HiggsBounds and HiggsSignals
— Introduction and Tutorial —

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http://higgsbounds.hepforge.org/

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1. Introduction to HiggsBounds
   - Exclusion limits from Higgs collider searches
   - The HiggsBounds program
   - Current status and new developments for HiggsBounds-4
2. A preview of HiggsSignals
3. Final example and short summary
4. Live demonstration
5. Exercises

Introduction to HiggsBounds

HiggsBounds - a program's portrait

- *Current version*: `HiggsBounds 3.8.1`
- *Code language*: `Fortran90/2003` and `Fortran77` (*until* `HB 3.7.0`)
- *First release*: Feb. 2009
- *Authors*: P. Bechtle, O. Brein ('09-'12), S. Heinemeyer, O. Stål ('12-now), T. Stefaniak ('11-now), G. Weiglein, K. E. Williams ('09-'11)
- *Website*: http://higgsbounds.hepforge.org/ (with *online version*)
- *Short description*: HiggsBounds confronts arbitrary Higgs sectors with exclusion limits from direct Higgs searches at LEP, Tevatron and LHC.
- *References:*
  Comput. Phys. Commun. **181** (2010) 138;
  Comput. Phys. Commun. **182** (2011) 2605;
  arXiv:1301.2345 (2013).

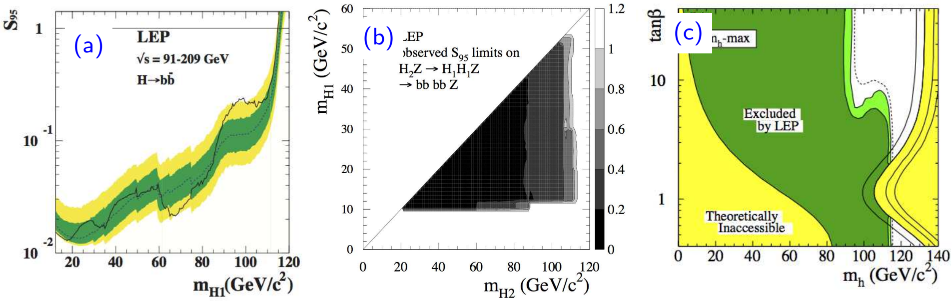
Higgs searches at LEP, Tevatron and LHC

Experiments publish their 95% C.L. exclusion results as

- model-independent cross section limit on a Higgs process, *e.g.* on

  (a) $e^+e^- \to HZ \to (b\bar{b})Z$ or (b) $e^+e^- \to H_2Z \to H_1H_1Z \to (b\bar{b})(b\bar{b})Z$

- excluded regions in a particular benchmark model (*e.g.* the $m_h^{\max}$ scenario, (c))



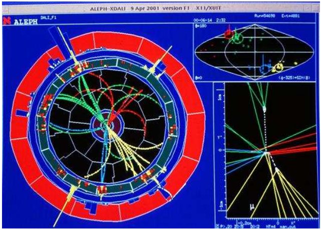
HiggsBounds idea: Use *model-independent limits* to constrain arbitrary Higgs models!

Higgsstrahlung:

1. $e^+e^- \to (h_k)Z \to (b\bar{b})Z$
2. $e^+e^- \to (h_k)Z \to (\tau^+\tau^-)Z$
3. $e^+e^- \to (h_k \to h_i h_i)Z \to (b\bar{b}b\bar{b})Z$
4. $e^+e^- \to (h_k \to h_i h_i)Z \to (\tau^+\tau^-\tau^+\tau^-)Z$
5. $e^+e^- \to (h_k \to h_i h_i)Z \to (b\bar{b})(\tau^+\tau^-)Z$
6. $e^+e^- \to (h_k)Z \to (...)Z$
7. $e^+e^- \to (h_k)Z \to (\gamma\gamma)Z$
8. $e^+e^- \to (h_k)Z \to (\text{invisible})Z$
9. $e^+e^- \to (h_k)Z \to (2\text{ jets})Z$

Higgs pair production:

1. $e^+e^- \to (h_k h_i) \to (b\bar{b}b\bar{b})$
2. $e^+e^- \to (h_k h_i) \to (\tau^+\tau^-\tau^+\tau^-)$
3. $e^+e^- \to (h_k \to h_i h_i)h_i \to (b\bar{b}b\bar{b})b\bar{b}$
4. $e^+e^- \to (h_k \to h_i h_i)h_i \to (\tau^+\tau^-\tau^+\tau^-)\tau^+\tau^-$
5. $e^+e^- \to (h_k \to b\bar{b})(h_i \to \tau^+\tau^-)$
6. $e^+e^- \to (h_k \to \tau^+\tau^-)(h_i \to b\bar{b})$



Yukawa production:

1. $e^+e^- \to b\bar{b}h_k \to b\bar{b}b\bar{b}$
   (h_k is a CP-eigenstate)
2. $e^+e^- \to b\bar{b}h_k \to b\bar{b}\tau^+\tau^-$
   (h_k is a CP-eigenstate)
3. $e^+e^- \to \tau^+\tau^- h_k \to \tau^+\tau^-\tau^+\tau^-$
   (h_k is a CP-eigenstate)

