SUSY Predictions for the LHC and the ILC

Sven Heinemeyer, IFCA (CSIC, Santander)

DESY Hamburg, 06/2010

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

1. Introduction and motivation
2. The models and the tools
3. Prediction of the lightest Higgs boson mass $M_h$
4. Testing SUSY with $m_t$ and $M_W$
5. LHC/ILC reach in the CMSSM/NUHM1
6. 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 . . . )
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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 . . .
Supersymmetry (SUSY): Symmetry between

\[ \text{Bosons} \leftrightarrow \text{Fermions} \]

\[ Q |\text{Fermion}\rangle \rightarrow |\text{Boson}\rangle \]
\[ Q |\text{Boson}\rangle \rightarrow |\text{Fermion}\rangle \]

Simplified examples:

\[ Q |\text{top, } t\rangle \rightarrow |\text{scalar top, } \tilde{t}\rangle \]
\[ Q |\text{gluon, } g\rangle \rightarrow |\text{gluino, } \tilde{g}\rangle \]

⇒ each SM multiplet is enlarged to its double size

Unbroken SUSY: All particles in a multiplet have the same mass

Reality: \( m_e \neq m_{\tilde{e}} \Rightarrow \text{SUSY is broken} \ldots \)

\ldots via soft SUSY-breaking terms in the Lagrangian (added by hand)

\textbf{SUSY} particles are made heavy: \( M_{\text{SUSY}} = \mathcal{O}(1 \text{ TeV}) \)
**Supersymmetry: Motivation**

The SM is in a pretty good shape.

Why MSSM? (Is it worth to double the particle spectrum?)

1.) Stability of the Higgs mass against higher-order corr.
2.) Unification of gauge couplings: Not possible in the SM, but in the MSSM (although it was not designed for it.)
3.) Spontaneous symmetry breaking via Higgs mechanism is automatic in SUSY GUTs
4.) SUSY provides CDM candidate
5.) …

![Unification of the Coupling Constants in the SM and the minimal MSSM](image)

[Amaldi, de Boer, Fürstenau '92]
The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

\[ [u, d, c, s, t, b]_{L,R} \quad [e, \mu, \tau]_{L,R} \quad [\nu_e, \mu, \tau]_L \quad \text{Spin } \frac{1}{2} \]

\[ [\tilde{u}, \tilde{d}, \bar{c}, \bar{s}, \bar{t}, \bar{b}]_{L,R} \quad [\tilde{e}, \tilde{\mu}, \tilde{\tau}]_{L,R} \quad [\tilde{\nu}_e, \mu, \tau]_L \quad \text{Spin } 0 \]

\[ g \quad W^\pm, H^\pm \quad \gamma, Z, H^0_1, H^0_2 \quad \text{Spin } 1 / \text{Spin } 0 \]

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

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales

→ CPV will mostly be neglected throughout this talk!
\( \bar{t}/\bar{b} \) sector of the MSSM: (scalar partner of the top/bottom quark)

Stop, sbottom mass matrices \( (X_t = A_t - \mu^*/\tan \beta, \ X_b = A_b - \mu^* \tan \beta) \):

\[
M_{\tilde{t}}^2 = \begin{pmatrix}
M_{\tilde{t}L}^2 + m_t^2 + DT_{t1} & m_t X_t^* \\
m_t X_t & M_{\tilde{t}R}^2 + m_t^2 + DT_{t2}
\end{pmatrix} \to \begin{pmatrix}
m_{\tilde{t}1}^2 & 0 \\
0 & m_{\tilde{t}2}^2
\end{pmatrix}
\]

\[
M_{\tilde{b}}^2 = \begin{pmatrix}
M_{\tilde{b}L}^2 + m_b^2 + DT_{b1} & m_b X_b^* \\
m_b X_b & M_{\tilde{b}R}^2 + m_b^2 + DT_{b2}
\end{pmatrix} \to \begin{pmatrix}
m_{\tilde{b}1}^2 & 0 \\
0 & m_{\tilde{b}2}^2
\end{pmatrix}
\]

mixing important in stop sector (also in sbottom sector for large \( \tan \beta \))

soft SUSY-breaking parameters \( A_t, A_b \) also appear in \( \phi-\bar{t}/\bar{b} \) couplings

\[
SU(2) \text{ relation } \Rightarrow M_{\tilde{t}L} = M_{\tilde{b}L}
\]

