Introduction to HiggsBounds

Tutorial and exercises

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Abstract

This tutorial introduces the use of **HiggsBounds** as a tool to study collider exclusion limits on Higgs sectors beyond the Standard Model. The reader becomes familiar with the SLHA and data files **HiggsBounds** input as well as the usage of the **HiggsBounds** subroutines. The first exercise studies the Higgs sector of the Minimal Supersymmetric Standard Model (MSSM), where the provided example parameter points exhibit a Higgs boson with a mass ~ 126 GeV. The second exercise elaborates upon the collider constraints on a SM-like Higgs boson with an additional decay mode to invisible particles.

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Introduction

`HiggsBounds` is a high energy physics software tool that combines theoretical model predictions (provided by the user) with experimental data on Higgs exclusion to provide collider limits on theories with extended Higgs sectors. The program works for theories with an extended number (< 10) of neutral and charged Higgs bosons where the narrow width approximation can be applied to separate predictions for Higgs production and decay. The current version of the program is `HiggsBounds-3.8.1`, which contains exclusion limits from LEP, the TEVATRON, and LHC7. An extension to include LHC8 results is on-going work and will be released shortly.

The program is freely available and can be downloaded from the webpage:

http://higgsbounds.hepforge.org

There is also a mailing list to which you can subscribe in order to receive information about updates:

http://www.hepforge.org/lists/listinfo/higgsbounds-announce

For more complete information about `HiggsBounds` — and how to use it — please consult the original manual [1].

Installation and Preparations

Download the `HiggsBounds-3.8.1` package from the website. Extract the `tar.gz` file via

```
tar xvzf HiggsBounds-3.8.1.tar.gz
```

This creates the directory `HiggsBounds-3.8.1` with the subdirectory `HiggsBounds`. Go to this subdirectory and open the file `configure` with your favorite text editor. Check the compiler settings. If you use `gfortran` make sure you have version 4.2 or higher installed. Then run on the command line

```
./configure
make
```

and verify that this produces the executable `HiggsBounds` as well as the file `libHB.a`. Before proceeding with the exercises, you need to download the tutorial package from

http://thp.uni-bonn.de/th/People/tim/HB/Cairo-tutorial.tar.gz

and unpack it in the main `HiggsBounds-3.8.1` directory. This creates a new directory called `tutorial`, where you find the files needed for the exercises.

Exercise 1: The MSSM with a Higgs boson at ~ 126 GeV

In this exercise we want to look at the constraints on the Higgs sector of the minimal supersymmetric standard model (MSSM) with real parameters.

Testing two SLHA files

In this first part, two parameter points provided as SLHA files are tested with `HiggsBounds`. The points chosen are of particular interest because they both feature one Higgs boson with mass $M_H \sim 126$ GeV, which is close to the signal discovered by ATLAS [2] and CMS [3] in July 2012. However, in the MSSM the Higgs decay rates into some channels can be enhanced or suppressed compared to the SM. Also, the MSSM features not one, but five, Higgs bosons. As a result there is a possibility that these models are excluded by Higgs searches. Let's find out!

You find the files specifying the two parameter points in the directory:

`tutorial/SLHA_examples/`

The spectra (given in the SLHA format) have been calculated with the program `FeynHiggs-2.9.0` [4]. The end of these two files consists of two special SLHA blocks,

`HiggsBoundsInputHiggsCouplingsBosons`

`HiggsBoundsInputHiggsCouplingsFermions`

which are needed by `HiggsBounds`.[1] These blocks contain the squared effective couplings (normalized to the SM values) to bosons and third generation fermions, respectively. They are needed to evaluate the production rates of the Higgs bosons at LEP, TEVATRON and LHC within `HiggsBounds`. In contrast, the branching ratios of the Higgs bosons are taken directly from the SLHA file.

