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.

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Introduction

`HiggsBounds` is a generic software tool that combines theoretical model predictions (provided by the user) with experimental data for Higgs exclusion to provide collider limits on theories with extended Higgs sectors. The program works for theories with arbitrary numbers (< 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 `HiggsBounds` is 3.8.0, and it contains 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].

Preparations

Make sure you find the HiggsBounds installation on the Virtual Machine under

`/home/expert/HiggsBounds-3.8.0`

All paths in this document will be given relative to this directory. To compile the code, which generates the main `HiggsBounds` library, simply do

```
make
```

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

`http://www.desy.de/~stal/HBtutorial.tar.gz`

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

1 Invisible Higgs

In the first 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 BR($H \to$ invisible) is anywhere between 0 and 1. This could be realized *e.g.* in models with additional light states s that cannot be detected experimentally when $H \to ss$ decays are open. The presence of the invisible decay leads to a modification of the total Higgs decay width according to

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

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/HB_SMinv.F`

which is compiled simply by giving the command (inside the `tutorial/SMinv` directory)

```
gfortran HB_SMinv.F -o HB_SMinv -L/home/expert/HiggsBounds-3.8.0 -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 required) produces several output files named `inv-XX-results.dat`, where `XX` refers to the size of BR($H \to$ invisible). These files contain tables of Higgs masses and the corresponding `HiggsBounds` output. A basic plotting script (`ROOT`) using these results is available:

`tutorial/SMinv/HB_SMinv.C`

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 `Key.dat` (as discussed in the introductory slides). If you run into problems, please ask your instructor or a friend for advice!

1. What mass range is excluded (at 95% *confidence level) for a SM Higgs boson? How large can* BR($H \to$ 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)?*

2 MSSM with a 125 GeV Higgs

In this second example we want to have a first look at the Higgs sector of the minimal supersymmetric standard model (MSSM), by testing two parameter points with `HiggsBounds`. The points chosen are of particular interest because they both feature one Higgs boson with a mass $M_H \approx 125$ GeV close to the signal recently discovered by ATLAS [2] and CMS [3]. However, since in the MSSM the Higgs decay rates into some channels can be enhanced compared to the SM (while others are suppressed), and since the MSSM features not one, but five, Higgs bosons 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 mainly 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)?

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

```
../../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
```

[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].

to the input file and, as before, 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`*?*

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 (in the cases 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?*

References

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[5] W. Porod, Comput. Phys. Commun. **153** (2003) 275 [hep-ph/0301101]; W. Porod and F. Staub, Comput. Phys. Commun. **183** (2012) 2458 [arXiv:1104.1573 [hep-ph]]. See also `http://spheno.hepforge.org/`.