Sometimes I drive recklessly, just to kill off close copies of me in the multiverse.
SUSY Dark Matter at the LHC

Sven Heinemeyer, IFCA (CSIC, Santander)

Heidelberg, 06/2015

1. Introduction

2. Preparations

3. Results in GUT based models

4. Results in the pMSSM10

5. Conclusions
1. Introduction

Some “recent” measurements:

- top quark mass
- Higgs boson mass
- Higgs boson “couplings”
- Dark Matter (properties)
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⇒ good motivation to look at SUSY!
The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

Problem in the MSSM: more than 100 free parameters

Nobody(?) believes that a model describing nature has so many free parameters!

Sven Heinemeyer, WIN (Heidelberg), 09.06.2015
A. Unconstrained models (MSSM):
agnostic about how SUSY breaking is achieved
no particular SUSY breaking mechanism assumed, parameterization of possible soft SUSY-breaking terms
most general case:
⇒ 105 new parameters: masses, mixing angles, phases
⇒ no model missed (within the MSSM)
⇒ $\mathcal{O}(100)$ parameters difficult to handle

B. Constrained models (CMSSM, NUHM1, NUHM2, ...):
assumption on the scenario that achieves spontaneous SUSY breaking
⇒ prediction for soft SUSY-breaking terms
  in terms of small set of parameters
− CMSSM: $m_0$, $m_{1/2}$, $A_0$, $\tan \beta$
− NUHM1: $m_0$, $m_{1/2}$, $A_0$, $\tan \beta$, $m_H$
− NUHM2: $m_0$, $m_{1/2}$, $A_0$, $\tan \beta$, $m_{Hu}$, $m_{Hd}$
⇒ easy to handle  ⇒ “likely”: correct model missed??
Problem: We cannot be sure about the SUSY-breaking mechanism

⇒ it is possible that with the CMSSM, NUHM1, NUHM2, ... we missed the "correct" mechanism

⇒ hint: strong connection between colored and uncolored sector
tension between low-energy EW effects and (colored) LHC searches
Problem: We cannot be sure about the SUSY-breaking mechanism

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tension between low-energy EW effects and (colored) LHC searches

Solution: investigate also the “general MSSM”

⇒ 10 parameters are manageable ⇒ pMSSM10

- squark mass parameters: $m_{\tilde{q}_{1,2}} =: m_{\tilde{q}}, m_{\tilde{q}_3}$
- slepton mass parameter: $m_{\tilde{l}}$
- gaugino masses: $M_1, M_2, M_3$
- trilinear coupling: $A$
- Higgs sector parameters: $M_A, \tan \beta$
- Higgs mixing parameter: $\mu$
pMSSM10 scanned parameter ranges:

<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) TeV</td>
<td>2</td>
</tr>
<tr>
<td>$M_2$</td>
<td>(0, 4) TeV</td>
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</tr>
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<td>$M_3$</td>
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<td>$\mu$</td>
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<tr>
<td>$\tan \beta$</td>
<td>(1, 60)</td>
<td>1</td>
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</tbody>
</table>

Total number of boxes: 128
2. Preparations  Our tool: Mastercode

⇒ collaborative effort of theorists and experimentalists
[Bagnaschi, Buchmüller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flächer, SH, Isidori, Mallik, Marouche, Martinez Santos, Olive, Sakurai, de Vries, Weiglein]

Über-code for the combination of different tools:

– Über-code original in Fortran, now re-written in C++
– tools are included as subroutines
– compatibility ensured by collaboration of authors of “MasterCode” and authors of “sub tools” /SLHA(2)
– sub-codes in Fortran or C++

⇒ evaluate observables of one parameter point consistently with various tools

cern.ch/mastercode
Status of the “MasterCode”:

− (so far) one model: *(MFV) MSSM*

− tools included:
  
  − our own *LHC SUSY search* implementation ⇒ NEW
    
    (3 search categories: colored, electroweak, compressed stop)
  
  − Higgs related observables, \((g - 2)_\mu\) *[FeynHiggs]*
  
  − Higgs signal strengths *[HiggsSignals]* ⇒ NEW
  
  − Higgs exclusion bounds *[HiggsBounds]* ⇒ NEW
  
  − *B*-physics observables *[SuFla]*
  
  − more *B*-physics observables *[SuperIso]*
  
  − Electroweak precision observables *[FeynWZ]*
  
  − Dark Matter observables *[MicrOMEGAs, SSARD]*
  
  − for GUT scale models: RGE running *[SoftSusy]*

⇒ all most-up-to-date codes on the market!
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  − Dark Matter observables [MicrOMEGAs, SSARD]
  − for GUT scale models: RGE running [SoftSusy]

⇒ all most-up-to-date codes on the market! ⇒ crucial for precision!
The $\chi^2$ evaluation:
3. Results in GUT based models