Have a look at the two spectrum files and answer the following questions (for each case separately):

> *1. What are the masses of the three neutral Higgs bosons? What are their dominant and subdominant decay modes? Do you expect the collider phenomenology for any of the Higgs bosons to be similar to that of a* SM *Higgs boson at the same mass (similar production and decay rates)?*

Example1:

Masses: $m_h = 127.1$ GeV, $m_H = 202.6$ GeV, $m_A = 200.0$ GeV

Decay modes (dom.): $BR(h \to b\bar{b}) = 76.95\%$, $BR(H \to b\bar{b}) = 77.39\%$, $BR(A \to b\bar{b}) = 74.5\%$

Decay modes (subdom.): $BR(h \to WW) = 9.59\%$, $BR(H \to \tau\tau) = 10.57\%$, $BR(A \to \tilde{\chi}_1^0\tilde{\chi}_1^0) = 15.73\%$

[1] `HiggsBounds` provides the example program `HBSLHAinputblocksfromFH` which runs `FeynHiggs` on an SLHA input file and appends these extra blocks. Furthermore, some MSSM spectrum generators already write these blocks automatically, *e.g.* `SPheno` [5].

H-g-g coupling: $g^2_{hgg} = 0.813$, $g^2_{Hgg} = 0.224$, $g^2_{Agg} = 0.068$
H-Z-Z couplings: $g^2_{hZZ} = 0.991$, $g^2_{HZZ} = 0.015$, $g^2_{AZZ} = 0.000$
Example2:
Masses: $m_h = 99.3$ GeV, $m_H = 126.3$ GeV, $m_A = 106.0$ GeV
Decay modes (dom.): $BR(h \to b\bar{b}) = 86.75\%$, $BR(H \to WW) = 41.44\%$, $BR(A \to b\bar{b}) = 86.59\%$
Decay modes (subdom.): $BR(h \to \tau\tau) = 13.06\%$, $BR(H \to b\bar{b}) = 27.49\%$, $BR(A \to \tau\tau) = 13.22\%$
H-g-g coupling: $g^2_{hgg} = 0.956$, $g^2_{Hgg} = 0.981$, $g^2_{Agg} = 0.753$
H-Z-Z couplings: $g^2_{hZZ} = 0.036$, $g^2_{HZZ} = 0.974$, $g^2_{AZZ} = 0.000$

Now, let's run `HiggsBounds` on the command-line. In the directory `SLHA_examples` you can execute `HiggsBounds` with

```
../../HiggsBounds/HiggsBounds LandH SLHA 3 1 SLHA_example1.in
```

which runs `HiggsBounds` with the option `whichanalyses=LandH` (*i.e.* it considers results from both lepton and hadron colliders) using the SLHA input file `SLHA_example1.in`. The numbers (3 and 1) are to specify that `HiggsBounds` should expect three neutral Higgs bosons and one charged Higgs boson.

After a successful run, `HiggsBounds` appends the new SLHA block

`HiggsBoundsResults`

to the input file and creates the textfile `Key.dat` with a list of all Higgs searches which have been considered. Run `HiggsBounds` on both parameter points and have a look at the `HiggsBoundsResults` block.

> *2. Are these parameter points experimentally excluded at* 95% *CL? Which Higgs searches are the most sensitive (and thus applied)? Which of the* MSSM *Higgs bosons do these searches constrain? What happens if we instead use the setting* `whichanalyses=onlyL`*?*

Example1: (LandH)
not excluded, obsratio = 0.35
$(pp) \to h_1/VBF/Vh_1/t\bar{t}h_1 \to \tau\tau + \ldots$ where h_1 is SM-like (CMS PAS HIG-11-029)
Example2: (LandH)
not excluded, obsratio = 0.73
$(pp) \to h_2 + \ldots$ where h_2 is SM-like ((hep-ex) arxiv:1202.1408 (ATLAS))
Example1: (onlyL)
not excluded, obsratio = 0.0015
$(ee) \to h_1 Z \to (2\text{jets})Z$ (LHWG (unpublished))
Example2: (onlyL)
not excluded, obsratio = 0.13
$(ee) - > h_1 Z \to (b\bar{b})Z$ (hep-ex/0602042, table 14b (LEP))

In the parameter point `SLHA_example1.in`, the two neutral Higgs bosons H and A are almost mass degenerate around $M_H \simeq M_A \simeq 200$ GeV. An optional feature of `HiggsBounds` is to enable the superposition of the signal rates of those Higgs bosons which are close in mass. This makes sense when it is *a)* not possible to resolve two separate signal peaks experimentally, and *b)* interference effects can be neglected. Both these conditions are fulfilled here.

