From “The Big Bang Theory”:
(episode 15/01)

Sister: I am always bragging to my friends about my brother, the rocket scientist.
Sheldon: You tell people I am a rocket scientist?
Sister: Well, yeah.
Sheldon: I am a theoretical physicist.
Sister: What is the difference?
Sheldon: What is the difference?
...
My god! Why don’t you just tell them that I am a toll taker at the Golden Gate bridge?
Rocket scientist... how humiliating!
HiggsBounds:
Limits on SUSY and other BSM Higgs sectors from LEP/Tevatron data

Sven Heinemeyer, IFCA (CSIC, Santander)

Boston, 06/2009

based on collaboration with
P. Bechtle, O. Brein, G. Weiglein and K. Williams

1. Introduction and motivation
2. The code HiggsBounds
3. Results
4. Conclusions
1. Introduction and motivation

Current status of knowledge: the Standard Model (SM)

⇒ all particles experimentally seen

Sven Heinemeyer, SUSY 09, 06/07/2008  http://www.ipp.dur.ac.uk/HiggsBounds
1. Introduction and motivation

Current status of knowledge: the Standard Model (SM)

⇒ all particles experimentally seen

⇒ but one particle is missing . . .
Solution in the SM: add one complex $SU(2)$ doublet $\Phi$

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$ (unitary gauge)

$H$: elementary scalar field, Higgs boson

Lagrange density:

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi)$$

$$- g_d \bar{Q}_L \Phi d_R - g_u \bar{Q}_L \Phi_c u_R$$

$$- V(\Phi)$$

with

$$iD_\mu = i\partial_\mu - g_2 \bar{\nabla}_\mu - g_1 Y B_\mu$$

$$\Phi_c = i\sigma_2 \Phi^\dagger$$

$$Q_L \sim \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \Phi \sim \begin{pmatrix} 0 \\ v \end{pmatrix}, \Phi_c \sim \begin{pmatrix} v \\ 0 \end{pmatrix}$$

Gauge invariant coupling to gauge fields

$\Rightarrow$ mass terms for gauge bosons and fermions
MSSM: Enlarged Higgs sector: Two Higgs doublets

\[
H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}
\]

\[
H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}
\]

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

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)

\[
\tan \beta = \frac{v_2}{v_1}, \quad M_A^2 = -m_{12}^2 (\tan \beta + \cot \beta)
\]
Other possibilities:

- **2HDM:**
  like SM, but two Higgs doublets
  like MSSM, but without SUSY restrictions/particles

- **NMSSM:**
  MSSM with additional Higgs singlet

- **Little Higgs models:**
  new particles, modified couplings

- **4th gen. model:**
  like SM, but with different (effective) Higgs couplings

- **many more options** (just check this conference!)
Experimental search for the Higgs(es):

- The search for Higgs bosons is a major cornerstone in the effort to unravel the nature of electroweak symmetry breaking

- So far: no Higgs signals.
  - LEP searched for them.
  - Tevatron is currently searching for them.

- Tevatron and LEP turn(ed) the non-observation of Higgs signals into 95% C.L. limits on rates/cross sections of ...
  a) ... individual signal topologies,
     e.g. $e^+e^- \rightarrow h_i Z \rightarrow b\bar{b}Z$, $p\bar{p} \rightarrow h_i \rightarrow W^+W^-$,
  b) ... combinations of signal topologies
     e.g. SM, MSSM combined limits.
Example 1: LEP SM combined limit

\[ S_{95}(m_{H1}) := \frac{\sigma_{\text{max}}(m_{H1})}{\sigma_{\text{SM}}(m_{H1})} \]

where \( \sigma_{\text{max}}(m_{H1}) \) is the maximal Higgs production cross section compatible with the background-only hypothesis at 95% C.L.

A SM-like model with
\[ \sigma_{\text{model}}(m_{H1}) > \sigma_{\text{max}}(m_{H1}) \]
or
\[ \sigma_{\text{model}}(m_{H1})/\sigma_{\text{max}}(m_{H1}) > 1 \]
is said to be excluded at the 95% C.L.