\( \Rightarrow \) relation between \( m_{\tilde{t}1}, m_{\tilde{t}2}, \theta_{\bar{t}}, m_{\tilde{b}1}, m_{\tilde{b}2}, \theta_{\bar{b}} \)
Enlarged Higgs sector: Two Higgs doublets

\[
\begin{align*}
H_1 &= \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix} \\
H_2 &= \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}
\end{align*}
\]

\[V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) + \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2\]

Gauge couplings, in contrast to SM

Physical states: \(h^0, H^0, A^0, H^\pm\)

Goldstone bosons: \(G^0, G^\pm\)

Input parameters: (to be determined experimentally)

\[\tan \beta = \frac{v_2}{v_1}, \quad M_A^2 = -m_{12}^2 (\tan \beta + \cot \beta)\]
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 ), . . .</td>
<td>( \text{SM, MSSM, . . .} )</td>
</tr>
</tbody>
</table>

⇓

Test of theory at quantum level: Sensitivity to loop corrections

\[ X \]

⇓

⇒ Information about unknown parameters

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

Theoretical prediction for $M_W$ in terms of $M_Z, \alpha, G_\mu, \Delta r$:

$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{\pi \alpha}{\sqrt{2} G_\mu} (1 + \Delta r)$$

⇑

loop corrections

→ can be approximated with the $\rho$-parameter:

$\rho$ measures the relative strength between neutral current interaction and charged current interaction

$$\rho = \frac{1}{1 - \Delta \rho}, \quad \Delta \rho = \frac{\Sigma_Z(0)}{M_Z^2} - \frac{\Sigma_W(0)}{M_W^2}, \quad \Delta M_W \approx \frac{M_W}{2} \frac{c_W^2}{c_W^2 - s_W^2} \Delta \rho$$

(leading, process independent terms)
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$\Delta \rho^{\text{SUSY}}$ from $\tilde{t}/\tilde{b}$ loops $> 0 \quad \Rightarrow M_W^{\text{SUSY}} \gtrsim M_W^{\text{SM}}$
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 $M_H^{SM}$
Example: Prediction for $M_W$ in the SM and the MSSM:


Experimental errors 68% CL:
- LEP2/Tevatron (today)

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

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Sven Heinemeyer, Theoretical Physics Seminar (DESY Hamburg), 23.06.2010
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![Graph showing prediction for $M_W$ in SM and MSSM](image)

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Heinemeyer, Hollik, Stockinger, Weber, Weiglein
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**Diagram:**

- Experimental errors 68% CL:
  - LEP2/Tevatron (2006/A)

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Global fit to all SM data:

[LEPEWWG '09]

$\Rightarrow \ M_H = 87^{+35}_{-26}\ GeV$

$M_H < 157 \ GeV, \ 95\% \ C.L.$

Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of Higgs mechanism

$\Rightarrow$ Higgs boson seems to be light, $M_H \lesssim 160 \ GeV$
Global fit to all SM data incl. direct searches:

\[GFitter \ '09\]

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

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

Assumption for the fit:
SM incl. Higgs boson

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

\[\Rightarrow \text{Higgs boson seems to be light, } m_H \lesssim 150 \text{ GeV}\]
Main idea of analysis:

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/ILC reach
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) ?

$\Rightarrow$ combination of EWPO, BPO, CDM ?
2. The models and the tools

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- Electroweak precision observables (EWPO)?
- $B$ physics observables (BPO)?
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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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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 $\text{BR}(b \rightarrow s\gamma)$: information on $\tan \beta$ and/or $M_{H^\pm}$ and/or $m_{\tilde{t}}$, $m_{\tilde{\chi}_\pm}$

CDM (LSP gives CDM): information on $m_{\tilde{\chi}^-_{1}}$ 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] [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, 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]
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
⇒ $\chi^2$ function to include all experimental results

3.) Priors ... (none)
χ² calculation:

→ global χ² 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: \( \Delta \alpha_{had}, m_t, M_Z \)
\( C_i \): experimentally measured value (constraint)
\( P_i \): MSSM parameter-dependent prediction for the corresponding constraint

Assumption: measurements are uncorrelated - fulfilled to a high degree
$\chi^2$ calculation:

$\rightarrow$ global $\chi^2$ likelihood function
combines all theoretical predictions with experimental constraints:

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

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What to do if only a lower/upper bound exists?

