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HiggsBounds-5: Testing Higgs sectors in the LHC 13 TeV era

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Abstract

We describe recent developments of the public computer codes HiggsBounds and HiggsSignals. In particular, these include the incorporation of LHC Higgs search results from Run II at a center-of-mass energy of 13 TeV, and an updated framework for the theoretical input that accounts for new and improved Higgs cross section and branching ratio predictions, according to the CERN Yellow Report 4 of the LHC Higgs cross section working group. The new code furthermore allows to approximate the exclusion likelihood for LHC searches for non-standard Higgs bosons decaying to $\tau\tau$ final states. We describe in detail the new and updated functionalities of the new version HiggsBounds-5 and provide several example applications.

Please note: This is a manual draft. Work is still in progress!

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1 Introduction

This manual draft documents the major changes between HiggsBounds-5 and its predecessor HiggsBounds-4. It hopefully provides the necessary information for the experienced user to adapt to the HiggsBounds-5 beta version. Both the full version of HiggsBounds-5 and this manual are still work in progress. For urgent questions contact Tim.

2 Theoretical input

2.1 General structure

In HiggsBounds-5 the variable whichinput only supports the values hadr (hadronic cross sections) effC (effective coupling approximation), and SLHA (SUSY Les Houches Accord), whereas the old mode part (partonic cross sections) has been removed and is no longer supported.

In general terms, the code only needs to know the phenomenologically relevant physical quantities of the Higgs sector, i.e. the number of neutral and charged Higgs bosons that should be considered, and their masses, total widths, production and decay rates. These quantities have to be calculated beforehand. In this way, the code maintains a flexible input framework with minimal model requirements (mainly imposed by the experimental analyses, e.g. , in many cases, the narrow width approximation).

The production cross sections can either be given directly to the code as inclusive hadronic cross sections for the various supported collider experiments and center-of-mass energies, namely LEP, Tevatron, LHC7, LHC8, LHC13. If the considered production mode also exists in the SM, the input cross section should usually be normalized to the corresponding SM prediction for the same Higgs mass.

2.2 Neutral Higgs bosons

The quantities needed to describe the production and decay rates of neutral Higgs bosons are listed in Tables 1–3. The hadronic cross sections (Table 1) are extended by separate input for gluon fusion and $b\bar{b}$ associated Higgs production, whereas HiggsBounds-4 only required the sum of the two processes (denoted as single Higgs production). Furthermore, we added the cross sections for Higgs production in association with a single top quark via the t- or s-channel (which are kinematically separable), as well as the input for non-resonant double Higgs production. Note, that the latter quantity is not normalized to the SM prediction, but instead given in pb.

The cross section input for LEP are unchanged with respect to HiggsBounds-4. For reference,

CS_gg_hj_ratio[j]	SM normalized inclusive hadronic cross section for the gluon fusion process, $pp/p\bar{p} \to gg \to h_j$. (NEW)
CS_bb_hj_ratio[j]	SM normalized inclusive hadronic cross section for the $b\bar{b}$ associated Higgs production, $pp/p\bar{p} \to b\bar{b}h_j$. (NEW)
CS_vbf_ratio[j]	SM normalized inclusive hadronic cross section for the Higgs production in vector boson fusion, $pp/p\bar{p} \to q\bar{q}h_j$.
CS_hjZ_ratio[j]	SM normalized inclusive hadronic cross section for Higgs production in association with a Z boson, $pp/p\bar{p} \to Zh_j$.
CS_hjW_ratio[j]	SM normalized inclusive hadronic cross section for Higgs production in association with a W boson, $pp/p\bar{p} \to Wh_j$.
CS_tthj_ratio[j]	SM normalized inclusive hadronic cross section for the $t\bar{t}$ associated Higgs production, $pp/p\bar{p} \to t\bar{t}h_j$.
CS_thj_tchan_ratio[j]	SM normalized inclusive hadronic cross section for single top quark associated Higgs production through t-channel exchange, $pp \to th_j$. (NEW)
CS_thj_schan_ratio[j]	SM normalized inclusive hadronic cross section for single top quark associated Higgs production through s-channel exchange, $pp \to th_j$. (NEW)
CS_hjhi[j,i]	Inclusive hadronic cross section for (non-resonant) double Higgs production, $pp/p\bar{p} \to h_jh_i$ (in pb). (NEW)

Table 1: Hadronic cross section input for neutral Higgs bosons.

these quantities are listed in Table 2.

