MasterCode: Status and Prospects

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based on collaboration with

1. Introduction
2. Codes and predictions
3. Models & Methods
4. Predictions for the LHC
5. Prospects
6. Conclusions
1. Introduction

Global fit to all SM data:

[LEPEWWG '10]

\[ \Rightarrow M_H = 89^{+35}_{-26} \text{ GeV} \]

\[ M_H < 158 \text{ GeV, 95\% C.L.} \]

Assumption for the fit:
SM incl. Higgs boson

\[ \Rightarrow \text{no confirmation of Higgs mechanism} \]
Global fit to all SM data incl. direct searches:

[GFitter ‘10]

\[ M_H = 119.1^{+13.5}_{-4.0} \text{ GeV} \]

\[ M_H < 157 \text{ GeV}, 95\% \text{ C.L.} \]

Assumption for the fit:
SM incl. Higgs boson

\[ \Rightarrow \text{no confirmation of Higgs mechanism} \]
Main idea of the MasterCode: do “the same” in Supersymmetry!

Combine all existing precision data:

- Electroweak precision observables (EWPO)
- $B$ physics observables (BPO)
- Cold dark matter (CDM)
- ...

Predict:

- best-fit points
- ranges for Higgs masses
- ranges for SM parameters
- ranges for SUSY masses $\Rightarrow$ LHC reach
2. Codes and predictions

Our tool:

The “MasterCode”

⇒ collaborative effort of theorists and experimentalists

[O. Buchmüller, R. Cavanaugh, D. Colling, A. De Roeck, M. Dolan, J. Ellis, H. Flächer, S.H., G. Isidori,
K. Olive, S. Rogerson, F. Ronga, G. 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”:

– one model: (MFV) MSSM (see next section)

– tools included:
  – $B$-physics observables [SuFla]
  – more $B$-physics observables [SuperIso]
  – Higgs related observables, $(g - 2) \mu$ [FeynHiggs]
  – Electroweak precision observables [FeynWZ]
  – Dark Matter observables [MicrOMEGAs, DarkSUSY]
  – for GUT scale models: RGE running [SoftSusy]

⇒ all most-up-to-date codes on the market!

– added: $\chi^2$ analysis code [Minuit]

– currently being implemented:
  – Higgs constraints (for $\chi^2$ contributions . . . ) [HiggsBounds]

– planned: inclusion of more tools / more models
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$\Rightarrow$ all most-up-to-date codes on the market! $\Rightarrow$ crucial for precision!

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(Some) Electroweak precision observables in the MasterCode

(→ as for blue band analysis, except $\Gamma_W$)

1. $M_W$ (LEP/Tevatron)

2. $A_{LR}^e$ (SLD)

3. $A_{FB}^b$ (LEP)

4. $A_{FB}^c$ (LEP)

5. $A_{FB}^l$

6. $A_b, A_c$

7. $R_b, R_c$

8. $\sigma_{\text{had}}^0$

⇒ largest impact: (1), (2), (3)
(Some) $B/K$ physics observables in the MasterCode

1. $\text{BR}(b \rightarrow s\gamma)$ (MSSM/SM)
2. $\text{BR}(B_s \rightarrow \mu^+\mu^-)$
3. $\Delta M_s$
4. $R(\Delta M_s/\Delta M_d)$
5. $\text{BR}(B_u \rightarrow \tau\nu\tau)$ (MSSM/SM)
6. $\text{BR}(B \rightarrow X_x\ell^+\ell^-)$
7. $\text{BR}(K \rightarrow \ell\nu)$ (MSSM/SM)
8. $\text{BR}(\Delta M_K)$ (MSSM/SM)

⇒ largest impact: (1) and (2)
Further low-energy observables

– anomalous magnetic moment of the muon: \((g - 2)_\mu\)
Further low-energy observables

- anomalous magnetic moment of the muon: \((g - 2)_\mu\)

Higgs physics observables in the MasterCode

- lightest Higgs mass: \(M_h\)
- effective mixing angle: \(\alpha_{\text{eff}}\), especially for \(\sin^2(\beta - \alpha_{\text{eff}})\)
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Dark Matter observables in the MasterCode

- CDM density: \(\Omega_{\chi}h^2\)
- Direct detection cross section: \(\sigma_p^{\text{SI}}\) (prediction; not incl. in the fit yet)
Further low-energy observables

- anomalous magnetic moment of the muon: \((g - 2)_\mu\)

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Dark Matter observables in the MasterCode

- CDM density: \(\Omega_\chi h^2\)
- Direct detection cross section: \(\sigma_p^{\text{SI}}\) (prediction; not incl. in the fit yet)

SM parameters

- top mass: \(m_t\)
- \(Z\) boson mass: \(M_Z\)
- hadronic contribution to fine structure constant: \(\Delta \alpha_{\text{had}}\)
3. Models & methods

Indirect constraints on $M_{\text{SUSY}}$ from existing data?

