herkömmliches Higgsprogramm  

Das neue FeynHiggs
1. Introduction and motivation

2. The models and the tools

3. Predictions for the LHC

4. Conclusions
1. Introduction

The big question:
Which Lagrangian describes the world?

My guess:
It is a supersymmetric one
⇒ concentrate on the MSSM from now on

(other people ⇒ other guesses ⇒ other priorities . . . )
1. Introduction

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⇒ is there any possibility to know what to expect?
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⇒ is there any possibility to know what to expect?

Let’s see . . .
The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

\[
\begin{align*}
[u, d, c, s, t, b]_{L,R} & \quad [e, \mu, \tau]_{L,R} & \quad [\nu_{e,\mu,\tau}]_{L} & \quad \text{Spin } \frac{1}{2} \\
[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}]_{L,R} & \quad [\tilde{e}, \tilde{\mu}, \tilde{\tau}]_{L,R} & \quad [\tilde{\nu}_{e,\mu,\tau}]_{L} & \quad \text{Spin } 0
\end{align*}
\]

\[g \quad W^\pm, H^\pm \quad \gamma, Z, H_1^0, H_2^0\] \quad \text{Spin } 1 / \text{Spin } 0

\[\tilde{g} \quad \tilde{\chi}_{1,2}^\pm \quad \tilde{\chi}_{1,2,3,4}^0\] \quad \text{Spin } \frac{1}{2}

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales

Problem in the MSSM: complex phases (← neglected here)
How to make a prediction?

Comparison of precision observables with theory:

<table>
<thead>
<tr>
<th>Precision data:</th>
<th>Theory:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_W, \sin^2 \theta_{\text{eff}}, a_\mu, \ldots$</td>
<td>SM, MSSM, \ldots</td>
</tr>
</tbody>
</table>

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections

$\Downarrow$

$\Rightarrow$ Information about unknown parameters

Very high accuracy of measurements and theoretical predictions needed
**Example:** Prediction for $M_W$ in the SM and the MSSM:


\[ S.H., W. Hollik, D. Stockinger, A. Weber, G. Weiglein '07 \]

160 165 170 175 180 185

\[ M_W \text{ [GeV]} \]

SM

MSSM

MSSM band:
scan over SUSY masses

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

SM band:
variation of $M_H^{SM}$

Heinemeyer, Hollik, Stockinger, Weber, Weiglein '09
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Sven Heinemeyer, Physics at the LHC (DESY Hamburg), 08.06.2010
Global fit to all SM data:

\[ [ \text{LEPEWWG '09} ] \]

\[ \Rightarrow M_H = 87^{+35}_{-26} \text{ GeV} \]

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

Assumption for the fit:
SM incl. Higgs boson

\[ \Rightarrow \text{no confirmation of Higgs mechanism} \]

\[ \Rightarrow \text{Higgs boson seems to be light, } M_H \lesssim 160 \text{ GeV} \]
Global fit to all SM data incl. direct searches:

\[ \Rightarrow M_H = 116.4^{+18.3}_{-1.4} \text{ GeV} \]

\[ M_H < 152 \text{ GeV, 95\% C.L.} \]

Assumption for the fit:
SM incl. Higgs boson

\[ \Rightarrow \text{no confirmation of Higgs mechanism} \]

\[ \Rightarrow \text{Higgs boson seems to be light, } M_H \lesssim 150 \text{ GeV} \]
2. The models and the tools

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?
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⇒ 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($b \to s\gamma$) : 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 . . .
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BPO BR($b \to s\gamma$): 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 . . .

⇒ combination makes only sense if all parameters are connected!