[LEP Higgs WG '03]
Example 2: LEP single topology limits, assuming $HZ$ production and . . .

$$BR(H \rightarrow b\bar{b}) = 1$$

$$BR(H \rightarrow \tau^+\tau^-) = 1$$

[Sven Heinemeyer, SUSY 09, 06/07/2008](http://www.ipp.dur.ac.uk/HiggsBounds)

[LEP Higgs WG '03]
Example 3: DØ limit on all SM limits combined:

DØ Preliminary, $L=0.9-4.2 \text{ fb}^{-1}$

SM Higgs Combination

95% CL Limit / SM

Observed Limit

 Expected Limit

 Expected ±1-σ

 Expected ±2-σ

Standard Model = 1.0

March 5, 2009

[DØ '09]

Sven Heinemeyer, SUSY 09, 06/07/2008 http://www.ipp.dur.ac.uk/HiggsBounds
Example 4: Tevatron combined (CDF/DØ) limit on SM Higgs:

Tevatron Run II Preliminary, L=0.9-4.2 fb$^{-1}$

LEC Exclusion

Expected
Observed
±1σ Expected
±2σ Expected

SM

March 5, 2009

[CD, DØ '09]

Sven Heinemeyer, SUSY 09, 06/07/2008  http://www.rippp.dur.ac.uk/HiggsBounds
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a) ... individual signal topologies,  
   e.g. $e^+e^- \rightarrow h_i Z \rightarrow b\bar{b}Z$, $p\bar{p} \rightarrow h_i \rightarrow W^+W^-$, 

b) ... combinations of signal topologies  
   e.g. SM, MSSM combined limits.

**Idea:** Use those limits to constrain the parameter space of (arbitrary) new physics models.
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Solution:

HiggsBounds

www.ippp.dur.ac.uk/HiggsBounds

[P. Bechtle, O. Brein, S.H., G. Weiglein, K. Williams '08]
2. The code HiggsBounds

Test theoretical predictions of models with arbitrary Higgs sectors against exclusion bounds obtained from Higgs searches at LEP and the Tevatron.

Advantages:

- **Easy access** to all relevant Higgs exclusion limits
- Applicable to models with **arbitrary Higgs sectors**
- Possibility to **combine results from LEP and Tevatron**
2. The code HiggsBounds

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Advantages:

- Easy access to all relevant Higgs exclusion limits
- Applicable to models with arbitrary Higgs sectors
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Disadvantages:

None (first and only program of this type)
HiggsBounds:

Limitations:

no charged Higgs limits included yet - work in progress
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Comparison with full experimental analysis:

Experimental analysis can combine all available channels to test one point
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Comparison with full experimental analysis:

Experimental analysis can combine all available channels to test one point

HiggsBounds has to do the following to obtain exclusion at the 95% C.L. exclusion bound:

1.) determine for a parameter point to be tested the best channel
   (the one with the best exclusion potential)
   \[ \frac{\sigma \times BR}{\text{input}} / \frac{\sigma \times BR}{\text{expected}} \]

2.) check only this channel
   \[ \frac{\sigma \times BR}{\text{input}} / \frac{\sigma \times BR}{\text{observed}} > 1 \quad \Leftrightarrow \text{excluded} \]

\[ \frac{\sigma \times BR}{\text{input}}: \text{user input} \]
\[ \frac{\sigma \times BR}{\text{expected}}, \frac{\sigma \times BR}{\text{observed}}: \text{experimental data} \]
HiggsBounds input: required from the user:

HiggsBounds requires the following input:
the predictions of the model (the parameter point to be tested) for:

- # of Higgs bosons $h_i$
- Higgs boson masses $m_{h_i}$
- total decay widths $\Gamma_{\text{tot}}(h_i)$

- normalized effective Higgs couplings squared, $\text{BR}(h_i \to h_j h_k)$

or

- normalized LEP XS, normalized partonic Tevatron XS, BRs

or

- normalized LEP XS, normalized hadronic Tevatron XS, BRs

If a channel is not provided $\Rightarrow$ assumed to be zero
HiggsBounds input: required from the user (II):

normalized means “divided by the SM equivalent” (where it exists, see manual for details)

