LHC and Dark Matter phenomenology of the Supersymmetric Non Universal Gaugino and Higgs Masses

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Work in collaboration with G. Bertone, A. Casas and R. Ruiz de Austri
LHC is working with impressive performance.

The discovery of a SM-like Higgs boson.

No hint of new physics Beyond SM.

Reasonable hope to find new physics in the next run of LHC.

The “hierarchy problem”

A paradigmatic scenario of new physics: Supersymmetry.

A candidate for Dark Matter → WIMPS
Introduction

- $m_h = 125\text{GeV}$ generically requires large SUSY masses

- However, there are still regions with light SUSY. Strictly speaking $m_h \sim 125\text{GeV}$ only constraints stop masses.

- It is difficult to put a robust constraint on a general Minimal Supersymmetric Standard Model (MSSM)

- Simplified versions: CMSSM, NUHM (Oversimplified?)

- Simplified Models: small number of masses and couplings.
  → Efficient exploration of a complex model
  → Enormous proliferation of simplified model

- Identifying the most representative Simplified Models
Outlook

1. The Model

2. The analysis

3. Results
   - The phenomenology of the model
   - Potentially accessible regions

4. Conclusions
The Model

Extending to the simplest scenario CMSSM, two directions:

(a) Degeneracy of sfermions

(b) Degeneracy of gauginos

Flavor and CP-violation process “requires” universality of sfermions of the same type and of the two first generation.

Non Universal Gaugino and Higgs masses

\[ \{M_1, M_2, M_3, A_0, m_H, m_0, B, \mu\} \]

\(M_1, M_2, M_3\) are the gaugino masses, \(A_0\) and \(m_0\) are the trilinear and scalar coupling, \(m_H\) and \(B\) are the universal mass and the bilinear soft-term for the higgs doublets, and \(\mu\): Higgs mass term in the superpotential.
Bayesian Statistics

The posterior probability density function (pdf), \( p(p_i^0 | \text{data}) \), is given by

\[
p(\theta_i^0 | \text{data}) = \frac{p(\text{data} | \theta_i^0) p(\theta_i^0)}{p(\text{data})}
\]

where

\[ p(\text{data} | \theta_i^0) \] is the likelihood,

\[ p(\theta_i^0) \] is the prior,

\[ p(\text{data}) \] is the evidence.
The Bayesian approach and the fine-tuning measure

From the minimization of the tree-level form of the scalar potential

\[ M_Z^2 = 2 \frac{m_{H_1}^2 - m_{H_2}^2 \tan^2 \beta}{\tan^2 \beta - 1} - 2 \mu_{low}^2. \]

Barbieri-Giudice fine-tuning parameters

\[ c_i = \left| \frac{\partial \ln M_Z^2}{\partial \ln p_i} \right|, \]

The global measure of the fine-tuning is taken as \( c \equiv \max \{c_i\} \) or \( c \equiv \sqrt{\sum c_i^2} \).
The Bayesian approach and the fine-tuning measure

Separate $M_Z$ from the rest of experimental data,

$$p(\text{data}|s, m, M, A, B, \mu) = N_Z \ e^{-\frac{1}{2} \chi^2_Z} \ L_{\text{rest}} ,$$

Use $M_Z$ to marginalize $\mu$

$$p(s, m, M, A, B| \text{data}) = \int d\mu \ p(s, m, M, A, B, \mu|\text{data})$$

$$= N_Z \ \int dM_Z \ \left[ \frac{d\mu}{dM_Z} \right] e^{-\chi^2_Z} \ L_{\text{rest}} \ p(s, m, M, A, B, \mu)$$

then,

$$p(s, m, M, A, B| \text{data}) = 2 \ \frac{\mu_0}{M_Z} \ \frac{1}{c_\mu} \ L_{\text{rest}} \ p(s, m, M, A, B, \mu_0)$$
Priors

The typical order of magnitude of the soft terms \((M_S)\) can be anything below \(M_x\) with equal probability.

**Standard Log Prior (S-log)**

Independent logarithmic prior for each parameter

\[
p(\theta_i) \propto \frac{1}{|M_1 M_2 M_3 A_0 m_0 m_H B \mu|}
\]

**Improved Log Prior (I-log)**

Flat prior for the soft parameters up to order \(M_S\) and a logarithmic prior on \(M_S\)

\[
p(\theta_i) \propto \frac{1}{\max\{|M_1|, |M_2|, |M_3|, |A_0|, m_0, m_H, |B|, |\mu|\}^8}
\]
# The data

