`HiggsBounds 3.0.0beta`: Confronting Arbitrary Neutral and Charged Higgs Sectors with Exclusion Bounds from LEP, Tevatron and LHC

P. Bechtle [a], O. Brein [b], S. Heinemeyer [c], T. Stefaniak [d], G. Weiglein [a] and K.E. Williams [d].

[a] *DESY, Notkestrasse 85, 22607 Hamburg, Germany*

[b] *Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Str. 3, D-79104 Freiburg im Breisgau, Germany*

[c] *Instituto de Fisica de Cantabria (CSIC-UC), Santander, Spain*

[d] *Bethe Center for Theoretical Physics, Physikalisches Institut der Universität Bonn, Nussallee 12, 53115 Bonn, Germany*

Abstract

`HiggsBounds 3.0.0beta` is a computer code which tests both neutral and charged Higgs sectors of new models against the current exclusion bounds from the Higgs searches at the LEP, Tevatron and LHC experiments. As input, it requires a selection of model predictions, such as Higgs masses, branching ratios, effective couplings and total decay widths. `HiggsBounds 3.0.0beta` then uses the expected and observed topological cross section limits from the Higgs searches to determine which points in the parameter space have already been excluded at 95% CL.

Key words: Higgs bosons, Higgs search, LEP, Tevatron, LHC, Beyond the Standard Model

1 Introduction

The search for Higgs bosons is a major cornerstone of the physics programmes of past, present and future high energy colliders. The LEP, Tevatron and LHC experiments, in particular, have been able to turn the non-observation of Higgs bosons into constraints on the Higgs sector, which can be very useful in reducing the available parameter space of particle physics models. Such constraints will need to be taken into account in the interpretation of any new physics.

These analyses usually take one of two forms. Dedicated analyses have been carried out in order to constrain some of the most popular models, such as the SM [1] and various benchmark scenarios in the MSSM [2]. In addition, model-independent limits on the cross sections of individual signal topologies (such as $e^+e^- \to h_i Z \to b\bar{b}Z$) have been published. The former type of analyses include detailed knowledge of the overlap between the individual experimental searches, and therefore have a high sensitivity, whereas the latter can be used to test a wide class of models.

There are certain issues involved with the application of these experimental constraints. The data is distributed over many different publications and the limits are given with a variety of normalisations. In the case of the Tevatron and the LHC, the results are also frequently updated. Furthermore, care must be taken when using more than one experimental analysis to ensure that the resulting exclusion bound has the same confidence level (CL) as each individual analysis. Each experimental analysis is not applicable to each Higgs boson in a new model. For example, if an analysis has been carried out under Standard Model assumption, it will not be applicable to Higgs bosons whose various production mechanism and decay rate mechanisms do not show a proportionate similarity to the Standard Model.

The Fortran code `HiggsBounds` has been designed to facilitate the task of comparing Higgs sector predictions with existing exclusion limits, thus allowing the user to quickly and conveniently check a wide variety of models against the state-of-the-art results from Higgs searches. `HiggsBounds` version `3.0.0beta` differs significantly from previous versions because it is the first to include LHC search limits. In addition, `HiggsBounds` can now be used with files in the SLHA format[3,4].

2   General Approach

The user provides the Higgs sector predictions of the model under consideration. For each Higgs boson H_i $(i = 1, \ldots, n_{H^0} + n_{H^\pm})$ in the model, this will include information on the Higgs mass, Higgs total decay width, Higgs and top quark branching ratios and neutral Higgs production cross sections:

$$M_{H_i}, \Gamma_{\text{tot}}(H_i), \text{BR}_{\text{model}}(H_i \to \ldots), \text{BR}_{\text{model}}(t \to \ldots), \frac{\sigma_{\text{model}}(P)}{\sigma_{\text{ref}}(P)} .$$

and whether each neutral Higgs boson is CP-odd, CP-even or has mixed CP. P is the Higgs production process. A full list is given in Sect. 3.1. Where it exists, $\sigma^{\text{SM}}(P)$ is used as the reference production cross section. Variations on this input format are offered, as described in detail in Sect. 3, which allow the user to specify a simpler set of input, when certain basic approximations are valid.

The `HiggsBounds` package includes sample programs which demonstrate how `HiggsBounds` can be used in conjunction with the widely used MSSM Higgs sector programs `FeynHiggs` [5–

8] (version 2.7.4) and `CPsuperH` [9,10] (version 2.2).

HiggsBounds version 3.0.0beta uses the following experimental analyses: [2,11–53]. This list includes results from LEP, the Tevatron and the LHC and consist of tables of expected (based on Monte Carlo simulations with no signal) and observed 95% CL cross section limits, with a variety of normalisations. The list mainly consists of analyses for which model-independent limits were published. However, we also include some dedicated analyses carried out for the case of the SM, or for Higgs bosons with certain CP properties. These analyses can only be applied to Higgs bosons which show these characteristics at the parameter point being considered.

We call the application of a Higgs search analysis to a particular Higgs boson (or two Higgs bosons, if the analysis involves two) of the model under study with particular mass(es) an "analysis application" X. [1] To each analysis application X corresponds a signal cross section prediction $\sigma(X)$ for the particular Higgs boson on which an upper limit is put by the analysis. For each X, `HiggsBounds` uses the input to calculate the relevant quantity $Q_{\text{model}}(X)$ in terms of which the limit is given (i.e., a conveniently normalised cross section $\sigma(X)$ times branching ratio).

The normalisation is carried out using SM predictions for Higgs boson production cross sections and decay branching ratios from `HDECAY` 3.532 [54], the TEV4LHC Higgs Working Group [55] (for full list of references, see Tab. 13), the online gluon fusion calculator at `http://theory.fi.infn.it/grazzini/hcalculators.html`, `VBFNLO` [56], `HAWK` 1.1 [57,58], `HJET` 1.3 [59–61], the LHC Higgs Cross Section Working Group [62] and `bbh@nnlo` 1.3 [63].

In order to ensure the correct statistical interpretation of the results, it is crucial to only consider the experimentally observed limit for one particular analysis application. Therefore, `HiggsBounds` must first determine X_0, which is defined as the analysis application with the highest statistical sensitivity for the model point under consideration. In order to do this, the program uses the tables of expected experimental limits to obtain a quantity Q_{expec} corresponding to each X. The analysis application with the largest value of $Q_{\text{model}}/Q_{\text{expec}}$ is chosen as X_0.

`HiggsBounds` then determines the (normalised) cross section limit $Q_{\text{obs}}(X_0)$ for the Higgs and analysis combination represented by X_0, using the appropriate table of experimentally observed limits. If

$$\frac{Q_{\text{model}}(X_0)}{Q_{\text{obs}}(X_0)} > 1 \,, \tag{1}$$

`HiggsBounds` returns that this particular parameter point is excluded at 95 % C.L. [2]

---

[1] As an example, suppose a model with three neutral Higgs bosons (h_1, h_2, h_3) should be checked against two neutral Higgs search analyses A_1 and A_2, then there are six possible analysis applications X (A_1 applied to h_1, h_2, h_3 and A_2 applied to h_1, h_2, h_3) that the model can be tested against.

[2] Note that if we had compared predicted cross sections directly against the experimentally measured limits for *all* available search channels and had excluded the model if at least one of them excludes it at 95 % C.L., the derived constraint would in general not correspond to a constraint

In order to use `HiggsBounds`, the narrow-width approximation must be valid for each Higgs boson described in the input. This is because the experimental exclusions bounds currently utilised within `HiggsBounds` have all been obtained under this approximation, which is presently the case for the majority of analyses. HiggsBounds can be used with models which do not

change the signature of the background processes considerably[3]. In addition, models should not significantly change the kinematical distributions of the signal topology X (e.g. η, p_T distributions of the final state particles) from that assumed in the corresponding analysis. For a full discussion, see Ref. [66] and Ref. [67].

Some of the analyses have been performed under certain model assumptions. Typical assumptions are, likeness to the SM, or models which fulfil $\mathrm{BR}(t \to W^+ b) + \mathrm{BR}(t \to H_i^+ b) = 1$, or Higgs bosons with certain CP properties. In these cases, `HiggsBounds` determines for a given model scenario which analyses can be applied to which Higgs boson.

In order to decide whether a model scenario is sufficiently 'SM-like' to be compared with an analysis carried out under SM assumptions, we use the following test. Firstly, for each of the N_{CS} distinct production cross sections $\sigma_{\mathrm{model}}(P_i(h))$ and the N_{BR} distinct decay branching ratios $\mathrm{BR}(h \to F_k)$ which appear in the list of M signal topologies in that particular analysis, we determine the normalised mean value and the deviation from the mean:

$$\bar{s} = \frac{1}{N_{\mathrm{CS}}} \sum_{i=1}^{N_{\mathrm{CS}}} s_i \,, \qquad\qquad \bar{b} = \frac{1}{N_{\mathrm{BR}}} \sum_{k=1}^{N_{\mathrm{BR}}} b_k \,, \tag{2}$$

$$\delta s_i = s_i - \bar{s} \,, \qquad\qquad \delta b_k = b_k - \bar{b} \,, \tag{3}$$

$$\text{with } s_i = \frac{\sigma_{\mathrm{model}}(P_i(h))}{\sigma_{\mathrm{SM}}(P_i(H))} \,, \qquad\qquad b_k = \frac{\mathrm{BR}_{\mathrm{model}}(h \to F_k)}{\mathrm{BR}_{\mathrm{SM}}(H \to F_k)} \,. \tag{4}$$

The parameter point is considered 'SM-like' for this particular analysis if the relative deviations of all individual production and decay combinations (i, k) from the mean $\bar{s}\bar{b}$ stay below a preset bound ϵ:

$$\max_{i,k} \left| \frac{\delta s_i}{\bar{s}} + \frac{\delta b_k}{\bar{b}} + \frac{\delta s_i \delta b_k}{\bar{s}\,\bar{b}} \right| < \epsilon \,. \tag{5}$$

By default, $\epsilon = 2\%$, i.e. the predictions for the different topological cross sections, normalised to the SM values, are required to result in the same common scale factor with at least 2% accuracy. This method is conservative and errs on the side of caution, but can occasionally be overly restrictive.

---

at 95 % C.L. The maximally 5 % probability of each individual comparison of Q_{model} and Q_{obs} to yield a false exclusion would yield an overall probability for false exclusion which is higher than 5 %.

[3] However, new physics models which show strong deviations from the SM in the background processes to Higgs production are not usually considered in the literature, since this would often put them in conflict with SM electroweak precision data[64,65].

After ensuring that a certain parameter point passes the SM-likeness test for this analysis, the normalised theoretical cross section Q_{model} is calculated simply by

$$Q_{\mathrm{model}} = \bar{s}\bar{b}. \tag{6}$$

If two or more neutral Higgs bosons have similar masses, then `HiggsBounds` allows the possibility of adding up their cross sections. If the mass difference between two neutral Higgs bosons is less than `delta_Mh_LEP`, `delta_Mh_TEV` or `delta_Mh_LHC` , then the full LEP, Tevatron, or LHC cross sections will be added respectively. The normalisation factor is calculated at the average mass of the Higgs bosons involved. Note that:

`delta_Mh_LEP`, `delta_Mh_TEV` and `delta_Mh_LHC` are set to zero by default.

To switch this feature on, the user should change these variables in the code and recompile (see the readme files about where to find these variables in the code). This should only be done if the user is confident that interference effects are small. We would recommend that `delta_Mh_LEP` ≤ 2 GeV, `delta_Mh_TEV` ≤ 10 GeV and `delta_Mh_LHC` ≤ 10 GeV. For analyses which require a SM-likeness test, the full cross sections are not added, regardless of the values of `delta_Mh_LEP`, `delta_Mh_TEV` and `delta_Mh_LHC`.

This feature can be very useful in, for example, the m_h^{max} scenario of the MSSM [68], where a CP even Higgs boson and the CP odd Higgs boson can have very similar masses but, naturally, they do not mix. In this case, the cross sections are commonly added, such as for example in Ref. [69] and Ref. [70].

3   Theoretical predictions required as input

The user can choose between four different input formats, labelled by the variable `whichinput`. We describe here in detail what is required from the user for each of the four settings (`hadr`, `part`, `effC` and `SLHA`). These are summarised in Tab. 5.

