Preprint typeset in JHEP style - PAPER VERSION

August 5, 2015

POWHEG-BOX-V2

The $W\gamma$ process in the POWHEG BOX-V2 user manual

Luca Barzè

PH-TH Department, CERN, CH-1211 Geneva, Switzerland

E-mail: Luca.Barze@cern.ch

Mauro Chiesa

Dipartimento di Fisica Nucleare e Teorica, Università di Pavia and INFN, Sezione di Pavia, Via A. Bassi 6, 27100 Pavia, Italy

E-mail: Mauro.Chiesa@pv.infn.it

Guido Montagna

Dipartimento di Fisica Nucleare e Teorica, Università di Pavia and INFN, Sezione di Pavia, Via A. Bassi 6, 27100 Pavia, Italy

E-mail: Guido.Montagna@pv.infn.it

Paolo Nason

INFN, Sezione di Milano-Bicocca, Piazza della Scienza 3, 20126 Milan, Italy

E-mail: Paolo.Nason@mib.infn.it

Oreste Nicrosini

INFN, Sezione di Pavia, Via A. Bassi 6, 27100 Pavia, Italy

E-mail: Oreste.Nicrosini@pv.infn.it

Fulvio Piccinini

INFN, Sezione di Pavia, Via A. Bassi 6, 27100 Pavia, Italy

E-mail: Fulvio.Piccinini@pv.infn.it

Valeria Prosperi

Dipartimento di Fisica Nucleare e Teorica, Università di Pavia and INFN, Sezione di Pavia, Via A. Bassi 6, 27100 Pavia, Italy

E-mail: Valeria.Prosperi@pv.infn.it

Abstract: This note documents the use of the package POWHEG-BOX-V2 for $W\gamma$ production process including QCD NLO corrections. Results can be easily interfaced to shower Monte Carlo programs, in such a way that both NLO and shower accuracy are maintained.

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. [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`.

This program is an implementation of the $W\gamma$ NLO cross sections $pp \to \ell\nu\gamma$ including QCD radiative corrections. A detailed description of the implementation can be found in Ref. [1]. In order to run the POWHEG BOX program, we recommend the reader to start from the POWHEG BOX user manual, which contains all the information and settings that are common between all subprocesses. In this note we focus on the settings and parameters specific to the $W\gamma$ implementation.

2. Generation of events

Build the executable

```
$ cd POWHEG-BOX-V2/Wgamma
$ make pwhg_main
```

Then do (for example)

```
$ cd test-c-nlo
$ ../pwhg_main
```

At the end of the run, the file `pwgevents.lhe` will contain 200000 events for $e^+\nu_e\gamma$ in the

Les Houches format. In order to shower them with PYTHIA6 do

```
$ cd POWHEG-BOX-V2/Wgamma
$ make main-PYTHIA-lhef
$ cd test-c-nlo
$ ../main-PYTHIA-lhef
```

If you prefer to shower the event with PYTHIA8 do

```
$ cd POWHEG-BOX-V2/Wgamma
$ make main-PYTHIA8-lhef
$ cd test-c-nlo
$ ../main-PYTHIA8-lhef
```

As a large number (some millions) of events is required in order to give a statistically significant sample, we recommend the use of parallel computation with the `manyseeds` option (all you need is in the `parallel_manyseeds` directory, see `POWHEG-BOX-V2/Docs/Manyseeds.pdf` for explanation).

3. Process specific input parameters

Mandatory parameters are those needed to select the final state leptonic species coming from the vector-boson:

```
idvecbos 24   !  PDG code for vector boson to be produced
              !  ( W+:  24 W-:  -24 )
vdecaymode 11 !  code for selected W decay
              !  (11(-11):  electronic; 13(-13):  muonic; 15(-15):  tauonic)
```

Together with the mandatory parameters, the POWHEG BOX input facility allows for an easy setting of EW and run parameters, by explicitly adding the relevant lines to the input card. If one of the following entries is not present in the input card the reported default value is assumed. In any case, these parameters are printed in the output of the program, so their values can be easily tracked down.

```
Wmass    80.385          !  W mass in GeV
Wwidth   2.085           !  W width in GeV
Zmass    91.1876         !  Z mass in GeV
Zwidth   2.4952          !  Z width in GeV
G_mu     1.16638d-5      !  Fermi constant in GeV^-2
alphaem0 1/137.03599911  !  em coupling alpha(0)
```

3.1 The NC, C-LO, C-NLO schemes for the $W\gamma$ process.

Three different schemes are available for the computation of the $W\gamma$ process at NLOPS (next-to-leading order interfaced to Parton Shower) accuracy in POWHEG:

- NC scheme.
  Selected by setting the flag `powheg-nc` to 1 in the powheg.input file (see the `test-nc` directory).
- C-LO scheme.
  Selected by setting the flag `powheg-c-lo` to 1 in the powheg.input file (see the `test-c-lo` directory).
- C-NLO scheme. Default scheme (`test-c-nlo` directory).