Charged Higgs pair production:

1. $e^+e^- \to H_k^+ H_k^- \to \tau^+\nu\tau^-\nu$
2. $e^+e^- \to H_k^+ H_k^- \to q_i\bar{q}_j q_l\bar{q}_m$
3. $e^+e^- \to H_k^+ H_k^- \to q_i\bar{q}_j\tau^\pm\nu$

...there are many Higgs search topologies... at the Tevatron

single neutral Higgs searches:

- $p\bar{p} \to Wh_i \to l\nu b\bar{b}$
- $p\bar{p} \to Wh_i \to W^+W^-W^\pm$
- $p\bar{p} \to Zh_i \to l^+l^- b\bar{b}$
- $p\bar{p} \to Zh_i \to \nu\bar{\nu}b\bar{b}$
- $p\bar{p} \to Wh_i/Zh_i \to b\bar{b} + E_T^{\text{miss.}}$ (SM)
- $p\bar{p} \to h_i \to W^+W^- \to l^+\nu l'^-\nu'$
- $p\bar{p} \to h_i/h_iW, h_i \to W^+W^-$(SM)
- $p\bar{p} \to (b/\bar{b})h_i, h_i \to b\bar{b},\ \tau^+\tau^-$
- $p\bar{p} \to h_i \to \tau^+\tau^-$
- $p\bar{p} \to h_i/h_iW/h_iZ/(\text{VBF}), h_i \to \tau^+\tau^-$ (SM)
- $p\bar{p} \to h_i/h_iW/h_iZ/(\text{VBF}), h_i \to \gamma\gamma$ (SM)
- $p\bar{p} \to t\bar{t}h_i \to t\bar{t}b\bar{b}$
- $p\bar{p} \to h_i + ... \to (Z\gamma) + ...$
- combined Higgs production and decay (SM)

two neutral Higgs searches:

- $p\bar{p} \to h_k \to h_ih_i \to \mu^+\mu^-\mu^+\mu^-$
- $p\bar{p} \to h_k \to h_ih_i \to \tau^+\tau^-\mu^+\mu^-$

light charged Higgs searches:

- $t \to H_k^+ b \to \tau^+\nu b$
- $t \to H_k^+ b \to q_i\bar{q}_j b$

single neutral Higgs searches:

- $pp \to h_i + \cdots \to W^+W^- \to l^+\nu l'^-\nu'$ (SM)
- $pp \to h_i + \cdots \to W^+W^- \to l^+\nu qq'$ (SM)
- $pp \to h_i + \cdots \to ZZ \to l^+l^-l^+l^-$ (SM)
- $pp \to h_i + \cdots \to ZZ \to l^+l^-q\bar{q}$ (SM)
- $pp \to h_i + \cdots \to \tau^+\tau^-$ (SM)
- $pp \to h_i \to \tau^+\tau^-$
- $pp \to Vh_i \to V\tau^+\tau^-$ $(V = W, Z)$
- $pp \to Vh_i \to Vb\bar{b}$ $(V = W, Z)$
- $pp \to Wh_i \to W^+W^-W^\pm$
- $pp \to Wh_i/Zh_i \to b\bar{b} + E_T^{\text{miss.}}$ (SM)
- $pp \to h_i + \cdots \to h_i \to \gamma\gamma$ (SM)
- $pp \to t\bar{t}h_i \to t\bar{t}b\bar{b}$
- combined Higgs production and decay (SM)

light charged Higgs searches:

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- $t \to H_k^+ b \to q_i\bar{q}_j b$

. . . there are many Higgs search topologies. . . at the LHC

single neutral Higgs searches:

- $pp \to h_i + \cdots \to W^+W^- \to l^+\nu l'^-\nu'$ (SM)
- $pp \to h_i + \cdots \to W^+W^- \to l^+\nu q q'$ (SM)
- $pp \to h_i + \cdots \to ZZ \to l^+l^-l^+l^-$ (SM)
- $pp \to h_i + \cdots \to ZZ \to l^+l^- q\bar{q}$ (SM)
- $pp \to h_i + \cdots \to \tau^+\tau^-$ (SM)
- $pp \to h_i \to \tau^+\tau^-$
- $pp \to Vh_i \to V\tau^+\tau^-$ $(V = W, Z)$
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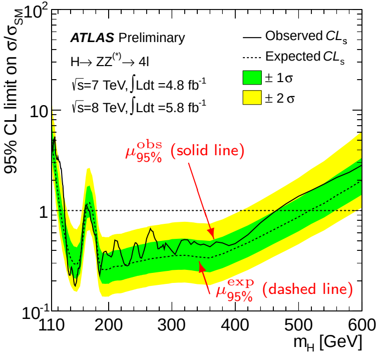
How to read a 95% C.L. cross section limit

- analysis assumes a SM Higgs boson:
  $\Rightarrow$ combines several signal topologies,
  $(\mathrm{ggf},\ \mathrm{VBF},\ HZ,\ HW,\ Ht\bar{t})_{SM} \times (H \to ZZ)$
- limit is set on a universal scale factor μ,

$$\mu = \frac{\sigma(\mathrm{ggf}) \times \mathcal{B}(H \to ZZ)}{\sigma(\mathrm{ggf})_{SM} \times \mathcal{B}(H \to ZZ)_{SM}} = \frac{\sigma(\mathrm{VBF}) \times \mathcal{B}(H \to ZZ)}{\sigma(\mathrm{VBF})_{SM} \times \mathcal{B}(H \to ZZ)_{SM}} = \ldots$$

(also called "signal strength modifier")



- If the observed limit, $\mu^{\mathrm{obs}}_{95\%}$, is less than 1, the SM Higgs is excluded at 95% C.L..

