Preprint typeset in JHEP style - PAPER VERSION

March 20, 2019
POWHEG-BOX-V2

The POWHEG BOX V2 user manual: Higgs boson pair production at NLO QCD with variations of the trilinear Higgs coupling

G. Heinrich
Max-Planck Institut für Physik, Föhringer 6, D-80805 Munich, Germany
E-mail: gudrun@mpp.mpg.de

S. P. Jones
Theoretical Physics Department, CERN, CH-1211 Geneva, Switzerland
E-mail: s.jones@cern.ch

M. Kerner
Institut für Physik, Universität Zürich, Winterthurerstr. 190, 8057 Zürich, Switzerland
E-mail: kerner@mpp.mpg.de

G. Luisoni
Max-Planck Institut für Physik, Föhringer 6, D-80805 Munich, Germany
E-mail: luisonig@gmail.com

L. Scyboz
Max-Planck Institut für Physik, Föhringer 6, D-80805 Munich, Germany
E-mail: scyboz@mpp.mpg.de

Abstract: This note documents the use of the package POWHEG-BOX-V2 for Higgs boson pair production in gluon fusion. The code allows to produce NLO results matched to a parton shower for HH production with full top quark mass dependence, and also allows variations of the Higgs boson trilinear coupling $c_{hhh} = \kappa_\lambda = \lambda/\lambda_{SM}$. By rescaling as described below, it also allows to vary the top-Higgs Yukawa coupling. Other run modes of the program can be used to calculate approximations: the $m_t \to \infty$ limit (also called HEFT approximation), the so-called Born-improved HEFT approximation, and the $\mathrm{FT}_{\mathrm{approx}}$ scheme.

Keywords: Shower Monte Carlo, POWHEG, NLO, Higgs.

Contents

1. Introduction

The `POWHEG-BOX` is a framework to implement NLO calculations in shower Monte Carlo programs according to the `POWHEG` method. An explanation of the method and a discussion of how the code is organized can be found in Refs. [2, 3, 4, 5]. The code is distributed according to the "MCNET Guidelines for Event Generator Authors and Users" and can be found at the web page

`http://powhegbox.mib.infn.it`

In this manual, we describe the `POWHEG` implementation of Higgs boson pair production in gluon fusion at NLO QCD, as described in Ref. [6], based on the calculation reported in Refs. [7, 8]. The variations of the trilinear Higgs boson coupling are based on Refs. [1, 9]. Please cite Refs. [1, 6] if you use this program.

The code can be found under `User-Processes-V2` in the `ggHH` process-directory. An example input card (`powheg.input-save`) and a run script (`run.sh`) are provided in the `testrun` folder accompanying the code.

This document describes the input parameters that are specific to the process. The parameters that are common to all `POWHEG-BOX` processes can be found in the manual `V2-paper.pdf` in the `POWHEG-BOX-V2/Docs` directory.

2. Running modes

The code contains the NLO QCD amplitudes for both, the full top quark mass dependence, for which HH-production is a loop-induced process, and the $m_t \to \infty$ limit (sometimes called Higgs Effective Field Theory, HEFT), containing effective Higgs-gluon couplings, as the top-quark loops are integrated out. A detailed description of the different approximations can be found in Ref. [8].

This allows to run the code in four different modes, either by changing the flag `mtdep` in the `POWHEG-BOX` run card `powheg.input-save`, or by using the script `run.sh [mode]`. The possible choices and the corresponding calculations are the following:

`mtdep=0`: computation using basic HEFT. All amplitudes are computed in the $m_t \to \infty$ limit.

`mtdep=1`: computation using Born-improved HEFT. In this approximation the fixed-order part is computed at NLO in the HEFT and reweighted pointwise in the phase-space by the LO matrix element with full mass dependence divided by the LO matrix element in HEFT.

`mtdep=2`: computation in the approximation $\mathrm{FT}_{\mathrm{approx}}$. In this approximation the matrix elements for the Born and the real radiation contributions are computed with full top quark mass dependence (using matrix elements generated by `GoSam` [10]), whereas the virtual part is computed as in the Born-improved HEFT.

`mtdep=3`: computation with full top quark mass dependence.

The `run.sh` script in the `testrun` folder allows to perform the runs of the different stages of `POWHEG` easily. By typing `./run.sh` without any argument a menu with the 4 `mtdep` running modes described above is shown. For all `mtdep` running modes the code goes through all the various steps (parallel stages) of the calculation:

`parallelstage=1`: generation of the importance sampling grid for the Monte Carlo integration;

`parallelstage=2`: calculation of the integral for the inclusive cross section and an upper bounding function of the integrand;

`parallelstage=3`: upper bounding factors for the generation of radiation are computed;

`parallelstage=4`: event generation, i.e. production of `pwgevents-*.lhe` files.

Please note: if you use the script `run.sh [mtdep]`, the value for `mtdep` given as an argument to `run.sh` will be used, even if you specified a different value for `mtdep` in `powheg.input-save`.

After running `parallelstage=4`, the LHE files produced by `POWHEG` can be directly showered by either `PYTHIA` or `HERWIG`. We provide a minimal setup for producing parton-shower matched distributions in `test-pythia8`, respectively `test-herwig7`. Both the angular-ordered and the dipole-shower implemented in `HERWIG` can be operated by changing the `showeralg` flag to either `'default'` or `'dipole'` in `HerwigRun.sh`.