3.1   The most general input form: `whichinput=hadr`

The option `whichinput=hadr` requires the model input in the most general form. It involves specifying (at most)

(1) masses for the neutral Higgs bosons h_k $(k = 1, n_{H^0})$ and singly charged Higgs bosons $H_j^\pm$ $(j = 1, n_{H^\pm})$,

$$m_{h_k}, m_{H_j^\pm},$$

(2) Higgs total decay widths,

$$\Gamma_{\text{tot}}(h_k), \Gamma_{\text{tot}}(H_k^{\pm}),$$

(3) whether the neutral Higgs boson is CP-even, CP-odd or mixed CP,

(4) neutral Higgs branching ratios with SM equivalents (OP=ordinary particles i.e. particles which exist in the SM),

$$\text{BR}_{\text{model}}(h_k \rightarrow \text{OP}) \text{ with}$$
$$\text{OP} = s\bar{s},\ c\bar{c},\ b\bar{b},\ \mu^+\mu^-, \tau^+\tau^-,\ W^+W^-,\ ZZ,\ Z\gamma,\ \gamma\gamma,\ gg,$$

(5) neutral Higgs branching ratios without SM equivalents

$$\text{BR}_{\text{model}}(h_k \rightarrow h_i h_i), \text{BR}_{\text{model}}(h_k \rightarrow \text{invisible}),$$

(6) charged Higgs branching ratios to SM particles

$$\text{BR}(H_j^+ \rightarrow \text{OP}) \text{ with OP} = c\bar{s},\ c\bar{b},\ \tau^+\nu_{\tau},$$

(7) top quark branching ratios

$$\text{BR}(t \rightarrow W^+b), \text{BR}(t \rightarrow H_j^+b),$$

(8) normalised cross section $R_{\sigma}(P)$ for LEP Higgs production process P

$$e^+e^- \rightarrow h_j Z,$$
$$e^+e^- \rightarrow b\bar{b}h_j,$$
$$e^+e^- \rightarrow \tau^+\tau^- h_j,$$
$$e^+e^- \rightarrow h_j h_i,$$
$$e^+e^- \rightarrow H_j^+ H_j^-,$$

(9) normalised cross section $R_{\sigma}(P)$ for Tevatron hadronic Higgs production process P

$$p\bar{p} \rightarrow h_j,$$
$$p\bar{p} \rightarrow bh_j,$$
$$p\bar{p} \rightarrow h_j W,$$
$$p\bar{p} \rightarrow h_j Z,$$
$$p\bar{p} \rightarrow h_j \text{ via VBF},$$
$$p\bar{p} \rightarrow t\bar{t}h_j.$$

(10) normalised cross section $R_{\sigma}(P)$ for LHC hadronic Higgs production process P at 7 TeV

$$pp \rightarrow h_j,$$
$$pp \rightarrow bh_j,$$
$$pp \rightarrow h_j W,$$
$$pp \rightarrow h_j Z,$$
$$pp \rightarrow h_j \text{ via VBF},$$
$$pp \rightarrow t\bar{t}h_j.$$

Note that only a subset of these inputs may be required. For example, if only the LEP limits are required by the user, no Tevatron or LHC cross sections will need to be given as input (see Sect. 4). If the user only wishes to test the neutral Higgs sector, no input involving the charged Higgs sector or top decays will be required.

The normalised cross section of a Higgs production process P is defined by

$$R_\sigma(P) = \frac{\sigma_{\text{model}}(P)}{\sigma_{\text{ref}}(P)}$$

Where the SM equivalent exists, the reference cross section $\sigma_{\text{ref}}(P)$ of a process P involving a Higgs boson h_k is $\sigma_{\text{ref}}(P) = \sigma_{\text{SM}}(P)|_{m_H^{\text{SM}} = m_{h_k}}$.

The only neutral Higgs production process without a SM equivalent considered in Higgs-Bounds up to now is $P = e^+e^- \to h_j h_i$. In this case, we choose a reference cross section for a fictitious production process of two scalar particles (H', H) with masses $m_{H'} = m_{h_j}$ and $m_H = m_{h_i}$ via a virtual Z exchange with a standardised squared coupling constant:

$$\left(g_{H'HZ}^{\text{ref}}\right)^2 = \frac{e^2}{4s_{\text{w}}^2 c_{\text{w}}^2}, \tag{7}$$

where e denotes the electromagnetic coupling constant, and s_{w} and c_{w} the sine and cosine of the weak mixing angle, respectively.

The cross section of this process in leading order is then completely determined by the Higgs masses and SM input and related to the SM Higgsstrahlung cross section via a simple phase space factor:

$$\sigma_{\text{ref}}(H'H \text{ production}) = \bar{\lambda}\left(m_{H'}, m_H, s\right) \sigma_{HZ}^{\text{SM}}(m_H), \tag{8}$$

$$\bar{\lambda}\left(m_{H'}, m_H, s\right) = \frac{\lambda_{H'H}^{3/2}(s)}{\lambda_{HZ}^{1/2}(s)\left(\lambda_{HZ}(s) + 12\frac{m_Z^2}{s}\right)},$$

$$\lambda_{ab}(s) = \left[1 - \frac{(m_a + m_b)^2}{s}\right]\left[1 - \frac{(m_a - m_b)^2}{s}\right].$$

This reference cross section coincides with the MSSM tree level cross section for the process $e^+e^- \to h^0 A^0$ if the Higgs mixing-angle dependent factor $\cos(\beta - \alpha)$ is divided out of the tree level coupling and m_{A^0} and m_{h^0} are chosen as $m_{H'}$ and m_H. Therefore, $R_\sigma(e^+e^- \to h^0 A^0)$ is simply given by $\cos^2(\beta - \alpha)$ in the MSSM (with real parameters) at tree level.

For the process $P = e^+e^- \to H_j^+ H_j^-$, the reference cross section is the cross section of the process $e^+e^- \to H^+ H^-$ in a 2 Higgs doublet model (e.g. the MSSM) at tree-level (i.e. s-channel γ and Z exchange). This reference cross section depends solely on the mass of the charged Higgs boson and SM quantities. As a consequence, in the MSSM, $R_\sigma(e^+e^- \to H_j^+ H_j^-) = 1$.

The invisible branching ratio $\mathrm{BR}_{\mathrm{model}}(h_k \to \mathrm{invisible})$ is defined as the branching ratio of a neutral Higgs boson into particles which only appear in the detector as missing energy. Examples of invisible particles include neutralinos in the MSSM or majorons in supersymmetric models with spontaneous breaking of R-parity.

The top quark branching ratios $\mathrm{BR}(t \to H_j^+ b)$ and $\mathrm{BR}(t \to W^+ b)$ are also required as input, when the model is compared with the charged Higgs searches from the Tevatron or LHC. $\mathrm{BR}(t \to W^+ b)$ is required for analyses in order to determine when analyses which assume $\mathrm{BR}(t \to H_j^+ b) + \mathrm{BR}(t \to W^+ b) \sim 1$ can be applied to the model point.

In order to make it more convenient for users to calculate this input, the `HiggsBounds` library provides a series of Fortran functions which allow the user to access the predictions of certain SM quantities, including the hadronic SM Higgs production cross sections at the Tevatron and the 7 TeV LHC, total decay width and branching ratios as a function of Higgs mass and $\Gamma^{\mathrm{SM}}(t \to W^+ b)$ as function of the top mass. These are listed in Tab. 13 together with the corresponding references.

3.2 Specifying some cross sections at the partonic level: `whichinput=part`

The input required for the option `whichinput=part` may be more convenient for the user to calculate than for the option `whichinput=hadr`, since most of the Tevatron cross section ratios can be specified at the partonic level rather than the hadronic level.

The input option `whichinput=part` requires, at most,

(1)-(8) as for `whichinput=hadr`

(9) normalised cross section $R_\sigma(P)$ for Tevatron (at 1.96 TeV) and LHC (at 7 TeV) hadronic neutral Higgs production process P

$$p\bar{p} \to h_j \text{ via VBF}$$
$$p\bar{p} \to t\bar{t}h_j$$
$$pp \to h_j \text{ via VBF}$$
$$pp \to t\bar{t}h_j$$

(10) normalised cross section $R_{nm}^{h_j+y}$ for partonic neutral Higgs production process $nm \to h_j + y$, which are valid for both the Tevatron and the LHC. The y indicates a particle produced in association with the Higgs boson (or none if y is omitted):

$$R_{nm}^{h_j}, \text{ with } nm = gg, b\bar{b},$$
$$R_{nm}^{h_j+W^+}, \text{ with } nm = u\bar{d}, c\bar{s},$$
$$R_{nm}^{h_j+W^-}, \text{ with } nm = d\bar{u}, s\bar{c},$$
$$R_{nm}^{h_j+Z}, \text{ with } nm = gg, d\bar{d}, u\bar{u}, s\bar{s}, c\bar{c}, b\bar{b},$$
$$R_{nm}^{h_j+b,h_j+\bar{b}}, \text{ with } nm = bg, \bar{b}g$$

The normalised cross section $R_{nm}^{h_j+y}$ for a partonic neutral Higgs production process is defined by

$$R_{nm}^{H+y} = \frac{\hat{\sigma}_{nm\rightarrow H+y}^{\mathrm{model}}}{\hat{\sigma}_{nm\rightarrow H+y}^{\mathrm{SM}}} \tag{9}$$

calculated for a parton-system centre-of-mass energy squared $\hat{s} = \hat{s}_0$, where $\hat{s}_0$ denotes the partonic production threshold $\hat{s}_0 = (m_H + m_y)^2$ (with $m_y = 0$ in the case of single Higgs boson production). This requires that the dependence on $\hat{s}$ is (at most) mild.

Internally, `HiggsBounds` uses the relation

$$R_\sigma(P)^{TEV} \approx \sum_{\{n,m\}} R_{nm}^{H+y} \frac{\sigma_{\mathrm{SM}}(p\bar{p} \rightarrow nm \rightarrow H+y)}{\sigma_{\mathrm{SM}}(p\bar{p} \rightarrow H+y)}, \tag{10}$$

$$R_\sigma(P)^{LHC,7\text{ TeV}} \approx \sum_{\{n,m\}} R_{nm}^{H+y} \frac{\sigma_{\mathrm{SM}}^{7\text{ TeV}}(pp \rightarrow nm \rightarrow H+y)}{\sigma_{\mathrm{SM}}^{7\text{ TeV}}(pp \rightarrow H+y)}, \tag{11}$$

to calculate the hadronic cross section ratios from the partonic cross section ratios. The ratios $\frac{\sigma_{\mathrm{SM}}(p\bar{p}\rightarrow nm\rightarrow H+y)}{\sigma_{\mathrm{SM}}(p\bar{p}\rightarrow H+y)}$ and $\frac{\sigma_{\mathrm{SM}}(pp\rightarrow nm\rightarrow H+y)}{\sigma_{\mathrm{SM}}(pp\rightarrow H+y)}$ are provided within `HiggsBounds`. For further explanation of the applicability of this approximation and details of how $\frac{\sigma_{\mathrm{SM}}(p\bar{p}\rightarrow nm\rightarrow H+y)}{\sigma_{\mathrm{SM}}(p\bar{p}\rightarrow H+y)}$ are calculated for the Tevatron, see [66]. For `HiggsBounds` `3.0.0beta`, we performed a calculation of this cross section ratios for the LHC with 7 TeV center of mass energy using the prediction of the LHC Higgs Cross Section Working Group [62] for the gluon fusion cross section and the HZ and HW cross sections, and the program `bbh@nnlo` 1.3 [63]. The results are shown in Fig. 1: the relative contributions from different parton configurations to the total hadronic cross section for single Higgs production, $HW^\pm$ production and HZ production.

The partonic cross section ratios R_{nm}^{H+y} are much easier to calculate than hadronic cross section ratios in a wide range of models. In addition, it is often possible to make the approximation

$$R_{nm}^{h_j+W^+} = R_{nm}^{h_j+W^-} = R_{qq'}^{h_j+Z} =: R^{h_j+V} \tag{12}$$

for all nm, thus substantially reducing the number of partonic cross section ratios which need to be provided by the user from 13 to 5.

For instance in the MSSM with real parameters, this ratio R^{h_j+V} can be calculated approximately from the normalised squared effective Higgs coupling to two Z bosons, i.e. $(g_{h_jZZ}^{\mathrm{model}}/g_{HZZ}^{\mathrm{SM}})^2$ (for definition of this coupling, see Sect. 3.3). Similarly, $R_{b\bar{b}}^{h_j}$ and $R_{bg,\bar{b}g}^{h_j+b,h_j+\bar{b}}$ can be taken to be approximately equal in the MSSM (and can also be calculated approximately from effective couplings: see Eq. (30)).
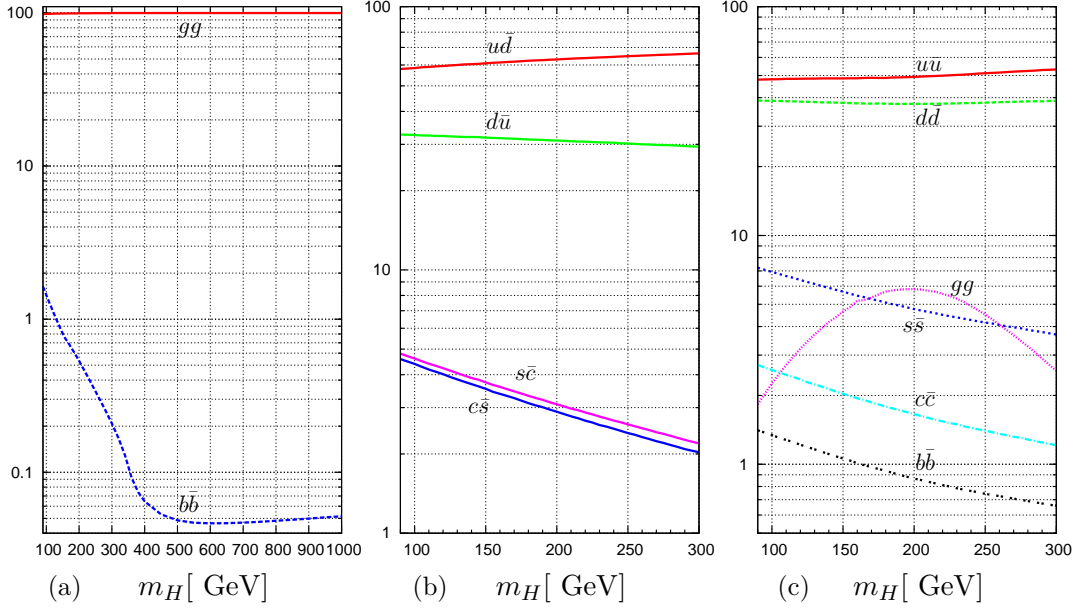
9

Fig. 1. *Relative contributions (in %) of different SM partonic processes to cross sections of hadronic processes at a 7 TeV proton–proton collider: (a) single Higgs production, (b) $HW^{\pm}$ production and (c) HZ production.*

3.3 The effective coupling approximation: `whichinput=effC`

The option `whichinput=effC` allows the user to specify a greatly reduced number of input parameters. It involves specifying (at most)

(1) masses for the neutral Higgs bosons h_k $(k = 1, n_{H^0})$ and singly charged Higgs bosons $H_j^{\pm}$ $(j = 1, n_{H^{\pm}})$,

$$m_{h_k}, m_{H_j^{\pm}},$$

(2) Higgs total decay widths,

$$\Gamma_{\text{tot}}(h_k), \Gamma_{\text{tot}}(H_k^{\pm}),$$

(3) normalised squared scalar and pseudoscalar effective couplings to fermions

$$\left(\frac{g_{s,h_k(\text{OP})}^{\text{model}}}{g_{H(\text{OP})}^{\text{SM}}}\right)^2, \left(\frac{g_{p,h_k(\text{OP})}^{\text{model}}}{g_{H(\text{OP})}^{\text{SM}}}\right)^2, \quad \text{OP} = s\bar{s}, c\bar{c}, b\bar{b}, t\bar{t}, \mu^+\mu^-, \tau^+\tau^-$$

(4) normalised squared effective couplings to bosons

$$\left(\frac{g_{h_i h_j Z}^{\text{model}}}{g_{H'HZ}^{\text{ref}}}\right)^2, \left(\frac{g_{h_k(\text{OP})}^{\text{model}}}{g_{H(\text{OP})}^{\text{SM}}}\right)^2, \quad \text{OP} = W^+W^-, ZZ, Z\gamma, \gamma\gamma, gg, ggZ$$

10

(5) neutral Higgs branching ratios without SM equivalents, charged Higgs branching ratios to SM particles and top quark branching ratios as before.