- Electroweak precision observables (EWPO)
- $B$ physics observables (BPO)
- Cold dark matter (CDM)

⇒ combination of EWPO, BPO, CDM
3. Models & methods

Indirect constraints on $M_{\text{SUSY}}$ from existing data?

- Electroweak precision observables (EWPO) ?
- $B$ physics observables (BPO) ?
- Cold dark matter (CDM) ?

⇒ combination of EWPO, BPO, CDM ?

**EWPO $M_W$** : information on $m_{\tilde{t}}$, $m_{\tilde{b}}$ or $M_A$, tan $\beta$ or . . .

**EWPO $(g-2)_{\mu}$** : information on tan $\beta$ and/or $m_{\tilde{\chi}^0}$, $m_{\tilde{\chi}^\pm}$ and/or $m_{\tilde{\mu}}$, $m_{\tilde{\nu}_\mu}$

**BPO BR($b \rightarrow s\gamma$)** : information on tan $\beta$ and/or $M_{H^\pm}$ and/or $m_{\tilde{t}}$, $m_{\tilde{\chi}^\pm}$

**CDM (LSP gives CDM)** : information on $m_{\tilde{\chi}^0_1}$ and $m_{\tilde{\tau}}$ or $M_A$ or . . .
3. Models & methods

Indirect constraints on $M_{\text{SUSY}}$ from existing data?

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- $B$ physics observables (BPO)?
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$\Rightarrow$ combination of EWPO, BPO, CDM?

EWPO $M_W$ : information on $m_{\tilde{t}}$, $m_{\tilde{b}}$ or $M_A$, tan $\beta$ or ...

EWPO $(g-2)_\mu$ : information on tan $\beta$ and/or $m_{\tilde{\chi}^0}$, $m_{\tilde{\chi}^\pm}$ and/or $m_{\tilde{\mu}}$, $m_{\tilde{\nu}_\mu}$

BPO BR($b \rightarrow s\gamma$) : information on tan $\beta$ and/or $M_{H^\pm}$ and/or $m_{\tilde{t}}$, $m_{\tilde{\chi}^\pm}$

CDM (LSP gives CDM) : information on $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\tau}}$ or $M_A$ or ...

$\Rightarrow$ combination (so far) makes only sense if all parameters are connected!

$\Rightarrow$ GUT based models, ...
In general:
The **MasterCode** can perform fits in the (MFV) MSSM
(ready for NMFV MSSM: [*FeynHiggs, SuFla*])

However:
Concentrating on **existing experimental data** fits make sense only in **GUT based models**:
- CMSSM
- NUHM1, NUHM2
- mSUGRA
- VCMSSM
- ...
The models: 1.) CMSSM (or mSUGRA):

⇒ Scenario characterized by

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

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

⇒ particle spectra from renormalization group running to weak scale
The models: 2.) NUHM1: (Non-universal Higgs mass model)

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

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

⇒ besides the CMSSM parameters

Further extension: NUHM2:
Assumption: no unification of the Higgs parameters at the GUT scale

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

⇒ besides the CMSSM parameters

$M_A$ and $\mu$
The models: 3.) VCMSSM: (Very Constrained MSSM)

⇒ In addition to CMSSM: assume relation between $A_0$ and $m_0$:

$$A_0 = m_0 + B_0$$

$tan \beta$ fixed (e.g. via CDM constraint)

Free parameters: $m_{1/2}, A_0, m_0$

Lightest SUSY particle (LSP) is the lightest neutralino

The models: 4.) mSUGRA: (Gravitino DM in mSUGRA)

⇒ In addition to CMSSM: assume relation between $A_0$ and $m_0$:

$$A_0 = m_0 + B_0$$

mSUGRA: $m_{\text{gravitino}} = m_0$ ⇒ gravitino can be the LSP

Free parameters: $m_{1/2}, A_0, m_0$

Lightest SUSY particle (LSP) is the gravitino
Different methods:

