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VBFNLO: A parton level Monte Carlo for processes with electroweak bosons – Manual for Version 2.5.0

K. Arnold[1], J. Bellm[1], G. Bozzi[2], M. Brieg[1], F. Campanario[1], C. Englert[3], B. Feigl[1], J. Frank[1], T. Figy[4], F. Geyer[1], C. Hackstein[1], V. Hankele[1], B. Jäger[5], M. Kerner[1], M. Kubocz[6], C. Oleari[2], S. Palmer[1], S. Plätzer[7], M. Rauch[1], H. Rzehak[8], F. Schissler[1], M. Spannowsky[9], M. Worek[10], D. Zeppenfeld[1]

[1] Institut für Theoretische Physik, Universität Karlsruhe, Karlsruhe Institute of Technology, 76128 Karlsruhe, Germany
[2] Dipartimento di Fisica, Università di Milano-Bicocca and INFN, Sezione di Milano-Bicocca, 20126 Milano, Italy
[3] Institute for Theoretical Physics, Heidelberg University, 69120 Heidelberg, Germany
[4] CERN, CH-1211 Geneva 23, Switzerland
[5] Institut für Physik (THEP), Johannes-Gutenberg-Universität, 55099 Mainz, Germany
[6] Institut für Theoretische Teilchenphysik und Kosmologie, RWTH Aachen University, 52056 Aachen, Germany
[7] DESY, Notkestr. 85, 22607 Hamburg, Germany
[8] Physikalisches Institut Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Str. 3, 79104 Freiburg im Breisgau, Germany
[9] Institute of Theoretical Science, University of Oregon, Eugene, OR 97403-5203, USA
[10] Fachbereich C Physik, Bergische Universität Wuppertal, 42097 Wuppertal, Germany

Abstract

VBFNLO is a flexible parton level Monte Carlo program for the simulation of vector boson fusion, double and triple vector boson production in hadronic collisions at next-to-leading order (NLO) in the strong coupling constant, as well as Higgs boson plus two jet production via gluon fusion at the one-loop level. In the new release – VERSION 2.5.0 – several new processes have been added at NLO QCD: vector boson fusion production of a Higgs boson plus a photon, vector boson fusion production of a photon, $W\gamma$ and WZ production plus a hadronic jet and the triboson production processes $WW\gamma, ZZ\gamma, WZ\gamma, W\gamma\gamma, Z\gamma\gamma$ and $\gamma\gamma\gamma$. The code has been extended to run in the Minimal Supersymmetric Standard Model (MSSM), and electroweak corrections to Higgs boson production via weak boson fusion have been included. Anomalous gauge boson couplings can be used in new processes and the Three-Site Higgsless model has been implemented for several processes. The simulation of Higgs boson production via gluon fusion has been improved.

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Contents

1 Introduction

The physics potential of the TeVatron and even more of the Lhc depends heavily on our ability to provide accurate cross section predictions for both signal and background processes. The latter are often generated by QCD interactions which give rise to weak bosons in the final state. A precise description of such hard QCD production processes is needed, as well as a method for simulating the measurable hadronic final states. Reaching these goals requires next-to-leading order (NLO) QCD calculations presented in the form of parton level Monte Carlo (MC) generators, which are an efficient solution when it comes to final states characterized by a high number of jets and/or identified particles. When kinematic cuts are imposed, as is mandatory for processes involving QCD radiation, analytic phase-space integration becomes impractical and implementation of results in the form of Monte Carlo programs becomes the method of choice.

VBFNLO is a flexible MC program for vector boson fusion (VBF), double and triple vector boson production processes at NLO QCD accuracy. Furthermore, the electroweak corrections to Higgs boson production via VBF (which are of the same order of magnitude as the QCD corrections in the experimentally accessible regions of phase-space) have been included. Since real emission processes are part of the NLO cross sections, VBFNLO provides the means to calculate cross sections for the corresponding process with one additional jet at leading order (LO) in the strong coupling. In addition, the simulation of $\mathcal{CP}$-even and $\mathcal{CP}$-odd Higgs boson production in gluon fusion, associated with two additional jets, is implemented at LO QCD. The full top- and bottom-quark mass dependence of the one-loop contributions in the Standard Model (SM), in the Minimal Supersymmetric Standard Model (MSSM) and in a generic two-Higgs-doublet model is included. VBFNLO can be run in the MSSM (with real or complex parameters), and anomalous couplings of the Higgs boson and gauge bosons have been implemented for certain processes. Additionally, two Higgsless extra dimension models are included – the Warped Higgsless scenario and a Three-Site Higgsless Model – for selected processes. These models can be used to simulate the production of technicolor-type vector resonances in VBF and triple weak boson production.

