herkömmliches Higgsprogramm

Das neue FeynHiggs
SUSY Prediction for the LHC

Sven Heinemeyer, IFCA (CSIC, Santander)

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based on collaboration with
O. Buchmüller, R. Cavanaugh, A. de Roeck, J. Ellis, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. Weiglein

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1. Introduction

The LHC is coming . . .
first collisions by the end of this year?

The ILC is still coming . . .
. . . a bit later than anticipated

⇒ New Physics is certainly around the corner

⇒ Time to get ready
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 . . . )
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⇒ is there any possibility to know what to expect?
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Which Lagrangian describes the world?

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

⇒ is there any possibility to know what to expect?

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

Superpartners for Standard Model particles

\[
\begin{bmatrix}
  u, d, c, s, t, b \\
  \tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}
\end{bmatrix}_{L,R} \quad
\begin{bmatrix}
  e, \mu, \tau \\
  \tilde{e}, \tilde{\mu}, \tilde{\tau}
\end{bmatrix}_{L,R} \quad
\begin{bmatrix}
  \nu_e, \mu, \tau \\
  \tilde{\nu}_e, \mu, \tau
\end{bmatrix}_{L}
\]

Spin \( \frac{1}{2} \)

\[
\begin{bmatrix}
  g, W^\pm, H^\pm \\
  \tilde{g}, \tilde{\chi}^{\pm}_{1,2} \\
  \tilde{\chi}^0_{1,2,3,4}
\end{bmatrix}
\]

Spin 1 / Spin 0

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>$\text{SM, MSSM, \ldots}$</td>
</tr>
</tbody>
</table>

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections

⇒ Information about unknown parameters

Very high accuracy of measurements and theoretical predictions needed
**Example:** Prediction for $M_W$ 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 $M^\text{SM}_H$
**Example:** Prediction for $M_W$ in the SM and the MSSM:


![Graph showing the relationship between $M_W$, $m_t$, and possible experimental errors 68% CL.]

- **MSSM band:**
  - scan over SUSY masses
  - overlap:
    - SM is MSSM-like
    - MSSM is SM-like

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

---

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Example: Prediction for $M_W$ in the SM and the MSSM:


[Diagram showing $M_W$ vs $m_t$ with experimental errors: LEP2/Tevatron (today), 68% CL, 95% CL. MSSM band: scan over SUSY masses. Overlap: SM is MSSM-like. SM band: variation of $M_H^{SM}$.

Heinemeyer, Hollik, Stockinger, Weber, Weiglein '09]
2. The MasterCode

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

Über-code for the combination of different tools:

– tools 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
⇒ consistent evaluation with the best codes available
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 (SUSYPope)]
  - 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]
    → see S.H.’s talk at SUSY 09

- planned: inclusion of more tools / more models
Example: \( B/K \) physics observables in the MasterCode

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

⇒ largest impact: (1) and (2)
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

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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 $m_{\chi^0}, m_{\chi^\pm}$ 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 $m_{\chi_1}$ and $m_{\tilde{\tau}}$ or $M_A$ or . . .
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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 $\text{BR}(b \rightarrow s\gamma)$ : 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 . . .

⇒ combination makes only sense if all parameters are connected!

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

**CMSSM/mSUGRA:**


[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]

**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]

**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]

**Finite Unified Theories:**  [S.H., M. Mondragón, G. Zoupanos '07]

→ Myriam Mondragon's talk at SUSY 09
The models: 1.) CMSSM (or 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
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 $\mu$
Different methods:

1.) Scanning:
- 3-dim scans (possibly with CDM fixing one dimension)
- multi-dim scans
  [O. Buchmueller et al. '07] [S.H., X. Miao, S. Su, G. Weiglein '08]
- multi-dim scans (with Markov Chain Monte Carlo technique)
  [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] [O. Buchmueller et al. '08][... others ...]
⇒ here: results using last one

2.) Fitting:
- Frequentist
  [O. Buchmueller et al. '07, '08] [S.H., X. Miao, S. Su, G. Weiglein '08]
- Bayesian
  [R. Ruiz de Austri, R. Trotta and L. Roszkowski '06, '07]
  [B. Allanach, C. Lester and A. Weber '06, '07][... others ...]
⇒ focus on Frequentist here

3.) Priors ... (none)
\( \chi^2 \) calculation:

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

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

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

→ especially important: \( M_h \)
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:

\[ e^+ e^- \rightarrow Z h, Z H \]

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

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

\[ e^+ e^- \rightarrow A h, A H \]

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

\[ \sigma_{HA} \propto \sin^2(\beta - \alpha_{\text{eff}}) \sigma_{hZ}^{\text{SM}} \]
Constraints from the Higgs search at LEP [LEP Higgs Working Group '06]

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):

$m_h > 92.8$ GeV
(expected: 94.9 GeV), 95% C.L.