The description of the three schemes can be found in [1].

The MiNLO prescription [5, 6] is strongly recommended, as motivated in [1], and it is used by default.
The transverse momentum generation cut (`bornktmin`) is set to 1 GeV.
The call to the `setlocalscales` subroutine has been modified in order to include information on the `alr` index of the current singular region, since the α_s rescaling depends not only on the underlying Born configuration, but also on the identity (parton or photon) of the radiated particle, and then on the flavour list of the `alr` region.
In the C-NLO scheme, the $\mathcal{O}(\alpha_s)$ expansion of the Sudakov form factor is subtracted from the Born contrbution in order to maintain the NLO accuracy.
For other process-dependent modifications of the MiNLO routines see [1].

The new definition of the d_i functions, operating the separation of the real cross section into singular regions, is used by default in `POWHEG-BOX-V2` (see [7]). In the ubprojections.f file the mergeisr and mergefsr functions, used in the computation of the $d^{ub}_{i,j}$ functions associated with the singular configurations of the underlying Born, have been modified in order to include singularities associated to photon emissions.

The `nlotestonly` option, activated by setting the `nlotestonly` flag to 1 in the powheg.input file (see the `test-nlo` directory), can be used to perform a pure NLO computation. The smooth isolation prescription [13] is implemented in this case as a cut in the real phase space, in order to avoid the collinear photon emission from the final state quark in gluon induced processes. The `nlotestonly` option is only useful for a NLO computation, and should not be used for the generation of events; if the number of calls `nubound` for the computation of the upper bounding function for radiation and the number of events `numevts` are set to a nonzero value the execution stops.

3.2 Other options.

Other options, specific to the $W\gamma$ process, can be selected in the powheg.input file.

- The `phspseparation` variable is the weight for the dual-channel sampling of the Born phase space. Its default value is 0.5.

If it is set to zero, the Born phase space is sampled as in the Wj process. If $0 < phspseparation < 1$, a second channel is opened, in order to provide also a suitable sampling for the FSR contribution, corresponding to photon radiation from the lepton. The weight variable is treated as an integration variable (one more dimension is added to the dimension counting for the integration in the nlegborn.h file) in order to take advantage of the adaptive integration.

- The variable `kt2minqed` is the equivalent of the `rad_ptsqmin` variable in the case of photon radiation from leptons. It sets the minimum relative transverse momentum squared for QED resolvable emissions.
  The default value is 0.8 GeV^2, as in the QCD radiation case. In fact, a minimum angular cone separation between the lepton and the photon candidates is required in the event selection ($\Delta R \sim 0.7$ for a realistic analysis), so that photons emitted with $p_T^{rel}(\gamma\text{-}l)$ below this value are unlikely to pass the cone cut.
  We verified the stability of our results against the variation of the `kt2minqed` value in an interval 0.1 GeV^2 <`kt2minqed`< 0.8 GeV^2.

- The flag `modept2gamlep` selects the definition of the transverse momentum of the photon relative to the lepton used for the scale setting in the MiNLO routines.
  It is set to zero by default, implying that the definition used is the same as in the d-functions of the FKS subtraction method, which determines the separation of the real cross section into singular contributions:

$$p_T^{rel}(\gamma\text{-}l) = 2\Big(\frac{E_\gamma E_l}{E\gamma + E_l}\Big)\sin\frac{\theta}{2} \tag{3.1}$$

  If `modept2gamlep` is set to 1 the following expression is used:

$$p_T^{rel}(\gamma\text{-}l) = \frac{p_T^\gamma p_T^l}{p_T^\gamma + p_T^l}\min(\Delta R, 1) \tag{3.2}$$

- The `Deltak_gam` and `Lambda_gam` flags set the values the anomalous triple gauge couplings for the $WW\gamma$ vertex. Their default values are zero.

4. Interface to PYTHIA6 and PYTHIA8

Interfaces to both PYTHIA6 [9] and PYTHIA8 [10] are provided for a QCD+QED interleaved shower of the generated events.
One can choose between the options `default` and `atlas` for the analysis in the Makefile; in the latter case, the selection cuts reproduce the experimantal ATLAS setup (of Ref. [8]) and the `fastjet` package is loaded for jet reconstruction.
Photon radiation from leptons can also be performed using PHOTOS (see for example Ref. [11]), by setting the `use_photos` flags to 1 in the powheg.input file. PYTHIA6 is interfaced to PHOTOS Fortran, while PYTHIA8 is interfaced to the C++ version [12]. In the latter, the switches of matrix element corrections in leptonic W decays and double bremsstrahlung generation (`me_corr` and `double_brem` flags in the powheg.input file) are

available (see Ref. [12]).

The `PYTHIA6` and `PYTHIA8` tunes can be selected by the options `pythiatune` and `py8tune` respectively in the powheg.input file.

`PYTHIA` and `PHOTOS` do not enforce the `SCALUP` veto in case of photon radiation from leptons.

