_{-30.6}$
- $A_0$: $426.2 \pm 734.1$
- $\text{sign}\mu$: +1
- $\chi^2/ndf$: 20.4/21
Projection: Low Energy Fit vs. Present and Future (?) LHC Exclusion

- Projection of how the LHC exclusion potential would evolve during the 7 TeV run compared to the LE data preferred region:
Combined Fit of real LE Data and Estimated Present ATLAS Exclusion

- Not surprisingly: Combined Fit allows a small area below LHC exclusion
Combined Fit of real LE Data and Estimated Present ATLAS Exclusion

- Not surprisingly: Combined Fit allows a small area below LHC exclusion

![Graph showing χ^2 vs. M_0 [GeV] for different data sets: no LHC, LHC 2fb^{-1}, total 2fb^{-1}. The graph highlights the area below the χ^2 = 2.05 line, indicating the exclusion region.]
Outlook for the Coloured Sector

- Not so strongly model dependent

Mass of $\tilde{q}_R$

<table>
<thead>
<tr>
<th>mass range [GeV]</th>
<th>no LHC</th>
<th>$35pb^{-1}$</th>
<th>$1fb^{-1}$</th>
<th>$2fb^{-1}$</th>
<th>$7fb^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$1\sigma$ Environment

$2\sigma$ Environment

Best Fit Value
Outlook for the Non-Coloured Sector

- Strongly model dependent

**Mass of \( \tilde{R} \)**

<table>
<thead>
<tr>
<th>Mass range [GeV]</th>
<th>1σ Environment</th>
<th>2σ Environment</th>
<th>Best Fit Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
- Strongly model dependent
- No LHC for mass range [GeV]
Is there a Tension Building Up?

- LE prefers low mass scales (for non-coloured sector),
- LHC prefers high mass scales (for coloured sector)

Using the present systematic uncertainties on the background estimation (and ignoring fine-tuning), even mSUGRA will survive the 2011/2012 run.

You may not find the model too attractive anymore, but that’s an entirely different question.
1 Introduction and Methods

2 Fit Results

3 Model Independent Data from LHC, Model Dependent Fits
Why SUSY is different than e.g. the Higgs-Sector

- Higgs Searches (at least at LEP) could be presented in terms of $S_{95}$ for each signature separately, because the signatures can be nicely isolated experimentally: $hZ \rightarrow b\bar{b}ll$, $hA \rightarrow b\bar{b}b\bar{b} \ldots$.

- Higgs: Only very few parameters: $m_h, m_A, \cos^2(\beta - \alpha)$, model-independent comparison with all possible models e.g. in PB et al. arXiv:0811.4169 [hep-ph]

- SUSY: incredibly complicated signatures possible, many masses and relations of couplings

\[ S_{95} \equiv \max(\cos^2(\beta - \alpha) \times B(H_i \rightarrow b\bar{b})) \]
Why SUSY is different than e.g. the Higgs-Sector

- Higgs Searches (at least at LEP) could be presented in terms of $S_{95}$ for each signature separately, because the signatures can be nicely isolated experimentally: $hZ \rightarrow b\bar{b}ll$, $hA \rightarrow b\bar{b}b\bar{b} \ldots$

- Higgs: Only very few parameters: $m_h, m_A, \cos^2(\beta - \alpha)$, model-independent comparison with all possible models e.g. in PB et al. arXiv:0811.4169 [hep-ph]

- SUSY: incredibly complicated signatures possible, many masses and relations of couplings
Why SUSY is different than e.g. the Higgs-Sector

- Higgs Searches (at least at LEP) could be presented in terms of $S_{95}$ for each signature separately, because the signatures can be nicely isolated experimentally: $hZ \rightarrow b\bar{b}ll$, $hA \rightarrow b\bar{b}b\bar{b} \ldots$

- Higgs: Only very few parameters: $m_h, m_A, \cos^2(\beta - \alpha)$, model-independent comparison with all possible models e.g. in PB et al. arXiv:0811.4169 [hep-ph]

- SUSY: incredibly complicated signatures possible, many masses and relations of couplings
Other Approaches to Parametrizations of Searches

- **Obvious**: For model independent results, everything has to be presented in terms of *(pseudo)observables* (e.g. $M_{\text{eff}}$, masses, couplings, . . .)
Other Approaches to Parametrizations of Searches

- **Obvious**: For model independent results, everything has to be presented in terms of *(pseudo)observables* (e.g. $M_{\text{eff}}$, masses, couplings, ...)