3. Running with full top quark mass dependence (`mtdep=3`)

The 2-loop virtual amplitudes in the NLO calculation with full top quark mass dependence are computed via a grid which encodes the dependence of the virtual 2-loop amplitude on the kinematic invariants $\hat{s}$ and $\hat{t}$ [6]. Please be aware that the numerical values $m_H = 125\,\mathrm{GeV}$ and $m_t = 173\,\mathrm{GeV}$ are **hardcoded** in this grid and therefore should not be changed in `powheg.input-save` when running in the `mtdep=3` mode. The grid is generated using python code and is directly interfaced to the `POWHEG-BOX` fortran code via

the Python/C API. In order for the grid to be found by the code, the files (`events.cdf`, `createdgrid.py`, `Virt_full_cHHH_{-1.0,0.0,1.0}.grid`) from the folder `Virtual` need to be copied into the local folder where the code is run. Instead of copying the files, we suggest to create a symbolic link to the needed files. Assuming the code is run from a subfolder (e.g. `testrun`) of the process folder, the link can be created in this subfolder as follows:

```
ln -s ../Virtual/events.cdf events.cdf

ln -s ../Virtual/creategrid.py creategrid.py

for grid in ../Virtual/Virt_full_cHHH_*.grid; do ln -s $grid ${grid##*/}; done
```

Once the links are in place, the code can be run with `mtdep=3` as usual. To ensure that the linked files are found, we recommend to add the run subfolder to `PYTHONPATH`. The python code `creategrid.py` will then combine the virtual grids generated with the three values of $c_{hhh} = -1, 0, 1$ to produce a new file `Virt_full.grid` corresponding to the value of `cHHH` chosen in the `powheg.input` file.

The python code for the grid is written in python 2.7 and relies on the `numpy` and `sympy` packages, which the user should install separately. When building the `ggHH` process the Makefile will find the embedded python 2.7 library via a call to `python2.7-config`, which the user should ensure is configured correctly and points to the correct library. Note that on some systems the Python/C API does not search for packages (such as `numpy` and `sympy`) in the same paths as the python executable would. Therefore the user should ensure that these packages can be found also by an embedded python program.

4. Physical input parameters

The bottom quark is considered massless in all four `mtdep` modes. The Higgs bosons are generated on-shell with zero width. A decay can be attached through the parton shower in the narrow-width approximation. However, the decay is by default switched off (see the `hdecaymode` flag in the example `powheg.input-save` input card in `testrun`).

The masses of the Higgs boson and the top quark are set by default to $m_h = 125\,\text{GeV}$, $m_t = 173\,\text{GeV}$, respectively, whereas their widths have been set to zero. The full SM 2-loop virtual contribution has been computed with these mass values hardcoded. It is no problem to change the values of m_h and m_t via the `powheg.input-save` input card when running with `mtdep` set to 0, 1 or 2. However, when running with `mtdep = 3`, **the values of the Higgs mass and the top mass should be kept fixed at $m_h = 125\,\text{GeV}$ and $m_t = 173\,\text{GeV}$**, and the widths should be zero. Otherwise the two-loop virtual part would contain a different top or Higgs mass than the rest of the calculation.

The `POWHEG-BOX` offers the possibility to use a damping factor $h =$ `hdamp` of the form [11, 12]

$$F = \frac{h^2}{(p_T^{\text{hh}})^2 + h^2}\,, \tag{4.1}$$

where $p_T^{\rm hh}$ is the transverse momentum of the Higgs boson pair, to limit the amount of hard radiation which is exponentiated in the Sudakov form factor. The default setting ($F \equiv 1$, corresponding to `hdamp`$= \infty$) results in quite hard tails for observables like $p_T^{\rm hh}$ [6]. Changing the damping factor F by setting the flag `hdamp` to some finite value in the input card brings the high transverse momentum tails down towards the fixed-order NLO predictions. Varying `hdamp` allows to assess shower untertainties within the `POWHEG` matching scheme. However, when choosing a value for `hdamp`, it is important not to cut into the Sudakov regime. In fact, a too low value for `hdamp` could spoil the logarithmic accuracy of the prediction. For this reason we suggest not to choose values for `hdamp` below ~ 200. Our default value is `hdamp=250`.

5. Trouble shooting

Below is a list of potential issues:

- With `mtdep=3`, the powheg *.log files contain the string "grid not found": make sure your run folder contains the following files (or symbolic links to these files located in the folder 'Virtual'): `events.cdf, creategrid.py` and the grid files `Virt_full_cHHH_*.grid`.
- The distributions contain spikes: make sure the flags `check_bad_st1` and `check_bad_st2` (present in `POWHEG` svn revisions ≥ 3600) are set to 1. These flags discard outliers in the xgrid files. If you still find outliers with these flags switched on, the "bad" runs should be removed (manually, or using the script `automated_removal.py` present in the subfolder `shell`).
- Problems related to the `gcc 6.3.0` compiler have been reported. They should not occur when using a more recent `gcc` compiler.

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