Narrow width approximation is assumed to hold
→ width effects are currently being investigated
→ inclusion in the mid-term future

Easy input via publicly available codes in the MSSM:
link to FeynHiggs available

www.feynhiggs.de
**LEP limits:**

We include expected and observed $S_{95}$ values for the following search channels *[LEP Higgs WG ’03]*

1. $e^+e^- \rightarrow (h_k)Z \rightarrow (b\bar{b})Z$,
2. $e^+e^- \rightarrow (h_k)Z \rightarrow (\tau^+\tau^-)Z$,
3. $e^+e^- \rightarrow (h_k \rightarrow h_i h_i)Z \rightarrow (b\bar{b}b\bar{b})Z$,
4. $e^+e^- \rightarrow (h_k \rightarrow h_i h_i)Z \rightarrow (\tau^+\tau^-\tau^+\tau^-)Z$,
5. $e^+e^- \rightarrow (h_k h_i) \rightarrow (b\bar{b}b\bar{b})$,
6. $e^+e^- \rightarrow (h_k h_i) \rightarrow (\tau^+\tau^-\tau^+\tau^-)$,
7. $e^+e^- \rightarrow (h_k \rightarrow h_i h_i)h_i \rightarrow (b\bar{b}b\bar{b})b\bar{b}$,
8. $e^+e^- \rightarrow (h_k \rightarrow h_i h_i)h_i \rightarrow (\tau^+\tau^-\tau^+\tau^-)\tau^+\tau^-$,
9. $e^+e^- \rightarrow (h_k \rightarrow h_i h_i)Z \rightarrow (b\bar{b})(\tau^+\tau^-)Z$,
10. $e^+e^- \rightarrow (h_k \rightarrow b\bar{b})(h_i \rightarrow \tau^+\tau^-)$,
11. $e^+e^- \rightarrow (h_k \rightarrow \tau^+\tau^-)(h_i \rightarrow b\bar{b})$,

Inclusion of additional channels, e.g. with $h_k \rightarrow$ invisible, is work in progress.
**Tevatron limits:** At the moment, the following analyses of Higgs production signatures by CDF and DØ have been included in HiggsBounds:

<table>
<thead>
<tr>
<th>search topology $X$ (analysis)</th>
<th>reference</th>
</tr>
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<tbody>
<tr>
<td>$p\bar{p} \rightarrow ZH \rightarrow l^+l^-b\bar{b}$ (CDF with 1.0 fb$^{-1}$)</td>
<td>[CDF '08] *</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow ZH \rightarrow l^+l^-b\bar{b}$ (CDF with 2.4 fb$^{-1}$)</td>
<td>[CDF note 9475]</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow ZH \rightarrow l^+l^-b\bar{b}$ (DØ with 2.3 fb$^{-1}$)</td>
<td>[D0 note 5570]</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow WH \rightarrow l\nu b\bar{b}$ (DØ with 1.7 fb$^{-1}$)</td>
<td>[D0 note 5472]</td>
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<td>[CDF note 9463]</td>
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<tr>
<td>$p\bar{p} \rightarrow WH \rightarrow W^+W^-W^\pm$ (DØ with 1.0 fb$^{-1}$)</td>
<td>[D0 note 5485]</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow WH \rightarrow W^+W^-W^\pm$ (CDF with 1.9 fb$^{-1}$)</td>
<td>[CDF note 7307]</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow H \rightarrow W^+W^- \rightarrow l^+l^-$ (DØ with 3.0 fb$^{-1}$)</td>
<td>[D0 note 5757]</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow H \rightarrow W^+W^- \rightarrow l^+l^-$ (CDF with 3.0 fb$^{-1}$)</td>
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</tr>
<tr>
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<td>[D0 '08] *</td>
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<tr>
<td>$p\bar{p} \rightarrow H \rightarrow \gamma\gamma$ (DØ with 2.68 fb$^{-1}$)</td>
<td>[D0 note 5737]</td>
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<td>[D0 '08] *</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow H \rightarrow \tau^+\tau^-$ (CDF with 1.8 fb$^{-1}$)</td>
<td>[CDF note 9071]</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow bH, H \rightarrow b\bar{b}$ (CDF with 1.9 fb$^{-1}$)</td>
<td>[CDF note 9284]</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow bH, H \rightarrow b\bar{b}$ (DØ with 1.0 fb$^{-1}$)</td>
<td>[D0 '08] *</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow bH, H \rightarrow b\bar{b}$ (DØ with 2.6 fb$^{-1}$)</td>
<td>[D0 note 5726]</td>
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**Tevatron limits:** At the moment, the following analyses of Higgs production signatures by CDF and DØ have been included in HiggsBounds:

