The POWHEG-BOX-B2/WWanomal manual

1 Introduction

The POWHEG-BOX-V2[1] program [1] can be used to generate predictions for the process $pp \to W^+W^- \to \ell^+\nu_\ell \ell'^-\bar{\nu}_{\ell'}$ at hadron colliders, at next-to-leading order in QCD with a matching to parton shower. The code includes anomalous 3-gauge-boson couplings, anomalous W- and Z-quark couplings, as well as a consistent effective field theory (EFT) expansion and the possibility to use direct EFT input in the Warsaw basis [2].

The code is based on the calculation presented in Refs. [1] and is an extension of a previous implementation containing anomalous 3-gauge-boson couplings only [3,4], which was based upon the calculations presented in Refs. [5–7]. Off-shell effects are fully included. The present code only works with different-flavor final states to avoid taking into account contributions from the ZZ process as well as its interference with the W^+W^- process.

This manual summarizes the settings and input parameters that are specific to this implementation in the POWHEG-BOX-V2 framework. The parameters that are common to all POWHEG BOX implementation are given in the POWHEG-BOX-V2/Docs directory. If you use the code, please cite the references [1, 3, 4].

Important note:
The code available was tested and developed for the POWHEG-BOX-V2 revision 3591. If you examine unexpected behavior or if you have problems compiling and running the code, please rewind or update your POWHEG-BOX-V2 version to the one it was developed for. To do this, use

```
$ svn info
$ svn up -r3591
```

in your POWHEG-BOX-V2 main directory.

2 Compiling the program

This program can be run on any Linux/UNIX computer (including Mac OS X). To get started, make sure you have a Fortran compiler (e.g. gfortran, at least version 5.2). Although this is not necessary, it is recommended to use LHAPDF [8] to manage the calls to parton distribution functions calls. Make sure that the corresponding library is installed on your workstation. You have to modify in the Makefile the parameter LHAPDF_CONFIG to provide the absolute path to your local lhapdf-config executable.

Important note for Mac OSX and some Linux users:
In order to link the object files properly with newer compiler versions it might be advisable to recompile all your own libraries using the -lstdc++ flag.

[1] The POWHEG-BOX project can be found at http://powhegbox.mib.infn.it/.

In the current code version several C preprocessor (cpp) flags are implemented. The preprocessor runs in traditional mode for gfortran. Any restrictions of the file format, especially the limits on line length, apply for preprocessed output as well, so it might be advisable to use the `-ffree-line-length-none` or `-ffixed-line-length-none` options (activated by default). If you want to change a preprocessor flag, it is imperative to run

```
$ make clean
```

before recompiling the source code.

There are several options for the command `make`:

```
$ make pwhg_main
```

compiles the main executable.

```
$ make main-PYTHIA-lhef
```

compiles the executable that is necessary to shower the events generated by `pwhg_main` using `PYTHIA`.

```
$ make main-HERWIG-lhef
```

compiles the executable that is necessary to shower the events generated by `pwhg_main` using `HERWIG` (Not tested! Use at your own risk!)

```
$ make clean
```

removes all object files in `./object-gfortran` (or `./object-ifort`), and deletes the executables `pwhg_main`, `main-HERWIG-lhef`, and `main-PYTHIAS-lhef`.

3 Generation of events

In the `WWanomal` directory, do

```
$ make pwhg_main
```

Then do (for example)

```
$ cd test
$ ../pwhg_main
```

At the end of the run, the file pwgevents.lhe will contain events for W^+W^- production in the Les Houches format. In order to shower them with `PYTHIA`:

```
$ make main-PYTHIA-lhef
$ cd test
$ ../main-PYTHIA-lhef
```

This generates `.top` files containing kinematical distributions including shower effects.

4 Input parameters

Here the parameters in the file `powheg.input` that are specific to anomalous W^+W^- pair production are presented. Use # when one parameter is meant to be deactivated.