<table>
<thead>
<tr>
<th>Observable</th>
<th>Mean value</th>
<th>Uncertainties</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EW precision</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_W$ [GeV]</td>
<td>80.399</td>
<td>0.023</td>
<td>0.015</td>
</tr>
<tr>
<td>$\sin^2 \theta_{\text{eff}}$</td>
<td>0.23153</td>
<td>0.00016</td>
<td>0.00015</td>
</tr>
<tr>
<td><strong>B-physics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$BR(\overline{B} \rightarrow X_s \gamma) \times 10^4$</td>
<td>3.55</td>
<td>0.26</td>
<td>0.30</td>
</tr>
<tr>
<td>$BR(\overline{B}_s \rightarrow \mu^+ \mu^-)$</td>
<td>$3.2 \times 10^{-9}$</td>
<td>$1.5 \times 10^{-9}$</td>
<td>10%</td>
</tr>
<tr>
<td><strong>LHC</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_h$ [GeV]</td>
<td>125.66</td>
<td>0.41</td>
<td>2.0</td>
</tr>
<tr>
<td>Sparticle masses</td>
<td></td>
<td>LEP Lower limits</td>
<td></td>
</tr>
<tr>
<td><strong>Cold Dark Matter</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Omega \chi h^2$</td>
<td>0.1196</td>
<td>0.0031</td>
<td>0.012</td>
</tr>
<tr>
<td>$m_\chi - \sigma_{\chi N}^{\text{SI}}$</td>
<td>XENON100 2012 limits</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**SuperBayeS** (SoftSusy, FeynHiggs, SuperIso, SusyBSG, MicrOMEGAs, DarkSusy)
Single Component Cold Dark Matter

Two regions are selected:

- **Higgsino-like** $\chi_1^0$ with mass of $\sim 1$ TeV,
- **Wino-like** $\chi_1^0$ with mass of $\sim 2.4$ TeV.
Single component Dark Matter

**XENON1T** will probe a substantial fraction of the viable parameter space: 71.6% (77.4%) of the total probability for I-log (S-log) priors.
Single-component CDM

Zooming at low values of $M_1$ : Higgs-funnel

→ Higgs-funnel require the LSP to be mostly bino.

In the CMSSM it imply far too-light gluinos, excluded by LHC.

→ Very small statistical weight.
Single component CDM

**Higgs-funnel**

\[
s( p p \rightarrow \chi \chi \rightarrow A_i A_j E_T^{\text{miss}} ) \ (pb)
\]

**LHC:** the most relevant production is \( W Z \) and \( W^+ W^- \). Present bounds on tri-lepton + missing energy

**DM searches:** a more complete way of testing this scenario.

LO cross sections at \( \sqrt{14} \) TeV computed with [Prospino], BR's with [SUSY-HIT]
Assuming $\chi_1$ is a fraction of the total amount of Dark Matter

→ Higgsino-like and wino-like $\chi_1$
→ No sharply selected masses
→ Xenon100 bounds are weaker.
→ Prior dependency (volume effects).
→ Light charginos but "invisible".
“Low Energy” Supersymmetry

A zoom into the phenomenology interested region for LHC.

At least one of the conditions must be satisfied.

\[
\begin{align*}
    m_{\tilde{q}} & \leq 3 \text{ TeV} \\
    m_{\tilde{g}} & \leq 3 \text{ TeV} \\
    m_{\tilde{t}_1} & \leq 1 \text{ TeV} \\
    m_{\chi^\pm_2} & \leq 800 \text{ GeV}
\end{align*}
\]

In addition we only require that the LSP abundance is equal or less than the observed DM abundance.
“Low Energy” Supersymmetry

Assuming $\chi_1$ is a fraction of the total amount of Dark Matter

**S-log priors**

→ Mainly light electrowikinos

→ Mainly wino-like $\chi_0^1$ and higgsino-like $\chi_0^2$

**I-Log priors**

→ Is able to explore regions with light color particles and/or electroweakinos.
Direct production of $\chi_{1,2}^\pm \chi_{1}^\mp$ with large cross section but "invisible" final state.

The main production processes:

$$ p p \rightarrow \chi_{2}^\pm \chi_{2}^\mp $$

$$ p p \rightarrow \chi_{2,3}^\pm \chi_{2}^\mp $$

Dominant BR's to gauge bosons.

The most promising final state $WZ$, $W^+ W^-$, $W^\pm W^\pm$
Supersymmetric signal at LHC: Colored particles

→ Squark-squark and squark-gluino are the dominant production cross section

→ If $\chi_1$ is higgsino-like, first and second generation of squarks will decay mainly to $\chi_2^\pm$, $\chi_3^0$,

→ Complementarity between electroweakinos and colored particle searches.
“Low Energy” Supersymmetry

Dark Matter detection

Complementarity between LHC and Dark Matter searches.

Future direct detection experiments will access regions that are very difficult to test at LHC.
Conclusions

- The production of electroweakinos may be one of the best motivated avenues to detect SUSY.

- NUGHM captures the rich phenomenology associated to electroweakinos in the general MSSM.

- If one requires that the neutralino makes all the DM in the Universe, two preferred regions: $m_{\chi_1} \simeq 1$ TeV, 2.4 TeV for (almost) pure higgsino and wino cases. A large region will be tested by Xenon1T.

- Requiring that the neutralino abundance is equal or less than the observed one, the masses of the lightest $\chi^0_1, \chi^\pm_1$ become typicaly between 100 and 1 TeV. The most typical signal is the production of heavy charginos and neutralinos which decay to $W Z$ of $W^\pm W^\pm$ and “traditional” signatures form gluino and squark.

- Complementarity between LHC and DM searches will play a crucial role.
Comparison with previous literature: The CMSSM

Balazs et al [1205.1568], Fowlie et al. [1206.0264], Akula et al. [1207.1839], Buchmueller et al. [1207.7315], Strege et al [1212.2636]

The contours enclose the 68% (yellow), 95% (blue) and 99.9% (black) of integrated probability.