How alive is constrained SUSY really?

Philip Bechtle, Klaus Desch, Herbert K. Dreiner, Matthias Hamer, Michel Krämer, Ben O’Leary, Werner Porod, Björn Sarrazin, Tim Stefaniak, Mathias Uhlenbrock, Peter Wienemann

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I. How the CMSSM came into such troubles

II. *The one thing* which at least still has to be done
Probing the CMSSM
Fittino

• Using the C++ program Fittino we combine a wide range of measurements sensitive to supersymmetry:

  • indirect constraints from low energy measurements
  • Higgs boson properties
  • direct searches for sparticles and BSM Higgs bosons
  • astrophysical observations

• Fittino uses

  • public codes to calculate model predictions
  • a $\chi^2$ function to compare measurements and predictions
  • an auto-adaptive Markov Chain to sample the parameter space
  • frequentist interpretation
some tension building up between low energy observables and LHC

increasing tension
direct and indirect astrophysical detection experiments
not yet sensitive to 2 sigma region
SM like Higgs well described by CMSSM

\( \chi^2/\text{ndf} \) decreases when the numerous Higgs measurements are taken into account.
## Updated measurements

### Low energy observables

<table>
<thead>
<tr>
<th>Observable</th>
<th>Measurement</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{BR}(B_s \rightarrow \mu^+\mu^-)$</td>
<td>$(2.90 \pm 0.70 \pm 0.76_{\text{theo}}) \times 10^{-9}$</td>
<td>CMS + LHCb ‘13</td>
</tr>
<tr>
<td>$\text{BR}(B^+\rightarrow\tau^+\nu)$</td>
<td>$(1.05 \pm 0.25 \pm 0.21) \times 10^{-4}$</td>
<td>PDG ‘13</td>
</tr>
<tr>
<td>$\text{BR}(b\rightarrow s \gamma)$</td>
<td>$(3.43 \pm 0.21 \pm 0.07 \pm 0.48_{\text{theo}}) \times 10^{-4}$</td>
<td>HFAG</td>
</tr>
<tr>
<td>$\Delta m_s$</td>
<td>$(17.719 \pm 0.036 \pm 0.023 \pm 4.200_{\text{theo}}) \text{ ps}^{-1}$</td>
<td>PDG ‘13</td>
</tr>
<tr>
<td>$a_\mu - a_\mu^{\text{SM}}$</td>
<td>$(28.7 \pm 8.0 \pm 2.0_{\text{theo}}) \times 10^{-10}$</td>
<td>Muon g-2, Davier et al</td>
</tr>
<tr>
<td>$m_t$</td>
<td>$(173.34 \pm 0.27 \pm 0.71) \text{ GeV}$</td>
<td>world average ‘14</td>
</tr>
<tr>
<td>$m_W$</td>
<td>$(80.385 \pm 0.015 \pm 0.010_{\text{theo}}) \text{ GeV}$</td>
<td>CDF + D0 ‘12</td>
</tr>
<tr>
<td>$\sin^2 \theta_{\text{eff}}$</td>
<td>$0.2311 \pm 0.00021 \pm 0.00012_{\text{theo}}$</td>
<td>LEP + SLD ‘06</td>
</tr>
</tbody>
</table>
Higgs boson properties and searches

• Higgs limits via HiggsBounds
• Higgs signals via HiggsSignals

Direct sparticle searches

• LEP chargino mass limit
• ATLAS MET + jets + 0 lepton search (20fb⁻¹)

Astrophysical observables

• We require $\chi^0_1$ to be the LSP
• $\Omega_{CDM}h^2 = 0.1187 \pm 0.0017 \pm 0.0119^{\text{theo}}$ (Planck ’13)
• Direct detection limit from LUX
Model Predictions

To evaluate the corresponding model predictions we use:

- **SPheno** for spectrum calculation
- **FeynHiggs** for Higgs properties, $a_\mu - a_\mu^{SM}$, $\sin^2 \theta_{\text{eff}}$, $m_W$
- **SuperIso** for $\text{BR}(B_s \rightarrow \mu^+\mu^-), \text{BR}(B^{\pm} \rightarrow \tau^{\pm}\nu), \text{BR}(b \rightarrow s\gamma)$
- **Prospino, Herwig++, Delphes** for direct sparticle searches
- **micrOMEGAs** for dark matter relic density
- **DarkSUSY** via AstroFit for direct detection cross section
Impact of new Higgs mass calculation

- Of course there are also improvements on the theory side

- The new Higgs mass calculation contained in FeynHiggs 2.10.0 makes it significantly easier to reach high Higgs masses

FeynHiggs 2.9.5

FeynHiggs 2.10.0
Preferred parameter region

- $\chi^2/\text{ndf} = 26.5/15$
- High mass region allowed at 1D 1sigma due to new Higgs mass calculation
• squark and gluino masses at best fit point about 2 TeV
• But now also masses of 10 TeV allowed at 1 sigma
Summary of part I

• In the CMSSM there is some tension between low energy observables and exclusions from LHC

• The CMSSM is in agreement with astrophysical measurements but on the other hand no convincing direct or indirect detection hints are found

• A SM like Higgs is well described by the CMSSM with large particle masses but no BSM Higgs sector is found

What do we do with the CMSSM now?

There’s at least one more thing to do!
How well does the CMSSM describe the data quantitatively?

**P-Value**

If the best fit point is realised in nature doing a global fit to the measurement how probable is it to get a minimal chi2 at least as bad as the one observed?
Difficulties

• If our $\chi^2$ - function would be $\chi^2$ - distributed we could just look up the integral

$$\int_{\chi^2_{\text{min}}}^{\infty} P_{\chi^2_{\text{ndf}}} (x) \, dx$$

• Unfortunately this is not necessarily true because of:
  • Non - linear dependence of observables on parameters
  • Non - gaussian uncertainties

• Similarly $\chi^2/\text{ndf}$ isn’t the appropriate goodness-of-fit measure
How well does the CMSSM describe the data quantitatively?

P-Value

If the best fit point is realised in nature

doing a global fit to the measurement

how probable is it to get a minimal chi2 at least as bad as the one observed?

Toy fits

Smearing observables around the best fit prediction

and fitting the model to each of these toy measurements

how often do you get

• Very common in HEP
• Hasn’t been done in global SUSY fits (extremely CPU intensive)
We repeat the fit described above 1600 times with smeared observables and get these predicted observable values at the best fit points.
Corresponding parameter values at the best fit points
World’s first very preliminary! p-value for the CMSSM

χ²/ndf overestimates goodness of fit.
Dependence on the input and its parametrization?

\textbf{p-Value describes agreement with given selected data}

e. g. we selected these Higgs rate measurements, adding 6 ndf

![Graph showing ATLAS and CMS Higgs rate measurements with 95% C.L. bands and mu hat values.](graph.png)
Dependence on the input and its parametrization?

p-Value describes agreement with given selected data

But what if we would have selected these 80 instead?
Outlook

• Study possible dependence of p-value on (Higgs-) observable parametrisation

• The CMSSM is not SUSY:
  Relieve tension by decoupling
  • Higgs sector
  • strong sector
  • electroweak sector

• Apply toy fits to other models which are more alive
Backup
$\chi^2$ contributions

At each parameter point $\tilde{P}$ calculate:

$$\chi^2 = \left( \tilde{O}_{\text{meas}} - \tilde{O}_{\text{pred}}(\tilde{P}) \right)^T \text{cov}^{-1} \left( \tilde{O}_{\text{meas}} - \tilde{O}_{\text{pred}}(\tilde{P}) \right) + \chi^2_{\text{limits}}$$