(Analyses combining topologies)

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<td>$p\bar{p} \rightarrow WH/ZH \rightarrow b\bar{b} + E_T^{\text{miss}}$ (CDF with 2.3 fb$^{-1}$)</td>
<td>[CDF note 9483]</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow WH/ZH \rightarrow b\bar{b} + E_T^{\text{miss}}$ (DØ with 2.1 fb$^{-1}$)</td>
<td>[DØ note 5586]</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow H/WH/ZH$ via VBF, $H \rightarrow \tau^+\tau^-$ (CDF with 2.0 fb$^{-1}$)</td>
<td>[CDF note 9248]</td>
</tr>
<tr>
<td>Combined SM analysis (CDF &amp; DØ with 0.9 - 1.9 fb$^{-1}$)</td>
<td>[hep-ex/0712.2383]</td>
</tr>
<tr>
<td>Combined SM analysis (CDF &amp; DØ with 1.0 - 2.4 fb$^{-1}$)</td>
<td>[hep-ex/0804.3423]</td>
</tr>
<tr>
<td>Combined SM analysis (CDF &amp; DØ with 3.0 fb$^{-1}$)</td>
<td>[hep-ex/0808.0534]</td>
</tr>
</tbody>
</table>

⇒ only applied if parameter point is sufficiently SM-like

⇒ New results from winter conferences 2009 are currently being included
How to run HiggsBounds:

1. Go to www.ippp.dur.ac.uk/HiggsBounds

2. Download the latest version

3. type ./configure
   
   make ⇒ HiggsBounds.exe is created
   
   or
   
   make libHB ⇒ library libHB.a is created

4. 3 possible ways to use HiggsBounds:

   A) Command-line mode
   B) called from a Fortran/C++ code
   C) WWW mode

   processing of Les Houches Accord data currently being implemented

5. Detailed instructions and help are provided in the hep-ph/0811.4169
3. Results

Application 1: reproducing the LEP exclusion limit

LEP bound ($m_h^{\text{max}}$)

HiggsBounds result

[LEP Higgs WG '03]

⇒ old result reproduced
⇒ Tevatron bounds included
Application 1: reproducing the LEP/Tevatron exclusion limit

\[ \tan \beta \]

\[ m_A \text{ [GeV]} \]

- Red: LEP exclusion
- Blue: Tevatron exclusion

- \( e^+ e^- \rightarrow hZ, h \rightarrow b\bar{b} \)
- \( e^+ e^- \rightarrow hA \rightarrow b\bar{b}b\bar{b} \)
- \( p\bar{p} \rightarrow h/A \rightarrow \tau^+\tau^- \)
- \( p\bar{p} \rightarrow h/H/A \rightarrow \tau^+\tau^- \)
- \( p\bar{p} \rightarrow H/A \rightarrow \tau^+\tau^- \)
- \( p\bar{p} \rightarrow hW \rightarrow b\bar{b}l\nu \)
- \( p\bar{p} \rightarrow H/A \rightarrow \tau^+\tau^- \)

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http://www.ippp.dur.ac.uk/HiggsBounds
⇒ strong impact of new contributions to $gg \rightarrow H$