⇒ GUT based models, . . .
Existing analyses for GUT based models: (involving precision observables)

**CMSSM/mSUGRA:**

- J. Ellis, S.H., K. Olive, G. Weiglein '04, '06, '07
- J. Ellis, S.H., K. Olive, A. Weber, G. Weiglein '07
- E. Baltz, P. Gondolo '04
- R. Ruiz de Austri, R. Trotta and L. Roszkowski '06, '07
- B. Allanach, C. Lester and A. Weber '06, '07
- F. Feroz, M. Hobson, L. Roszkowski and R. Ruiz de Austri, R. Trotta '08
- O. Buchmueller et al. '07
- O. Buchmueller et al. '08
- O. Buchmueller et al. '09
- M. Cabrera, A. Casas, R. Ruiz de Austri '09
- Y. Akrami, P. Scott, J. Edsjo, J. Conrad, L. Bergstrom '09

**NUHM (Non-Universal Higgs Mass model):**

- J. Ellis, S.H., K. Olive, G. Weiglein '06
- J. Ellis, T. Hahn, S.H., K. Olive, G. Weiglein '07
- O. Buchmueller et al. '08
- O. Buchmueller et al. '09

**VCMSSM (Very Constrained MSSM):**

- J. Ellis, S.H., K. Olive, G. Weiglein '06
- L. Roszkowski, R. Ruiz de Austri, R. Trotta, Y. Tsai, T. Varley '09

**mSUGRA (GDM) (Gravitino Dark Matter):**

- J. Ellis, S.H., K. Olive, G. Weiglein '06

**CMSSM, mGMSB, mAMSB:**

- S.H., X. Miao, S. Su, G. Weiglein '08

**CNMSSM:**

- D. Lopez-Fogliani, L. Roszkowski, R. Ruiz de Austri, T. Varley '09

**Finite Unified Theories:**

- S.H., M. Mondragón, G. Zoupanos '07

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*Sven Heinemeyer, Physics at the LHC (DESY Hamburg), 08.06.2010*
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)

⇒ here: results using last two

2.) Fitting:
   - Frequentist
   - Bayesian

⇒ focus on Frequentist here

3.) Priors . . . (none)
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
⇒ Lightest SUSY particle (LSP) is the lightest neutralino
⇒ particle spectra from renormalization group running to weak scale

\[ M_0 = 300 \text{ GeV}, \quad M_{1/2} = 100 \text{ GeV}, \quad A_0 = 0 \]

\[ \begin{align*}
\tilde{q} & \quad 300 \\
\tilde{g} & \quad 200 \\
\tilde{H} & \quad 100 \\
\tilde{W} & \quad 0 \\
\tilde{B} & \quad 0
\end{align*} \]

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

SPS home page:
www.ippp.dur.ac.uk/~georg/sps
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 $M_A$ or $\mu$

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 $\mu$
Our tool:

The “MasterCode”

⇒ collaborative effort of theorists and experimentalists
[Buchmüller, Cavanaugh, De Roeck, Ellis, Flächer, Hahn, SH, Isidori, Olive, Ronga, Weiglein]

Über-code for the combination of different tools:

– calculations of POs are included as subroutines
– compatibility ensured by collaboration of
  authors of “MasterCode” and authors of “sub tools” /SLHA(2)
– one “MasterCode” for one model . . .

⇒ evaluate observables of one parameter point consistently
  with various tools

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

- one model: (MFV) MSSM

- 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]

- added: $\chi^2$ analysis code
  (→ similar directions as SFitter, Fittino)

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

- planned: inclusion of more tools
  inclusion of more models
**\( \chi^2 \) calculation:**

→ global \( \chi^2 \) likelihood function

combines all theoretical predictions with experimental constraints:

\[
\chi^2 = \sum_{i}^{N} \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \sum_{i}^{M} \frac{(f_{SM_i}^{obs} - f_{SM_i}^{fit})^2}{\sigma(f_{SM_i})^2}
\]

- **\( N \):** number of observables studied
- **\( M \):** SM parameters: \( \Delta \alpha_{\text{had}}, m_t, M_Z \)
- **\( C_i \):** experimentally measured value (constraint)
- **\( P_i \):** MSSM parameter-dependent prediction for the corresponding constraint
\( \chi^2 \) calculation:

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

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\]

\( N \): number of observables studied
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What to do if only a lower/upper bound exists?