Using more than one exclusion limit

When using more than one exclusion limit, care needs to be taken to ensure that the exclusion is still at 95% C.L..

1. Calculate predicted signal strength, μ^{pred}, for each search channel.
2. Determine which search channel has the highest statistical sensitivity, *i.e.* which search channel has the largest $\mu^{\mathrm{pred}}/\mu^{\mathrm{exp}}_{95\%}$, using the expected limits based on simulations with no signal (*dashed line*).
3. Compare μ^{pred} and $\mu^{\mathrm{obs}}_{95\%}$ for this channel only:

   If $\mu^{\mathrm{pred}}/\mu^{\mathrm{obs}}_{95\%} > 1$, then this parameter point is excluded at 95% C.L..

Calculation of $\mu^{\rm pred}$: HiggsBounds input

- To determine the model predictions the user has to provide HiggsBounds with sufficient input:
  - Higgs masses and total decay widths,
  - normalized Higgs production cross sections,
  - Higgs branching ratios, top quark branching ratios.

  This can be done at hadronic level, parton level, via effective couplings

Examples for the effective coupling approximation

$$\sigma(e^+e^- \to Z^* \to Zh) = g_{hZZ}^2\ \sigma(e^+e^- \to Z^* \to Zh)_{\rm SM}\ \text{(tree-level)}$$
$$\sigma(gg \to h) = g_{hgg}^2\ \sigma(gg \to h)_{\rm SM}\ \text{(loop-induced)}$$
$$\Gamma(h \to \gamma\gamma) = g_{h\gamma\gamma}^2\ \Gamma(h \to \gamma\gamma)_{\rm SM}\ \text{(loop-induced)}$$

- HiggsBounds contains fitted functions for SM Higgs production cross sections and partial widths to normalize predictions correctly.
- *Assumption*: Narrow width approximation is applicable.

Calculation of μ^{pred}

Given a SM Higgs analysis combining N search channels
(*i.e.* production process $\times$ decay process).

The total model-predicted signal rate (normalized to the SM) is then:

$$\mu^{\text{pred}} = \frac{\sum_{i=1}^{N} \epsilon_i \; [\sigma \times \mathcal{B}]_i}{\sum_{i=1}^{N} \epsilon_i \; [\sigma_{\text{SM}} \times \mathcal{B}_{\text{SM}}]_i}, \qquad \epsilon_i : \text{ efficiency of channel } i$$

Problem: Experiments usually do *not* publish channel efficiencies ϵ_i!

Calculation of $\mu^{\rm pred}$

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$\Rightarrow$ Have to *neglect* channel efficiencies!

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Problem: Experiments usually do *not* publish channel efficiencies ϵ_i!
$\Rightarrow$ Have to *neglect* channel efficiencies!

Way out: Require that the model is sufficiently SM-like in the relevant channels, *i.e.* their relative proportions are similar as in the SM.

If not $\Rightarrow$ Do not apply this analysis (conservative approach).

more information on *SM-likeness test* in [arXiv:1301.2345].

Interfaces to HiggsBounds

There are many public programs which can be used to calculate the HiggsBounds input in various models, *e.g.*

- **FeynHiggs*** [T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, G. Weiglein, K. E. Williams] for the MSSM
- **CPsuperH*** [(J. S. Lee, A. Pilaftsis, M. Carena, S. Y. Choi, M. Drees, J. Ellis, C. Wagner)] for the complex MSSM
- **2HDMC†** [D. Eriksson, J, Rathsman, O. Stål] for Two-Higgs-Doublet-Models
- **DarkSUSY†** [P. Gondolo, J. Edsjö, P. Ullio, L. Bergström, M. Schelke, E.A. Baltz, T. Bringmann, G. Duda]
- **NMSSMTools** [D. Das, U. Ellwanger, J. F. Gunion, C. Hugonie, C. C. Jean-Louis, A. Teixeira] for the NMSSM, interface written by C. Wymant: http://www.ippp.dur.ac.uk/∼SUSY/
- **SuperIso†** [F. Mahmoudi] for 2HDM's, MSSM and NMSSM.
- **Spheno†** [W. Porod, F. Staub] for MSSM. → see Florian's tutorial.
- **SARAH+Spheno†** [F. Staub] for any model implemented with SARAH. → see Florian's tutorial.