[C. Anastasiou, R. Boughezal, F. Petriello ’08]

⇒ strong impact of new PDFs [MSTW ’08]
⇒ strong impact of PDF uncertainties \textit{[MSTW '08]}
(not included in Tevatron analysis)
Application 3: reevaluating the CPX hole(s) at LEP

**CPX:** benchmark scenario in the cMSSM

[M. Carena, J. Ellis, A. Pilaftsis, C. Wagner ’00]

The LEP analysis showed an unexcluded hole in the $m_{h_1}$–tan $\beta$ plane at $m_{h_1} \approx 45$ GeV, tan $\beta \approx 8$

New theoretical developments:

– phase dependent $O(\alpha_t \alpha_s)$ corrections to Higgs self-energies
  [S.H., W. Hollik, H. Rzehak, G. Weiglein ’07]

– phase dependent one-loop correction to $\Gamma(h_a \rightarrow h_b h_c)$
  [G. Weiglein, K. Williams ’08]

⇒ effects on CPX hole(s)?
Application 3: reevaluating the CPX hole(s) at LEP

\[ h_1 Z \to \bar{b} \bar{b} Z \]

\[ h_2 Z \to \bar{b} \bar{b} Z \]

\[ h_2 Z \to h_1 h_1 Z \to \bar{b} \bar{b} \bar{b} \bar{b} Z \]

\[ h_2 h_1 \to \bar{b} \bar{b} \bar{b} \]

\[ h_2 h_1 \to h_1 h_1 h_1 \to \bar{b} \bar{b} \bar{b} \bar{b} \bar{b} \bar{b} \]

\[ : \text{theor. inaccessible} \]

\[ : \text{excluded} \]

\[ : \text{not excluded} \]

\[ : \text{theor. inaccessible} \]

\[ \Rightarrow \text{hole(s) confirmed} \]
Application 4: 4th generation model

Assume the SM with a 4th generation of heavy fermions

Relevant changes:

1. additional contribution to $gg \rightarrow H$ :

\[ g \quad t \quad t \quad \rightarrow \quad H \quad + \quad g \quad t' \quad t' \quad \rightarrow \quad H \]

$\Rightarrow$ factor of $\sim 9$ in Higgs production cross section

2. additional contribution to $\Gamma(H \rightarrow gg)$
   $\Rightarrow$ reduced $\text{BR}(H \rightarrow b\bar{b})$
Application 4: 4th generation model

[P. Bechtle, O. Brein, S.H., G. Weiglein, K. Williams ’08]

⇒ only $110 \text{ GeV} \lesssim M_H \lesssim 140 \text{ GeV}, \ M_H \gtrsim 220 \text{ GeV}$ still allowed
⇒ will be tested very soon by the Tevatron

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4. Conclusions

- The Higgs boson:
  - cornerstone of the SM, MSSM and many other extensions
  - searched for: LEP (past), Tevatron (present), LHC (future)

- New code: HiggsBounds
  
  www.ippp.dur.ac.uk/HiggsBounds

- Features:
  - can be applied to any (neutral) Higgs sector
  - user input: # of Higgses, masses, effective couplings, ...
  - uses LEP and Tevatron exclusion data
  - determines strongest channel
  - tests point against this channel \( \Rightarrow 95\% \text{ C.L. exclusion limit} \)

- command line mode / called from Fortran/C++ code / on-line version

- Results:
  - old LEP results reproduced (now with LEP and Tevatron combined)
  - Tevatron \( gg \rightarrow H \rightarrow WW(*) \) results reproduced/"improved"
  - 4th generation model:
    only \( 110 \text{ GeV} \lesssim M_H \lesssim 140 \text{ GeV}, \ M_H \gtrsim 220 \text{ GeV} \) still allowed
Higgs Days at Santander 2009
Theory meets Experiment
14.-18. September

contact: Sven.Heinemeyer@cern.ch
http://www.ifca.es/HDays09

http://www.ippp.dur.ac.uk/HiggsBounds