1.) Scanning:
   - 3-dim scans (possibly with CDM fixing one dimension)
   - multi-dim scans
   - multi-dim scans (with Markov Chain Monte Carlo technique)
⇒ MasterCode: multi-dim scans with MCMC technique

2.) Fitting:
   - Frequentist
   - Bayesian
⇒ MasterCode: Frequentist
⇒ $\chi^2$ function to include all experimental results

3.) Priors . . . (none)
\[ \chi^2 \text{ calculation:} \]

\[ \rightarrow \text{global } \chi^2 \text{ likelihood function} \]

\[ \text{combines all theoretical predictions with experimental constraints:} \]

\[ \chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \sum_i^M \frac{(f_{\text{SM}_i}^{\text{obs}} - f_{\text{SM}_i}^{\text{fit}})^2}{\sigma(f_{\text{SM}_i})^2} \]

\[ N: \text{ number of observables studied} \]

\[ M: \text{ SM parameters: } \Delta \alpha_{\text{had}}, m_t, M_Z \]

\[ C_i: \text{ experimentally measured value (constraint)} \]

\[ P_i: \text{ MSSM parameter-dependent prediction for the corresponding constraint} \]
\( \chi^2 \) calculation:

→ global \( \chi^2 \) likelihood function
combines all theoretical predictions with experimental constraints:

\[
\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \sum_i^M \frac{(f_{\text{obs}}^{SM_i} - f_{\text{fit}}^{SM_i})^2}{\sigma(f_{\text{SM}_i})^2}
\]

\( N \): number of observables studied
\( M \): SM parameters: \( \Delta \alpha_{\text{had}}, m_t, M_Z \)
\( C_i \): experimentally measured value (constraint)
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What to do if only a lower/upper bound exists?

→ especially important: \( M_h \) → see the back-up
4. Predictions for the LHC

- combine all electroweak precision data as in the SM
- combine with $B$ physics observables
- combine with CDM and $(g - 2)_\mu$
- include SM parameters with their errors: $m_t, M_Z, \Delta \alpha_{\text{had}}$

⇒ $\chi^2$ function

⇒ scan over the full CMSSM/NUHM1/VCMSSM/mSUGRA parameter space

~ $2.5 \times 10^7$ points samples with MCMC

statistical measure: $\chi^2$ function (Frequentist, no priors)

⇒ final minimum: Minuit

$\Delta \chi^2$: 68, 95% C.L. contours

⇒ preferred CMSSM/NUHM1 parameters

⇒ LHC reach
### Best-fit points:

<table>
<thead>
<tr>
<th>Model</th>
<th>Min. $\chi^2$</th>
<th>Probability</th>
<th>$m_{1/2}$</th>
<th>$m_0$</th>
<th>$A_0$</th>
<th>tan $\beta$</th>
<th>$M_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>mSUGRA</td>
<td>29.3</td>
<td>6.0%</td>
<td>550</td>
<td>230</td>
<td>430</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>VCMSSM</td>
<td>33.2</td>
<td>2.2%</td>
<td>130</td>
<td>2110</td>
<td>980</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>CMSSM</td>
<td>22.5</td>
<td>31%</td>
<td>300</td>
<td>60</td>
<td>30</td>
<td>9</td>
<td>109</td>
</tr>
<tr>
<td>NUHM1</td>
<td>22.4</td>
<td>26%</td>
<td>330</td>
<td>70</td>
<td>-260</td>
<td>11</td>
<td>106</td>
</tr>
<tr>
<td></td>
<td>19.7</td>
<td>29%</td>
<td>260</td>
<td>100</td>
<td>9300</td>
<td>7</td>
<td>120</td>
</tr>
</tbody>
</table>

- VCMSSM, CMSSM, NUHM1 have similar high probabilities
- $M_h$ does not include direct LEP constraints
  - ⇒ no severe tension between the models and LEP bound
LHC (CMS) \oplus CMSSM analysis:

\[ M_{1/2}[\text{GeV/c}^2] \]

\[ M_0[\text{GeV/c}^2] \]

\[ \Rightarrow \text{best-fit point and part of 68\% C.L. can be tested in 2011} \]
LHC (CMS) ⊕ NUHM1 analysis:

\[ \tan^2 \beta = 10, \; A_0 = 0, \; \mu > 0 \]

CMS preliminary
\[ \sqrt{s} = 7 \text{ TeV} \]

Hadronic search, 95% C.L. curves

\[
\begin{align*}
L = 1000/pb \\
L = 100/pb
\end{align*}
\]

⇒ best-fit point and part of 68% C.L. are can be tested in 2011
LHC (CMS) ⊕ CMSSM analysis:

[CMS ’07]

jets + MET (CMS)

$$\tan\beta = 10, \ A_0 = 0, \ \mu > 0$$

- $1/\text{fb} @ 14 \text{ TeV}$
- $100/\text{pb} @ 14 \text{ TeV}$
- $50/\text{pb} @ 10 \text{ TeV}$

⇒ excellent prospects even with lower luminosity!
LHC (CMS) ⊕ NUHM1 analysis:

CMS '07 ⇒ excellent prospects even with lower luminosity!