To activate this feature, open the file

`S95tables.f90`

in the `HiggsBounds` package and change the parameters `delta_Mh_LEP`, `delta_Mh_TEV` or `delta_Mh_LHC` to a non-zero value. `HiggsBounds` will then consider the superposition of neutral Higgs bosons which overlap within these values in LEP, TEVATRON or LHC Higgs searches, respectively, where a superposition is generally allowed. Note that after making changes to this file you have to recompile `HiggsBounds` with `make`.

> *3. Set `delta_Mh_LHC=10` GeV (keep the others at zero) and run `HiggsBounds` again for `SLHA_example1.in` (using the `LandH` setting). What is now the result?*

The parameter point is excluded with obsratio = 1.104 by $(pp) \to h_2 + h_3 \to \tau\tau$ (CMS PAS HIG-11-029).

Studying the $(\mathbf{m_A},\ \tan\beta)$ plane with data files input

In the second part of this exercise we want to run `HiggsBounds` on many points in the $(m_A,\ \tan\beta)$ parameter plane using the data files input format. You find the provided input files in the following directory:

`tutorial/mAtanb-example/`

The parameter points have been calculated with `FeynHiggs-2.9.4`. The fixed MSSM parameters are

$$M_{\text{SUSY}} = 1\ \text{TeV},\ X_t = 2.4\ \text{TeV},\ \mu = 1\ \text{TeV},\ M_1 = 100\ \text{GeV},\ M_2 = 200\ \text{GeV},\ M_3 = 800\ \text{GeV}.$$

All necessary data files for the effective couplings input approximation are provided. From the directory `tutorial/mAtanb-example/` `HiggsBounds` can be run, for instance using lepton and hadron collider constraints and the effective coupling input, as

```
../../HiggsBounds/HiggsBounds LandH effC 3 1 heavyHiggs_
```

This creates the files `heavyHiggs_HiggsBoundsResults.dat` and `heavyHiggs_Key.dat`. They contain the results of the `HiggsBounds` run. In the file `heavyHiggs_HiggsBoundsResults.dat` the scan parameters M_A and $\tan\beta$ are denoted as `additional(1)` and `additional(2)`, respectively.

> *4. Run `HiggsBounds` (with settings `LandH` and `effC`) on the provided data files, first not allowing the combination of Higgs bosons (i.e. change back to `delta_Mh_LHC=0 GeV`). Have a look at the `HiggsBounds` output files. Which Higgs bosons can potentially be combined in which parameter regions? Which Higgs boson might be the best candidate for the LHC signal at 126 GeV?*

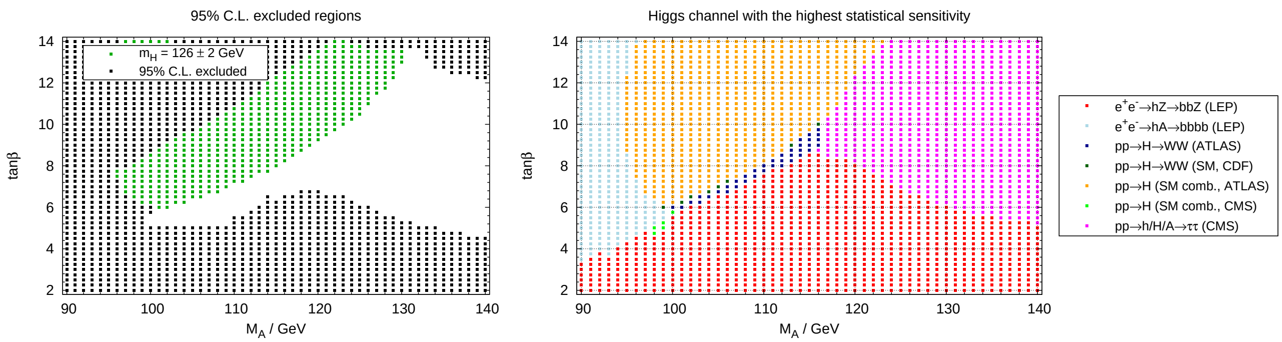

Figure 1: `HiggsBounds` results with `effC`, `LandH` and $\delta m_{h^0}^{LHC} = 0$ GeV.