In `PYTHIA6` and `PHOTOS`, an iterated procedure is introduced in order to enforce the veto, as explained in [1]. An event is showered, then, for each final state photon originating from a $l \to l\gamma$ splitting, the transverse momentum of the photon relative to the daughter lepton is computed. If this value is above the `SCALUP` value, the shower is repeated until the requirement is fulfilled.

In `PYTHIA8` the same veto procedure is used by default. However, an internal veto procedure can be used instead, setting the `py8veto` flag to 1 in the powheg.input file.

The internal veto procedure in `PYTHIA8` is the same used for the parton shower. The `SpaceShower:pTmaxMatch` and `TimeShower:pTmaxMatch` options are set to 2, and a veto for initial and final state emissions is applied, in order to ensure the correct matching between the hardness variable (p_T) definitions for NLO and shower emissions. The `POWHEG` p_T definition is chosen setting `POWHEG:pTdef` to 1 (see the `PYTHIA8` online manual [10], Section *POWHEG merging*, for further information). The same matching is then applied to photon emissions from leptons.

The flag `nohad` is used to switch off hadronization in `PYTHIA8`.

In the NC scheme the QED shower is turned off, while it is on (`PYTHIA` default) for the C-LO and C-NLO schemes.

In the NC scheme some complications arise, since the `SCALUP` choice is not uniquely defined as in the default `POWHEG` method, i.e. as the transverse momentum of the hardest radiation relative to the emitter (see [1]). For $Wj(+\gamma)$ events, `SCALUP` is set to the p_T of the Born level parton, in order to account for QCD radiation harder than the photon (as no QCD radiation mechanism from a Wj underlying Born configuration is included in `POWHEG` in the NC case). The lhefread.f file has been modified in this sense, with a redefinition of `SCALUP` for $Wj(+\gamma)$ events.

The cutoff for QED shower from leptons is set to 1 GeV to effectively mimic the calorimetric definition of dressed leptons (see Ref. [1]):

- `PYTHIA6`:
  `parj(90)=1d0` (default=0.0001).

- `PYTHIA8`:
  `pythia.readString("TimeShower:pTminChgL=1.0")` (default=0.0005).

The main radiative hadron decays are switched off in order to suppress the background from non-prompt photons. The switches for the radiative decays can be modified by the user, acting on the subroutine `UPINIT` in the `setup-PYTHIA-lhef.f` file for `PYTHIA6`, or on the function `pythia_init_` in the `pythia8F77.cc` file for `PYTHIA8`.

For instance (the code 111 refers to π^0):

- PYTHIA6:
  ```
  mdcy(pycomp(111),1)=0
  ```

- PYTHIA8:
  ```
  pythia.readString("111:mayDecay = off");
  ```

References

[1] L. Barzè, M. Chiesa, G. Montagna, P. Nason, O. Nicrosini, F. Piccinini and V. Prosperi, "$W\gamma$ production in hadronic collisions using the POWHEG+MiNLO method," JHEP **12** (2014) 039 arXiv:1408.5766 [hep-ph].

[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 [hep-ph]].

[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," [arXiv:1002.2581 [hep-ph]].

[5] K. Hamilton, P. Nason, G. Zanderighi, "MINLO: Multi-scale improved NLO," arXiv:1206.3572 [hep-ph].

[6] K. Hamilton, P. Nason, C. Oleari, and G. Zanderighi, "Merging H/W/Z + 0 and 1 jet at NLO with no merging scale: a path to parton shower + NNLO matching," JHEP **1305** (2013) 082, [arXiv:1212.4504].

[7] J. M. Campbell, R. K. Ellis, P. Nason and G. Zanderighi, "W and Z bosons in association with two jets using the POWHEG method," arXiv:1311.1365 [hep-ph].

[8] **ATLAS Collaboration** Collaboration, G. Aad et al., "Measurements of $W\gamma$ and $Z\gamma$ production in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector at the LHC," Phys. Rev. D **87** (2013) 112003, [arXiv:1302.1283].

[9] T. Sjostrand, S. Mrenna, and P. Z. Skands, "PYTHIA 6.4 Physics and Manual," JHEP **0605** (2006) 026, [hep-ph/0603175].

[10] For the PYTHIA8 version see the PYTHIA8 online manual, http://home.thep.lu.se/ torbjorn/pythia81html/Welcome.html.

[11] Z. Was, P. Golonka, G. Nanava, "PHOTOS Monte Carlo for precision simulation of QED in decays: History and properties of the project," PoS ACAT (2007) 071, arXiv:0707.3044.

[12] N. Davidson, T. Przedzinski, Z. Was, "PHOTOS Interface in C++: Technical and Physics Documentation," CERN-PH-TH/2010-261, arXiv:1011.0937.

[13] S. Frixione, "Isolated photons in perturbative QCD," Phys. Lett. B **429** (1998) 369-374, [hep-ph/9801442].