$\rightarrow$ especially important: $M_h$ → backup
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

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

\[ q \sim l \sim H \sim g \sim W \sim B \]

⇒ 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:

- 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

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
  
  ($\rightarrow$ similar directions as SFitter, Fittino)

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

− planned: inclusion of more tools

  inclusion of more models
3. Constraining the lightest MSSM Higgs mass $M_h$

Contrary to the SM: $M_h$ is not a free parameter

MSSM tree-level bound: $M_h < M_Z$, excluded by LEP Higgs searches

Large radiative corrections:

Dominant one-loop corrections:

$$\Delta M_h^2 \sim G_\mu m_t^4 \log \left( \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \right)$$

The MSSM Higgs sector is connected to all other sector via loop corrections (especially to the scalar top sector)

Measurement of $M_h$, Higgs couplings $\Rightarrow$ test of the theory

LHC: $\Delta M_h \approx 0.2$ GeV
ILC: $\Delta M_h \approx 0.05$ GeV

$\Rightarrow$ $M_h$ will be (the best?) electroweak precision observable
Fit of $M_h$ in Supersymmetry?
Fit of $M_h$ in Supersymmetry?

Advantages of fits in the MSSM vs. SM

- $(g - 2)_\mu$ can be used as a constraint
- Cold Dark Matter can be used as a constraint
- $\text{BR}(B_s \to \mu^+\mu^-)$ can be used as a constraint
- $M_h$ can be predicted from other parameters
  \[ \Rightarrow \text{stronger constraints possible} \]
Fit of $M_h$ in Supersymmetry?

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- many independent mass scales
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  $\Rightarrow$ more difficult to disentangle effects
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Note: LEP limits on $M_h$ are not included in this (part of the) fit
Prediction of $M_h$ in the CMSSM/NUHM1

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

General idea:

Take the most simple MSSM version: CMSSM/NUHM1
→ just three/four GUT scale parameters + tan $\beta$
Prediction of $M_h$ in the CMSSM/NUHM1

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

General idea:

Take the most simple MSSM version: CMSSM/NUHM1
→ just three/four GUT scale parameters + tan $\beta$

– combine all electroweak precision data as in the SM (i.e. not $M_h$)
– combine with $B$ physics observables
– combine with CDM and $(g - 2)_\mu$
– include SM parameters with their errors: $m_t$, ...

– scan over the full CMSSM/NUHM1 parameter space
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$\Rightarrow$ preferred $M_h$ values
CMSSM: red band plot:

\[ M_h = 108 \pm 6 \text{ (exp)} \pm 1.5 \text{ (theo)} \text{ GeV} \]
$M_h = 121^{+1}_{-14} \, \text{(exp)} \pm 1.5 \, \text{(theo)} \, \text{GeV} \quad \Rightarrow \text{naturally above LEP limit}$
Prediction of $M_{H}^{SM}$ (blue band) and $M_{h}$ in the MSSM (red band):

$$M_{h}^{CMSSM} = 108 \pm 6 \pm 1.5 \text{ GeV}$$

⇒ as good as the SM

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

⇒ above the LEP limit
4. Testing SUSY with $m_t$ and $M_W$

Sensitive test of any model:

Fit $m_t$ and/or $M_W$ and compare with experimental values:

$$m_t^{\text{exp}} = 173.1 \pm 1.3 \text{ GeV}$$
$$M_W^{\text{exp}} = 80.399 \pm 0.023 \text{ GeV}$$

[LEPEWWG '09]
[TevEWWG '09]

$$m_t^{\text{fit,SM,excl.}} = 172.6^{+13.3}_{-10.2} \text{ GeV}$$
$$m_t^{\text{fit,SM,incl.}} = 179.3^{+11.6}_{-8.5} \text{ GeV}$$
$$M_W^{\text{fit,SM,excl.}} = 80.363 \pm 0.032 \text{ GeV}$$
$$M_W^{\text{fit,SM,incl.}} = 80.364 \pm 0.020 \text{ GeV}$$