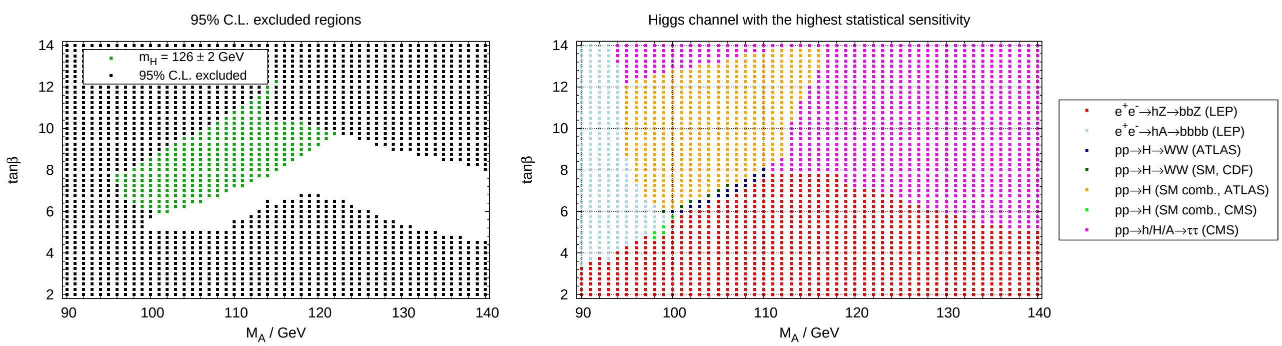

Figure 2: `HiggsBounds` results with `effC`, `LandH` and $\delta m_{h^0}^{LHC} = 10$ GeV.

5. Use the provided bash (gnuplot) script `plot.bat` *to plot the excluded parameter regions, the most sensitive Higgs channel and* `obsratio` *from the* `HiggsBounds` *results. Furthermore, indicate the parameter region where your prefered Higgs boson candidate has a mass value of* 126 ± 2 GeV *by green dots in the exclusion plot.*

6. Run `HiggsBounds` *again on the data files, now allowing the combination of Higgs bosons (i.e. changing again to* `delta_Mh_LHC=10 GeV`*). Create the same plots as in the previous exercise for the new results and compare them with the previous results. Which parameter region with a prefered mass value* $\sim 126 \pm 2$ GeV *is left unexcluded? Why can we infer already from the Higgs channel sensitivity plot that the Higgs candidate has roughly* SM*-like couplings in this region?*

4) Combinations (for $\delta m = 10$ GeV): h and A at larger values of $\tan\beta$. H and A for $m_A \gtrsim 116$ GeV. All three Higgs bosons for larger values of $\tan\beta$ and $m_A \approx 123 - 135$ GeV. Best Higgs candidate is H, but all three Higgs bosons can reach $m \sim 126$ GeV. The pseudoscalar Higgs boson A alone is not a good explanation of the LHC signal due to the $\gamma\gamma$ signal. In the whole scan region we have $m_H > 126$ GeV. The mass is lowest in the low m_A - high $\tan\beta$ region.

5) See Fig. 1.

6) See Fig. 2. It is SM-like since the combined search for the SM Higgs boson looking at $H \to WW, ZZ, \gamma\gamma$, applies (SM likeness test succeeds). This guarantees that at least in these signal topologies it is similar to the SM.

Further reading:

In this example we encountered the possibility of having the heavier CP-even Higgs boson of the MSSM with SM-like couplings and mass ~ 126 GeV. These interesting scenarios have been studied in Ref. [6]. The parameter plane studied in the second part of this exercise was investigated with `HiggsBounds-3.8.0` and a preliminary version of `HiggsSignals` in Ref. [7].

Exercise 2: Invisible Higgs decays

In this example of `HiggsBounds` application we are going to study the case of a single (SM-like) Higgs boson H with an invisible decay mode, such that $\mathrm{BR}(H \to \text{invisible})$ is anywhere between 0 and 1. This could be realized *e.g.* in models with additional light states χ that cannot be detected experimentally when $H \to \chi\chi$ decays are open. The presence of the invisible decay leads to a modification of the total Higgs decay width according to

$$\Gamma^H_{\text{tot}} = \frac{\Gamma^H_{\text{SM}}}{1 - \mathrm{BR}(H \to \text{invisible})}. \tag{1}$$

The size of the new branching ratio and its relation to the total width is in fact all the information necessary for `HiggsBounds` to reinterpret the existing limits from Higgs searches (usually performed for the SM Higgs) in models with such an invisible decay.