- evolution of results in the CMSSM, NUHM1

- results for the DM mass predictions in the CMSSM, NUHM1

- results in the $m_{\tilde{\chi}_1^0}$-$\sigma_p^{\text{SI}}$ plane for the CMSSM, NUHM1, NUHM2

- analysis of DM anihilation processes

- ...
$m_0$-$m_{1/2}$ plane including LHC 20/fb:

**CMSSM**

- dotted: LHC 5/fb 7 TeV
- solid: LHC 20/fb 8 TeV

⇒ shift to even higher masses
  even larger allowed ranges . . .
LSP mass incl. 20/fb of LHC data

⇒ only very large values are favored

Sven Heinemeyer, WIN (Heidelberg), 09.06.2015
σ_{p}^{SI} \text{ incl. } 20/fb \text{ of LHC data}

⇒ only very large values are favored

Sven Heinemeyer, WIN (Heidelberg), 09.06.2015
CMSSM DM prediction

Mechanisms for relic dark matter density fulfillment in the CMSSM

- CMSSM: best fit, 1σ, 2σ

- CMSSM (4 parameters)

- stau coann.
- H/A-funnel
- chargino coann.
- stop coann.

29/09/2014
Kees Jan de Vries; Mastercode; BSM RT Workshop 2014

Imperial College London
Mechanisms for relic dark matter density fulfillment in the CMSSM
Mechanisms for relic dark matter density fulfillment in the CMSSM

CMSSM (4 parameters)

Sven Heinemeyer, WIN (Heidelberg), 09.06.2015
Mechanisms for relic dark matter density fulfillment in the NUHM1

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

NUHM1 (5 parameters)

\[ m_{1/2} \text{[GeV]} \]
\[ m_0 \text{[GeV]} \]

- stau coann.
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Mechanisms for relic dark matter density fulfillment in the NUHM1

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

NUHM1: best fit, 1\sigma, 2\sigma

NUHM1 (5 parameters)

- stau coann.
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29/09/2014

Kees Jan de Vries; Mastercode; BSM fit workshop 2014

Sven Heinemeyer, WIN (Heidelberg), 09.06.2015
Mechanisms for relic dark matter density fulfillment in the NUHM2

$M^2_{H_u} \neq M^2_{H_d} \neq M^0_0$

NUHM2 (6 parameters)

$M_{1/2}$ [GeV]

$M_0$ [GeV]

- stau coann.
- H/A-funnel
- stop coann.
- chargino coann.
Mechanisms for relic dark matter light in the NUHM2

NUHM2: best fit, 1σ, 2σ

NUHM2 (6 parameters)
Mechanisms for relic dark matter density fulfillment in the NUHM2
Red circle is meant to represent predictions from SUSY. Let's see what our models say.
MSSM DM prediction

Future searches would significantly probe the CMSSM
MSSM DM prediction

Some of the parameter of the NUHM1 space lies beyond the intrinsic background from atmospheric neutrinos.
MSSM DM prediction

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

- preferred pMSSM mass ranges
  in particular for \( m_{\tilde{\chi}_1^0} \), our DM mass

- identification of DM annihilation mechanism

- results in the \( m_{\tilde{\chi}_1^0} - \sigma_p^{SI} \) plane for the pMSSM10

- no “no lose” theorem for DD experiments

- . . .
pMSSM10 prediction: DM mass vs. light stop mass:

![Graph showing pMSSM10 predictions for DM mass vs. light stop mass.](image)

- Star: pMSSM10 w LHC8: best fit, 1σ, 2σ
- Blue solid line: pMSSM10 w LHC8: best fit, 1σ, 2σ
- Red dashed line: pMSSM10 w/o LHC8: best fit, 1σ, 2σ

Sven Heinemeyer, WIN (Heidelberg), 09.06.2015
pMSSM10 prediction: DM mass vs. light stop mass:

- Red line: pMSSM10 with LHC8: best fit, 1σ, 2σ
- Blue line: pMSSM10 without LHC8: best fit, 1σ, 2σ

Sven Heinemeyer, WIN (Heidelberg), 09.06.2015
pMSSM10 prediction: DM mass vs. light stop mass:

\[ M_1 \approx M_2 \]

⇒ chargino co-annihilation

\[ m_{\chi}^0 \] vs. \[ m_{\chi^\pm} \]

Sven Heinemeyer, WIN (Heidelberg), 09.06.2015
pMSSM10 prediction: best-fit masses

⇒ high colored masses
⇒ relatively low electroweak masses
    partially with not too large ranges
⇒ clear prediction for $m_{\tilde{\chi}_1^0}$
pMSSM10 prediction: DM mass

⇒ pMSSM10 predicts much lower DM mass than GUT-based models

Sven Heinemeyer, WIN (Heidelberg), 09.06.2015
pMSSM10 prediction: $m_{\tilde{\chi}_1^0}$ vs. $\sigma_p^{\text{SI}}$:

$\Rightarrow$ LHC bounds try to “rescue” DD experiments!