$\Rightarrow$ non-trivial success of the SM
$\Rightarrow$ quantum corrections up to two-loop needed
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 $M^\text{SM}_H$
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 $M_H^{SM}$
$M_W$ fit: $M_W$ not included, $m_t$ fit: $m_t$ not included

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

⇒ CMSSM and NUHM1 fit amazingly well $m_t$ and $M_W$
⇒ better than the SM: smaller errors, better best-fit points
5. LHC/ILC reach in the CMSSM/NUHM1

[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
$\Rightarrow L_{\text{SUSY}}$

$\Rightarrow$ LHC/ILC reach
Best-fit points:

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

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

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

Hadronic search, 95% C.L. curves

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

 ⇒ best-fit point and part of 68% C.L. are can be tested in 2011
**LHC (CMS) ⊕ NUHM1 analysis:**

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

**CMS preliminary**

\( \sqrt{s} = 7 \text{ TeV} \)

Hadronic search, 95% C.L. curves

- \( L = 1000/pb \)
- \( L = 100/pb \)

\( \tau_1 \, \text{LSP} \)

**Parameter space**

- 68% C.L.
- 95% C.L.

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

\( M_0 \) [GeV/c^2]

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

\[ \text{CMSSM analysis:} \]

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

\[ [2008] \]

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

\[ \text{jets + MET (CMS)} \]

\[ \text{excellent prospects even with lower luminosity!} \]

Sven Heinemeyer, Theoretical Physics Seminar (DESY Hamburg), 23.06.2010

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LHC (CMS) ⊕ NUHM1 analysis:

CMS '07

⇒ excellent prospects even with lower luminosity!

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

- 1/\text{fb} @ 14 \text{ TeV}
- 100/\text{pb} @ 14 \text{ TeV}
- 50/\text{pb} @ 10 \text{ TeV}
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
Some more predictions: $m_\tilde{g} - m_\tilde{q}_L$

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

$\Rightarrow$ 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 $1 \text{ fb}^{-1} \@ 7 \text{ TeV}$

**blue solid:** 95% C.L. exclusion with $1 \text{ fb}^{-1} \@ 7 \text{ TeV}$

$\Rightarrow$ 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

\[ 1-\text{CL} \]

\[ 0 \]

\[ 0.1 \]

\[ 0.2 \]

\[ 0.3 \]

\[ 0.4 \]

\[ 0.5 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 10^{-40} \]

\[ 10^{-41} \]

\[ 10^{-42} \]

\[ 10^{-43} \]

\[ 10^{-44} \]

\[ 10^{-45} \]

\[ 10^{-46} \]

\[ 10^{-47} \]

\[ 10^{-48} \]

\[ 0 \]

\[ 10^1 \]

\[ 10^2 \]

\[ 10^3 \]

\[ m_{\chi_1}^0 [\text{GeV/c}^2] \]

\[ \sigma_p [\text{cm}^2] \]

\[ \text{CDMS: 2004+2005 (reanalysis) +2008 Ge} \]

\[ \text{XENON10 2007 (Net 136 kg-d)} \]

\[ \text{SuperCDMS (Projected) 25kg (7-ST@Snolab)} \]

⇒ only partially covered by future experiments
6. 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): $M_h = 108 \pm 6 \pm 1.5$ GeV
  - **NUHM1:** $m_{1/2} = 270$ GeV, $m_0 = 150$ GeV, $A_0 = -1300$ GeV,
    $\tan \beta = 11$, $\mu = 1140$ GeV, $M_A = 310$ 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.!) 
  - $\Rightarrow$ 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:
\[ e^+ e^- \rightarrow ZH: \]

\[ e^- \quad \rightarrow \quad Z \quad \rightarrow \quad H \]

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

\[ H \quad \rightarrow \quad b \quad \rightarrow \quad b \]

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

\[ e^+ e^- \rightarrow Z_h, Z_H \]

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

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

\[ e^+ e^- \rightarrow A_h, A_H \]

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

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

$\delta M_{h^0} \approx 3$ 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
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) reach with 1 fb$^{-1}$: NUHM1 analysis

[MasterCode '08] [CMS '07]

⇒ excellent prospects in various channels!