From this input, the input corresponding to the option `part` is calculated.

We define the scalar and pseudoscalar Higgs coupling to fermions in the usual way, via the Feynman rule for the coupling of a generic neutral Higgs boson h to fermions:

$$G(hf\bar{f}) = i(g_s \mathbf{1} + ig_p \gamma_5), \tag{13}$$

where g_s and g_p are real-valued scalar and pseudoscalar coupling constants respectively, and $\mathbf{1}$ and γ_5 are the usual matrices in Dirac space. A scalar particle, like the SM Higgs boson, has $g_p = 0$ and a pseudoscalar particle has $g_s = 0$.

Where it exists, the reference couplings squared $(g_{H(\text{OP})}^{\text{SM}})^2$ are the SM tree-level equivalents:

$$(g_{HZZ}^{\text{SM}})^2 = \left(\frac{e}{s_{\text{w}}} \frac{m_W}{c_{\text{w}}^2}\right)^2, \tag{14}$$

$$(g_{HWW}^{\text{SM}})^2 = \left(\frac{e}{s_{\text{w}}} m_W\right)^2, \tag{15}$$

$$(g_{Hf\bar{f}}^{\text{SM}})^2 = \left(\frac{1}{2} \frac{e}{s_{\text{w}}} \frac{m_f}{m_W}\right)^2, \tag{16}$$

where m_W and m_f denote the masses of the W boson and fermion f, respectively. $(g_{H'HZ}^{\text{ref}})^2$ is defined in Eq. (7) above.

The effective couplings $(g_{h_k(\text{OP})}^{\text{model}}/g_{H(\text{OP})}^{\text{SM}})^2$, with OP $= Z\gamma$, $\gamma\gamma$, are loop-induced. They can be defined via

$$\left(\frac{g_{h_k(\text{OP})}^{\text{model}}}{g_{H(\text{OP})}^{\text{SM}}}\right)^2 = \frac{\Gamma_{h_k \to \text{OP}}^{\text{model}}(m_{h_k})}{\Gamma_{H \to \text{OP}}^{\text{SM}}(m_H)|_{m_H = m_{h_k}}} \tag{17}$$

The Higgs-gluon-gluon-Z effective coupling squared is also loop induced and is defined as

$$\left(\frac{g_{h_k ggZ}^{\text{model}}}{g_{HggZ}^{\text{SM}}}\right)^2 = R_{gg}^{h_k Z}. \tag{18}$$

There is a choice of definition of the Higgs-gluon-gluon effective coupling squared $(g_{h_k gg}^{\text{model}}/g_{Hgg}^{\text{SM}})^2$. It can either be defined via decay widths:

$$\left(\frac{g_{h_k gg}^{\text{model}}}{g_{Hgg}^{\text{SM}}}\right)^2 = \frac{\Gamma_{h_k gg}^{\text{model}}(m_{h_k})}{\Gamma_{H \to gg}^{\text{SM}}(m_H)|_{m_H = m_{h_k}}} \tag{19}$$

or via partonic cross sections:

$$\left(\frac{g_{h_k gg}^{\text{model}}}{g_{Hgg}^{\text{SM}}}\right)^2 = R_{gg}^{h_k}. \tag{20}$$

In general, the input option `whichinput=effC` should only be used when both definitions result in very similar values for $(g_{h_k gg}^{\text{model}}/g_{Hgg}^{\text{SM}})^2$. However, in certain circumstances, this condition can be relaxed. For example, in a model in which the LEP searches for Higgs bosons decaying into hadrons are not relevant, the normalised gluon-gluon-Higgs effective coupling can be defined solely by Eq. (20). Conversely, if the gluon fusion Higgs production mechanism is not relevant, the normalised gluon-gluon-Higgs effective coupling can be defined solely by Eq. (19).

The normalised LEP cross sections are calculated from the normalised effective couplings using the relations:

$$R_\sigma(e^+ e^- \to h_k Z) = \left(\frac{g_{h_k ZZ}^{\text{model}}}{g_{HZZ}^{\text{SM}}}\right)^2, \tag{21}$$

$$R_\sigma(e^+ e^- \to h_k h_i) = \left(\frac{g_{H'HZ}^{\text{model}}}{g_{H'HZ}^{\text{ref}}}\right)^2, \tag{22}$$

$$R_\sigma(e^+ e^- \to b\bar{b} h_k^{\text{CP even}}) = \left(\frac{g_{s,h_k b\bar{b}}^{\text{model}}}{g_{Hb\bar{b}}^{\text{SM}}}\right)^2, \tag{23}$$

$$R_\sigma(e^+ e^- \to b\bar{b} h_k^{\text{CP odd}}) = \left(\frac{g_{p,h_k b\bar{b}}^{\text{model}}}{g_{Hb\bar{b}}^{\text{SM}}}\right)^2, \tag{24}$$

$$R_\sigma(e^+ e^- \to \tau^+ \tau^- h_k^{\text{CP even}}) = \left(\frac{g_{s,h_k \tau^+ \tau^-}^{\text{model}}}{g_{H\tau^+ \tau^-}^{\text{SM}}}\right)^2, \tag{25}$$

$$R_\sigma(e^+ e^- \to \tau^+ \tau^- h_k^{\text{CP odd}}) = \left(\frac{g_{p,h_k \tau^+ \tau^-}^{\text{model}}}{g_{H\tau^+ \tau^-}^{\text{SM}}}\right)^2. \tag{26}$$

The analyses currently in `HiggsBounds` which use $\sigma_{\text{model}}(e^+ e^- \to b\bar{b} h_k)$ or $\sigma_{\text{model}}(e^+ e^- \to \tau^+ \tau^- h_k)$ apply only to Higgs bosons which are CP eigenstates.

The partonic cross section ratios are calculated by

$$R_{gg}^{h_k} = \left(\frac{g_{h_k gg}^{\text{model}}}{g_{Hgg}^{\text{SM}}}\right)^2 , \tag{27}$$

$$R_{gg}^{h_k Z} = \left(\frac{g_{h_k ggZ}^{\text{model}}}{g_{HggZ}^{\text{SM}}}\right)^2 , \tag{28}$$

$$R_{b\bar{b}}^{h_k} = R_{bg,\bar{b}g}^{h_k b, h_k \bar{b}} = \left(\frac{g_{s,h_k b\bar{b}}^{\text{model}}}{g_{Hb\bar{b}}^{\text{SM}}}\right)^2 + \left(\frac{g_{p,h_k b\bar{b}}^{\text{model}}}{g_{Hb\bar{b}}^{\text{SM}}}\right)^2 , \tag{29}$$

$$R_{q\bar{q}'}^{h_k W^+} = R_{q'\bar{q}}^{h_k W^-} = \left(\frac{g_{h_k WW}^{\text{model}}}{g_{HWW}^{\text{SM}}}\right)^2 , \tag{30}$$

$$R_{q''\bar{q}''}^{h_k Z} = \left(\frac{g_{h_k ZZ}^{\text{model}}}{g_{HZZ}^{\text{SM}}}\right)^2 , \tag{31}$$

where $(q, q') \in \{(u,d),(c,s)\}$ and $q'' \in \{u,d,c,s,b\}$.

The normalised hadronic cross section for $t\bar{t}$ production together with a CP-even Higgs for the Tevatron is obtained using

$$R_\sigma(p\bar{p} \to t\bar{t}h_k^{\text{CP even}}) = \left(\frac{g_{s,h_k t\bar{t}}^{\text{model}}}{g_{Ht\bar{t}}^{\text{SM}}}\right)^2 , \tag{32}$$

and for the LHC:

$$R_\sigma(pp \to t\bar{t}h_k^{\text{CP even}}) = \left(\frac{g_{s,h_k t\bar{t}}^{\text{model}}}{g_{Ht\bar{t}}^{\text{SM}}}\right)^2 . \tag{33}$$

The normalised hadronic cross sections for h_k production via VBF is calculated using the approximate relations:

$$R_\sigma(p\bar{p} \to h_k \text{ via VBF}) = R_{\text{VBF,TEV}}^{WW} \left(\frac{g_{h_k WW}^{\text{model}}}{g_{HWW}^{\text{SM}}}\right)^2 + R_{\text{VBF,TEV}}^{ZZ} \left(\frac{g_{h_k ZZ}^{\text{model}}}{g_{HZZ}^{\text{SM}}}\right)^2 \tag{34}$$

$$R_\sigma^{7\,\text{TeV}}(pp \to h_k \text{ via VBF}) = R_{\text{VBF,LHC},7\,\text{TeV}}^{WW} \left(\frac{g_{h_k WW}^{\text{model}}}{g_{HWW}^{\text{SM}}}\right)^2 + R_{\text{VBF,LHC},7\,\text{TeV}}^{ZZ} \left(\frac{g_{h_k ZZ}^{\text{model}}}{g_{HZZ}^{\text{SM}}}\right)^2 \tag{35}$$

where the numbers

$$R_{\text{VBF,TEV}}^{WW} := \frac{\sigma_{\text{SM}}(p\bar{p} \to H \text{ via } WW \text{ fusion})}{\sigma_{\text{SM}}(p\bar{p} \to H \text{ via VBF})} = 77\% , \tag{36}$$

$$R_{\text{VBF,TEV}}^{ZZ} := \frac{\sigma_{\text{SM}}(p\bar{p} \to H \text{ via } ZZ \text{ fusion})}{\sigma_{\text{SM}}(p\bar{p} \to H \text{ via VBF})} = 23\% \tag{37}$$

have been calculated for $p\bar{p}$ collisions with 1.96 TeV centre-of-mass energy using VBFNLO [56].

$R_{\text{VBF,LHC,7 TeV}}^{WW}$ and $R_{\text{VBF,LHC,7 TeV}}^{ZZ}$ are obtained from functions fitted to results from HAWK [57,58] 1.1 for pp collisions with 7 TeV centre-of-mass energy. Although the m_H dependence of this quantities is mild, an approximation by constant values, as done in the Tevatron case, would not be accurate enough.

Within `HiggsBounds`, the neutral Higgs decay widths to ordinary particles in the effective coupling input option are then calculated by

$$\Gamma_{h_k \to \text{OP}}^{\text{model}}(m_{h_k}) = \left(\frac{g_{h_k(\text{OP})}^{\text{model}}}{g_{H(\text{OP})}^{\text{SM}}} \right)^2 \Gamma_{H \to \text{OP}}^{\text{SM}}(m_H) \Big|_{m_H = m_{h_k}}$$
$$\text{for OP} = W^+W^-,\, ZZ,\, Z\gamma,\, \gamma\gamma,\, gg, \tag{38}$$

$$\Gamma_{h_k \to \text{OP}}^{\text{model}}(m_{h_k}) = \left(\left(\frac{g_{s,h_k(\text{OP})}^{\text{model}}}{g_{H(\text{OP})}^{\text{SM}}} \right)^2 + \left(\frac{g_{p,h_k(\text{OP})}^{\text{model}}}{g_{H(\text{OP})}^{\text{SM}}} \right)^2 \beta_f^{-2}(m_{h_k}) \right) \Gamma_{H \to \text{OP}}^{\text{SM}}(m_H) \Big|_{m_H = m_{h_k}}$$
$$\text{for OP} = s\bar{s},\, c\bar{c},\, b\bar{b},\, \mu^+\mu^-,\, \tau^+\tau^-, \tag{39}$$

with $\beta_f^2(m_{h_k}) = 1 - 4m_f^2/m_{h_k}^2$. These are converted to branching ratios via

$$\text{BR}_{h_k \to \text{OP}}^{\text{model}}(m_{h_k}) = \frac{\Gamma_{h_k \to \text{OP}}^{\text{model}}(m_{h_k})}{\Gamma_{\text{tot}}(h_k)} \tag{40}$$

Note that this means that it is especially important for the user to give an accurate $\Gamma_{\text{tot}}(h_k)$ when using this input option.

Using effective couplings as input, the CP properties of the neutral Higgs bosons can be inferred, at least as far as the signal properties considered here are concerned. In the present implementation, we set the CP value of a Higgs h_k in the following way:

$$\text{CP}(h_k) \to +1 \qquad \text{if} \quad \max_f \left(\frac{g_{p,h_k f\bar{f}}^{\text{model}}}{g_{Hf\bar{f}}^{\text{SM}}} \right)^2 < 10^{-16},$$

$$\text{CP}(h_k) \to -1 \qquad \text{if} \quad \max_f \left(\frac{g_{s,h_k f\bar{f}}^{\text{model}}}{g_{Hf\bar{f}}^{\text{SM}}} \right)^2 < 10^{-16},$$

$$\text{CP}(h_k) \to 0 \qquad \text{if neither of the above conditions is met.}$$

For the implemented set of analyses, the limits on topological cross sections are applicable with high accuracy to models where the Higgs sector can be faithfully parametrised with effective couplings (See Ref. [66] for details).