→ especially important: \( M_h \)

→ backup
3. Predictions for the LHC

[Buchmüller, Cavanaugh, De Roeck, Ellis, Flächer, S.H., Isidori, Olive, Ronga, Weiglein ’09]

- 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: $m_t$, $M_Z$, $\Delta \alpha_{\text{had}}$

$\Rightarrow \chi^2$ function

$\rightarrow$ scan over the full CMSSM/NUHM1 parameter space
$\sim 2.5 \times 10^7$ points samples with MCMC

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

$\rightarrow$ final minimum: Minuit

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

$\Rightarrow$ preferred CMSSM/NUHM1 parameters $\Rightarrow \mathcal{L}_{\text{SUSY}}$

Sven Heinemeyer, Physics at the LHC (DESY Hamburg), 08.06.2010
Best-fit points:

**CMSSM:**

\[ m_{1/2} = 310 \text{ GeV}, \; m_0 = 60 \text{ GeV}, \; A_0 = 130 \text{ GeV}, \]
\[ \tan \beta = 11, \; \mu = 400 \text{ GeV}, \; M_A = 450 \text{ GeV} \]
\[ \chi^2/N_{dof} = 20.6/19 \ (36 \% \text{ probability}) \]

\Rightarrow \text{very similar to SPS 1a :-)}

**NUHM1:**

\[ m_{1/2} = 270 \text{ GeV}, \; m_0 = 150 \text{ GeV}, \; A_0 = -1300 \text{ GeV}, \]
\[ \tan \beta = 11, \; \mu = 1140 \text{ GeV}, \; M_A = 310 \text{ GeV} \]

(similar probability)

\Rightarrow \mathcal{L}_{\text{SUSY}}
Masses for best-fit points: CMSSM

⇒ largely accessible spectrum for LHC (and ILC)
Masses for best-fit points: NUHM1

⇒ largely accessible spectrum for LHC (and ILC)
LHC (CMS) ⊕ CMSSM analysis:

\[ \tan(\beta) = 10, \quad A_0 = 0, \quad \mu > 0 \]

CMS preliminary
\[ \sqrt{s} = 7 \text{ TeV} \]
Hadronic search, 95% C.L. curves

- L = 1000/pb
- L = 100/pb

\[ M_{1/2} \rightarrow \text{best-fit point and part of 68% C.L. are can be tested in 2011} \]

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LHC (CMS) ⊕ NUHM1 analysis:

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

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- \( L = 1000/\text{pb} \)
- \( L = 100/\text{pb} \)

\[ M_{1/2} [\text{GeV}/c^2] \]
\[ M_0 [\text{GeV}/c^2] \]

maple

\[ \Rightarrow \text{best-fit point and part of 68\% C.L. are can be tested in 2011} \]
Some more predictions: $m_{\tilde{g}} - m_{\tilde{q}_L}$

$\Rightarrow m_{\tilde{g}}$ often largest mass, but exceptions are possible
Some more predictions: $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$

$\Delta \chi^2$ vs $\text{BR}(B_s \rightarrow \mu \mu)$

- **CMSSM**
- **NUHM1**

$\Rightarrow$ best-fit similar to SM, larger value would favor NUHM1
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: direct search for dark matter

CMSSM

NUHM1

$\Rightarrow$ only partially covered by future experiments
Prediction of $M^\text{SM}_H$ (blue band) and $M_h$ in the MSSM (red band): 

$$M_h^{\text{CMSSM}} = 108 \pm 6 \pm 1.5 \text{ GeV}$$  
$\Rightarrow$ as good as the SM

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

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**Top-Quark Mass [GeV]**

- **Exp. average**: $173.1 \pm 1.3$
- **SM fit**: $179.3^{+11.6}_{-8.5}$
- **CMSSM fit**: $173.8^{+3.2}_{-3.1}$
- **NUHM1 fit**: $169.5^{+8.8}_{-3.4}$

**W boson Mass [GeV]**

- **Exp. average**: $80.399 \pm 0.023$
- **SM fit**: $80.363 \pm 0.032$
- **CMSSM fit**: $80.379^{+0.013}_{-0.014}$
- **NUHM1 fit**: $80.370^{+0.024}_{-0.011}$

⇒ **CMSSM and NUHM1 fit amazingly well $m_t$ and $M_W$**
⇒ **better than the SM: smaller errors, better best-fit points**
4. Conclusions