- 95% CL Limit on $\sigma \times \prod_i B_i$ for a given signature
  - 95% CL not very useful for global fits $\rightarrow$ need full CL$_{s+b}$ space
  - Very high dimensional binning would be needed (many masses)
  - Can any given signature be isolated experimentally? If yes (e.g. $\ell\ell$ edge), much less sensitive for discovery or exclusion

- 95% CL Limit on the number of events for a given selection
  - Simulation needed to determine number of events for any model prediction

- Distributions of $b, d$ in discriminating variables corrected for detector effects, acceptances
  - Sounds nice, but probably impossible: Correction depends on many factors (many masses, couplings)

- 95% CL Limit on “Simplified Model”: see CL above, + not *(yet?)* proven that for each model point in a global fit there is a matching simplified model.
Conclusion Based on Our Experience

- As obviously already done here and in many other approaches, and in the first papers by ATLAS and CMS: Publish distributions of $b$, $d$ in any discriminating variable/regions **not** corrected for any detector effects or acceptances.
- Determine $s$ from a simulation for **every model** in an appropriate way.
- Use very fast rate calculations (e.g. Dreiner et al. arXiv:1003.2648) to check parameter space for the necessary grid dimensions and spacing.
Conclusion Based on Our Experience

- As obviously already done here and in many other approaches, and in the first papers by ATLAS and CMS: Publish distributions of $b, d$ in any discriminating variable/regions not corrected for any detector effects or acceptances.
- Determine $s$ from a simulation for every model in an appropriate way.
- Use very fast rate calculations (e.g. Dreiner et al. arXiv:1003.2648) to check parameter space for the necessary grid dimensions and spacing.
- Significant challenges:
  - Probably cannot produce MC for every point tested in the fit – parametrization in N-dimensional grid.
  - Need reliable simulation within $\mathcal{O}(\text{syst})$.
Conclusion Based on Our Experience

As obviously already done here and in many other approaches, and in the first papers by ATLAS and CMS: Publish distributions of $b, d$ in any discriminating variable/regions not corrected for any detector effects or acceptances.

Determine $s$ from a simulation for every model in an appropriate way.

Use very fast rate calculations (e.g. Dreiner et al. arXiv:1003.2648) to check parameter space for the necessary grid dimensions and spacing.

Significant challenges:

- Probably cannot produce MC for every point tested in the fit – parametrization in N-dimensional grid.
- Need reliable simulation within $\mathcal{O}(\text{syst})$.
- Very personal addition: The Power of Open Source
  ATLAS and CMS could release officially endorsed, public, fast simulation tools.
Conclusion and Outlook

- It is possible to reconcile the LE measurements (dominated by \((g - 2)_\mu\) and \(\Omega_{DM}\)) with a possible non-discovery of mSUGRA at the LHC in 2011/2012.

- As expected, LHC generally moves the lower bounds on sparticles to higher values (directly true only for coloured ones).

- As expected, but less obvious: As long as global fit \(\chi^2/ndf\) remain acceptable: LHC moves up the upper bound on sparticles very significantly.

- For other SUSY than mSUGRA, the coloured and non-coloured sector can be more decoupled, no definite statements on non-coloured sector yet.

- Outlook:
  - Use real search results as input
  - Study more, and more general, models
Conclusion and Outlook

- It is possible to reconcile the LE measurements (dominated by \((g - 2)\mu\) and \(\Omega_{\text{DM}}\)) with a possible non-discovery of mSUGRA at the LHC in 2011/2012.

- As expected, LHC generally moves the lower bounds on sparticles to higher values (directly true only for coloured ones).

- As expected, but less obvious:
  - As long as global fit \(\chi^2/ndf\) remain acceptable: LHC moves up the upper bound on sparticles very significantly.

- For other SUSY than mSUGRA, the coloured and non-coloured sector can be more decoupled, no definite statements on non-coloured sector yet.

- **Outlook:**
  - Use real search results as input
  - Study more, and more general, models
  - Find and Identify New Physics
Backup Slides
Agreement of our Implementation with the Actual ATLAS Analysis with Data
Full Results for no LHC

Mass Spectrum of SUSY Particles no LHC

- 1σ Environment
- 2σ Environment
- Best Fit Value

Particle Mass [GeV]

h^0 A^0 H^0 \chi_1^0 \chi_2^0 \chi_3^0 \chi_4^0 \chi_1^+ \chi_2^+ \tilde{\tau}_1 \tilde{\tau}_2 \tilde{q}_R \tilde{q}_L \tilde{b}_1 \tilde{b}_2 \tilde{t}_1 \tilde{t}_2 \tilde{g}
Full Results for $35\, \text{pb}^{-1}$ ATLAS Search

- Model Independent Data from LHC, Model Dependent Fits
- Full Results for $35\, \text{pb}^{-1}$ ATLAS Search

- Particle Mass [GeV]
  - $0$ to $4000$
- Mass Spectrum of SUSY Particles $35\, \text{pb}^{-1}$
- 1σ Environment
- 2σ Environment
- Best Fit Value

- Environment
- Best Fit Value

- Particle Mass [GeV]
  - $0$ to $3500$
- Mass Spectrum of SUSY Particles $35\, \text{pb}^{-1}$
- 1σ Environment
- 2σ Environment
- Best Fit Value

