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POWHEG BOX RES 1.0

The POWHEG BOX V2 user manual: double Higgs boson production with variations of the Higgs self-coupling

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Abstract: This note documents the use of the package POWHEG-BOX-V2 for the production of a Higgs boson pair by gluon fusion. The code allows to produce NLO results matched to parton shower for HH production in the Standard Model with full mass dependence, and also in the Higgs effective field theory (HEFT) approximation, in the so-called Born-improved HEFT approximation, and in the $\mathrm{FT}_{\mathrm{approx}}$ scheme.

Keywords: POWHEG, Shower Monte Carlo, NLO.

Contents

1. Introduction

The `POWHEG BOX` program is a framework for implementing 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. [1, 2, 3, 4]. 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, as described in ref. [6], based on the calculation reported in refs. [7, 8]. This document describes the input parameters that are specific to this implementation. The parameters that are common to all `POWHEG BOX` processes can be found in the manual in the `POWHEG-BOX-V2/Docs` directory.

The code can be found in the `HH` directory under `User-Processes-V2`, and can be used to generate NLO+PS QCD corrections to Higgs boson pair production at hadronic colliders. An example input card (`powheg.input-save`) and a run script (`run.sh`) are provided in the `testrun` folder accompanying the code.

2. Running modes

The code contains the amplitudes for both, the full Standard Model (SM), for which HH-production is a loop-induced process, and the Higgs Effective Field Theory (HEFT), where the Higgs boson couples directly to gluons and the top-quark is integrated out ($m_t \to \infty$ limit). This allows to run the code in four different modes by changing the flag `mtdep` in the `POWHEG BOX` run card. The possible choices and the corresponding calculations are the following:

`mtdep=0:` computation using basic HEFT. All amplitudes are computed in the limit of an inifinitely large top quark mass ($m_t \to \infty$).

`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 Born matrix element with full mass dependence.

`mtdep=2:` computation in the approximation $\mathrm{FT}_{\mathrm{approx}}$. In this approximation the matrix element for the the Born and the real radiation contributions are computed with full mass dependence (using matrix elements generated by `GoSam` [5]), whereas the virtual part is computed as in the Born-improved HEFT.

`mtdep=3:` computation in the full SM. All the matrix elements are computed using the full top-quark mass dependence.

The `run.sh` script in the `testrun` folder allows to quickly start some test runs. By simply typing `./run.sh` a menu with the various running modes is shown. In all cases the code goes through all the various steps (parallelstages) of the calculation, from the generation of the (`MINT`) grid to the production of LHE files.

3. Running in the full SM (`mtdep=3`)

The 2-loop virtual amplitudes in the full SM 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 note 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 the `mtdep=3` mode. The grid is generated using a python code and, in the newest version (after revision number 3507), the code is directly interfaced to the `POWHEG BOX` fortran code. The procedure for the computation with full top quark mass dependence is similar to the one for the other running modes. However, 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 of the needed files. Assuming the code is run from a subfolder of the process folder, the link can be created 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` suited to the value of `cHHH` chosen in the `powheg.input` file.

4. Physical input parameters

The bottom quark is considered massless in all four 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).

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 values for the masses hardcoded. Therefore, although it is possible 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, **the values of the Higgs mass and the top mass should be kept fixed at $m_h = 125\,\text{GeV}$ and $m_t = 173\,\text{GeV}$ when running with `mtdep = 3`.**

The `POWHEG BOX` offers the possibility to use a damping factor of the form [9, 10]

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

where p_T^{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 ($F \equiv 1$), results in quite hard tails for observables like p_T^{hh} [6]. Changing the damping factor F by setting the flag `hdamp`$(= h)$ to some finite value in the input card brings the high transverse momentum tails back onto the fixed 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 250.

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