- **Idea**: Predict most probable MSSM parameter regions using existing data: EWPO, BPO, CDM, ...
- **Models**: CMSSM, NUHM1
- **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
- **Best-fit points**:
  - **CMSSM**: $m_{1/2} = 310$ GeV, $m_0 = 60$ GeV, $A_0 = 240$ GeV,
    \[ \tan \beta = 11, \mu = 380 \text{ GeV}, M_A = 410 \text{ GeV} \]
  \[ \Rightarrow \text{very similar to SPS 1a :-) } \]
  - Prediction of $M_h$ (no LEP bound): $M_h = 108 \pm 6 \pm 1.5$ GeV
  - **NUHM1**: $m_{1/2} = 270$ GeV, $m_0 = 150$ GeV, $A_0 = -1300$ GeV,
    \[ \tan \beta = 11, \mu = 1140 \text{ GeV}, M_A = 310 \text{ GeV} \]
  - Prediction of $M_h$ (no LEP bound): best fit: $M_h \approx 121$ GeV
- **68% C.L. areas**: partially covered with $\sim 1 \text{ fb}^{-1} @ 7 \text{ TeV}$ (u.d.)
  \[ \Rightarrow \text{early LHC data could be very conclusive!} \]
Higgs Days at Santander 2010
Theory meets Experiment
13.-16. October

contact: Sven.Heinemeyer@cern.ch
http://www.ifca.es/HDays10
SM Higgs search at LEP:

**Dominant SM production process:**

\[ e^+ e^- \rightarrow ZH: \]

**Dominant decay process:**

\[ H \rightarrow b\bar{b}: \]

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

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

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

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

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

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

\[ \sigma_{HA} \propto \sin^2(\beta - \alpha_{\text{eff}}) \sigma^{\text{SM}}_{hZ} \]
Constraints from the Higgs search at LEP  

Experimental search vs. upper $M_h$-bound  

$(FeynHiggs 2.0)$  

$m_{h}^{\text{max}}$-scenario ($m_t = 174.3$ GeV, $M_{\text{SUSY}} = 1$ TeV):  

\[ m_h > 92.8 \text{ GeV} \]  
(expected: 94.9 GeV), 95% C.L.  

\[ M_A > 93.4 \text{ GeV} \]  
(expected: 95.2 GeV)
$\sin^2(\beta - \alpha_{\text{eff}})$ in the CMSSM, NUHM1:
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

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

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

We use FeynHiggs
In CMSSM:
SM bound of $M_H$ search can be used \cite{LEP Higgs Working Group '03}

$\Delta M_h^{\text{intr}} \approx 3 \text{ GeV}$

We use \textit{FeynHiggs}

\textbf{Interested in MSSM Higgs physics? Try our code \texttt{FeynHiggs} \newline \url{www.feynhiggs.de}}
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
LHC (CMS) ⊕ CMSSM analysis:

jets + MET (CMS)

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

- 1/fb @ 14 TeV
- 100/pb @ 14 TeV
- 50/pb @ 10 TeV

 ⇒ excellent prospects even with lower luminosity!

Sven Heinemeyer, Physics at the LHC (DESY Hamburg), 08.06.2010
LHC (CMS) reach with 1 fb$^{-1}$:

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

- jets + MET (CMS)
- 0 lepton + 4 jets (ATLAS)
- 1 lepton + 4 jets (ATLAS)
- SS 2$\mu$ (CMS)
- Higgs (2/fb) (CMS)

⇒ excellent prospects in various channels!
LHC (CMS) ⊕ NUHM1 analysis:

jets + MET (CMS)

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

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Sven Heinemeyer, Physics at the LHC (DESY Hamburg), 08.06.2010
LHC (CMS) reach with $1 \text{ fb}^{-1}$: NUHM1 analysis

[$\text{MasterCode '08}$] [$\text{CMS '07}$]

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

- jets + MET (CMS)
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$\Rightarrow$ excellent prospects in various channels!

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Some more predictions: preferred $M_A$–$\tan \beta$ parameter space

$\Rightarrow$ best-fit regions missed by LHC, better for ILC(1000)