4.1 Standard Model parameters and electroweak scheme

The parameter `ewscheme` controls the set of electroweak parameters that are used as input parameters. The user can choose between five schemes:

1. `ewscheme`=1: The Fermi constant G_F, $\alpha^{-1}(M_Z)$, and M_Z are the input parameters; $\sin^2(\theta_W)$ and M_W are calculated.
2. `ewscheme`=2: The Fermi constant G_F, $\sin^2(\theta_W)$, and M_Z are the input parameters; $\alpha^{-1}(M_Z)$ and M_W are calculated.
3. `ewscheme`=3 (default scheme): The Fermi constant G_F, M_W, and M_Z are the input parameters; $\alpha^{-1}(M_Z)$ and $\sin^2(\theta_W)$ are calculated.
4. `ewscheme`=4: $\alpha^{-1}(0)$, M_W, and M_Z are the input parameters; $\alpha^{-1}(M_Z)$ and $\sin^2(\theta_W)$ are calculated.
5. `ewscheme`=5: $\alpha^{-1}(M_Z)$, M_W, and M_Z are the input parameters; $\sin^2(\theta_W)$ is calculated.

The user has to set the Z and W widths, the default value correspond to the PDG 2016 [9]. The default input parameters for the electroweak scheme are also taken from the PDG 16.

4.2 Optional parameters

The user can use either a fixed renormalization/factorization scale (`fixedscale`=1) set at $\mu_0 = M_W$, or a dynamical scale (default, with `fixedscale`=0) set at the invariant mass of the process, $\mu_0 = M_{WW}$. The parameters `renscfact` and `facscfact` are rescaling factor around the central value μ_0.

The input file `powheg.input` contains also input parameters that were already defined in Ref. [4] and that control the calculation of the matrix elements:

```
dronly 0       !  default 0; if 1 only double resonant diagrams
zerowidth 0    !  default 0 (off-shell Ws); if 1 generate W's on shell
```

If `zerowidth` is absent or equal to zero, the W-bosons are given a finite width. Singly resonant graphs are also included by default, unless the `dronly` flag is set to 1. If `zerowidth` is set to 1, `dronly` is set to 1 regardless of what is in the `powheg.input` file.

4.3 Decay modes

Several decay modes can be selected by an appropriate flag in the `powheg.input` file. **IMPORTANT: Do NOT use the decay modes involving (semi-)hadronic final states! They are there as legacy.**

```
e+e- 1         !  only electrons
mu+mu- 1       !  only muons
e+mu- 1        !  e+ nu_e mu- nu_mu mode
```

```
mu+e- 1        !  mu+ nu_mu e- nu_e mode
emu 1          !  electron+muon mode
leptonic 1     !  fully leptonic mode
hadronic 1     !  fully hadronic mode
semileptonic 1 !  fully semi-leptonic mode
```

More conditions can be easily added, by editing the `alloweddec` function in the `init_processes.f` file. Notice that conditions must all be fulfilled. If no conditions are specified, you get all possible decays (this is NOT recommended!).

4.4 Standard cuts

The input file `powheg.input` contains already several cut parameters that are implemented at the analysis level. If `cutflag`=0 (default value), no cuts are used at all; if `cutflag`=1, cuts are applied and only histograms including the cuts are produced; if `cutflag`=2, both histograms with and without cuts are produced. The standard cuts are the following:

```
ptlcut1  1350.0d0     !  (default 0) min.  pT cut on leading lepton
ylcut1      2.5d0     !  (default 100) max.  rapidity cut on leading lepton
ptlcut2    30.0d0     !  (default 0) min.  pT cut on sub-leading lepton
ylcut2      2.5d0     !  (default 100) max.  rapidity cut on sub-leading lepton

rjet        0.4d0     !  (default 0.4) R-parameter for the jet definition
ptjcut     35.0d0     !  (default 10) Minimum pt to define a jet
yjcut       4.5d0     !  (default 0) Maximum rapidity to define a jet
jetveto        1      !  (default 0) if 1 perform jet veto

etmiss     20.0d0     !  (default 0) min.  missing ET
mllcut     10.0d0     !  (default 0) min.  di-lepton invariant mass
```