For this task we are going to use the program

```
tutorial/SMinv_example/HB_SMinv.F
```

which runs some `HiggsBounds` subroutines from the `HiggsBounds` library. It is compiled simply by giving the command (inside the `tutorial/SMinvisible` directory):

```
gfortran HB_SMinv.F -o HB_SMinv -L../../HiggsBounds -lHB
```

Open the code in your favorite editor, look at the different parts, and try to understand what they do. Running this program (no arguments are required) produces several output files named `inv-XX-results.dat`, where `XX` refers to the size of $\mathrm{BR}(H \to \text{invisible})$. These files contain tables of Higgs masses and the corresponding `HiggsBounds` output. A simple bash script running `gnuplot` to plot the output is available:

```
tutorial/SMinv_example/plot_SMinv.bat
```

Try to answer the questions below by changing the options, modifying and running the example program and plotting the results (possibly several times). Remember that you can use all the `HiggsBounds` output and the information in `Key.dat`.

1. *What mass range is excluded (at 95% confidence level) for a* SM *Higgs boson? How large can* $\mathrm{BR}(H \to \text{invisible})$ *be without modifying significantly the excluded mass range?*

2. *For what mass ranges is the exclusion limit determined by the* LEP *(*LHC*) experiements? Does this depend on the branching ratio of Higgs to invisible?*

3. *Can you think of a reason for the* stronger *exclusion of a Higgs around* $M_h = 90$ *GeV observed with a sizable invisible branching ratio compared to the pure* SM *case (no invisible decay)?*

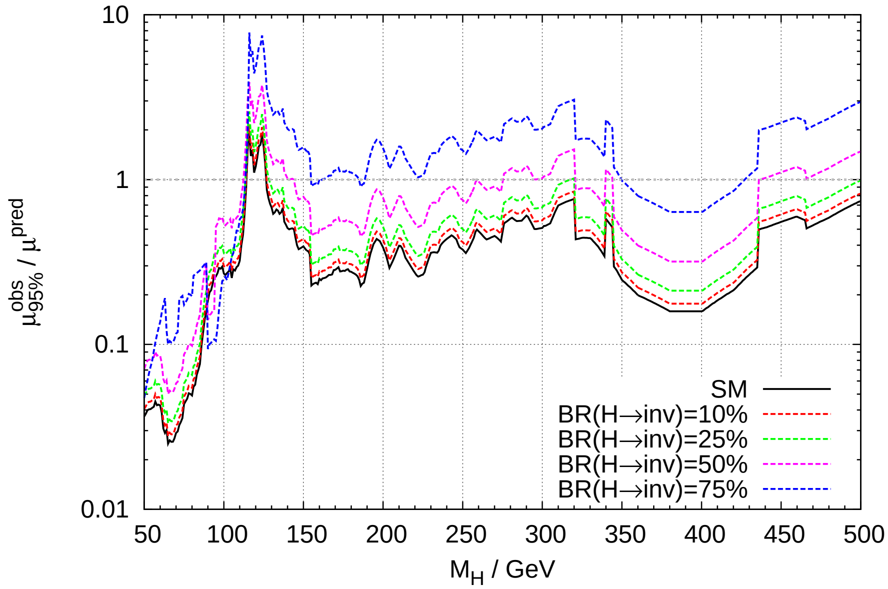

Figure 3: `HiggsBounds` results (showing 1/`obsratio`) for a SM-like Higgs boson with additional decay mode to an invisible final state.

1) The full range shown, except between 114.4 GeV and 126.5 GeV (note no July results!) The change is very small including up to 50% invisible decay.

2) LEP for $M_h \leq 115$ GeV ($M_h \leq 117$ GeV for 90% invisible), in SM case one bin of TEVATRON (116 GeV), then LHC. No big difference with/without invsible decay (but different LEP channels, Q3)

3) Dedicated search for $e^+e^- \to Z^* \to Zh$, with $h \to$ invisible possible by reconstructing recoil of visible Z in final state. More sensitive than usual $h \to b\bar{b}$ in this mass range.

References

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