† includes interface to HiggsBounds

∗ interface to this program is included in HiggsBounds package

Run options of HiggsBounds

- Supported input format: data files, SLHA[1] or via subroutines.
- Run HiggsBounds via web-interface on http://higgsbounds.hepforge.org.
- May select different experimental data sets: onlyL, onlyH, LandH
  (L: lepton-collider (LEP), H: hadron-collider (Tevatron, LHC))
- The signal rates of Higgs bosons with similar masses can be combined.

→ more in tutorial and exercises.

[1] MSSM and NMSSM supported, need two extra blocks for effective Higgs couplings.

HiggsBounds Output

SLHA output block (appended to SLHA input file):

```
Block HiggsBoundsResults      # results from HiggsBounds http://projects.hepforge.org/higgsbounds
# HBresult    : scenario allowed flag (1: allowed, 0: excluded, -1: unphysical)
# chan id number: most sensitive channel (see below). chan=0 if no channel applies
# obsratio    : ratio [sig x BR]_model/[sig x BR]_limit (<1: allowed, >1: excluded)
# ncomb       : number of Higgs bosons combined in most sensitive channel
# Note that the HB channel id number varies depending on the HB version and setting "whichanalyses"
#
    0    3.7.0     ||LandH||          # version of HB used to produce these results,the HB setting "whichanalyses"
#
#CHANNELTYPE 1: channel with the highest statistical sensitivity
    1           1           1                 # channel id number
    1           2           0                 # HBresult
    1           3    3.7765434478424251       # obsratio
    1           4           1                 # ncombined
    1           5 ||(e e)->(h1)Z->(b b-bar)Z   (hep-ex/0602042, table 14b (LEP))|| # text description of channel
#
```

- Channel ID number - Which channel was most sensitive
- HBresult - A value of 0 means 95% C.L. excluded, 1 means allowed
- obsratio - Ratio $r = \mu^{\text{pred}}/\mu^{\text{obs}}_{95\%}$ of predicted cross section to observed limit in most sensitive channel. $r > 1 \rightarrow \text{exclusion}$
- ncombined - Number of Higgs bosons combined for this analysis
- Human-readable information about all the experimental analyses considered are written to `Key.dat`

The current version HiggsBounds-3.8.1 only contains LHC results from the 7 TeV data. We are about to release the new version HiggsBounds-4 with the following new features:

- framework and results for 8 TeV LHC data (extended input, new SM cross section functions, etc.)
- treatment of theoretical mass uncertainties (→ next slide),
- LEP exclusion χ^2 information (useful for global BSM fits),

Treatment of theoretical mass uncertainties

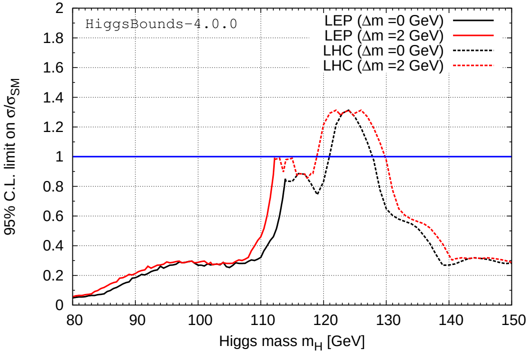
- If the Higgs mass m_i is a model prediction (e.g. in SUSY) we have to take into account its theoretical uncertainty Δm_i.
- HiggsBounds-4 is run for the three mass values m_i, $m_i \pm \Delta m_i$. The *most conservative result* is taken as the final result.

Toy example:

SM Higgs boson with a theoretical mass uncertainty:

$\Delta m = 0$ GeV and $\Delta m = 2$ GeV.

$\Rightarrow$ unexcluded region broadens to $m_H \approx (119 - 130)$ GeV.



A preview of HiggsSignals

HiggsSignals

Since July 4th, 2012 we have a discovery in the neutral Higgs searches!

$\Rightarrow$ Need to confront arbitrary Higgs sector predictions with the observations / discoveries in Higgs searches.

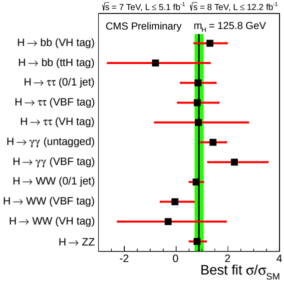
The currently developed program HiggsSignals

- evaluates the total χ^2 for both the signal strengths and/or the mass measurements, featuring two distinct χ^2 methods (peak- and mass-centered χ^2 methods),
- includes correlations among the major systematic uncertainties (*cross sections, branching ratios, luminosity, theory mass uncertainty*),
- includes many other features. . . (*e.g. automatic combination of nearly mass degenerate Higgs bosons, framework to include signal efficiencies, toy observables, etc.*).

HiggsSignals is a stand-alone program using the HiggsBounds libraries. Coding language is Fortran90/2003.

Peak-centered χ^2 method

Tests agreement (model $\leftrightarrow$ data) at the *observed* mass.