4.5 Anomalous coefficients and EFT parameters

The input file `powheg.input` contains a block dedicated to the EFT parameters. Three switches control the calculation:

```
EFTswitch       0
EFTsu2          1
nLambdaEFT      0
```

If `EFTswitch`=0 (default), anomalous couplings are used. They are δg_1^Z, δg_1^γ (should be zero due to gauge invariance), λ^Z, λ^γ, $\delta\kappa^Z$, $\delta\kappa^\gamma$, δg_L^W, δg_R^W (taken to be zero), δg_L^{Zu}, δg_R^{Zu}, δg_L^{Zd}, and δg_R^{Zd}. They are all defined in Ref. [1]. If instead `EFTswitch`=1, EFT Wilson coefficients as defined in the Warsaw basis are directly used, see Ref. [10] for the conversion between the anomalous couplings and the Wilson coefficients.

If `EFTsu2`=1 (default), $SU(2)$ gauge invariance is enforced. The default anomalous couplings input parameters are then reduced to the following 7 parameters,

$$\lambda^Z,\ \delta g_1^Z,\ \delta\kappa^Z,\ \delta g_L^{Zu},\ \delta g_L^{Zd},\ \delta g_R^{Zu},\ \text{and}\ \delta g_R^{Zd}.$$

Any value for the other anomalous couplings given by the user will be discarded as they are calculated internally using the $SU(2)$ relations.

The integer n=`nLambdaEFT` controls the EFT expansion, up to $\mathcal{O}(1/\Lambda^{2n})$. In particular, $n = 0$ corresponds to the Standard Model calculation.

Important note: The parameter `tevscale` has been discarded and is a legacy parameter right now.

5 Additional notes

This code is published under the GNU General Public License (GPL) version 2. More details can be found in the LICENSE file in the `./Doc/` directory.

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References

[1] J. Baglio, S. Dawson, and I. M. Lewis, *NLO Effects in EFT Fits to W^+W^- Production at the LHC*, 1812.00214.

[2] B. Grzadkowski, M. Iskrzynski, M. Misiak, and J. Rosiek, *Dimension-Six Terms in the Standard Model Lagrangian*, *JHEP* **10** (2010) 085, [1008.4884].

[3] T. Melia, P. Nason, R. Rontsch, and G. Zanderighi, *W^+W^-, WZ and ZZ production in the POWHEG BOX*, *JHEP* **11** (2011) 078, [1107.5051].

[4] P. Nason and G. Zanderighi, *W^+W^- , WZ and ZZ production in the POWHEG-BOX-V2*, *Eur. Phys. J.* **C74** (2014), no. 1 2702, [1311.1365].

[5] L. J. Dixon, Z. Kunszt, and A. Signer, *Helicity amplitudes for $\mathcal{O}(\alpha_s)$ production of W^+W^-, $W^\pm Z$, ZZ, $W^\pm\gamma$, or $Z\gamma$ pairs at hadron colliders*, *Nucl.Phys.* **B531** (1998) 3–23, [hep-ph/9803250].

[6] L. J. Dixon, Z. Kunszt, and A. Signer, *Vector boson pair production in hadronic collisions at order α_s: Lepton correlations and anomalous couplings*, *Phys. Rev.* **D60** (1999) 114037, [hep-ph/9907305].

[7] J. M. Campbell and R. K. Ellis, *An Update on vector boson pair production at hadron colliders*, *Phys.Rev.* **D60** (1999) 113006, [hep-ph/9905386].

[8] A. Buckley, J. Ferrando, S. Lloyd, K. Nordström, B. Page, M. Rüfenacht, M. Schönherr, and G. Watt, *LHAPDF6: parton density access in the LHC precision era*, *Eur. Phys. J.* **C75** (2015) 132, [1412.7420].

[9] **Particle Data Group** Collaboration, C. Patrignani *et al.*, *Review of Particle Physics*, *Chin. Phys.* **C40** (2016), no. 10 100001.

[10] J. Baglio, S. Dawson, and I. M. Lewis, *An NLO QCD effective field theory analysis of W^+W^- production at the LHC including fermionic operators*, *Phys. Rev.* **D96** (2017), no. 7 073003, [1708.03332].