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

![CMSSM and NUHM1 comparison](image-url)
In CMSSM:
SM bound of $M_H$ search can be used [LEP Higgs Working Group '03]

$CL_s$ can be used/transferred 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 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

Interested in MSSM Higgs physics? Try our code FeynHiggs
www.feynhiggs.de

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

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

$\Rightarrow$ take into account the LEP SM Higgs bound . . .

. . . but shifted according to the reduced coupling

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

$\Rightarrow \chi^2$ 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

$\Rightarrow$ LHC/ILC reach

$\rightarrow$ not yet existing results in Henning Flächer’s talk at SUSY 09
Best-fit points:

**CMSSM:**

\[ m_{1/2} = 310 \text{ GeV}, \quad m_0 = 60 \text{ GeV}, \quad A_0 = 240 \text{ GeV}, \]
\[ \tan \beta = 11, \quad \mu = 380 \text{ GeV}, \quad M_A = 410 \text{ GeV} \]

\[ \chi^2/N_{\text{dof}} = 20.4/19 \ (37.3 \ % \ \text{probability}) \]

⇒ very similar to SPS 1a :-)

**NUHM1:**

\[ m_{1/2} = 240 \text{ GeV}, \quad m_0 = 100 \text{ GeV}, \quad A_0 = -930 \text{ GeV}, \]
\[ \tan \beta = 7, \quad \mu = 870 \text{ GeV}, \quad M_A = 300 \text{ GeV} \]

(39 % probability)
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!

Sven Heinemeyer, BSM/LHC '09 (pre-SUSY 09), 06/03/2009
LHC (CMS):

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

⇒ excellent prospects even with lower luminosity!

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

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

jets + MET (CMS)

Sven Heinemeyer, BSM/LHC '09 (pre-SUSY 09), 06/03/2009
LHC (CMS) reach with 1 fb$^{-1}$: NUHM1 analysis

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

- jets + MET (CMS)
- 0 lepton + 4 jets (ATLAS)
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$\tau_1$ LSP

$m_{1/2}$ [GeV]

$1$/fb

$\Rightarrow$ excellent prospects in various channels!

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LHC (CMS): NUHM1 analysis

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

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

$\tilde{\tau}_1 \text{ LSP}$

$\Rightarrow$ excellent prospects even with lower luminosity!
Masses for best-fit points:

\[
\begin{array}{c}
\text{CMSSM} \\
\end{array}
\]

\[
\begin{array}{c}
\text{NUHM1} \\
\end{array}
\]

⇒ largely accessible spectrum for LHC and ILC

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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):

\[ (m_0, m_{1/2}) \]

\[ \Rightarrow \text{strong impact of } (g-2)_\mu \]

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

$\Delta (g-2)$

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

-strong improvement possible from $M_W$, $\text{BR}(b \rightarrow s\gamma)$, $(g-2)_\mu$, $\text{BR}(B_u \rightarrow \tau\nu)$
Predictions for $\text{BR}(B_s \to \mu^+\mu^-)$:

CMSSM:

$\Rightarrow$ similar to SM

$\Rightarrow$ accessible at LHCb
Predictions for $\text{BR}(B_s \rightarrow \mu^+\mu^-)$:

**NUHM1:**

$\Rightarrow$ much larger than in the CMSSM possible

$\Rightarrow$ accessible at the Tevatron(?) / LHCb
Prediction for $M_h$:

(LEP bounds not included!)

CMSSM:

⇒ LEP bound relatively easily avoided
Prediction for $M_h$:

(LEP bounds not included!)

NUHM1:

$\Rightarrow M_h > 114.4 \text{ GeV}$ appears naturally
5. 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,
  $\tan \beta = 11$, $\mu = 380$ GeV, $M_A = 410$ GeV
  $\Rightarrow$ very similar to SPS 1a :-)
  Prediction of $M_h$ (no LEP bound): $M_h = 109 \pm 6 \pm 3$ GeV (prelim.!) 
  NUHM1: $m_{1/2} = 240$ GeV, $m_0 = 100$ GeV, $A_0 = -930$ GeV,
  $\tan \beta = 7$, $\mu = 870$ GeV, $M_A = 300$ GeV
  Prediction of $M_h$ (no LEP bound): best fit: $M_h \approx 120$ GeV (prelim.!) 
- **95% C.L. areas**: mostly covered with $\sim 1$ fb$^{-1}$ (u.d.!) 
  $\Rightarrow$ early LHC data could be very conclusive!
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- **Best-fit points**:
  
  **CMSSM**: $m_{1/2}$, $\tan \beta$, $\mu$, $M_A$ 
  
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