CS_lep_hjZ_ratio[j]	SM normalized LEP cross section for Higgs production in association with a Z boson, $e^+e^- \to Zh_j$.
CS_lep_bbhj_ratio[j]	SM normalized LEP cross section for the $b\bar{b}$ associated Higgs production, $e^+e^- \to b\bar{b}h_j$.
CS_lep_tautauhj_ratio[j]	SM normalized LEP cross section for the $\tau^+\tau^-$ associated Higgs production, $e^+e^- \to \tau^+\tau^-h_j$.
CS_lep_hjhi_ratio[j,i]	SM normalized LEP cross section for double Higgs production, $e^+e^- \to h_jh_i$.

Table 2: LEP cross section input for neutral Higgs bosons.

The branching ratio input for the neutral Higgs bosons (Table 3) have been extended by Higgs decays into top quarks, flavor changing leptonic Higgs decays, as well as a variety of Higgs-to-Higgs decays. Here, we generalized the neutral Higgs-to-neutral Higgs-neutral Higgs decay array to allow for different Higgs bosons in the final states, and added arrays for neutral Higgs-to-neutral Higgs-Z boson and neutral Higgs-to-charged Higgs-W boson decays. Most of these decay modes (with the notable exceptions of $h_j \to h_iZ$ and $h_j \to h_ih_i$)

`BR_hjcc[j]`	Branching ratio for $h_j \to c\bar{c}$.
`BR_hjss[j]`	Branching ratio for $h_j \to s\bar{s}$.
`BR_hjtt[j]`	Branching ratio for $h_j \to t\bar{t}$. (NEW)
`BR_hjbb[j]`	Branching ratio for $h_j \to b\bar{b}$.
`BR_hjmumu[j]`	Branching ratio for $h_j \to \mu^+\mu^-$.
`BR_hjtautau[j]`	Branching ratio for $h_j \to \tau^+\tau^-$.
`BR_hjWW[j]`	Branching ratio for $h_j \to W^+W-$.
`BR_hjZZ[j]`	Branching ratio for $h_j \to ZZ$.
`BR_hjgaga[j]`	Branching ratio for $h_j \to \gamma\gamma$.
`BR_hjZga[j]`	Branching ratio for $h_j \to Z\gamma$.
`BR_hjgg[j]`	Branching ratio for $h_j \to gg$.
`BR_hjinvisible[j]`	Branching ratio for $h_j \to$ invisible.
`BR_hkhjhi[k,j,i]`	Branching ratio for $h_k \to h_j h_i$. (NEW)
`BR_hjhiZ[j,i]`	Branching ratio for $h_j \to h_i Z$. (NEW)
`BR_hjemu[j]`	Branching ratio for $h_j \to e^\pm\mu^\mp$. (NEW)
`BR_hjetau[j]`	Branching ratio for $h_j \to e^\pm\tau^\mp$. (NEW)
`BR_hjmutau[j]`	Branching ratio for $h_j \to \mu^\pm\tau^\mp$. (NEW)
`BR_hjHpiW[j,i]`	Branching ratio for $h_j \to H_i^\pm W^\mp$. (NEW)

Table 3: Branching ratios for neutral Higgs bosons.

are currently not probed by the LHC experiments, but will hopefully be searched for in the upcoming years.

Instead of giving the hadronic and leptonic Higgs production cross sections and branching fractions directly, `HiggsBounds` also features an effective coupling (or scale factor) approximation for all these quantities. In case this approximation is employed, the effective couplings listed in Table 4 have to be provided. With respect to `HiggsBounds-4` we have changed the entire input from *squared* couplings (or scale factors) to the *sign-sensitive* single couplings (or scale factors). This allows us to take into account interference effects e.g. in the approximation of the h_jZ production cross section. Furthermore, we removed the effective (squared) h_jggZ present in earlier versions. Instead, the $gg \to h_jZ$ contribution is approximated from the h_jtt and h_jbb effective couplings. Note that we still keep the loop-induced h_jgg nad $h_j\gamma\gamma$ couplings as free input quantities and do not derive them from the other coupling parameters.

2.3 Charged Higgs bosons

The `HiggsBounds` framework has been broadly extended for the charged Higgs sector. We list all relevant charged Higgs sector quantities in Table 5. The framework now supports

ghjcc_s[j], ghjcc_p[j]	SM normalized scalar (_s) and pseudoscalar (_p) effective Higgs coupling to charm quarks
ghjss_s[j], ghjss_p[j]	SM normalized scalar (_s) and pseudoscalar (_p) effective Higgs coupling to strange quarks
ghjtt_s[j], ghjtt_p[j]	SM normalized scalar (_s) and pseudoscalar (_p) effective Higgs coupling to top quarks
ghjbb_s[j], ghjbb_p[j]	SM normalized scalar (_s) and pseudoscalar (_p) effective Higgs coupling to bottom quarks
ghjmumu_s[j], ghjmumu_p[j]	SM normalized scalar (_s) and pseudoscalar (_p) effective Higgs coupling to muons
ghjtautau_s[j], ghjtautau_p[j]	SM normalized scalar (_s) and pseudoscalar (_p) effective Higgs coupling to tau leptons
ghjWW[j]	SM normalized effective Higgs coupling to W bosons
ghjZZ[j]	SM normalized effective Higgs coupling to Z bosons
ghjZga[j]	SM normalized effective Higgs coupling to a Z boson and a photon
ghjgaga[j]	SM normalized effective Higgs coupling to photons
ghjgg[j]	SM normalized effective Higgs coupling to gluons
ghjhiZ[j,i]	SM normalized effective $h_j h_i Z$ coupling

Table 4: (SM normalized) effective Higgs couplings for neutral Higgs bosons.

arrays for direct charged Higgs boson production at hadron colliders, including H_j^+ production in association with a top or charm quark and a bottom quark, or flavor-suppressed production in association with lighter quark jets. We also include charged Higgs production in association with a vector boson or a neutral Higgs boson, as well as charged Higgs boson production in vector boson fusion and charged Higgs pair production. Note that all hadronic cross sections are directly given in pb, and not specified as normalized quantities.

For light charged Higgs bosons with mass below the top quark mass, the most important search channel is top pair production with successive decay of one top quark to a charged Higgs boson and a bottom quark. HiggsBounds thus also require the branching fractions for $t \to H_j^+ b$ and $t \to W^+ b$ (needed to check for model assumptions) as input. The charged Higgs branching fractions have been extended by the decays to top and bottom quarks, W and Z bosons, as well as neutral Higgs and W bosons.

CS_Hpjtb[j]	Hadronic cross section (in pb) for $pp \to H_j^+ tb$ production. (NEW)
CS_Hpjcb[j]	Hadronic cross section (in pb) for $pp \to H_j^+ cb$ production. (NEW)
CS_Hpjbjet[j]	Hadronic cross section (in pb) for $pp \to H_j^+ bj$ production, with light jet j. (NEW)
CS_Hpjcjet[j]	Hadronic cross section (in pb) for $pp \to H_j^+ cj$ production, with light jet j. (NEW)
CS_Hpjjetjet[j]	Hadronic cross section (in pb) for $pp \to H_j^+ jj$ production, with two light jets j. (NEW)
CS_HpjW[j]	Hadronic cross section (in pb) for $pp \to H_j^\pm W^\mp$ production.(NEW)
CS_HpjZ[j]	Hadronic cross section (in pb) for $pp \to H_j^+ Z$ production.(NEW)
CS_vbf_Hpj[j]	Hadronic cross section (in pb) for $pp \to H_j^+$ production in vector boson fusion. (NEW)
CS_HpjHmj[j]	Hadronic cross section (in pb) for $pp \to H_j^+ H_j^-$ production. (NEW)
CS_Hpjhi[j,i]	Hadronic cross section (in pb) for $pp \to H_j^+ h_i$ production.(NEW)
BR_tWpb[j]	Branching ratio for the top quark decay $t \to W^+ b$.
BR_tHpjb[j]	Branching ratio for the top quark decay $t \to H_j^+ b$.
BR_Hpjcs[j]	Branching ratio for $H_j^+ \to c\bar{s}$.
BR_Hpjcb[j]	Branching ratio for $H_j^+ \to c\bar{b}$.
BR_Hpjtaunu[j]	Branching ratio for $H_j^+ \to \tau^+ \nu_\tau$.
BR_Hpjtb[j]	Branching ratio for $H_j^+ \to tb$. (NEW)
BR_HpjWZ[j]	Branching ratio for $H_j^+ \to W^+ Z$. (NEW)
BR_HpjhiW[j,i]	Branching ratio for $H_j^+ \to h_i W^+$. (NEW)

Table 5: Hadronic cross sections (in pb), top quark branching ratios, and branching ratios for charged Higgs bosons.

3 User Operating Instructions

3.1 Installation

As in previous versions:

```
./configure
make
make <name-of-example-program>
make hyperclean
```

3.2 `Fortran` subroutines

We describe here only the `Fortran` subroutines that have been changed or added with respect to `HiggsBounds` version 4 (or earlier), and refer to the `HiggsBounds-4` manual for a description of the remaining subroutines. The `HiggsBounds` subroutines for providing the model input are listed in Table 6, including their arguments and their data format. The arguments are either of double precision (*dp*) or integer (*int*) format, and the dimensions of the arrays are either the number of neutral Higgs bosons, N_{h^0}, or the number of charged Higgs bosons, N_{H^+}. The various input quantities appearing as arguments have been discussed in Section 2, see Tables 1–5. The argument `collider` specifies for which hadron collider and center-of-mass energy the input data is provided, i.e. `collider = 2, 7, 8` or `13` for Tevatron, LHC7, LHC8 or LHC13, respectively.

The subroutine `HiggsBounds_neutral_input_properties` provides the masses, total widths and $\mathcal{CP}$-values of the neutral Higgs bosons. The neutral Higgs production rates can either be approximated using effective Higgs couplings which are provided by the subroutine `HiggsBounds_neutral_input_effC`, or can directly be specified at the hadronic level using the subroutine `HiggsBounds_neutral_input_hadr`. If the effective Higgs couplings are employed, the branching ratios for the Higgs decays to SM particles are also approximated from these couplings by default. However, the user can also choose to provide these branching ratios directly via the subroutine `HiggsBounds_neutral_input_SMBR` (which is often more accurate). If the hadronic cross section input is being used, the branching ratios must be set through this subroutine. In addition, if Higgs decays modes beyond the SM Higgs decays exist, these need to be specified using the subroutine `HiggsBounds_neutral_input_nonSMBR`.

If charged Higgs bosons are present in the model, their masses, total widths, normalized pair production cross section at LEP[1] and branching fractions are specified via the subroutine `HiggsBounds_charged_input`. The cross sections (in pb) for direct charged Higgs production

[1]See Ref. [1] for the definition.

Subroutine	Arguments
HiggsBounds_neutral_input_properties	*dp*(N_{h^0}) :: Mh, *dp*(N_{h^0}) :: GammaTotal, *dp*(N_{h^0}) :: CP_value
HiggsBounds_neutral_input_effC	*dp*(N_{h^0}) :: ghjss_s, *dp*(N_{h^0}) :: ghjss_p, *dp*(N_{h^0}) :: ghjcc_s, *dp*(N_{h^0}) :: ghjcc_p, *dp*(N_{h^0}) :: ghjbb_s, *dp*(N_{h^0}) :: ghjbb_p, *dp*(N_{h^0}) :: ghjtt_s, *dp*(N_{h^0}) :: ghjtt_p, *dp*(N_{h^0}) :: ghjmumu_s, *dp*(N_{h^0}) :: ghjmumu_p, *dp*(N_{h^0}) :: ghjtautau_s, *dp*(N_{h^0}) :: ghjtautau_p, *dp*(N_{h^0}) :: ghjWW, *dp*(N_{h^0}) :: ghjZZ, *dp*(N_{h^0}) :: ghjZga, *dp*(N_{h^0}) :: ghjgaga, *dp*(N_{h^0}) :: ghjgg, *dp*(N_{h^0},N_{h^0}) :: ghjhiZ
HiggsBounds_neutral_input_SMBR	*dp*(N_{h^0}) :: BR_hjss, *dp*(N_{h^0}) :: BR_hjcc, *dp*(N_{h^0}) :: BR_hjbb, *dp*(N_{h^0}) :: BR_hjtt, *dp*(N_{h^0}) :: BR_hjmumu, *dp*(N_{h^0}) :: BR_hjtautau, *dp*(N_{h^0}) :: BR_hjWW, *dp*(N_{h^0}) :: BR_hjZZ, , *dp*(N_{h^0}) :: BR_hjZga, *dp*(N_{h^0}) :: BR_hjgaga, *dp*(N_{h^0}) :: BR_hjgg
HiggsBounds_neutral_input_nonSMBR	*dp*(N_{h^0}) :: BR_hjinvisible, *dp*(N_{h^0},N_{h^0},N_{h^0}) :: BR_hkhjhi, *dp*(N_{h^0},N_{h^0}) :: BR_hjhiZ, *dp*(N_{h^0}) :: BR_hjemu, *dp*(N_{h^0}) :: BR_hjetau, *dp*(N_{h^0}) :: BR_hjmutau, *dp*(N_{h^0},N_{H^+}) :: BR_hjHpiW
HiggsBounds_neutral_input_LEP	*dp*(N_{h^0}) :: CS_ee_hjZ_ratio, *dp*(N_{h^0}) :: CS_ee_bbhj_ratio, *dp*(N_{h^0}) :: CS_ee_tautauhj_ratio ,*dp*(N_{h^0}, N_{h^0}) :: CS_ee_hjhi_ratio
HiggsBounds_neutral_input_hadr	*int* :: collider, *dp*(N_{h^0}) :: CS_hj_ratio, *dp*(N_{h^0}) :: CS_gg_hj_ratio, *dp*(N_{h^0}) :: CS_bb_hj_ratio, *dp*(N_{h^0}) :: CS_hjW_ratio, *dp*(N_{h^0}) :: CS_hjZ_ratio, *dp*(N_{h^0}) :: CS_vbf_ratio, *dp*(N_{h^0}) :: CS_tthj_ratio, *dp*(N_{h^0}) :: CS_thj_tchan_ratio, *dp*(N_{h^0}) :: CS_thj_schan_ratio, *dp*(N_{h^0},N_{h^0}) :: CS_hjhi_ratio
HiggsBounds_charged_input	*dp*(N_{H^+}) :: Mhplus, *dp*(N_{H^+}) :: GammaTotal, *dp*(N_{H^+}) :: CS_lep_HpjHmj_ratio, *dp*(N_{H^+}) :: BR_tWpb, *dp*(N_{H^+}) :: BR_tHpjb, *dp*(N_{H^+}) :: BR_Hpjcs, *dp*(N_{H^+}) :: BR_Hpjcb, *dp*(N_{H^+}) :: BR_Hpjtaunu, *dp*(N_{H^+}) :: BR_Hpjtb, *dp*(N_{H^+}) :: BR_HpjWZ, *dp*(N_{H^+},N_{h^0}) :: BR_HpjhiW
HiggsBounds_charged_input_hadr	*int* :: collider, *dp*(N_{H^+}) :: CS_Hpjtb, *dp*(N_{H^+}) :: CS_Hpjcb, *dp*(N_{H^+}) :: CS_Hpjbjet, *dp*(N_{H^+}) :: CS_Hpjcjet, *dp*(N_{H^+}) :: CS_Hpjjetjet, *dp*(N_{H^+}) :: CS_HpjW, *dp*(N_{H^+}) :: CS_HpjZ, *dp*(N_{H^+}) :: CS_vbf_Hpj, *dp*(N_{H^+}) :: CS_HpjHmj, *dp*(N_{H^+},N_{h^0}) :: CS_Hpjhi

Table 6: HiggsBounds input subroutines and their arguments. For each argument we also specify the Fortran data type [double precision (*dp*) or integer (*int*)] and array length (if applicable).

at hadron colliders can be specified with the subroutine HiggsBounds_charged_input_hadr. If this subroutine is not called these cross sections are set to zero.

The subroutines HiggsBounds_neutral_input_nonSMBR and HiggsBounds_charged_input also require a two-dimensional input array with its dimensions given by the number of neutral and charged Higgs bosons, namely the input quantities BR_hjHpiW and BR_HpjhiW, respectively. In case that no neutral or charged Higgs bosons are present in the model, these arrays are of length zero and need not be given to the subroutines.

Besides these model input subroutines we have introduces a couple of other subroutines that access details of the HiggsBounds output. These will be described in Section 3.4.

3.3 Command-line version

On the command line HiggsBounds can be run as

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

where the arguments specify the following: <whichanalyses> specifies which experimental data is selected for the model test [see ...], <whichinput> specifies whether the model input on the production and decay rates is provided in the effective couplings approximation ('effC'), at the hadronic cross section level ('hadr'), or via an SLHA input file ('SLHA'). As before, the arguments <nHzero> and <nHplus> specify the number of neutral and charged Higgs bosons, respectively. The argument <prefix> is a string variable that directs to the input file(s), i.e. it specifies the (relative) path and the first part of the filename that is common to all input file(s).

3.3.1 HiggsBounds data files input

If HiggsBounds is run from the command line with the option <whichinput>=effC or hadr the model input needs to be specified via HiggsBounds specific input files.

With respect to HiggsBounds version 4 (and before), the input files for the *partonic* cross section input scheme have been removed. Moreover, structural changes have been made in various input data files, as listed below.

- In effC.dat all input arrays now quantify the SM-normalized effective Higgs coupling, *not* the *squared* SM-normalized effective Higgs couplings as in earlier versions. Moreover, the effective coupling for the Higgs-gluon-gluon-Z boson interaction has been removed;
- BR_H_OP.dat has been extended by the branching fraction for Higgs to top quark decays (BR_hjtt);

- BR_H_NP.dat has been extended by the branching fractions for Higgs to Higgs-Z boson decays (BR_hjhiZ), flavor violating leptonic Higgs decays (BR_hjemu, BR_hjetau, BR_hjmutau), as well as for neutral Higgs to charged Higgs-W boson decays (BR_hjHpiW). Moreover, the neutral Higgs to neutral Higgs decay branching fraction input has been generalized to allow for different final state Higgs bosons (BR_hkhjhi);

- BR_Hplus.dat has been extended by the branching fractions for charged Higgs decays to top and bottom quarks (BR_Hptb), to W and Z bosons (BR_HpWZ), and to a neutral Higgs boson h_i and a W boson (BR_HphiW);

- The files *collider*_1H_hadCS_ratios.dat [where *collider* specifies the corresponding hadron collider, i.e. the Tevatron (TEV) or the LHC at center-of-mass energies of 7, 8 or 13 TeV (LHC7, LHC8, LHC13)] have been extended by dedicated (SM-normalized) hadronic cross section input for gluon fusion, $gg \to h_j$ (CS_*collider*_gg_hj_ratio), and $b\bar{b}$ associated Higgs production, $gg \to b\bar{b}h_j$ (CS_*collider*_bb_hj_ratio), as well as for the t-channel and s-channel mediated Higgs production in association with a single top quark (CS_*collider*_thj_tchan_ratio, CS_*collider*_thj_tchan_ratio);

- New files *collider*_Hplus_hadCS.dat (with *collider*=TEV, LHC7, LHC8, LHC13) have been introduced to specify the absolute hadronic cross section (in pb) for the charged Higgs production in association with a top and a bottom quark (CS_*collider*_Hpjtb), with a bottom quark and a light jet (CS_*collider*_Hpjbjet), with a W or Z boson (CS_*collider*_HpjW, CS_*collider*_HpjZ), charged Higgs production in vector boson fusion (CS_*collider*_vbf_Hpj), double charged Higgs production (CS_*collider*_HpjHmj) and charged Higgs production in association with a neutral Higgs boson (CS_*collider*_Hpjhi).

An overview of all data input files and their data structure is given in Table 7. For some higher dimensional arrays only some elements have to be specified, as will be explained below. The table also specifies whether the data file is required for either of the two HiggsBounds input schemes (effC or hadr), or used as optional input. Indeed, in case a required file is not provided as input, HiggsBounds warns the user but proceeds to run while setting the unspecified input quantities to zero. In Table 7 we assume that both neutral and charged Higgs bosons are present in the model. Obviously, if either the number of neutral or charged Higgs bosons is zero, some of the input files listed in Table 7 are also not required.

For the two-dimensional input arrays ghjhiZ and CS_lep_hjhi only the lower left triangle (including the diagonal) is required, since they are symmetric matrices. As an example, for

Data file name	effC	hadr	Contents
MH_GammaTot.dat	y	y	k, Mh, MhGammaTot
MHplus_GammaTot.dat	y	y	k, Mhplus, MhplusGammaTot
MHall_uncertainties.dat	o	o	k, dMh, dMhplus
CP_values.dat	n	y	k, $\mathcal{CP}$_value
effC.dat	y	n	k, ghjss_s, ghjss_p, ghjcc_s, ghjcc_p, ghjbb_s, ghjbb_p, ghjtt_s, ghjtt_p, ghjmumu_s, ghjmumu_p, ghjtautau_s, ghjtautau_p, ghjWW, ghjZZ, ghjZga, ghjgaga, ghjgg, some elements of ghjhiZ (see example)
BR_H_OP.dat	o	y	k, BR_hjss, BR_hjcc, BR_hjbb, BR_hjtt, BR_hjmumu, BR_hjtautau, BR_hjWW, BR_hjZZ, BR_hjZga, BR_hjgaga, BR_hjgg
BR_H_NP.dat	y	y	k, BR_hjinvisible, some elements of BR_hkhjhi (see example), some elements of BR_hjhiZ (see example), BR_hjemu, BR_hjetau, BR_hjmutau, BR_hjHpiW
BR_t.dat	y	y	k, BR_tWpb, BR_tHpb
BR_Hplus.dat	y	y	k, BR_Hpcs, BR_Hpcb, BR_Hptaunu, BR_Hptb, BR_HpWZ, BR_HpjhiW
additional.dat	o	o	k, ...
LEP_HZ_CS_ratios.dat	y	y	k, CS_lep_hjZ_ratio
LEP_H_ff_CS_ratios.dat	y	y	k, CS_lep_bbhj_ratio, CS_lep_tautauhj_ratio
LEP_2H_CS_ratios.dat	y	y	k, some elements of CS_lep_hjhi_ratio (see example)
LEP_HpHm_CS_ratios.dat	y	y	k, CS_lep_HpjHmj_ratio
*collider*_1H_hadCS_ratios.dat (*collider* = TEV, LHC7, LHC8, LHC13)	n	y	k, CS_hj_ratio, CS_gg_hj_ratio, CS_bb_hj_ratio, CS_hjW_ratio, CS_hjZ_ratio, CS_vbf_ratio, CS_tthj_ratio, CS_thj_tchan_ratio, CS_thj_schan_ratio
*collider*_Hplus_hadCS.dat (*collider* = LHC8, LHC13)	y	y	k, CS_Hpjtb, CS_Hpjcb, CS_Hpjbjet, CS_Hpjcjet, CS_Hpjjetjet, CS_HpjW, CS_HpjZ, CS_vbf_Hpj, CS_HpjHmj, CS_Hpjhi

Table 7: File names and data format for the contents of HiggsBounds input files. The right column shows the order of the input data arrays within one row of the input file (k is the line number). For the order of elements within the arrays, see the text for details. The middle columns indicate whether the files are required in the effective couplings approximation (effC) or hadronic cross section (hadr) input scheme [(y)es, (n)o, (o)ptional].

three neutral Higgs bosons ($N_{h^0} = 3$), for a symmetric matrix A,

$$\mathtt{A} = \begin{pmatrix} \mathtt{A(1,1)} & \mathtt{A(1,2)} & \mathtt{A(1,3)} \\ \mathtt{A(2,1)} & \mathtt{A(2,2)} & \mathtt{A(2,3)} \\ \mathtt{A(3,1)} & \mathtt{A(3,2)} & \mathtt{A(3,3)} \end{pmatrix},$$

the input file should contain the required elements in the order

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

In contrast, for the two-dimensional input array BR_hjhiZ, all off-diagonal elements need to be specified. Again for the $N_{h^0} = 3$ example, we have

$$\mathtt{BR\_hjhiZ} = \begin{pmatrix} \mathtt{BR\_hjhiZ(1,1)} & \mathtt{BR\_hjhiZ(1,2)} & \mathtt{BR\_hjhiZ(1,3)} \\ \mathtt{BR\_hjhiZ(2,1)} & \mathtt{BR\_hjhiZ(2,2)} & \mathtt{BR\_hjhiZ(2,3)} \\ \mathtt{BR\_hjhiZ(3,1)} & \mathtt{BR\_hjhiZ(3,2)} & \mathtt{BR\_hjhiZ(3,3)} \end{pmatrix},$$

thus, the elements should be specified as

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

For the three-dimensional input array BR_hkhjhi[k,j,i], there is a symmetry under exchange of the indices i and j (i.e. the indices of the final state Higgs bosons), whereas those elements with k=j or k=i are zero (k is the index of the decaying Higgs boson). Removing the redundant elements, we are left with $N_{h^0}^2(N_{h^0} - 1)/2$ elements that can be specified in the following way: For every $\mathtt{k} \in \{1, N_{h^0}\}$ we specify the lower left triangle (including the diagonal), but with the kth column and kth row removed. For our previous example ($N_{h^0} = 3$), we thus obtain the following input structure:

```
BR_hkhjhi[1,2,2], BR_hkhjhi[1,3,2], BR_hkhjhi[1,3,3],
BR_hkhjhi[2,1,1], BR_hkhjhi[2,3,1], BR_hkhjhi[2,3,3],
BR_hkhjhi[3,1,1], BR_hkhjhi[3,2,1], BR_hkhjhi[3,2,2].
```

The input arrays BR_hjHpiW, BR_HpjhiW and CS_Hpjhi are not reducible. These should thus be specified row by row in the input files.