Sven Heinemeyer, WIN (Heidelberg), 09.06.2015
pMSSM10 prediction: $m_{\tilde{\chi}_1^0}$ vs. $\sigma_p^{\text{SI}}$: future expectations

$\Rightarrow$ 68% CL areas covered by next round of DD experiments
pMSSM10 analysis: DD experiments: $p$- vs. $n$-scattering

$\sigma^\text{SI}_p$ is evaluated for $p$-scattering

Can $n$-scattering come to rescue?

Some points with low $\sigma^\text{SI}_p$ have even lower $\sigma^\text{SI}_n$

$\Rightarrow$ no “no-lose theorem” for DD experiments!
5. Conclusions

- **SUSY** is (still) the best-motivated BSM scenario
  - constrained models: CMSSM, NUHM1, NUHM2, ...
  - general models: pMSSM10, ...

- Our tool: **MasterCode**
  combination of LHC searches, Higgs measurements, EWPO, BPO, CDM $\Rightarrow \chi^2$ evaluation

- Preferred fit ranges in the pMSSM10:
  - $m_{\tilde{\chi}^0_1} \lesssim 400$ GeV
  - important: chargino co-annihilation
  - $M_1 \sim M_2$ at the EW scale

- Predictions for DD experiments:
  - at the 68% CL accessible at the next generation of DD
  - at the 95% CL even below “neutrino floor”
  - no “no-loose theorem” for DD experiments
Back-up
GUT based models: 1.) CMSSM (sometimes wrongly called mSUGRA):

⇒ Scenario characterized by

\[ m_0, m_{1/2}, A_0, \tan \beta, \text{sign} \mu \]

- \( m_0 \): universal scalar mass parameter
- \( m_{1/2} \): universal gaugino mass parameter
- \( A_0 \): universal trilinear coupling
- \( \tan \beta \): ratio of Higgs vacuum expectation values
- \( \text{sign}(\mu) \): sign of supersymmetric Higgs parameter

⇒ particle spectra from renormalization group running to weak scale
⇒ Lightest SUSY particle (LSP) is the lightest neutralino ⇒ DM!
GUT based models: 1.) CMSSM (sometimes wrongly called mSUGRA):

⇒ particle spectra from renormalization group running to weak scale

\[ M_0 = 300 \text{ GeV}, \ M_1/2 = 100 \text{ GeV}, \ A_0 = 0 \]

⇒ one parameter turns negative ⇒ Higgs mechanism for free
“Typical” CMSSM scenario
(SPS 1a benchmark scenario):

Strong connection between
all the sectors
GUT based models: 2.) NUHM1: (Non-universal Higgs mass model)

Assumption: no unification of scalar fermion and scalar Higgs parameter at the GUT scale

⇒ effectively $M_A$ as free parameters at the EW scale

⇒ Scenario characterized by

$$m_0, \frac{m_1}{2}, A_0, \tan \beta, \text{sign} \mu \text{ and } M_A$$

GUT based models: 3.) NUHM2: (Non-universal Higgs mass model 2)

Assumption: no unification of scalar Higgs parameter at the GUT scale

⇒ effectively $M_A$ and $\mu$ as free parameters at the EW scale

⇒ Scenario characterized by

$$m_0, \frac{m_1}{2}, A_0, \tan \beta, \mu \text{ and } M_A$$
What is happening to the $\chi^2$?

Low energy data (mostly $(g - 2)_\mu$) favors low SUSY mass scales

LHC data favors higher SUSY scales

$M_h$ “measurement” moves the fit to even higher scales

$\Rightarrow$ tension, reflected in rising $\chi^2$:

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Probabilities still “so so”, but this might change with LHC run II data.

Not finding SUSY now does not make SUSY prospects look bad, makes some very constrained models look bad!
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An MSSM Higgs at 125 GeV makes CMSSM/NUHM1 less likely.
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<td>3420</td>
<td>1380</td>
<td>3140</td>
<td>39</td>
</tr>
</tbody>
</table>

Probabilities still “so so”, but this might change with LHC run II data.

Not finding SUSY now does not make SUSY prospects look bad, makes some very constrained models look bad!

An MSSM Higgs at 125 GeV makes CMSSM/NUHM1 less likely

And requires SUSY realizations that are in agreement with

- higher colored mass scales (LHC limits)
- lower uncolored mass scales (EWPO; $(g - 2)_\mu) \Rightarrow DM$ predictions
“Typical” CMSSM scenario
(SPS 1a benchmark scenario):

Strong connection between all the sectors
SPS1a variant (I)
colored and uncolored
sector decoupled:
SPS1a variant (II)
colored and uncolored
sector decoupled: