The POWHEG-BOX-V2 user manual: Higgs boson decay into pair of b-quarks at NNLOPS

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1 Introduction

In this manual, we describe the POWHEG-BOX-V2 implementation of the Higgs boson decay into a pair of b-quarks accompanied by a gluon,

$$H \longrightarrow b + \bar{b} \ + g \,, \tag{1}$$

at NLO QCD accuracy. The program is equipped with the MiNLO procedure, introduced in Refs. [6, 7], that ensures that one retains NLO QCD accuracy for $H \to b\bar{b}$ observables upon integrating out the additional real radiation. Furthermore, the accuracy for the $H \to b\bar{b}$ observables can by upgraded to NNLO QCD by a suitable reweighting of the Les Houches events. The details of the MiNLO procedure as well as NNLO reweighting are investigated in the Ref. [1].

This document is organised as follows: in Sec. 2 we briefly describe how to generate and reweight the h_bbg event samples; in Sec. 3 we explain how to interface the h_bbg event sample with a specific Higgs production event sample, where the Higgs is undecayed. Finally, in Sec. 4 we describe how to match the produced event sample with parton shower. We list all physical and technical input parameters used in the h_bbg code in App. A and App. B respectively.

2 Generation of h_bbg events

2.1 Generation of event sample with POWHEG

→ Download the h_bbg user process into the POWHEG-BOX-V2 directory.

→ Navigate to the user process directory and build the executable

```
$> cd POWHEG-BOX-V2/h_bbg
$> make pwhg_main
```

→ Run the code (for example)

```
$> cd testrun
$> ../pwhg_main
```

Successful run should produce the file `pwgevents.lhe` containing 1000 `h_bbg` events in the Les Houches format and should terminate in only a few seconds. The physical and technical input parameters can be changed by editing the `powheg.input` card, which are listed in App. A and App. B. It is also possible to run the code in parallel mode - for this a `powheg.input-save` card and relevant scripts from `testrun-parallel` can be used as an example.

Such event sample(s) can be already interfaced with a user's Higgs production process. However, in order to achieve NNLOPS QCD accuracy, an NNLO reweighting is required, see Sec. 2.2.

2.2 NNLO reweighting of the event sample

The NNLO reweighting is performed along the lines of the standard `MiNNLO` technique, outlined in Sec. 5 of Ref. [7]. In this particular case, due to simplicity of the $H \to b\bar{b}$ process, the `MiNNLO` procedure boils down to a 0-dimensional NNLO reweighting that is driven only by the total decay width (Γ_{NNLO}) and its `MiNLO` counter-part ($\Gamma_{\texttt{MiNLO}}$). Weights of all events should be adjusted using a reweighting factor

$$\mathcal{W} = \frac{\Gamma_{\text{NNLO}}}{\Gamma_{\texttt{MiNLO}}}\,. \tag{2}$$

In a more refined scheme, described in Sec. 2.2 of Ref. [1], which we adopt as our default, the reweighting also depends on the three-jet resolution parameter y_3 through a function

$$\mathcal{W}(y_3) = h(y_3) \cdot \frac{\Gamma_{\text{NNLO}} - \Gamma_{\texttt{MiNLO},\text{B}}}{\Gamma_{\texttt{MiNLO},\text{A}}} + (1 - h(y_3))\,, \tag{3}$$

where we have introduced a function $h(y_3)$,

$$h(y_3) = \frac{1}{1 + (y_3/y_{3,\text{ref}})^{\alpha}} \qquad \text{with} \qquad \left\{ \begin{array}{l} \alpha > 0 \\ y_{3,\text{ref}} > 0 \end{array} \right., \tag{4}$$

that is used to classify the hardness of an event, i.e. $h(y_3)$ approaches one for $y_3 \to 0$ and $h(y_3) \ll 1$ for hard events, so that for hard events $\mathcal{W} = 1$. As a default values we choose $y_{3,\text{ref}} = e^{-4}$ and $\alpha = 2$.

In order to perform the NNLO reweighting of an event sample `pwgevents.lhe`:

→ Navigate to the user process directory `POWHEG-BOX-V2/h_bbg`

→ Compile the program `hdec` which will drive the reweighting process

```
$> make hdec -f makefile.hdec
```

After program is compiled, syntax can be checked by executing

```
$> ./hdec
```

→ Analyse existing event samples in order to calculate values $\Gamma_{\texttt{MiNLO},\text{A/B}}$

```
$> cd testrun
$> ../hdec -histprep -events pwgevents.lhe -out hist.dat
```

This will produce file `hist.dat` which contains necessary information used later for the NNLO reweighting. Note that the values of parameters $y_{3,\mathrm{ref}}$ and α, cf. Eq. (4), can be altered using optional arguments `-y3ref` and `y3pow`.

The output file `hist.dat` contains results for a different renormalization scale variation, as specified in the `powheg.input file`. In the following, the number of weights at the `MiNLO` level will be denoted as `num-lhef-wgt`. For example, if the original `MiNLO` events were obtained with a reweighting that performs a standard 3-point variation ($\mu_R = K_R^{\mathrm{MiNLO}}\mu_0$, with $K_R^{\mathrm{MiNLO}} = \{1.0, 0.5, 2.0\}$), then `num-lhef-wgt`=3.

In case of parallel run (`testrun-parallel`), remember to analyse all produced event files and merge the obtained histograms. The analysis of multiple event files can be performed either by specifying a number of event files following keyword `-events` in the above example. Alternatively, analyse files separately and direct the output to various output files which can be specified using `-out` keyword, for example

```
$> cd testrun
$> ../hdec -histprep -events pwgevents-0001.lhe -out hist-0001.dat
$> ../hdec -histprep -events pwgevents-0002.lhe -out hist-0002.dat
$> ...
$> ...
```

Various output files `hist-????.dat` should be merged by running

```
$> ../hdec -histmerge -files hist-????.lhe -out hist.dat
```

which will combine results saved in all histograms into a single output file `hist.dat` which will be used later for the NNLO reweighting.

→ Having obtained the histogram file `hist.dat`, the NNLO reweighting can be performed by running

```
$> ../hdec -minnlo -hist hist.dat -events pwgevents.lhe
```

which will produce a reweighted event file `pwgevents.lhe-minnlo`, where the NNLO weights were appended after the `MiNLO` ones. Multiple files can be reweighted at once simply by specifying a number of arguments after the keyword `-events`; each file name will be supplied with the "`-minnlo`" suffix after reweighting.

Note that, by default, the NNLO reweighting will prepare all possible combinations of weights, i.e. for each of `MiNLO` weights, the reweighted file will contain three weights related to scale variation in the computation of Γ_{NNLO} with $K_R^{\mathrm{NNLO}} = \{1.0, 0.5, 2.0\}$.

The user can constrain the possible scale combinations by preparing a file `wgt.dat` which contains a list of desired scale combinations. Each line of this file must contain the identifier of a given `MiNLO` weight (`minlo_wgt=1,2,...,num-lhef-wgt`) followed by the factor to be used to perform the (renormalisation) scale variation in the computation of Γ_{NNLO} (`nnlo_renscfact`=K_R^{NNLO}).

For example, if one wants to perform a totally correlated scale variation (i.e. $K_R^{\text{MiNLO}} = K_R^{\text{NNLO}}$), then the `wgt.dat` file should be

```
1   1.0
2   0.5
3   2.0
```

It is responsibility of the user to make sure that the correct order is used for the `minlo_wgt` values: in the above example, `minlo_wgt=1,2,3` must correspond to $K_R^{\text{MiNLO}} = \{1.0,\ 0.5,\ 2.0\}$, respectively.

The file `wgt.dat` that contains desired scale combinations should be passed to the reweighter programm using keyword `-weights`, i.e.

```
$> ../hdec -minnlo -hist hist.dat -events pwgevents.lhe -weights wgt.dat
```

Note that while the $\Gamma_{\texttt{MiNLO}}$ is computed on the fly using the event file generated, Γ_{NNLO} is computed internally using the Higgs mass which is read off from the event file. The value of the strong coupling used for calculation is by default set to $\alpha_s(M_Z) = 0.1181$. This value can be changed using keyword `-asmz` followed by the desired value.

3 Interface of `h_bbg` events with a specific production mode

In this section we describe how to combine a sample of $H \to b\bar{b}$ decays (at `MiNLO` accuracy in the decay, or upgraded to NNLOPS) together with a sample of events containing the production of an undecayed Higgs boson and other final state particles (at NLOPS, `MiNLO`, or NNLOPS accuracy in production). The resulting event sample will contain the full production kinematics, upgraded with the $H \to b\bar{b}$ decay at (N)NLO.

From now on we assume that the user has generated a LH event file containing $H \to b\bar{b}$ decays following the steps described in Sec. 2. In the following we denote this file as `pwgdecays.lhe` (`pwgdecays-0001.lhe`, `pwgdecays-0002.lhe`, ..., if they were obtained through parallel runs). We also assume that the user has generated events for Higgs production. We call this file `pwgproduction.lhe` (`pwgproduction-0001.lhe`, `pwgproduction-0002.lhe`, ..., if they were obtained through parallel runs).

- Compile the `hdec` program in the main `h_bbg` directory

```
$> cd POWHEG-BOX-V2/h_bbg
$> make hdec -f makefile.hdec
```

- The interface can be performed by running

```
$> ../hdec -interface -decay pwgdecays.lhe -prod pwgproduction.lhe
```

The combined events will be saved into `pwgproduction.lhe-hbb` file. The user should check that the number of decay events is greater or equal to the number of production events. If more than one decay file is needed to satisfy this requirement, a number of files can be specified after the `-decay` keyword.

Note that, by default, program will prepare all possible combinations of the weights in the production and decay files. In order to constrain ththe possible scale combinations, the user should prepare a file `scales-comb.dat` that lists desired combinations. Each line of this file should contain two integers, the first is the identifier of the production file weight and the second identifies the decay file weight. The file should be passed to the programm using `-weights` keyword, i.e.

```
$> ../hdec -interface -decay pwgdecays.lhe -prod pwgproduction.lhe
          -weights scale-comb.dat
```

For example, if the production file contains 7 weights, corresponding to renormalisation and factorisation scale variations

$$(K_R^{\rm prod}, K_F^{\rm prod}) = \{(1.0, 1.0),\ (1.0, 0.5),\ (1.0, 2.0),\ (0.5, 0.5),\ (0.5, 1.0),\ (2.0, 1.0),\ (2.0, 2.0)\,\}\,, \tag{5}$$

and the decay file contains 3 weights corresponding to

$$K_R^{\rm dec} = \{1.0,\ 0.5,\ 2.0\}\,, \tag{6}$$

and one wants to correlate the production and decay renormalisation scale variation, the file `scale-comb.dat` should read

```
1  1
2  1
3  1
4  2
5  2
6  3
7  3
```

The default value of the branching ratio that is used for the $H \to b\bar{b}$ decay is set to $\mathrm{Br} = 0.5824$. This value can be modified by using the keyword `-BrHbb` followed by the desired value of the branching ratio.

4 Matching with parton shower

In this section we describe how to parse $H \to b\bar{b}$ Les Houches events, interfaced with a desired Higgs production channel, to a parton shower. We stress that since after the interface Les Houches record is a compound prepared from two sources, production and decay of the Higgs boson, and as such contains two separate veto scales: `scalup_prod` and `scalup_dec` for production and decay respectively. Radiation generated by a parton shower, depending on its origin, should respect the relevant bound. We supply a parton shower driver that allows a user to process events produced along the instructions of Sec. 3 with a `Pythia8` parton shower [8].

In order to prepare a drive, one should

- Prepare a desired phenomenological analysis by modifying a subroutines `init_hists` and `analysis` of the `src/f77/pwhg_analysis.f` file, by default it contains only an entry for a calculation of the total cross section.

  It is possible to use the default `POWHEG` histogramming facility or link user's external analysis. The connection should be established withing the `src/f77/pwhg_analysis.f` file.

- Compile the `Pythia8` driver in the main `h_bbg` directory.

```
$> cd POWHEG-BOX-V2/h_bbg
$> make main-PYTHIA-lhef
```

- To process parton shower, navigate to directory with Les Houches event files and run the shower driver

```
$> cd testrun
$> echo <event-file> | ../main-PYTHIA-lhef
```

  where `<event-file>` is an event file to be showered. Successful run should produce histogram files with a `.top` extension.

We note that a state-of-the-art `Pythia8` parton shower, provides its own facility to veto emissions off various resonances. For that reason it is possible to use the built-in tools known as the `UserHooks`. For more details please refer to the original `Pythia8` reference guide on this topic [9, 10].

A Physical input parameters

A list of physical parameters that can be adjusted by the user in the `powheg.input` card. Floating point numbers should be simply specified as numbers, the logical variables are specified with 0/1 for True/False, respectively.

- `hmass` [float]: mass of the Higgs boson, in GeV.
- `hwidth` [float]: total width of the Higgs boson resonance, in GeV.
- `bmass` [float]: b-quark pole mass, in GeV, used for calculation of the Yukawa coupling (the dependence cancels out once an $H \to b\bar{b}$ branching fraction is applied for during the interface). The kinematics of the decay is always calculated with massless b-quarks.
- `mb_running` [logical]: if False the pole b-quark Yukawa will not be transformed into $\overline{\text{MS}}$ one calculated at the renormalization scale.
- `massive_b_lhe` [logical]: if True the Les Houches event file will contain massive b-quarks (calculation is performed in the massless approximation, reshuffling is applied at the stage of generating of the Les Houches file)

Moreover we have

- `renscfact` [float]: modification of a renormalization scale, $\mu_R = \texttt{renscfact} \cdot \mu_0$, with μ_0 equal to the Higgs mass.

- `xresummation` [float]: modification of the resummation scale, $Q_{\rm res} = \texttt{xresummation} \cdot Q_0$, with Q_0 equal to the Higgs mass.

- `sudscalevar` [logical]: if True scale variation is also performed in the Sudakov radiator.

B Technical parameters

All technical parameters in the `powheg.input` card can be modified by the user. The most relevant include:

- `itmx1`/`itmx2` [integer]: number of Monte Carlo subsequent runs at `stage1` and `stage2` of a `POWHEG` run (if using parallel version of the run, `itmx1` is ignored and set to 1).

- `ncall1`/`ncall2` [integer]: number of Monte Carlo sampling points at `stage1` and `stage2` of a `POWHEG` run.

- `nubound` [integer]: number of sampling points at `stage3` of a `POWHEG` run.

- `numevts` [integer]: number of requested event records in a single Les Houches event file.

References

[1] W. Bizon, E. Re, and G. Zanderighi, "NNLOPS description of the H→ $b\bar{b}$ decay with `MiNLO`," .

[2] P. Nason, "A new method for combining NLO QCD with shower Monte Carlo algorithms," JHEP **0411** (2004) 040 [arXiv:hep-ph/0409146].

[3] S. Frixione, P. Nason and C. Oleari, "Matching NLO QCD computations with Parton Shower simulations: the POWHEG method," JHEP **0711** (2007) 070 [arXiv:0709.2092].

[4] S. Alioli, P. Nason, C. Oleari and E. Re, "A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX," JHEP **1006** (2010) 043 [arXiv:1002.2581].

[5] T. Jezo and P. Nason, "On the Treatment of Resonances in Next-to-Leading Order Calculations Matched to a Parton Shower," JHEP **1512** (2015) 065 [arXiv:1509.09071].

[6] K. Hamilton, P. Nason and G. Zanderighi, JHEP **1210** (2012) 155 doi:10.1007/JHEP10(2012)155 [arXiv:1206.3572 [hep-ph]].

[7] K. Hamilton, P. Nason, C. Oleari and G. Zanderighi, JHEP **1305** (2013) 082 doi:10.1007/JHEP05(2013)082 [arXiv:1212.4504 [hep-ph]].

[8] T. Sjöstrand *et al.*, Comput. Phys. Commun. **191** (2015) 159 doi:10.1016/j.cpc.2015.01.024 [arXiv:1410.3012 [hep-ph]].

[9] http://home.thep.lu.se/Pythia/pythia82html/UserHooks.html

[10] http://home.thep.lu.se/Pythia/pythia82html/POWHEGMerging.html