Note that, if the user is interested in Higgs masses below 10 GeV, the input option `whichinput=effC` will not usually be appropriate. Users should enter the branching ratios for this light Higgs themselves.

In summary, users may find it convenient to use the input option `whichinput=effC` for cases in which Eq. (10), Eqs. (21) – (34), and Eqs. (38) and (39) are valid to a satisfactory level of accuracy. Of course, if only some of the analyses are relevant to the model, not all of these relations need to hold. As discussed above, for a model in which LEP searches for Higgs bosons decaying into hadrons are not relevant, Eq. (19) does not need to be valid.

3.4 Susy Les Houches Accord: `whichinput=SLHA`

For the convenience of researchers studying supersymmetric models, a SLHA input option is offered. The option `whichinput=SLHA` involves extracting (at most) the following numbers from the SLHA file:

(1) masses for the neutral Higgs bosons h_k $(k = 1, n_{H^0})$ and singly charged Higgs bosons $H_j^{\pm}$ $(j = 1, n_{H^{\pm}})$,

$$m_{h_k}, m_{H_j^{\pm}},$$

(2) Higgs total decay widths,

$$\Gamma_{\text{tot}}(h_k), \Gamma_{\text{tot}}(H_k^{\pm}),$$

(3) neutral Higgs branching ratios with SM equivalents (OP=ordinary particles i.e. particles which exist in the SM)

$$\text{BR}_{\text{model}}(h_k \to OP) \text{ with } OP = s\bar{s}, c\bar{c}, b\bar{b}, \mu^+\mu^-, \tau^+\tau^-, W^+W^-, ZZ, Z\gamma, \gamma\gamma, gg$$

(4) neutral Higgs branching ratios without SM equivalents

$$\text{BR}_{\text{model}}(h_k \to h_i h_i), \text{BR}_{\text{model}}(h_k \to \text{invisible}),$$

(5) charged Higgs branching ratios to SM particles

$$\text{BR}(H_j^+ \to \text{OP}) \text{ with } OP = c\bar{s}, c\bar{b}, \tau^+\nu_\tau$$

(6) top quark branching ratios

$$\text{BR}(t \to W^+ b), \text{BR}(t \to H_j^+ b),$$

(7) normalised scalar and pseudoscalar effective couplings to fermions squared

$$\left(\frac{g^{\text{model}}_{s,h_k(OP)}}{g^{\text{SM}}_{H(OP)}} \right)^2, \left(\frac{g^{\text{model}}_{p,h_k(OP)}}{g^{\text{SM}}_{H(OP)}} \right)^2, OP = b\bar{b}, t\bar{t}, \tau^+\tau^-$$

(8) normalised squared effective couplings to bosons

$$\left(\frac{g_{h_i h_j Z}^{\text{model}}}{g_{H'HZ}^{\text{ref}}}\right)^2 \ , \ \left(\frac{g_{h_k(OP)}^{\text{model}}}{g_{H(OP)}^{\text{SM}}}\right)^2 , OP = W^+ W^-, ZZ, gg, ggZ$$

Any masses not specified in the SLHA file will be set to minus one. Any other parameters that are not specified in the SLHA file will be set to zero.

The normalised squared effective couplings are used to calculate the normalised Higgs production cross sections and the CP properties within `HiggsBounds`. Note that (unlike the option whichinput='effC') effective couplings are not used to calculate the branching ratios: branching ratios are taken directly from the decay blocks in the SLHA file (or set zero if they are not specified in these decay blocks).

`HiggsBounds` requires two extra ('SLHA'-inspired) blocks to specify the normalised squared effective couplings. The format of these blocks is shown in Fig. 2.

`HiggsBounds` is *unable* to use the SLHA file if

- the Block MODSEL indicates that there is R-parity violation
- `nHzero` is greater than 5
- `nHplus` is greater than 1

(recall that `nHzero` and `nHplus` are given as input, either as arguments to the subroutine `initialize_HiggsBounds` or on the command line).

If either Block SPINFO or Block DCINFO contains an entry with the label '4', `HiggsBounds` will consider the file to contain an unphysical parameter point and not attempt to extract any further information from the file.

Table 1 contains the sequence of PDG numbers which can be considered as neutral Higgs bosons. `nHzero` is used to specify how many of these PDG numbers are used, counting from the top of table 1 downwards. For example, if `nHzero=3`, the properties of particles with the PDG numbers 25,35,36 are read from the SLHA file. If `nHzero=5`, particles with the PDG numbers 25,35,36,45,46 are read in. Note that no CP properties are inferred from the PDG numbers of neutral Higgs.

The invisible Higgs branching ratio is obtained from the branching ratio of the Higgs into a weakly-interacting lightest supersymmetric particle (LSP). Table 2 contains the particles which are considered as possible weakly-interacting LSP candidates. `HiggsBounds` finds the weakly-interacting candidate with the lowest mass and then confirms that this particle is indeed the LSP by comparing its mass against the masses of the charged leptons, lightest chargino and gluino. If it is not the LSP, the invisible Higgs branching ratio is set to zero.

Neutral Higgs bosons	
Common notation	PDG number
h^0 or h_1	25
H^0 or h_2	35
A^0 or h_3 or A_1^0	36
h_3	45
A_2^0	46

Table 1

PDG numbers which can represent neutral Higgs bosons. `nHzero` *of these will be considered by* `HiggsBounds`, *starting from the top row.*

Weakly-interacting LSP candidates	
Common notation	PDG number
χ_1^0	1000022
$\tilde{\nu}_e$ or $\tilde{\nu}_1$ or $\tilde{\nu}_{1S}$	1000012
$\tilde{\nu}_\mu$ or $\tilde{\nu}_2$ or $\tilde{\nu}_{2S}$	1000014
$\tilde{\nu}_\tau$ or $\tilde{\nu}_3$ or $\tilde{\nu}_{3S}$	1000016
$\tilde{\nu}_{1A}$	1000017
$\tilde{\nu}_{2A}$	1000018
$\tilde{\nu}_{3A}$	1000019

Table 2

PDG numbers which can represent a weakly-interacting LSP. `HiggsBounds` *will check whether one of these particles is indeed the LSP, and if it is, takes the branching ratio of neutral Higgs into this LSP as the invisible Higgs branching ratio.*

4 New `HiggsBounds` Operating Instructions

There are three formats in which the program `HiggsBounds` can be used:

- Library of subroutines
- Command-line version
- Online version

The most widely applicable format of `HiggsBounds` is the command-line version, since this reads all the model data from text files and thus this model data can be generated using any package the user wishes. The library of `HiggsBounds` subroutines allows `HiggsBounds` to be called within other programs. If the user just wishes to check a few parameter points, the online version provides quick access to all the functionality of `HiggsBounds`, without the need to install the code.

The `HiggsBounds` code, the online version and documentation can all be found at the URL `http://projects.hepforge.org/higgsbounds/`.

The `HiggsBounds 3.0.0beta` code is currently provided in Fortran 90 (with a few Fortran 2003 features). The code has been tested with a variety of Fortran compilers, including the free gnu compilers which accompany most Linux distributions.

The library of subroutines, the command-line version and the online version share a common set of features, which we will describe first. We will then give operating instructions for each of these three `HiggsBounds` formats individually.

4.1 Common features: Input

`HiggsBounds` requires five types of input:

- the number of neutral Higgs bosons in the model under study (`nHzero`)
- the number of singly, positively charged Higgs bosons in the model under study (`nHplus`)
- the set of experimental analyses which should be considered (`whichanalyses`)
- the theoretical predictions of the model under study (a set of input arrays)
- the format of these theoretical predictions (`whichinput`)

Tab. 3 contains further information on the variable `nHzero` and `nHplus`, and the possible values of `whichanalyses` are described in Tab. 4. Note that the option `whichanalyses='singH'` should only be used if neither processes involving Higgs pair production at LEP nor processes involving the $h_j \to h_i h_i$ decay are relevant. However, if these conditions are met, this option can save significantly on computing time.

`HiggsBounds` expects the theoretical input to be in one of three formats, labelled by the variable `whichinput`. These formats were described in detail in Sect. 3 and are briefly summarised in Tab. 5. In Tab. 6, Tab. 7, Tab. 8 and Tab. 9 we assign names to all of the possible input arrays (each array is defined in terms of the notation used in Sect. 3). These names will prove useful when we describe the input requirements of each version of `HiggsBounds` individually.

nHzero	nHplus	(integer)
0-9	0-9	This is the default range.
		It can easily be extended by the user if required.

Table 3
The possible values of the variable `nHzero`, *which labels the number of neutral Higgs bosons in the model under study and the variable* `nHplus`, *which labels the number of singly, positively charged Higgs.*

whichanalyses	(character(LEN=5))
LandH	analyses from both lepton and hadron colliders (i.e. LEP, Tevatron and LHC)
onlyL	only LEP analyses
onlyH	analyses from hadron colliders only (i.e. Tevatron and LHC)
onlyP	only published analyses (defined as analyses with an arXiv number)

Table 4
The possible values of the variable `whichanalyses`, *which indicates which subset of experimental analyses will be considered by* `HiggsBounds`.

whichinput	(character(LEN=4))
effC	Masses, total decay widths, ratios of effective couplings squared, some branching ratios.
part	Masses, total decay widths, ratios of LEP cross sections, mainly ratios of partonic hadron-collider cross sections, branching ratios.
hadr	Masses, total decay widths, ratios of LEP cross sections, ratios of Tevatron hadronic cross sections, ratios of LHC hadronic cross sections, branching ratios.

Table 5
The possible values of the variable `whichinput`, *which indicates the format of the theoretical predictions provided by the user for the neutral Higgs sector. (See Sect. 3 for a more detailed description of each of these settings).*

```
Block HiggsBoundsInputHiggsCouplingsFermions
# For exact definitions of NormEffCoupSq see HiggsBounds manual
# ScalarNormEffCoupSq PseudoSNormEffCoupSq    NP    IP1      IP2       IP3 # Scalar, Pseudoscalar Normalised Effective Coupling Squared
      1.0000001E+00        1.0000101E+00        3     25       5         5 # h0-b-b eff. coupling^2, normalised to SM
      1.0000002E+00        1.0000102E+00        3     35       5         5 # HH-b-b eff. coupling^2, normalised to SM
      1.0000003E+00        1.0000103E+00        3     36       5         5 # A0-b-b eff. coupling^2, normalised to SM
#
      1.0000004E+00        1.0000104E+00        3     25       6         6 # h0-top-top eff. coupling^2, normalised to SM
      1.0000005E+00        1.0000105E+00        3     35       6         6 # HH-top-top eff. coupling^2, normalised to SM
      1.0000006E+00        1.0000106E+00        3     36       6         6 # A0-top-top eff. coupling^2, normalised to SM
#
      1.0000007E+00        1.0000107E+00        3     25      15        15 # h0-tau-tau eff. coupling^2, normalised to SM
      1.0000008E+00        1.0000108E+00        3     35      15        15 # HH-tau-tau eff. coupling^2, normalised to SM
      1.0000009E+00        1.0000109E+00        3     36      15        15 # A0-tau-tau eff. coupling^2, normalised to SM
#
Block HiggsBoundsInputHiggsCouplingsBosons
# For exact definitions of NormEffCoupSq see HiggsBounds manual
      1.0000010E+00     3     25      24        24 # h0-W-W effective coupling^2, normalised to SM
      1.0000011E+00     3     35      24        24 # HH-W-W effective coupling^2, normalised to SM
      1.0000012E+00     3     36      24        24 # A0-W-W effective coupling^2, normalised to SM
#
      1.0000013E+00     3     25      23        23 # h0-Z-Z effective coupling^2, normalised to SM
      1.0000014E+00     3     35      23        23 # HH-Z-Z effective coupling^2, normalised to SM
      1.0000015E+00     3     36      23        23 # A0-Z-Z effective coupling^2, normalised to SM
#
      1.0000016E+00     3     25      21        21 # h0-gluon-gluon effective coupling^2, normalised to SM
      1.0000017E+00     3     35      21        21 # HH-gluon-gluon effective coupling^2, normalised to SM
      1.0000018E+00     3     36      21        21 # A0-gluon-gluon effective coupling^2, normalised to SM
#
      1.0000019E+00     3     25      25        23 # h0-h0-Z effective coupling^2, normalised
      1.0000020E+00     3     25      35        23 # h0-HH-Z effective coupling^2, normalised
      1.0000021E+00     3     25      36        23 # h0-A0-Z effective coupling^2, normalised
      1.0000022E+00     3     35      35        23 # HH-HH-Z effective coupling^2, normalised
      1.0000023E+00     3     35      36        23 # HH-A0-Z effective coupling^2, normalised
      1.0000024E+00     3     36      36        23 # A0-A0-Z effective coupling^2, normalised
#
      1.0000025E+00     4     25      21        21      23 # h0-gluon-gluon-Z effective coupling^2, normalised to SM
      1.0000026E+00     4     35      21        21      23 # HH-gluon-gluon-Z effective coupling^2, normalised to SM
      1.0000027E+00     4     36      21        21      23 # A0-gluon-gluon-Z effective coupling^2, normalised to SM
```

Fig. 2. *Examples of the Block HiggsBoundsInputHiggsCouplingsFermions and Block HiggsBoundsInputHiggsCouplingsBosons, which are required by HiggsBounds if using the SLHA input option.*

input arrays	(double precision)	
`Mh(nHzero)`	m_{h_i}	in GeV
`MhGammaTot(nHzero)`	$\Gamma_{\text{tot}}(h_i)$	in GeV
`Mhplus(nHplus)`	$m_{H_i^\pm}$	in GeV
`MhplusGammaTot(nHplus)`	$\Gamma_{\text{tot}}(H_i^\pm)$	in GeV
`g2hjss_s(nHzero)`	$\left(\dfrac{g^{\text{model}}_{s,h_j(\text{OP})}}{g^{\text{SM}}_{H(\text{OP})}}\right)^2,$ OP =	$s\bar{s}$
`g2hjcc_s(nHzero)`		$c\bar{c}$
`g2hjbb_s(nHzero)`		$b\bar{b}$
`g2hjtoptop_s(nHzero)`		$t\bar{t}$
`g2hjmumu_s(nHzero)`		$\mu^+\mu^-$
`g2hjtautau_s(nHzero)`		$\tau^+\tau^-$
`g2hjss_p(nHzero)`	$\left(\dfrac{g^{\text{model}}_{p,h_j(\text{OP})}}{g^{\text{SM}}_{H(\text{OP})}}\right)^2,$ OP =	$s\bar{s}$
`g2hjcc_p(nHzero)`		$c\bar{c}$
`g2hjbb_p(nHzero)`		$b\bar{b}$
`g2hjtoptop_p(nHzero)`		$t\bar{t}$
`g2hjmumu_p(nHzero)`		$\mu^+\mu^-$
`g2hjtautau_p(nHzero)`		$\tau^+\tau^-$
`g2hjWW(nHzero)`	$\left(\dfrac{g^{\text{model}}_{h_j(\text{OP})}}{g^{\text{SM}}_{H(\text{OP})}}\right)^2,$ OP =	W^+W^-
`g2hjZZ(nHzero)`		ZZ
`g2hjZga(nHzero)`		$Z\gamma$
`g2hjgaga(nHzero)`		$\gamma\gamma$
`g2hjgg(nHzero)`		gg
`g2hjggZ(nHzero)`		ggZ
`g2hjhiZ(nHzero,nHzero)`	$\left(\dfrac{g^{\text{model}}_{h_j h_i Z}}{g^{\text{ref}}_{HH'Z}}\right)^2$	

Table 6

Input arrays for model predictions for effective normalised squared couplings recognised by `Higgs-Bounds`. *The size of each array is given in brackets in the first column. See Sect. 3 for the description of the notation used in the second column.*

input arrays cont.	(integer)		
CP_value(nHzero), where CP_value(i)	= -1	if ith neutral Higgs is CP-odd
	= 0	if ith neutral Higgs has mixed CP
	= 1	if ith neutral Higgs is CP-even

Table 7
Input array to specify the CP properties of each of the neutral Higgs bosons predicted by the model. The size of the array is given in brackets in the first column.

input arrays cont.	(double precision)		
BR_hjss(nHzero)	$BR(h_j \to OP)$,	$OP =$	$s\bar{s}$
BR_hjcc(nHzero)			$c\bar{c}$
BR_hjbb(nHzero)			$b\bar{b}$
BR_hjmumu(nHzero)			$\mu^+\mu^-$
BR_hjtautau(nHzero)			$\tau^+\tau^-$
BR_hjWW(nHzero)			W^+W^-
BR_hjZZ(nHzero)			ZZ
BR_hjZga(nHzero)			$Z\gamma$
BR_hjgaga(nHzero)			$\gamma\gamma$
BR_hjgg(nHzero)			gg
BR_hjinvisible(nHzero)	$BR(h_j \to \text{invisible})$		
BR_hjhihi(nHzero,nHzero)	$BR(h_j \to h_i h_i)$		
BR_tWpb	$BR(t \to W^+ b)$		
BR_tHpjb(nHplus)	$BR(t \to H_j^+ b)$		
BR_Hpjcs(nHplus)	$BR(H_j^+ \to OP)$,	$OP =$	$c\bar{s}$
BR_Hpjcb(nHplus)			$c\bar{b}$
BR_Hpjtaunu(nHplus)			$\tau^+\bar{\nu}_\tau$

Table 8
Input arrays for model predictions for branching ratios recognised by HiggsBounds. The size of each array is given in brackets in the first column. See Sect. 3 for the description of the notation used in the second column. The elements of BR_hjhihi are ordered such that BR_hjhihi(j,i)= $BR(h_j \to h_i h_i)$.

input arrays cont.	(double precision)		
CS_lep_hjZ_ratio(nHzero)	$R_\sigma(P),$	$P =$	$e^+e^- \to h_j Z$
CS_lep_bbhj_ratio(nHzero,nHzero)			$e^+e^- \to b\bar{b}h_j$
CS_lep_tautauhj_ratio(nHzero,nHzero)			$e^+e^- \to \tau^+\tau^- h_j$
CS_lep_hjhi_ratio(nHzero,nHzero)			$e^+e^- \to h_j h_i$
CS_lep_HpjHmj_ratio(nHzero)			$e^+e^- \to H_j^+ H_j^-$
CS_tev_hj_ratio(nHzero)			$p\bar{p} \to h_j$
CS_tev_hjb_ratio(nHzero)			$p\bar{p} \to bh_j$
CS_tev_hjW_ratio(nHzero)			$p\bar{p} \to h_j W$
CS_tev_hjZ_ratio(nHzero)			$p\bar{p} \to h_j Z$
CS_tev_vbf_ratio(nHzero)			$p\bar{p} \to h_j$ via VBF
CS_tev_tthj_ratio(nHzero)			$p\bar{p} \to t\bar{t}h_j$
CS_lhc7_hj_ratio(nHzero)			$pp \to h_j$ at 7 TeV
CS_lhc7_hjb_ratio(nHzero)			$pp \to bh_j$ at 7 TeV
CS_lhc7_hjW_ratio(nHzero)			$pp \to h_j W$ at 7 TeV
CS_lhc7_hjZ_ratio(nHzero)			$pp \to h_j Z$ at 7 TeV
CS_lhc7_vbf_ratio(nHzero)			$pp \to h_j$ via VBF at 7 TeV
CS_lhc7_tthj_ratio(nHzero)			$pp \to t\bar{t}h_j$ at 7 TeV
CS_gg_hj_ratio(nHzero)	$R_{nm}^{h_j},$	$nm =$	gg
CS_bb_hj_ratio(nHzero)			$b\bar{b}$
CS_ud_hjWp_ratio(nHzero)	$R_{nm}^{h_j+W^+},$	$nm =$	$u\bar{d}$
CS_cs_hjWp_ratio(nHzero)			$c\bar{s}$
CS_ud_hjWm_ratio(nHzero)	$R_{nm}^{h_j+W^-}$	$nm =$	$d\bar{u}$
CS_cs_hjWm_ratio(nHzero)			$s\bar{c}$
CS_gg_hjZ_ratio(nHzero)	$R_{nm}^{h_j+Z}$	$nm =$	gg
CS_dd_hjZ_ratio(nHzero)			$d\bar{d}$
CS_uu_hjZ_ratio(nHzero)			$u\bar{u}$
CS_ss_hjZ_ratio(nHzero)			$s\bar{s}$
CS_cc_hjZ_ratio(nHzero)			$c\bar{c}$
CS_bb_hjZ_ratio(nHzero)			$b\bar{b}$
CS_bg_hjb_ratio(nHzero)	$R_{nm}^{h_j+b,h_j+\bar{b}}$	$nm =$	$bg, \bar{b}g$

Table 9

Input arrays for model predictions for cross section ratios recognised by `HiggsBounds`. The size of each array is given in brackets in the first column. The LEP or hadronic Tevatron and LHC cross section ratios $R_\sigma(P)$ are defined in Eq. (7), and the partonic Tevatron cross section ratios $R_{nm}^{h_j+y}$ are defined in Eq. (9).

`HiggsBounds` provides the user with four types of output:

- whether the parameter point is excluded at the 95% C.L. or not (`HBresult`)
- the reference number of the analysis application (X_0) with the highest statistical sensitivity (`chan`).
- the number of Higgs bosons which have contributed to the theoretical rate for the corresponding process (`ncombined`)
- the ratio of the theoretical rate Q_{model} to the observed limit Q_{obs} for this process (`obsratio`).

Tab. 10 shows the possible values of `HBresult` and `obsratio`, which are complementary. Tab. 11 and Tab. 12 gives information on `chan` and `ncombined` respectively. If the library of subroutines or the command-line versions are used, the key associating the reference numbers with the analysis applications is written in the file `Key.dat`. In the online version, this information appears on the screen.

HBresult	obsratio	
(integer)	(double precision)	
0	≥ 1.0	parameter point is excluded
1	< 1.0	parameter point is not excluded
-1	≤ 0.0	invalid parameter set

Table 10
The possible values of the output variables `HBresult` *and* `obsratio`, *which indicate whether a parameter point has been excluded at the 95% C.L. by the experimental results under consideration.*

chan	(integer)
0-[# of considered analyses]	See the file `Key.dat` for the definition of each reference number. `Key.dat` is automatically generated when either the command line or the subroutine version of `HiggsBounds` are used.

Table 11
Further information about the output variable `chan`, *which stores the reference number of the analysis application with the highest statistical sensitivity. (0= no process applies)*

4.2.1   Block `HiggsBoundsResults`

The `HiggsBounds` results can be added to SLHA files in the form of a new block: `HiggsBoundsResults`. An example is shown in Fig. 3. Strings are wrapped with '||'.

ncombined	(integer)
1-nHzero	Number of neutral (or singly, positively charged) Higgs bosons which have contributed to the theoretical rate for this process.

Table 12
Further information about the output variable `ncombined`.

4.3   Library of subroutines

Installation

The `HiggsBounds` code can be compiled to form a library of subroutines using the following commands:

```
./configure
make
```

A program for which the `HiggsBounds` subroutines should be used can be compiled and linked to the library by adding `-L<HBpath> -lHB` to the command line, for example,

```
gfortran myprog.f90 -o myprog -L<HBpath> -lHB
```

where `<HBpath>` is the location of the `HiggsBounds` library.

The `HiggsBounds` subroutines make use of the file handles 10, 11, 44, 45 and 87 (i.e. users should avoid using these file handles in the program which calls these subroutines.).

Subroutine `initialize_HiggsBounds`

The subroutine `initialize_HiggsBounds` must be called before any other `HiggsBounds` subroutine. It performs some preparatory operations such as reading in the tables of data. It is called as:

```
call initialize_HiggsBounds(nHzero, nHplus, whichanalyses)
```

When using the subroutines in another code, the subroutine `initialize_HiggsBounds` must be called only once, before any other `HiggsBounds` subroutine is called.

If the user does not wish to test the neutral Higgs sector with `HiggsBounds`, then he/she should set `nHzero=0`. Similarly, if the user does not wish to test the charged Higgs sector with `HiggsBounds`, then he/she should set `nHplus=0`.

Subroutines `HiggsBounds_neutral_input_effC`,
`HiggsBounds_neutral_input_part` *and* `HiggsBounds_neutral_input_hadr`

The neutral Higgs sector input can be passed to `HiggsBounds` using one of the subroutines `HiggsBounds_neutral_input_effC`, `HiggsBounds_neutral_input_part` or `HiggsBounds_neutral_input_hadr`. They set the value of `whichinput` to be `effC`, `part` and `hadr` respectively and therefore require different arguments. The use of one of these subroutines is only required if `nHzero` is non-zero (recall that `nHzero` is set in subroutine `initialize_HiggsBounds`). These subroutines are called as:

```
call HiggsBounds_neutral_input_effC(Mh,MhGammaTot,
     &  g2hjss_s,g2hjss_p,g2hjcc_s,g2hjcc_p,g2hjbb_s,g2hjbb_p,
     &  g2hjtoptop_s,g2hjtoptop_p,
     &  g2hjmumu_s,g2hjmumu_p,g2hjtautau_s,g2hjtautau_p,
     &  g2hjWW,g2hjZZ,g2hjZga,g2hjgaga,g2hjgg,g2hjggZ,
     &  g2hjhiZ,BR_hjinvisible,BR_hjhihi                   )


call HiggsBounds_neutral_input_part(Mh,MhGammaTot, CP_value,
     &  CS_lep_hjZ_ratio,CS_lep_bbhj_ratio,CS_lep_tautauhj_ratio,
     &  CS_lep_hjhi_ratio,
     &  CS_gg_hj_ratio,  CS_bb_hj_ratio,
     &  CS_bg_hjb_ratio,
     &  CS_ud_hjWp_ratio,CS_cs_hjWp_ratio,
     &  CS_ud_hjWm_ratio,CS_cs_hjWm_ratio,
     &  CS_gg_hjZ_ratio, CS_dd_hjZ_ratio, CS_uu_hjZ_ratio,
     &  CS_ss_hjZ_ratio, CS_cc_hjZ_ratio,
     &  CS_bb_hjZ_ratio,
     &  CS_tev_vbf_ratio, CS_tev_tthj_ratio,
     &  CS_lhc7_vbf_ratio, CS_lhc7_tthj_ratio,
     &  BR_hjss,BR_hjcc,BR_hjbb,BR_hjmumu,BR_hjtautau,
     &  BR_hjWW,BR_hjZZ,BR_hjZga,BR_hjgaga,BR_hjgg,BR_hjinvisible,
     &  BR_hjhihi                                          )


call HiggsBounds_neutral_input_hadr(Mh,MhGammaTot, CP_value,
     &  CS_lep_hjZ_ratio,CS_lep_bbhj_ratio,CS_lep_tautauhj_ratio,
     &  CS_lep_hjhi_ratio,
     &  CS_tev_hj_ratio,  CS_tev_hjb_ratio,
     &  CS_tev_hjW_ratio, CS_tev_hjZ_ratio,
     &  CS_tev_vbf_ratio, CS_tev_tthj_ratio,
     &  CS_lhc7_hj_ratio,  CS_lhc7_hjb_ratio,
     &  CS_lhc7_hjW_ratio, CS_lhc7_hjZ_ratio,
     &  CS_lhc7_vbf_ratio, CS_lhc7_tthj_ratio,
     &  BR_hjss,BR_hjcc,BR_hjbb,BR_hjmumu,BR_hjtautau,
     &  BR_hjWW,BR_hjZZ,BR_hjZga,BR_hjgaga,BR_hjgg,BR_hjinvisible,
     &  BR_hjhihi                                          )
```

Each of these arguments must be supplied. However, if a branching ratio, effective coupling or cross section is believed to be irrelevant, the corresponding array may be filled with zeros. This will ensure that the value of Q_{model} for processes involving this quantity will also be zero. For example, in the MSSM, scenarios exist where the decay $h_j \to \gamma\gamma$ will certainly not be the process with the highest statistical sensitivity of $Q_{\text{model}}/Q_{\text{expec}}$ and, consequently, it may be convenient to set the arrays g2hjgaga and BR_hjgaga to zero for simplicity in such a case. Note that if a quantity used in a SM-likeness test is set to zero, the model point will fail that SM-likeness test, even if the corresponding SM quantity is very small.

Also, depending on the value given for whichanalyses, some of the input arrays will be ignored within HiggsBounds. For example, if whichanalyses='onlyH', the branching ratio for the Higgs cascade decay $h_j \to h_i h_i$ will not be relevant. Therefore, setting this array to zero will not affect the HiggsBounds results in this case.

Subroutine HiggsBounds_charged_input

The subroutine HiggsBounds_charged_input gives the charged Higgs sector input to Higgs-Bounds. The use of this subroutine is only required if nHplus is non-zero (recall that nHplus is set in subroutine initialize_HiggsBounds). It is called as:

```
call HiggsBounds_charged_input(MHplus, MHplusGammaTot
    &   CS_lep_HpjHmi_ratio,
    &   BR_tWpb,BR_tHpjb,BR_Hpjcs,BR_Hpjcb,BR_Hptaunu        )
```

Subroutine HiggsBounds_input_SLHA

The subroutine HiggsBounds_input_SLHA can be used as an alternative to the subroutines HiggsBounds_neutral_input_effC, HiggsBounds_neutral_input_part, HiggsBounds_neutral_input_hadr and HiggsBounds_charged_input. It is called as

```
call HiggsBounds_input_SLHA(SLHAfilename)
```

where SLHAfilename is a variable of type character(len=100) and contains the name of the SLHA file (including the path to this file if it is not in the current working directory.)

Subroutine run_HiggsBounds

This subroutine performs the main part of the HiggsBounds calculations. It is called as:

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

Subroutine `HiggsBounds_SLHA_output`

The subroutine `HiggsBounds_SLHA_output` can be called after `run_HiggsBounds` in order to write the block `HiggsBoundsResults` to the SLHA file. It is called as

```
call HiggsBounds_SLHA_output
```


Subroutine `finish_HiggsBounds`

The subroutine `finish_HiggsBounds` should be called once at the end of the program, after all other `HiggsBounds` subroutines [4]. It is called as:

```
call finish_HiggsBounds
```


Functions for SM branching ratios, total decay width and cross sections

The `HiggsBounds` library also allows users access to the SM Higgs branching ratios, total decay width and production cross sections, which are used internally by `HiggsBounds`. We use SM Higgs branching ratios and total decay width from the program HDECAY 3.532 [54]. The Tevatron SM hadronic cross sections have been obtained from the TEV4LHC Higgs Working Group [55] (see Tab. 13 for references to the original works) with the exception of the $\sigma^{\mathrm{SM}}(p\bar{p} \to gg \to H)$, $\sigma^{\mathrm{SM}}(p\bar{p} \to bg \to bH)$ and $\sigma^{\mathrm{SM}}(p\bar{p} \to \bar{b}g \to \bar{b}H)$ cross sections. $\sigma^{\mathrm{SM}}(p\bar{p} \to gg \to H)$ was fitted to results obtained from the online calculator at `http://theory.fi.infn.it/grazzini/hcalculators.html` [71–85]. $\sigma^{\mathrm{SM}}(p\bar{p} \to bg \to bH)$ and $\sigma^{\mathrm{SM}}(p\bar{p} \to \bar{b}g \to \bar{b}H)$ have been calculated with the program HJET 1.3 [59–61] for a set of different cuts on the transverse momentum and pseudo-rapidity of the b-quark, which are needed internally in order to apply correctly the results of some Tevatron analyses and which were not available from Ref. [55]. From this set, only the cross section without cuts is externally provided.

The LHC SM hadronic cross sections are given in Tab. 14. The majority have been obtained from the LHC Higgs Cross Section Working Group [62], with the exception of $\sigma^{\mathrm{SM}}(pp \to bb \to H)$, which was fitted to numbers generated with `bbh@nnlo` 1.3 [63].

Also included is a function for the SM top quark decay width into W^+b in GeV, which depends on the top quark pole mass in GeV, given at next-to-leading-order, neglecting terms of order m_b^2/m_t^2, α_s^2 and $(\alpha_s/\pi)\, M_W^2/m_t^2$, as quoted in [86] (original reference: [87]). This is not used within `HiggsBounds`, but may prove useful when calculating $\mathrm{BR}(t \to H^+b)$.

Note that these functions are only valid within certain mass ranges, which are sufficient for the requirements of `HiggsBounds`. If a function is called with an argument outside this range, it returns a value of -1.

---

[4] In the Fortran 90 version of the code, the subroutine `finish_HiggsBounds` is used to deallocate the allocatable arrays used within `HiggsBounds`.

function	(double precision)			
SMGamma_h(Mh)	$\Gamma^{\mathrm{SM}}_{\mathrm{tot}}(h_i)$			[54]
SMBR_Hss(Mh)	$\mathrm{BR}^{\mathrm{SM}}(H \to \mathrm{OP})$,	OP=	$s\bar{s}$	[54]
SMBR_Hcc(Mh)			$c\bar{c}$	[54]
SMBR_Hbb(Mh)			$b\bar{b}$	[54]
SMBR_Htoptop(Mh)			$t\bar{t}$	[54]
SMBR_Hmumu(Mh)			$\mu^-\mu^+$	[54]
SMBR_Htautau(Mh)			$\tau^-\tau^+$	[54]
SMBR_HWW(Mh)			W^+W^-	[54]
SMBR_HZZ(Mh)			ZZ	[54]
SMBR_HZgam(Mh)			$Z\gamma$	[54]
SMBR_Hgamgam(Mh)			$\gamma\gamma$	[54]
SMBR_Hgg(Mh)			gg	[54]
SMGamma_tWpb(Mtop)	$\Gamma^{\mathrm{SM}}(t \to W^+b)$			[87]
SMCS_tev_HW(Mh)	$\sigma^{\mathrm{SM}}(P)$,	P=	$p\bar{p} \to HW$	[88–90]
SMCS_tev_HZ(Mh)			$p\bar{p} \to HZ$	[88–90]
SMCS_tev_gg_H(Mh)			$p\bar{p} \to gg \to H$	[71–85]
SMCS_tev_bb_H(Mh)			$p\bar{p} \to b\bar{b} \to H$	[63]
SMCS_tev_vbf_H(Mh)			$p\bar{p} \to H$ via VBF	[56,91–93]
SMCS_tev_ttH(Mh)			$p\bar{p} \to t\bar{t}H$	[94–96]
SMCS_tev_bg_Hb(Mh)	$\sigma^{\mathrm{SM}}(p\bar{p} \to bg \to Hb) + \sigma^{\mathrm{SM}}(p\bar{p} \to \bar{b}g \to H\bar{b})$			[59–61]

Table 13

SM Higgs branching ratios, total decay widths in units of GeV and hadronic Tevatron and LHC cross sections in units of pb provided as functions by HiggsBounds, *together with references. Each function takes a Higgs mass* Mh (double precision) *as its argument. Also included is the SM top quark decay width into* W^+b *in GeV, which depends on the top quark pole mass in GeV. If a function is called with an argument outside its mass range, it returns a value of -1.*

Examples

We have provided three example programs which demonstrate the use of the HiggsBounds subroutines. The first example relates to the Fourth Generation Model and is contained in the file example-SM_vs_4thGen.F. This program uses the HiggsBounds functions for the SM branching ratios and SM total decay width to calculate the Higgs decay width and the effective normalised squared couplings in the SM and a simple Fourth Generation Model. This information is then used as input for the subroutine HiggsBounds_neutral_input_effC,

function	(double precision)	
SMCS_lhc7_HW(Mh)	$\sigma^{\mathrm{SM}}(P)$ at 7 TeV, P=	$pp \rightarrow HW$ [62]
SMCS_lhc7_HZ(Mh)		$pp \rightarrow HZ$ [62]
SMCS_lhc7_gg_H(Mh)		$pp \rightarrow gg \rightarrow H$ [62]
SMCS_lhc7_bb_H(Mh)		$pp \rightarrow b\bar{b} \rightarrow H$ [63]
SMCS_lhc7_vbf_H(Mh)		$pp \rightarrow H$ via VBF [62]
SMCS_lhc7_ttH(Mh)		$pp \rightarrow t\bar{t}H$ [62]

Table 14
LHC cross sections in units of pb provided as functions by HiggsBounds, *together with references. Each function takes a Higgs mass* Mh (double precision) *as its argument. If a function is called with an argument outside its mass range, it returns a value of -1.*

which is called once with SM input and once with Fourth Generation Model input. Once the HiggsBounds library has been compiled (using ./configure ; make libHB as described previously), the code example-SM_vs_4thGen.F can be compiled and run with the commands:

```
gfortran example-SM_vs_4thGen.F -o example-SM_vs_4thGen \
        -L<HBpath> -lHB
./example-SM_vs_4thGen
```

where <HBpath> is the location of the HiggsBounds library.

The files HBwithFH.F and HBwithCPsuperH.f demonstrate the use of the subroutine version of HiggsBounds with the publicly available programs FeynHiggs [5–8] and CPsuperH [9,10], respectively. We refer the reader to the extensive comments contained within these example files for further details.

4.4 Command line version

Installation

In order to be able to call HiggsBounds from the command line, it should be compiled using the commands

```
./configure
make
```

In the command-line usage of `HiggsBounds`, the arrays containing the theoretical model predictions are read from text files. The other options are specified in the command line, which is of the form:

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

The variable `<prefix>` is a string which is added to the front of input and output file names and may include directory names or other identifying information. (If `whichinput=SLHA`, `<prefix>` is the entire name of the SLHA file, including the path if it is not in the current working directory.)

Tab. 15 and Tab. 16 describe the contents of each input file. Note that each input file should start with a line number. The input files should not contain any comments or blank lines. The line number identifies the predictions which belong to the same model parameter point in different files. The file `BR_H_OP.dat` contains neutral Higgs branching ratios with a SM equivalent (i.e. 'OP'='ordinary particles'), whereas the file `BR_H_NP.dat` contains neutral Higgs branching ratios without a SM equivalent (i.e. 'NP'='new particles')

Care should be taken with the order of the array elements in the files. This is best illustrated by an example, where we will use $n_H = 3$. The one dimensional arrays, e.g. `Mh`, should be given in the order

```
Mh(1), Mh(2), Mh(3).
```

```
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    3.0.0beta     ||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   23.531085611946065          # obsratio
   1         4          1                    # ncombined
   1         5 ||(ee)->(h1)Z->(b b-bar)Z    (hep-ex/0602042, table 14b (LEP))|| # text description of channel
```

Fig. 3. *Example of the Block HiggsBoundsResults.*

file name	data format
`MH_GammaTot.dat`	k, Mh, MhGammaTot
`MHplus_GammaTot.dat`	k, Mhplus, MhplusGammaTot
`effC.dat`	k, g2hjss_s,g2hjss_p,g2hjcc_s,g2hjcc_p
	g2hjbb_s,g2hjbb_p,g2hjtoptop_s,g2hjtoptop_p
	g2hjmumu_s,g2hjmumu_p,
	g2hjtautau_s,g2hjtautau_p,
	g2hjWW,g2hjZZ,g2hjZga,
	g2hjgaga,g2hjgg,g2hjggZ
	some elements of g2hjhiZ
	(lower left triangle - see example)
`LEP_HZ_CS_ratios.dat`	k, CS_lep_hjZ_ratio
`LEP_H_ff_CS_ratios.dat`	k, CS_lep_bbhj_ratio, CS_lep_tautauhj_ratio
`LEP_2H_CS_ratios.dat`	k, some elements of CS_lep_hjhi_ratio
	(lower left triangle - see example)
`LEP_HpHm_CS_ratios.dat`	k, CS_lep_HpjHmj_ratio
`TEVLHC_H_0jet_partCS_ratios.dat`	k, CS_gg_hj_ratio,CS_bb_hj_ratio
`TEVLHC_H_1jet_partCS_ratios.dat`	k, CS_bg_hjb_ratio
`TEVLHC_HW_partCS_ratios.dat`	k, CS_ud_hjWp_ratio,CS_cs_hjWp_ratio,
	CS_ud_hjWm_ratio,CS_cs_hjWm_ratio
`TEVLHC_HZ_partCS_ratios.dat`	k, CS_gg_hjZ_ratio, CS_dd_hjZ_ratio, CS_uu_hjZ_ratio,
	CS_ss_hjZ_ratio, CS_cc_hjZ_ratio,
	CS_bb_hjZ_ratio
`TEV_H_vbf_hadCS_ratios.dat`	k, CS_tev_vbf_ratio
`TEV_H_tt_hadCS_ratios.dat`	k, CS_tev_tthj_ratio
`TEV_1H_hadCS_ratios.dat`	k, CS_tev_hj_ratio, CS_tev_hjb_ratio,
	CS_tev_hjW_ratio,CS_tev_hjZ_ratio,
	CS_tev_vbf_ratio
	CS_tev_tthj_ratio
`LHC7_H_vbf_hadCS_ratios.dat`	k, CS_lhc7_vbf_ratio
`LHC7_H_tt_hadCS_ratios.dat`	k, CS_lhc7_tthj_ratio
`LHC7_1H_hadCS_ratios.dat`	k, CS_lhc7_hj_ratio, CS_lhc7_hjb_ratio,
	CS_lhc7_hjW_ratio,CS_lhc7_hjZ_ratio,
	CS_lhc7_vbf_ratio
	CS_lhc7_tthj_ratio

Table 15

Names and data format of all `HiggsBounds` *input files (part I). The right column shows the order of the input data arrays within one line of the input file. For the order within the arrays, see example.* `k` *is the line number. Note that the arrays* `CS_tev_vbf_ratio`*,* `CS_tev_tthj_ratio`*,*`CS_lhc_vbf_ratio`*,* `CS_lhc_tthj_ratio` *all appear in two different input files. However, these files will never be required by* `HiggsBounds` *simultaneously.*

file name	data format
`BR_H_OP.dat`	`k`, `BR_hjss`, `BR_hjcc`,`BR_hjbb`,`BR_hjmumu`,`BR_hjtautau`, `BR_hjWW`,`BR_hjZZ`,`BR_hjZga`, `BR_hjgaga`,`BR_hjgg`
`BR_H_NP.dat`	`k`, `BR_hjinvisible`, some elements of `BR_hjhihi` (row by row, without diagonal - see example)
`BR_t.dat`	`k`, `BR_tWpb`, `BR_tHpb`
`BR_Hplus.dat`	`k`, `BR_Hpcs`, `BR_Hpcb`, `BR_Hptaunu`
`CP_values.dat`	`k`, `CP_value`
`additional.dat`(optional)	`k`, ...

Table 16

Names and data format of all `HiggsBounds` *input files (part II). The right column shows the order of the input data arrays within one line of the input file. For the order within the arrays, see example.* `k` *is the line number.*

However, not all of the elements of the two dimensional arrays are required. Only the lower left triangle (including the diagonal) is required from the arrays g2hjhiZ and lepCS_hjhi_ratio, since they are symmetric, e.g.

$$\begin{pmatrix} \texttt{g2hjhiZ}(1,1) & \texttt{g2hjhiZ}(1,2) & \texttt{g2hjhiZ}(1,3) \\ \texttt{g2hjhiZ}(2,1) & \texttt{g2hjhiZ}(2,2) & \texttt{g2hjhiZ}(2,3) \\ \texttt{g2hjhiZ}(3,1) & \texttt{g2hjhiZ}(3,2) & \texttt{g2hjhiZ}(3,3) \end{pmatrix}$$

i.e. the elements in the input file should be written in the order

    g2hjhiZ(1,1), g2hjhiZ(2,1), g2hjhiZ(2,2), g2hjhiZ(3,1),
    g2hjhiZ(3,2), g2hjhiZ(3,3) .

For the array BR_hjhihi, only the off-diagonal components are required

$$\begin{pmatrix} \texttt{BR\_hjhihi}(1,1) & \texttt{BR\_hjhihi}(1,2) & \texttt{BR\_hjhihi}(1,3) \\ \texttt{BR\_hjhihi}(2,1) & \texttt{BR\_hjhihi}(2,2) & \texttt{BR\_hjhihi}(2,3) \\ \texttt{BR\_hjhihi}(3,1) & \texttt{BR\_hjhihi}(3,2) & \texttt{BR\_hjhihi}(3,3) \end{pmatrix}$$

since the diagonal elements are not physical quantities. Therefore, the elements should be written in the order

    BR_hjhihi(1,2), BR_hjhihi(1,3), BR_hjhihi(2,1), BR_hjhihi(2,3),
    BR_hjhihi(3,1), BR_hjhihi(3,2)

in the input file.

The file additional.dat is optional. If it is included, it can have any number of columns greater than 1 (as for the previous files, the first entry on each line should be the line number). It is envisaged that this input file will be particularly useful when parameter scans are performed over a variable which is not required by HiggsBounds but helpful when plotting the results. For example, in the case of the MSSM, additional.dat could be used to store the values of $\tan\beta$.

As in the subroutine version, the command line version of HiggsBounds expects a subset of the total list of input arrays, which depends on the chosen setting of whichinput. The maximal list of files used for each value of whichinput is given in Tab. 4.

As discussed for the subroutine version, some of the arrays will not be relevant for some of the choices for whichanalyses. The command line version of HiggsBounds will consider the list of input files appropriate to the setting whichinput and then only attempt to read any of these input files if the value chosen for whichanalyses means that at least one of the arrays it contains will be directly used. Tab. 18 contains a list of which input files are actually relevant to each value of whichanalyses. For example, if whichinput = hadr, whichanalyses = LandH, nHzero > 0 and nHplus > 0 then HiggsBounds requires the input files:

MH_GammaTot.dat, MHplus_GammaTot.dat, CP_values.dat,
BR_H_NP.dat, BR_H_OP.dat, BR_t.dat, BR_Hplus.dat,
LEP_HZ_CS_ratios.dat, LEP_H_ff_CS_ratios.dat, LEP_2H_CS_ratios.dat,
LEP_HpHm_CS_ratios.dat, TEV_1H_hadCS_ratios.dat, LHC7_1H_hadCS_ratios.dat .

However, if `whichinput = hadr`, `whichanalyses = onlyL`, `nHzero > 0` and `nHplus > 0` HiggsBounds requires the input files:

MH_GammaTot.dat, MHplus_GammaTot.dat, CP_values.dat,
BR_H_NP.dat, BR_H_OP.dat, BR_Hplus.dat,
LEP_HZ_CS_ratios.dat, LEP_H_ff_CS_ratios.dat, LEP_2H_CS_ratios.dat,
LEP_HpHm_CS_ratios.dat.

As a third example, if `whichinput = hadr`, `whichanalyses = onlyH`, `nHzero > 0` and `nHplus > 0` HiggsBounds requires the input files:

MH_GammaTot.dat, MHplus_GammaTot.dat, CP_values.dat,
BR_H_NP.dat, BR_H_OP.dat, BR_t.dat, BR_Hplus.dat,
TEV_1H_hadCS_ratios.dat,LHC7_1H_hadCS_ratios.dat .

In each of these three examples, HiggsBounds will also read the file

additional.dat

if it exists.

As for the subroutine version, if the user does not require processes involving a particular branching ratio or cross section ratio to be checked by HiggsBounds, that particular array can be filled with zeros.

Output file format

When the command line version of HiggsBounds is used with `whichinput=hadr` , `part` or `effC`, the output is written to the file `<prefix>HiggsBounds_results.dat`. A sample of the output is shown in Fig. 4. The key to the process numbering is written to `<prefix>Key.dat`.

When the command line version of HiggsBounds is used with `whichinput=SLHA`, the Higgs-Bounds results are added to the SLHA file in the form of the block `HiggsBoundsResults`.

Note that using the command-line version of HiggsBounds with SLHA input is not efficient for large parameter scans, since the experimental tables must be read in again for each SLHA file.

If this is a concern, a better option is to use the subroutines to create a program which can be called from the command line. An example of this is `HBwithSLHA.F90`, which is included in the HiggsBounds package, and is compiled default. In this example, `<whichanalyses>=LandH`,

36

whichinput = part,	hadr,	effC
MH_GammaTot.dat	MH_GammaTot.dat	MH_GammaTot.dat
MHplus_GammaTot.dat	MHplus_GammaTot.dat	MHplus_GammaTot.dat
BR_H_NP.dat	BR_H_NP.dat	effC.dat
BR_H_OP.dat	BR_H_OP.dat	BR_H_NP.dat
BR_t.dat	BR_t.dat	BR_t.dat
BR_Hplus.dat	BR_Hplus.dat	BR_Hplus.dat
LEP_HZ_CS_ratios.dat	LEP_HZ_CS_ratios.dat	LEP_HpHm_CS_ratios.dat
LEP_H_ff_CS_ratios.dat	LEP_H_ff_CS_ratios.dat	additional.dat
LEP_2H_CS_ratios.dat	LEP_2H_CS_ratios.dat	
LEP_HpHm_CS_ratios.dat	LEP_HpHm_CS_ratios.dat	
TEVLHC_H_0jet_partCS_ratios.dat	TEV_1H_hadCS_ratios.dat	
TEVLHC_H_1jet_partCS_ratios.dat	LHC7_1H_hadCS_ratios.dat	
TEVLHC_HW_partCS_ratios.dat	CP_values.dat	
TEVLHC_HZ_partCS_ratios.dat	additional.dat	
TEV_H_vbf_hadCS_ratios.dat		
TEV_H_tt_hadCS_ratios.dat		
LHC7_H_vbf_hadCS_ratios.dat		
LHC7_H_tt_hadCS_ratios.dat		
CP_values.dat		
additional.dat		

Table 17

The list of possible input files for each value of whichinput. *Note that some input files may not be relevant, depending on the values of* whichanalyses, nHzero *and* nHplus. *In this case, they are not required. See Tab. 18 and Tab. 19 for more details.*

<nHzero>=3 and <nHplus>=1. The set of SLHA files to be used as input should be named <stem>.i where i runs from 1 to npoints. It is called from the command line as

./example_programs/HiggsBounds <npoints> <stem>

The block HiggsBoundsResults will be added to each SLHA file. In addition, the Higgs-Bounds results (i, HBresult, chan ,obsratio, ncombined) are collected together in a file called <stem>-fromHB.

name of input file	values of `whichanalyses` which this file is relevant to			
	LandH	onlyL	onlyH	onlyP
`MH_GammaTot.dat`	y	y	y	y
`MHplus_GammaTot.dat`	y	y	y	y
`effC.dat`	y	y	y	y
`LEP_HZ_CS_ratios.dat`	y	y		y
`LEP_H_ff_CS_ratios.dat`	y	y		y
`LEP_2H_CS_ratios.dat`	y	y		y
`LEP_HpHm_CS_ratios.dat`	y	y		y
`TEVLHC_H_0jet_partCS_ratios.dat`	y		y	y
`TEVLHC_H_1jet_partCS_ratios.dat`	y		y	y
`TEVLHC_HW_partCS_ratios.dat`	y		y	y
`TEVLHC_HZ_partCS_ratios.dat`	y		y	y
`TEV_H_vbf_hadCS_ratios.dat`	y		y	y
`TEV_H_tt_hadCS_ratios.dat`	y		y	y
`TEV_1H_hadCS_ratios.dat`	y		y	y
`LHC7_H_vbf_hadCS_ratios.dat`	y		y	y
`LHC7_H_tt_hadCS_ratios.dat`	y		y	y
`LHC7_1H_hadCS_ratios.dat`	y		y	y
`BR_H_OP.dat`	y	y	y	y
`BR_H_NP.dat`	y	y	y	y
`BR_t.dat`	y		y	y
`BR_Hplus.dat`	y	y	y	y
`CP_values.dat`	y	y	y	y
`additional.dat` (optional)	y	y	y	y

Table 18

List of input files, specifying which values of `whichanalyses` *each input file is relevant to (marked by 'y'). Note that some input files may not be relevant, depending on the values of* `whichinput`, `nHzero` *and* `nHplus`. *In this case, they are not required. See Tab. 17 and Tab. 19 for more details.*

Examples

The `HiggsBounds` package includes a full set of sample input files for the case $n_H = 3$, $n_{H^+} = 1$, contained in the folder `example_data`. Each filename is prefixed with `HB_randomtest50points_`.

name of input file	only relevant if nHzero > 0	only relevant if nHplus > 0
MH_GammaTot.dat	y	
MHplus_GammaTot.dat		y
effC.dat	y	
LEP_HZ_CS_ratios.dat	y	
LEP_H_ff_CS_ratios.dat	y	
LEP_2H_CS_ratios.dat	y	
LEP_HpHm_CS_ratios.dat		y
TEVLHC_H_0jet_partCS_ratios.dat	y	
TEVLHC_H_1jet_partCS_ratios.dat	y	
TEVLHC_HW_partCS_ratios.dat	y	
TEVLHC_HZ_partCS_ratios.dat	y	
TEV_H_vbf_hadCS_ratios.dat	y	
TEV_H_tt_hadCS_ratios.dat	y	
TEV_1H_hadCS_ratios.dat	y	
LHC7_H_vbf_hadCS_ratios.dat	y	
LHC7_H_tt_hadCS_ratios.dat	y	
LHC7_1H_hadCS_ratios.dat	y	
BR_H_OP.dat	y	
BR_H_NP.dat	y	
BR_t.dat		y
BR_Hplus.dat		y
CP_values.dat	y	
additional.dat	(optional)	(optional)

Table 19

List of files, showing which relate to the neutral Higgs searches and which relate to the charged Higgs searches. Note that some input files may not be relevant, depending on the values of whichinput *and* whichanalyses*. In this case, they are not required. See Tab. 17 and Tab. 18 for more details.*

To run the command-line version of **HiggsBounds** with these files as input, use, for example,

```
./configure
make
./HiggsBounds LandH effC 3 1 'example_data/HB_randomtest50points_'
```

where the values of `whichanalyses` and `whichinput` can be varied as desired. The setting `nHplus = 0` can be used if the user does not wish to test the charged Higgs sector, e.g.

```
./HiggsBounds LandH effC 3 0 'example_data/HB_randomtest50points_'
```

4.5 Online version

The online version can be reached via the website

```
http://projects.hepforge.org/higgsbounds/ .
```

It allows the user to select the required number of neutral Higgs and charged Higgs bosons and then generates a `html` form accordingly. The values of `whichinput` and `whichanalyses` can be chosen and the appropriate theoretical input entered. `HiggsBounds` will then be called with these settings and the result outputted to screen. The online version contains the additional feature that it notifies the user about the processes with the second and third highest statistical sensitivities and the values of `obsratio` for these processes. This is designed to give guidance to the user who, for example, wishes to find an excluded region iteratively by adjusting the input quantities.

The website also contains a selection of pre-filled `html` forms as examples, including entries for the SM, the fermiophobic Higgs model and the MSSM with real and complex parameters.

There is also the possibility of copying and pasting the results from the online version of `FeynHiggs` (the 'FeynHiggs User Control Center' [5]) into a box on the `HiggsBounds` website for the CP-conserving MSSM. This text is then converted to a filled-in `HiggsBounds` input `html` form (which can be further edited by the user if necessary) that can then be immediately submitted to `HiggsBounds`.

References

[1] LEP Working Group for Higgs boson searches, R. Barate et al., Phys. Lett. B565 (2003) 61, `hep-ex/0306033`.

[2] ALEPH, S. Schael et al., Eur. Phys. J. C47 (2006) 547, `hep-ex/0602042`.

[3] B.C. Allanach et al., Comp. Phys. Commun. 180 (2009) 8, `arXiv:0801.0045`.

[4] P.Z. Skands et al., JHEP 07 (2004) 036, `hep-ph/0311123`.

[5] S. Heinemeyer, W. Hollik and G. Weiglein, Comput. Phys. Commun. 124 (2000) 76, `hep-ph/9812320`.

---

[5] `http://www.feynhiggs.de`

[6] S. Heinemeyer, W. Hollik and G. Weiglein, Eur. Phys. J. C9 (1999) 343, `hep-ph/9812472`.

[7] G. Degrassi et al., Eur. Phys. J. C28 (2003) 133, `hep-ph/0212020`.

[8] M. Frank et al., JHEP 02 (2007) 047, `hep-ph/0611326`.

[9] J.S. Lee et al., Comput. Phys. Commun. 156 (2004) 283, `hep-ph/0307377`.

[10] J.S. Lee et al., Comput. Phys. Commun. 180 (2009) 312, `arXiv:0712.2360`.

[11] CDF and D0, (2009), `arXiv:0911.3930`.

[12] D0, V.M. Abazov et al., Phys. Lett. B698 (2011) 97, `arXiv:1011.1931`.

[13] CDF and D0, T. Aaltonen et al., (2011), `arXiv:1103.3233`.

[14] D0, V.M. Abazov et al., Phys. Rev. Lett. 104 (2010) 151801, `arXiv:0912.0968`.

[15] OPAL, G. Abbiendi et al., Eur. Phys. J. C27 (2003) 311, `hep-ex/0206022`.

[16] D0, V.M. Abazov et al., Phys. Rev. Lett. 101 (2008) 071804, `arXiv:0805.2491`.

[17] CDF, T. Aaltonen et al., Phys. Rev. Lett. 103 (2009) 201801, `arXiv:0906.1014`.

[18] D0, V.M. Abazov et al., Phys. Rev. Lett. 105 (2010) 251801, `arXiv:1008.3564`.

[19] CDF and D0, T. Aaltonen et al., (2010), `arXiv:1005.3216`.

[20] LEP Higgs Working for Higgs boson searches, (2001), `hep-ex/0107032`.

[21] CDF, T. Aaltonen et al., Phys. Rev. Lett. 104 (2010) 141801, `arXiv:0911.3935`.

[22] CDF, T. Aaltonen et al., Phys. Rev. Lett. 104 (2010) 061803, `arXiv:1001.4468`.

[23] DELPHI, J. Abdallah et al., Eur. Phys. J. C32 (2004) 475, `hep-ex/0401022`.

[24] D0, V.M. Abazov et al., Phys. Lett. B663 (2008) 26, `arXiv:0712.0598`.

[25] D0, V.M. Abazov et al., Phys. Rev. Lett. 104 (2010) 071801, `arXiv:0912.5285`.

[26] OPAL, G. Abbiendi et al., Phys. Lett. B682 (2010) 381, `arXiv:0707.0373`.

[27] LEP Higgs Working Group for Higgs boson searches, (2001), `hep-ex/0107031`.

[28] CDF, T. Aaltonen et al., Phys. Rev. Lett. 103 (2009) 101803, `arXiv:0907.1269`.

[29] D0, V.M. Abazov et al., Phys. Lett. B671 (2009) 349, `arXiv:0806.0611`.

[30] D0, V.M. Abazov et al., Phys. Rev. Lett. 103 (2009) 061801, `arXiv:0905.3381`.

[31] Tevatron New Phenomena and Higgs Working Group, D. Benjamin et al., (2010), `arXiv:1003.3363`.

[32] OPAL, G. Abbiendi et al., Eur. Phys. J. C23 (2002) 397, `hep-ex/0111010`.

[33] CDF and D0, T.T.E.V.N.P.H..W. Group, (2008), `arXiv:0804.3423`.

[34] CDF, T. Aaltonen et al., Phys. Rev. Lett. 105 (2010) 251802, `arXiv:1009.3047`.

[35] L3, P. Achard et al., Phys. Lett. B609 (2005) 35, `hep-ex/0501033`.

[36] D0, V.M. Abazov et al., Phys. Lett. B698 (2011) 6, `arXiv:1012.0874`.

[37] G. Bernardi et al., (2008), `arXiv:0808.0534`.

[38] CDF and D0, T. Aaltonen et al., Phys. Rev. Lett. 104 (2010) 061802, `arXiv:1001.4162`.

[39] CDF, T. Aaltonen et al., Phys. Rev. Lett. 102 (2009) 021802, `arXiv:0809.3930`.

[40] CDF, T. Aaltonen et al., Phys. Rev. Lett. 103 (2009) 101802, `arXiv:0906.5613`.

[41] D0, V.M. Abazov et al., Phys. Lett. B682 (2009) 278, `arXiv:0908.1811`.

[42] TEVNPH Working Group and CDF and D0, (2007), `arXiv:0712.2383`.

[43] CDF and D0, (2010), `arXiv:1007.4587`.

[44] D0, V.M. Abazov et al., Phys. Rev. Lett. 102 (2009) 251801, `arXiv:0903.4800`.

[45] DELPHI, J. Abdallah et al., Eur. Phys. J. C34 (2004) 399, `hep-ex/0404012`.

[46] D0, V.M. Abazov et al., Phys. Rev. Lett. 104 (2010) 061804, `arXiv:1001.4481`.

[47] D0, V.M. Abazov et al., Phys. Rev. Lett. 102 (2009) 231801, `arXiv:0901.1887`.

[48] DELPHI, J. Abdallah et al., Eur. Phys. J. C38 (2004) 1, `hep-ex/0410017`.

[49] CDF, CDF Notes 7307 10235 10432 10439 10239 10105 9999 10065 10212 10010 7712.

[50] D0, D0 Notes 6008 6177 6083 6170 5985 6091 5974 5739 5845 5757 6182 6179 5726 5871 6183 6171 6092 6089 6087 5873 5740.

[51] LHWG, LHWG Notes 2002-02.

[52] CMS, CMS PAS HIG-11-002.

[53] Atlas, ATLAS-CONF-2011-005, ATLAS-CONF-2011-025, ATLAS-CONF-2011-052.

[54] A. Djouadi, J. Kalinowski and M. Spira, Comput. Phys. Commun. 108 (1998) 56, `hep-ph/9704448`.

[55] U. Aglietti et al., (2006), `hep-ph/0612172`.

[56] T. Figy, C. Oleari and D. Zeppenfeld, Phys. Rev. D68 (2003) 073005, `hep-ph/0306109`.

[57] M. Ciccolini, A. Denner and S. Dittmaier, Phys. Rev. Lett. 99 (2007) 161803, `arXiv:0707.0381`.

[58] M. Ciccolini, A. Denner and S. Dittmaier, Phys. Rev. D77 (2008) 013002, `arXiv:0710.4749`.

[59] O. Brein and W. Hollik, Phys. Rev. D68 (2003) 095006, `hep-ph/0305321`.

[60] O. Brein and W. Hollik, Phys. Rev. D76 (2007) 035002, `arXiv:0705.2744`.

[61] O. Brein, Phys. Rev. D81 (2010) 093006, `arXiv:1003.4438`.

[62] LHC Higgs Cross Section Working Group, S. Dittmaier et al., (2011), `arXiv:1101.0593`.

[63] R.V. Harlander and W.B. Kilgore, Phys. Rev. D68 (2003) 013001, `hep-ph/0304035`.

[64] ALEPH, Phys. Rept. 427 (2006) 257, `hep-ex/0509008`.

[65] ALEPH, J. Alcaraz et al., (2006), `hep-ex/0612034`.

[66] P. Bechtle et al., Comput. Phys. Commun. 181 (2010) 138, `arXiv:0811.4169`.

[67] P. Bechtle et al., (2011), `arXiv:1102.1898`.

[68] M.S. Carena et al., Eur. Phys. J. C26 (2003) 601, `hep-ph/0202167`.

[69] CDF, CDF Note 10105.

[70] D0, D0 Note 5726.

[71] S. Catani, D. de Florian and M. Grazzini, JHEP 05 (2001) 025, `hep-ph/0102227`.

[72] R.V. Harlander and W.B. Kilgore, Phys. Rev. D64 (2001) 013015, `hep-ph/0102241`.

[73] R.V. Harlander and W.B. Kilgore, Phys. Rev. Lett. 88 (2002) 201801, `hep-ph/0201206`.

[74] C. Anastasiou and K. Melnikov, Nucl. Phys. B646 (2002) 220, `hep-ph/0207004`.

[75] V. Ravindran, J. Smith and W.L. van Neerven, Nucl. Phys. B665 (2003) 325, `hep-ph/0302135`.

[76] C. Anastasiou, R. Boughezal and F. Petriello, JHEP 04 (2009) 003, `arXiv:0811.3458`.

[77] S. Dawson, Nucl. Phys. B359 (1991) 283.

[78] A. Djouadi, M. Spira and P.M. Zerwas, Phys. Lett. B264 (1991) 440.

[79] M. Spira et al., Nucl. Phys. B453 (1995) 17, `hep-ph/9504378`.

[80] U. Aglietti et al., Phys. Lett. B595 (2004) 432, `hep-ph/0404071`.

[81] G. Degrassi and F. Maltoni, Phys. Lett. B600 (2004) 255, `hep-ph/0407249`.

[82] S. Actis et al., Phys. Lett. B670 (2008) 12, `arXiv:0809.1301`.

[83] S. Actis et al., Nucl. Phys. B811 (2009) 182, `arXiv:0809.3667`.

[84] S. Catani et al., JHEP 07 (2003) 028, `hep-ph/0306211`.

[85] D. de Florian and M. Grazzini, Phys. Lett. B674 (2009) 291, `arXiv:0901.2427`.

[86] Particle Data Group, C. Amsler et al., Phys. Lett. B667 (2008) 1.

[87] M. Jezabek and J.H. Kuhn, Nucl. Phys. B314 (1989) 1.

[88] O. Brein, A. Djouadi and R. Harlander, Phys. Lett. B579 (2004) 149, `hep-ph/0307206`.

[89] M.L. Ciccolini, S. Dittmaier and M. Kramer, Phys. Rev. D68 (2003) 073003, `hep-ph/0306234`.

[90] Higgs Working Group, K.A. Assamagan et al., (2004), `hep-ph/0406152`.

[91] T. Han, G. Valencia and S. Willenbrock, Phys. Rev. Lett. 69 (1992) 3274, `hep-ph/9206246`.

[92] J.M. Campbell and R.K. Ellis, Phys. Rev. D60 (1999) 113006, `hep-ph/9905386`.

[93] E.L. Berger and J.M. Campbell, Phys. Rev. D70 (2004) 073011, `hep-ph/0403194`.

[94] W. Beenakker et al., Phys. Rev. Lett. 87 (2001) 201805, `hep-ph/0107081`.

[95] L. Reina and S. Dawson, Phys. Rev. Lett. 87 (2001) 201804, `hep-ph/0107101`.

[96] S. Dawson et al., Phys. Rev. D67 (2003) 071503, `hep-ph/0211438`.

```
# generated with HiggsBounds version 3.0.0beta on 10.05.2011 at 16:36
# settings: LandH, part
#
# column abbreviations
#   n          : line id of input
#   Mh(i)      : Neutral Higgs boson masses in GeV
#   Mhplus(i)  : Charged Higgs boson masses in GeV
#   HBresult   : scenario allowed flag (1: allowed, 0: excluded, -1: unphysical)
#   chan       : 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
#   additional : optional additional data stored in <prefix>additional.dat (e.g. tan beta)
#
# channel numbers used in this file
#          1 : (e e)->(h1)Z->(b b-bar)Z    (hep-ex/0602042, table 14b (LEP))
#          9 : (e e)->(h3)Z->(...)Z   (hep-ex/0206022 (OPAL))
#         11 : (e e)->(h2)Z->(invisible)Z   (hep-ex/0107032v1 (LEP))
#        322 : (p p)->h2->tau tau ([hep-ex] arXiv: 1104:1619(CMS))
# (for full list of processes, see Key.dat)
#
#cols:  n      Mh(1)     Mh(2)     Mh(3)  Mhplus(1)  HBresult   chan    obsratio    ncomb   additional(1)

       1    359.121   114.647   68.4914   222.503        0      9     1.13768        1      0.140555
       2    51.7469   262.589   298.823   120.352        0      1     6.14275        1      0.770019
       3    282.838   90.5346   100.815   268.857        0     14     8.08590        1      0.534344
       4    11.1752   137.117   289.158   331.256        1    322   0.447275E-04     1      0.00000
```

Fig. 4. *Sample output file (written to* `<prefix>HiggsBounds_Results.dat`*)*