3.3.2 SLHA

In earlier HiggsBounds versions (4 and before) the two SLHA blocks named HiggsBoundsCouplingInputBosons and HiggsBoundsCouplingInputFermions provided the SM normalized *squared* effective Higgs couplings to bosons and third generation fermions, respectively. In HiggsBounds-5 we replaced these blocks by very similar blocks named HiggsCouplingsBosons and HiggsCouplingsFermions, however, these blocks contain the (sign sensitive) SM normalized effective Higgs couplings, *not* the squared value. In case only the old blocks are specified in the SLHA input file for HiggsBounds-5, the effective Higgs couplings are taken to be the positive square-root of the given values.

In addition, we introduce new SLHA input blocks that enable the user to specify the hadronic cross sections for direct charged Higgs boson production. In absence of a corresponding SLHA convention, we name these input blocks as "ChargedHiggsLHC8" and "ChargedHiggsLHC13" for the predictions for the LHC at 8 and 13 TeV, respectively.[2] The first three columns specify the final state particle PDG numbers in increasing order (modulo sign in case of anti-particles). In case of a two-body final state the first column is filled by a zero. The fourth column gives the cross section in pb. An example (employing the particle spectrum of a 2HDM Higgs sector) for one of these SLHA blocks is given in Table 8.

3.4 HiggsBounds output

Some new handy HiggsBounds output routines. Description follows...

`HiggsBounds_get_most_sensitive_channels`

`(rank,HBresult,chan,obsratio,predratio,ncombined)`

`HiggsBounds_get_most_sensitive_channels_per_Higgs`

`(i,rank,HBresult,chan,obsratio,predratio,ncombined)`

`HiggsBounds_want_key` (*logical* :: `wantkey`)

3.5 Example programs and example data

- HBeffC
- HBwithFH
- HBwithFH_SLHA
- HBSLHAinputblocksfromFH

  (creates two files: 1) original SLHA with HB blocks appended, 2) entirely new SLHA output from FeynHiggs including HB blocks)
- HBwithLHClikelihood

[2]Corresponding blocks for Tevatron and LHC at 7 TeV are irrelevant because no charged Higgs searches for these production processes have been performed.

```
Block ChargedHiggsLHC13   # (in pb)
5      6   37   1.2800     # t-b-Hpm production
4      5   37   0.4180     # c-b-Hpm production
2      5   37   0.0002     # u-b-Hpm production
3      4   37   0.5100     # c-s-Hpm production
1      4   37   1.1200     # c-d-Hpm production
1      2   37   0.0001     # u-d-Hpm production
2      3   37   0.0010     # u-s-Hpm production
0     24   37   0.0150     # W-Hpm production
1      1   37   0.0000     # Hpm vector-boson-fusion production
0    -37   37   0.0003     # HpHm production
0     25   37   0.0005     # Hpmh0 production
0     35   37   0.0002     # HpmH0 production
0     36   37   0.0004     # HpmA0 production
```

Table 8: Example for the new SLHA Block `ChargedHiggsLHC13` containing various charged Higgs production cross sections (in pb). The cross sections for charged Higgs production in association with one or two light flavor quarks (u, d, s) are generally combined to inclusive production processes containing one or two untagged jets. For the vector boson fusion process we set both quark PDG numbers to 1 in order to differentiate it from the other quark-associated production processes. All cross sections correspond to the sum of H^+ and H^- production, hence, all PDG numbers are taken to be positive (except for H^+H^- production).

- `HBwithLEPlikelihood` (formerly `HBchisq`)
  (requires LEP χ^2 extension, see Ref. [1])
- `HBwithLEPlikelihood_SLHA` (formerly `HBchisqSLHA`)

References

[1] P. Bechtle, O. Brein, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein et al., HiggsBounds − 4*: Improved Tests of Extended Higgs Sectors against Exclusion Bounds from LEP, the Tevatron and the LHC*, *Eur. Phys. J.* **C74** (2014) 2693, [1311.0055].