- Environment
- Best Fit Value

- Particle Mass [GeV]
  - $0$ to $3500$
- Mass Spectrum of SUSY Particles $35\, \text{pb}^{-1}$
- 1σ Environment
- 2σ Environment
- Best Fit Value

- Environment
- Best Fit Value
Full Extrapolated Results for $1 \text{ fb}^{-1}$ ATLAS Search

Introduction and Methods

Fit Results

Model Independent Data from LHC, Model Dependent Fits

Particle Mass [GeV]

0 500 1000 1500 2000 2500 3000 3500 4000

Mass Spectrum of SUSY Particles 1fb$^{-1}$

P. Bechtle: mSUGRA Fits with LHC  Moriond EW 15.03.2011
Full Extrapolated Results for $2\,\text{fb}^{-1}$ ATLAS Search
Full Extrapolated Results for $7 \text{ fb}^{-1}$ ATLAS Search

![Image of mass spectrum and parameter space plots for SUSY particles]

- Model Independent Data from LHC, Model Dependent Fits
- Fit Results
- Full Extrapolated Results for $7 \text{ fb}^{-1}$ ATLAS Search

P. Bechtle: mSUGRA Fits with LHC

Moriond EW 15.03.2011
Why does $\tan \beta$ move to higher values for growing LHC exclusions?
Why does $\tan \beta$ move to higher values for growing LHC exclusions?
Why does $\tan \beta$ move to higher values for growing LHC exclusions?
Why does $\tan \beta$ move to higher values for growing LHC exclusions?
Why does $\tan \beta$ move to higher values for growing LHC exclusions?
Why are global fits of SUSY so CPU-consuming?

... and impossible with naively employing Minuit?

Looking at any correlations for all other allowed parameters:

Looks OK
Why are global fits of SUSY so CPU-consuming?

... and impossible with naively employing Minuit?

Looking at any correlations for fixed other parameters:

Looks Terrible
Why are global fits of SUSY so CPU-consuming?

... and impossible with naively employing Minuit?

Looking at any correlations for regions of other parameters:

Correlations growing for higher mass parameters
**Search Cuts**

<table>
<thead>
<tr>
<th>Number of jets</th>
<th>( \geq 2 ) jets</th>
<th>( \geq 3 ) jets</th>
<th>( \geq 4 ) jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading jet ( P_T ) (GeV)</td>
<td>( &gt; 180 )</td>
<td>( &gt; 100 )</td>
<td>( &gt; 100 )</td>
</tr>
<tr>
<td>Other jets ( P_T ) (GeV)</td>
<td>( &gt; 50 ) (Jet 2)</td>
<td>( &gt; 40 ) (Jet 2-3)</td>
<td>( &gt; 40 ) (Jet 2-4)</td>
</tr>
<tr>
<td>( \Delta \phi(\text{jet}_i,E_T^{miss}) )</td>
<td>([ &gt; 0.2, &gt; 0.2] )</td>
<td>([ &gt; 0.2, &gt; 0.2, &gt; 0.2] )</td>
<td>([ &gt; 0.2, &gt; 0.2, &gt; 0.2, &gt; 0.0] )</td>
</tr>
<tr>
<td>( E_T^{miss} &gt; f \times M_{\text{eff}} )</td>
<td>( f = 0.3 )</td>
<td>( f = 0.25 )</td>
<td>( f = 0.2 )</td>
</tr>
</tbody>
</table>

Table 1: Cuts on the \( P_T \) of the leading jet, the \( P_T \) of the other jets, the azimuthal angle between the leading jets and the missing transverse energy vector and the cut on the missing transverse energy expressed as a fraction of the effective mass. The cuts are shown for each of the studied jet multiplicities.

In the following we describe the event selection criteria for the 0, 1 and 2 lepton channels.

**Zero-lepton channels** In addition to the electron crack veto, the pre-selection cuts are:

1. Reject events with at least one lepton having \( P_T > 20 \) GeV.
2. Cut on the number of jets and jet transverse momenta as defined in Table 1.
3. Missing transverse energy \( E_T^{miss} > 80 \) GeV.
4. Cut on ratio \( f \) between \( E_T^{miss} \) and \( M_{\text{eff}} \) as defined in Table 1.
5. Cut on \( \Delta \phi(\text{jet}_i,E_T^{miss}) \) as defined in Table 1.
6. Transverse sphericity, \( S_T > 0.2 \).
Calculating the $\chi^2$ from LHC

\[ Q = \prod_{i=1}^{N_{\text{bins}}} \frac{\mathcal{L}(\mu_i = s_i + b_i; n_i)}{\mathcal{L}(\mu_i = b_i; n_i)}. \]  

\[ \text{CL}_{s+b} = \int_{t_{\text{obs}}}^{\infty} P_{s+b}(t) \, dt < 0.05. \]  

\[ \chi^2 = 2[\text{erf}^{-1}(1 - 2 \text{CL}_{s+b})]^2. \]