- Define observables by the best-fit signal strength, $\hat{\mu}$, at a *hypothetical* Higgs mass $\hat{m}$.
- The total χ^2 consists of a signal strength and a Higgs mass part,

$$\chi^2_{\text{total}} = \chi^2_\mu + \sum_{\text{assigned Higgses } i} \chi^2_{m_i},$$

where

$$\chi^2_\mu = (\hat{\mu} - \mu)^T \mathbf{C}_\mu^{-1} (\hat{\mu} - \mu) \quad \text{and} \quad \chi^2_{m_i} = (\hat{\mathbf{m}} - \mathbf{m}_i)^T \mathbf{C}_{m_i}^{-1} (\hat{\mathbf{m}} - \mathbf{m}_i).$$

- Only analyses with a *good mass measurement* enter $\chi^2_{m_i}$ $(H \to \gamma\gamma, ZZ)$.

$\Rightarrow$ Good method to get a global picture on Higgs coupling properties.

Scaling of vector boson and fermion couplings

- scale fermion couplings by $\kappa_F \equiv g_{Hff}$ and vector boson couplings by $\kappa_V \equiv g_{HVV}$.

$\rightarrow$ non-trivial scaling of loop-induced $H\gamma\gamma$ coupling.

$\rightarrow$ loop-induced Hgg coupling scales with κ_F (effectively a fermion loop).

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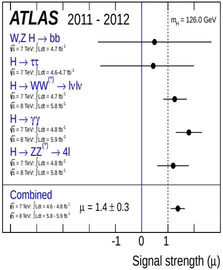

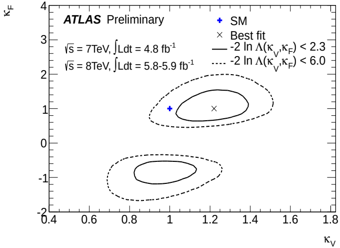

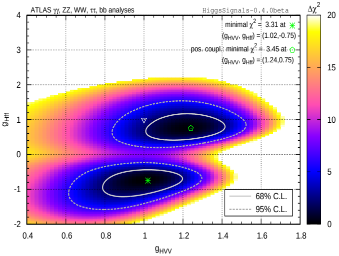

$\Rightarrow$ Pretty good agreement!

Scaling of loop-induced gluon and photon couplings

- scale gluon couplings by κ_g and photon couplings by κ_γ.
- keep tree-level couplings at their SM value.

$\rightarrow$ probing new physics contributions to loop-induced couplings.

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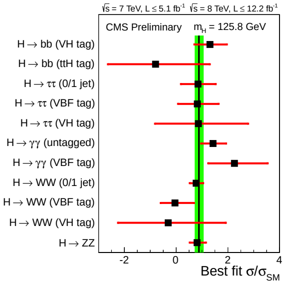
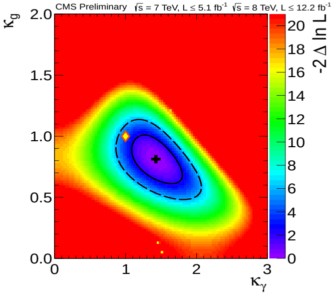
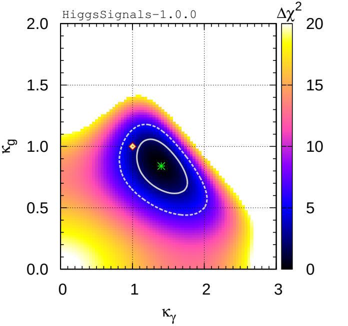
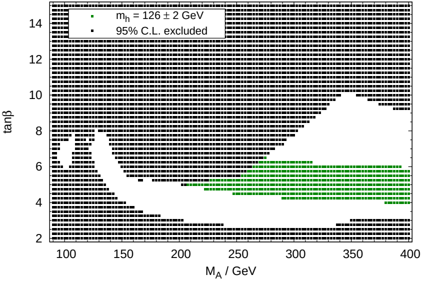






Final example: The m_h^{max} scenario

The $m_h^{\max}$ scenario of the MSSM

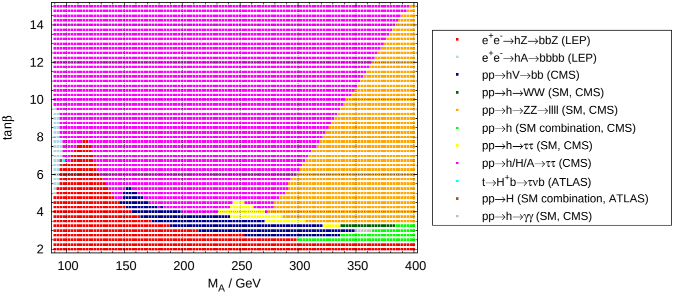


MSSM benchmark model where the radiative corrections to the lightest Higgs mass are maximized.

← HiggsBounds-4 (preliminary)

. . . now, also run

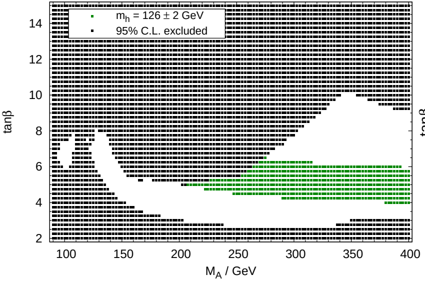
HiggsSignals-1 (preliminary)!