Sven Heinemeyer, LPCC workshop: Global BSM fits and LHC data, 10.02.2011
Masses for best-fit points: CMSSM

$\Rightarrow$ largely accessible spectrum for LHC and ILC
Masses for best-fit points: NUHM1

⇒ largely accessible spectrum for LHC and ILC
Masses for best-fit points: VCMSSM

⇒ largely accessible spectrum for LHC and ILC

Sven Heinemeyer, LPCC workshop: Global BSM fits and LHC data, 10.02.2011
Masses for best-fit points: mSUGRA (co-annihilation region)

⇒ largely accessible spectrum for LHC and ILC

Sven Heinemeyer, LPCC workshop: Global BSM fits and LHC data, 10.02.2011
Masses for best-fit points: mSUGRA (funnel region)

⇒ possibly much more difficult for the LHC (but high $\chi^2$!)

Sven Heinemeyer, LPCC workshop: Global BSM fits and LHC data, 10.02.2011
Relevance of $(g - 2)_\mu$: $m_0$ with and without:

$\Rightarrow$ same minimum, but much more shallow
CMSSM: red band plot: (LEP bounds not included!)  

\[ M_h = 109 \pm 6 \text{(exp)} \pm 1.5 \text{(theo)} \text{ GeV} \]
**NUHM1:** red band plot: (LEP bounds not included!)

\[ M_h = 121^{+1}_{-14} \text{(exp)} \pm 1.5 \text{(theo)} \text{ GeV} \quad \Rightarrow \text{naturally above LEP limit} \]
Prediction of $M_H^{SM}$ (blue band) and $M_h$ in the MSSM (red band):

$M_h^{CMSSM} = 109.5 \pm 6 \pm 1.5 \text{ GeV}$

⇒ as good as the SM

$M_h^{NUHM1} = 121^{+1}_{-14} \pm 1.5 \text{ GeV}$

⇒ above the LEP limit
$M_W$ fit: $M_W$ not included, $m_t$ fit: $m_t$ not included

(SM fit: $M_H$ not included – CMSSM/NUHM1 fit: $M_h$ included)

$\Rightarrow$ CMSSM and NUHM1 fit amazingly well $m_t$ and $M_W$

$\Rightarrow$ better than the SM: smaller errors, better best-fit points
Comparison of **direct** and **indirect** determination of $m_t$ and $M_W$ in the **SM** and the **MSSM**:

- **MSSM band:**
  - scan over SUSY masses
- **overlap:**
  - SM is MSSM-like
  - MSSM is SM-like
- **SM band:**
  - variation of $M_H^{SM}$

### Graph

- **uncertainties 68% CL:**
  - exp.: LEP2/Tevatron
  - **light SUSY**
  - **MSSM**
  - **heavy SUSY**

### Axes
- **$M_W$ [GeV]**
- **$m_t$ [GeV]**

### Points
- **$M_H = 114$ GeV**
- **$M_H = 750$ GeV**
- **SM**
- **MSSM**
- **both models**
Comparison of direct and indirect determination of $m_t$ and $M_W$ in the SM and the MSSM:

MSSM band: scan over SUSY masses

overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of $M_H^{SM}$
Some more predictions: \( m_{\tilde{g}} - m_{\tilde{q}_L} \)

\( \Rightarrow m_{\tilde{g}} \) often largest mass, but exceptions are possible
Some more predictions: preferred $M_A$–tan $\beta$ parameter space

**CMSSM**

**NUHM1**

red dotted: discovery with 1 fb$^{-1}$ @ 7 TeV  
blue solid: 95% C.L. exclusion with 1 fb$^{-1}$ @ 7 TeV  
⇒ preferred regions missed in 2010-2011 run
Some more predictions: preferred $M_A$–$\tan \beta$ parameter space

CMS analysis for 30 fb$^{-1}$ @ 14 TeV
⇒ still best-fit regions missed by LHC, better for ILC(1000)
Some more predictions: direct search for dark matter

CMSSM

NUHM1

⇒ only partially covered by future experiments
5. Prospects

Plans for the near future:

- Include ATLAS/CMS data on SUSY searches
  Needed:
  - exclusion bounds as model independent as possible
  - at least exclusion bounds in “our” models
  - more detailed information than “just” 95% CL exclusion bounds

- Include LHCb data

- Include DM search data (Xenon100, ...)