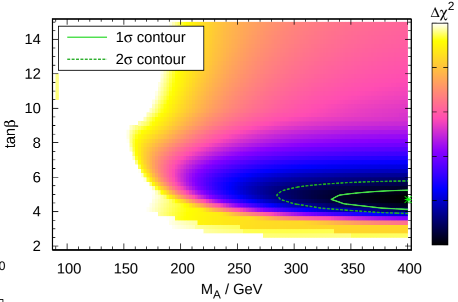


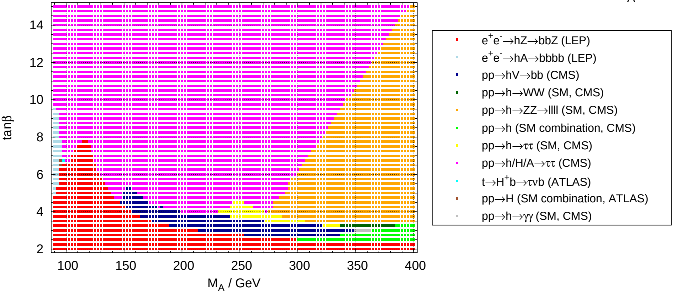
Theory mass uncertainties:

$\Delta m_h = 0$ GeV
$\Delta m_H = 0$ GeV
$\Delta m_A = 0$ GeV
$\Delta m_{H^+} = 0$ GeV

The $m_h^{\max}$ scenario of the MSSM







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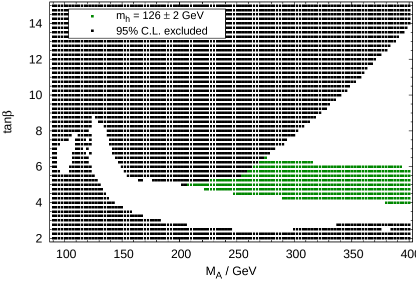
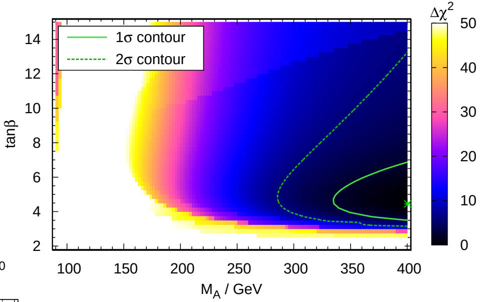
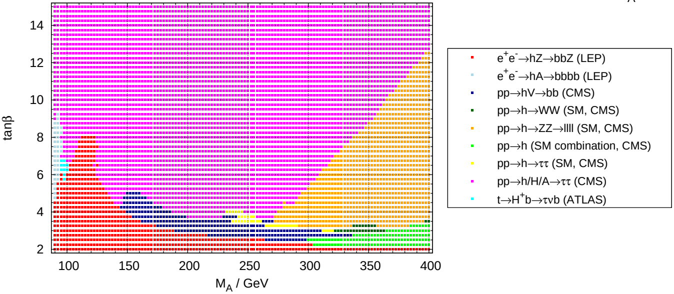






Theory mass uncertainties:

$\Delta m_h = 2$ GeV
$\Delta m_H = 2$ GeV
$\Delta m_A = 0$ GeV
$\Delta m_{H^+} = 0$ GeV

Short summary

HiggsBounds is testing arbitrary Higgs models against 95% C.L. exclusion limits from LEP, Tevatron and LHC in a statistically well-defined way.

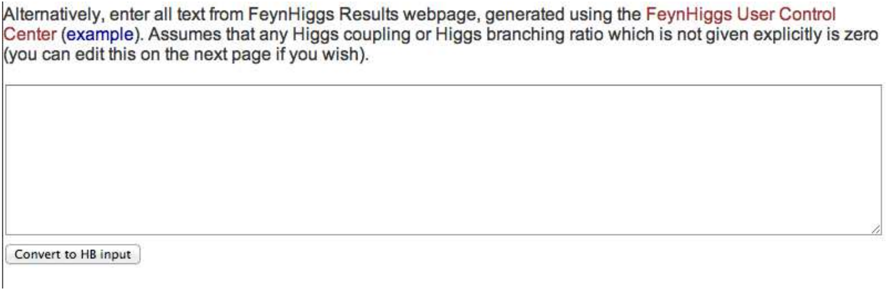
HiggsSignals performs a total χ^2 evaluation for arbitrary Higgs model predictions against the signal rate and mass measurements in Higgs collider searches (Tevatron, LHC). In this evaluation correlations among the major systematic uncertainties are taken into account.

Performance studies of HiggsSignals on effective coupling benchmark models show nice agreement with official ATLAS and CMS results.

Live demonstration

Running the HiggsBounds web-interface

- The web-interface on http://higgsbounds.hepforge.org is a quick and convenient way to check a single parameter point.
- For the MSSM, the output from the FeynHiggs User Control Center can be converted to HB input by *copy and paste* into a text field.



Installing HiggsBounds

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

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

and navigate into the new folder:

```
cd HiggsBounds-3.8.1/HiggsBounds/
```

Check the `configure` file for correct paths (*e.g.* to `FeynHiggs`) and compiler settings. Then run

```
./configure
make
```

The example programs using the `FeynHiggs` library need a separate compilation:

```
make HBwithFH
```

(Note: `gfortran` users need version 4.2 or higher.)

Running HiggsBounds from the command-line

If HiggsBounds is run on the command-line the model predictions are given via datafiles or as a SLHA file. We call

```
./HiggsBounds whichanalyses whichinput nHzero nHplus prefix
```

whichanalyses = onlyL, onlyH, LandH (experimental analyses)

whichinput = effC, part, hadr, SLHA (input format)

nHzero / nHplus: number of neutral / charged Higgs boson of the model

prefix: common prefix of input files (including relative path)

Let's try for the provided example data:

```
./HiggsBounds LandH SLHA 3 1 ../SLHA_examples/SLHA_example1.in
./HiggsBounds LandH effC 3 1 ../mhmax_example/mhmax_
```

. . . but before, let's have a closer look at the required input. . .

The SLHA input

HiggsBounds approximates the production cross sections via effective couplings from the two SLHA blocks

```
Block HiggsBoundsInputHiggsCouplingsBosons
Block HiggsBoundsInputHiggsCouplingsFermions
```

The Higgs branching ratios are taken directly from the DECAY blocks[2].

The HiggsBounds package contains example programs demonstrating how to write these blocks with FeynHiggs. SPheno can write them directly.

After a successful HiggsBounds run, the output is written to a new SLHA block

```
Block HiggsBoundsResults
```

Note: The SLHA interface is restricted to the MSSM and NMSSM particle content due to the SLHA conventions.

[2]The HiggsBounds SLHA interface is restricted to 2-body decays, *i.e.* the DECAY blocks should *e.g.* contain $H \to ZZ^{(*)}$ instead of $H \to e^+e^-\mu^+\mu^-$.

The datafiles input

For the *effective couplings input*, we need the following datafiles:

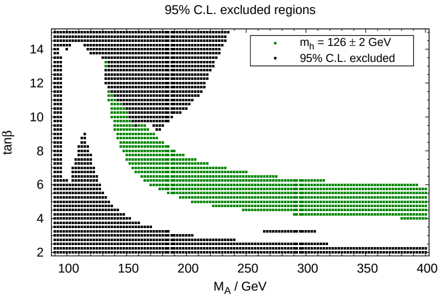
```
<prefix>MH_GammaTot.dat
<prefix>MHplus_GammaTot.dat
<prefix>effC.dat
<prefix>BR_H_NP.dat
<prefix>BR_t.dat
<prefix>BR_Hplus.dat
<prefix>LEP_HpHm_CS_ratios.dat
<prefix>additional.dat
```

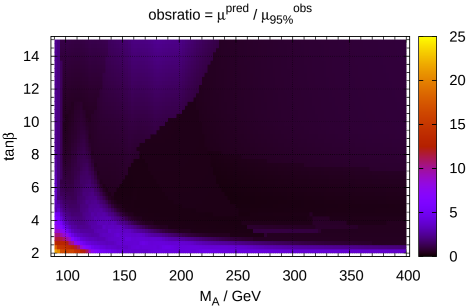
(detailed description → `HiggsBounds` manual)

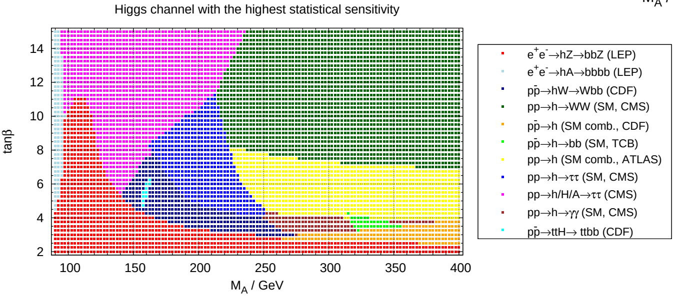
Each row in these files corresponds to one parameter point. After the `HiggsBounds` run, the results are contained in

```
<prefix>MH_HiggsBounds_results.dat
<prefix>MH_Key.dat
```

The $m_h^{\max}$ scenario







$m_t = 173.1$ GeV,
$M_{SUSY} = 1$ TeV,
$\mu = 200$ GeV,
$2M_1 = M_2 = 200$ GeV,
$M_3 = 0.8 M_{SUSY}$,
$X_t = 2M_{SUSY}$,
$(X_t = A_t - \mu/\tan\beta)$
$A_b = A_t$

Combine Higgs bosons with similar masses

In many models the signal rates of Higgs bosons, whose masses are similar, can be added incoherently, *i.e.*

$$\mu^{\text{pred}} = \sum_i \mu_{h_i}^{\text{pred}},$$

for analyses with poor mass resolution. This can lead to stronger exclusions.