- In case of a “SUSY-like” signal:
  go beyond the simple GUT based models
LHC (CMS) reach with 1 fb$^{-1}$:

CMSSM analysis incl. leptonic edge measurements

⇒ excellent prospects from early leptonic edge measurements!
Impact of various constraints (CMSSM):

⇒ strong impact of \((g-2)_{\mu}\)
⇒ strong improvement possible from
  \(M_W, \text{BR}(b \to s\gamma), (g-2)_{\mu}, \text{BR}(B_u \to \tau\nu)\)
Impact of various constraints (CMSSM):

$\Rightarrow$ strong impact of $(g-2)_{\mu}$

$\Rightarrow$ strong improvement possible from $M_w$, BR$(b \rightarrow s\gamma)$, $(g-2)_{\mu}$, BR$(B_u \rightarrow \tau\nu)$
6. Conclusions

- Models: (MFV) MSSM
  Analyses: CMSSM, NUHM1, mSUGRA, VCMSSM

- Codes included: SuFla, SuperIso, FeynHiggs, FeynWZ, MicrOMEGAs, DarkSUSY, SoftSUSY, Minuit (HiggsBounds)
  ⇒ all most-up-to-date codes on the market!  ⇒ crucial for precision!
  ⇒ predictions for: EWPO, BPO, CDM, . . .
  (EWPO: (nearly) as for the blue band plot)

- Statistical measure: $\chi^2$ function (Frequentist, no priors)
  $\sim 2.5 \times 10^7$ points samples with MCMC / $\Delta\chi^2$: 68, 95% C.L. contours

- Results exist for:
  - best-fit points, 68, 95% C.L. areas
  - predictions for SUSY masses ⇒ LHC reach
  - predictions for $M_h$ (red band plot)
  - predictions for SM parameters: $M_W$, $m_t$
  - predictions for flavor observables
  - predictions for astro-physical observables

- Prospects: inclusion of ATLAS/CMS, LHCb, Xenon100 data . . .
Back-up
SM Higgs search at LEP:

Dominant SM production process:
\[ e^+e^- \rightarrow ZH:\]

\[ e^- \]
\[ e^+ \]
\[ Z \]
\[ H \]

Dominant decay process:
\[ H \rightarrow b\bar{b}:\]

\[ b \]
\[ \bar{b} \]

Bounds valid in the CMSSM? NUHM1? MSSM?
Search for neutral SUSY Higgs bosons:

\[ e^+ e^- \rightarrow Zh, ZH \]

\[ \sigma_{hZ} \approx \sin^2(\beta - \alpha_{\text{eff}}) \sigma_{hZ}^{\text{SM}} \]

\[ \sigma_{HZ} \approx \cos^2(\beta - \alpha_{\text{eff}}) \sigma_{hZ}^{\text{SM}} \]

\[ e^+ e^- \rightarrow Ah, AH \]

\[ \sigma_{hA} \propto \cos^2(\beta - \alpha_{\text{eff}}) \sigma_{hZ}^{\text{SM}} \]

\[ \sigma_{HA} \propto \sin^2(\beta - \alpha_{\text{eff}}) \sigma_{hZ}^{\text{SM}} \]
\[ \sin^2(\beta - \alpha_{\text{eff}}) \] in the CMSSM, NUHM1:

![CMSSM and NUHM1 Plots](image-url)
In CMSSM:

SM bound of $M_H$ search can be used [LEP Higgs Working Group '03]

$CL_s$ can be used/transformed into $\chi^2$ values

$\Rightarrow$ can be included into $\chi^2$ evaluation

$\delta M_h^{\text{intr.}} \approx 3 \text{ GeV}$

We use *FeynHiggs*
In the NUHM1:
SM bound on $M_H$ is reduced: $S_{95} \sim \sin^2(\beta - \alpha_{\text{eff}})$

⇒ take into account the LEP SM Higgs bound . . .
    . . . but shifted according to the reduced coupling