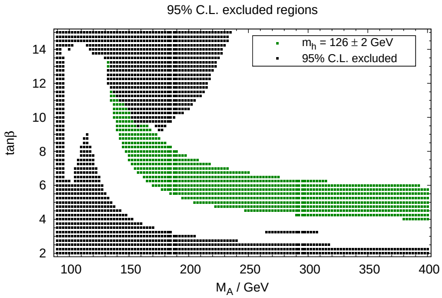
Open the file `S95tables.f90` and change in line 48-49 the parameters `delta_Mh_LHC` and `delta_Mh_TEV` to a non-zero value (*e.g.* 10 GeV).

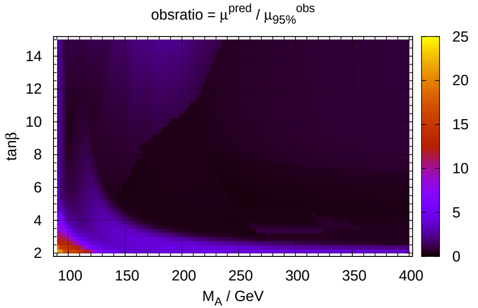
If the mass difference of two Higgs bosons is *less* than this value they are combined (for some analyses of the specific experiment).

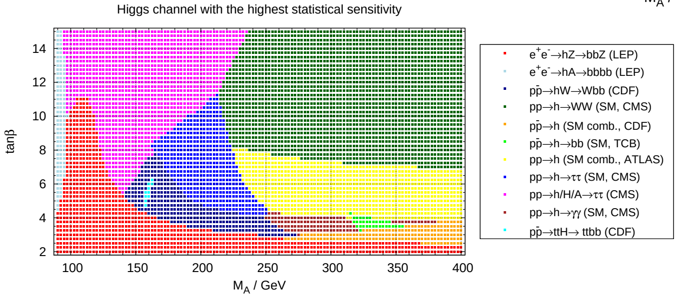
After changing the code, don't forget to recompile by running

```
make
```

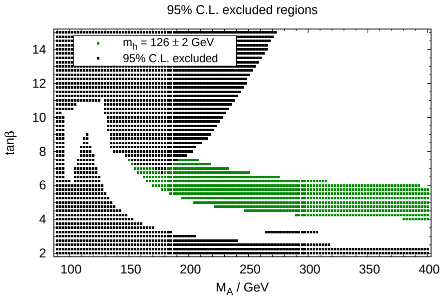
The $m_h^{\max}$ scenario ($\delta m_{h^0}^{TEV} = \delta m_{h^0}^{LHC} = 0$ GeV)

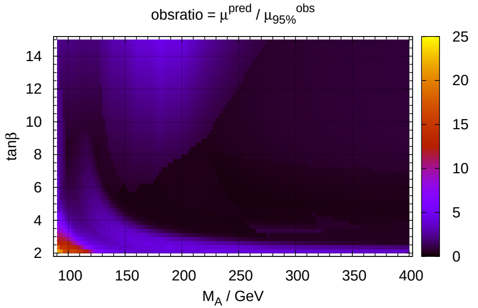


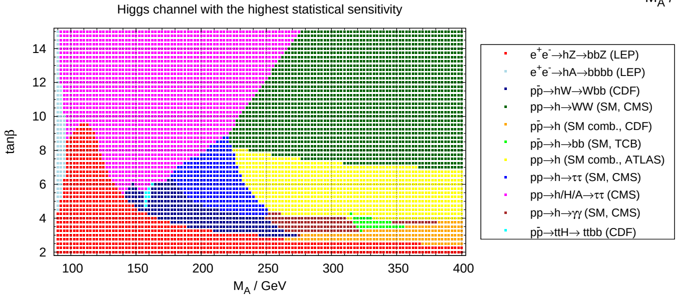




The $m_h^{\max}$ scenario ($\delta m_{h^0}^{TEV} = \delta m_{h^0}^{LHC} = 10$ GeV)







Running HiggsBounds via its subroutines

The main subroutines of HiggsBounds are:

`initialize_HiggsBounds(nHzero, nHplus, whichanalyses)`

→ allocates internal arrays, reads in SM branching ratios, experimental data, etc.

Then, the model predictions have to be given using one of the input formats

`HiggsBounds_neutral_input_effC(...)` or

`HiggsBounds_neutral_input_part(...)` or

`HiggsBounds_neutral_input_hadr(...)`

and (if $nHplus > 0$)

`HiggsBounds_charged_input(...)`

Then, HiggsBounds can be run by calling

`run_HiggsBounds(HBresult, chan, obsratio, ncombined)`

At the end, the arrays should be deallocated by calling

`finish_HiggsBounds`

→ Exercise: SM-like Higgs with decay to invisible particles

Exercises

1. The MSSM with a Higgs boson at ~ 126 GeV
   - A closer look at two SLHA input files

     ($\rightarrow$ SLHA `HiggsBounds` input)
   - A study of the (m_A, $\tan\beta$) plane

     ($\rightarrow$ data files `HiggsBounds` input)
2. Invisible decays of a SM-like Higgs boson

   ($\rightarrow$ usage of `HiggsBounds` subroutines)