Arbitrary cuts can be specified as well as various scale choices. Any currently available parton distribution function (PDF) set can be used through the Lhapdf library. In addition, CTEQ6L1 for LO and CT10 for NLO calculations, as well as MRST2004qed and MSTW2008, are hard-wired into the code. For most processes implemented at leading order the program is capable of generating event files in the Les Houches Accord (LHA) and the HepMC format. When working in the MSSM, the SUSY parameters can be input via a standard SLHA file.

This manual supersedes the previous version [1] released with VBFNLO Version 2.0. The following additional processes have been included to NLO QCD accuracy:

- Vector boson fusion production of a Higgs boson in association with a photon and two jets,
- VBF production of a photon plus two jets,
- diboson (WZ and $W\gamma$) plus a hadronic jet production,
- $WW\gamma$, $ZZ\gamma$, $WZ\gamma$ triboson production,
- $W^{\pm}\gamma\gamma$, $Z\gamma\gamma$ triboson production,

- $\gamma\gamma\gamma$ production.

Additionally, various new features have been introduced:

- Anomalous quartic gauge boson couplings for triboson production,
- Extension to the MSSM,
- Electroweak corrections to VBF Higgs boson production in the SM and MSSM,
- Triple vector boson production in Higgsless Kaluza-Klein models.

The VBFNLO webpage – `http://www-itp.particle.uni-karlsruhe.de/vbfnlo/` – contains, in addition to the latest version of the code, extra information such as the explicit implementation of the electroweak parameters and couplings, as well as optimised grid files for all processes for a set of standard cuts. To enable a simple installation test VBFNLO is shipped with a complete set of example results, together with input files, in the `regress` directory.

2 Installing VBFNLO

The source code of the current version of VBFNLO can be downloaded from the VBFNLO webpage

`http://www-itp.particle.uni-karlsruhe.de/vbfnlo/`

and includes a GNU conforming build system for portability and an easy build and installation procedure.

2.1 Prerequisites

The basic installation requires GNU `make`, a FORTRAN77[1] and a C++ compiler. VBFNLO offers the possibility of using the LHAPDF[2] [2] library for parton distribution functions. In order to include the electroweak corrections, the program LoopTools[3] [3, 4] is required. Additionally, FeynHiggs[4] [5–8] can be linked to the code in order to calculate the Higgs boson sector of the MSSM, although a SLHA file can be used as an alternative. If the simulation of Kaluza-Klein resonances is enabled, an installation of the GNU Scientific Library (GSL)[5] is required. VBFNLO can also be linked to ROOT[6] and HepMC[7] to produce histograms and event files in those formats.

2.2 Compilation and installation

After unpacking the source archive and entering the source directory, the `configure` script can be invoked with several options, a complete list of which are available via `./configure --help`. Among these, the most important ones are:

- `--prefix=[path]`
  Install VBFNLO in the location given by `[path]`.

- `--enable-processes=[list]`
  By default, the code for all available processes is compiled. Optionally, `[list]` gives a comma-separated list of selected processes to be compiled. Possible process names are:

`vbf`	Vector boson fusion processes
`diboson`	Double gauge boson production
`triboson`	Triple gauge boson production
`dibosonjet`	Double gauge boson production with a hadronic jet
`hjjj`	Higgs boson plus three jet production via vector boson fusion
`ggf`	Higgs boson plus two jet production via gluon fusion

- `--disable-NLO`
  Disable the next-to-leading order QCD corrections.

[1] The following compilers have been tested: `g77` and `gfortran`. The `ifort` compiler has also been tested with a basic installation (i.e. without linking to any external programs).

[2] `http://projects.hepforge.org/lhapdf/`

[3] `http://www.feynarts.de/looptools/`

[4] `http://www.feynhiggs.de/`

[5] `http://www.gnu.org/software/gsl/`

[6] `http://root.cern.ch/`

[7] `http://lcgapp.cern.ch/project/simu/HepMC/`

- `--enable-kk`
  Enable simulation of Kaluza-Klein resonances. Disabled by default, the Kaluza-Klein option requires the installation of the GNU Scientific Library, which needs to be specified via `--with-gsl`.

- `--with-gsl=[path]`
  Enable the use of the GNU Scientific Library. `[path]` specifies the location of the GSL installation.

- `--with-LHAPDF=[path]`
  Enable the use of LHAPDF in addition to the built-in PDF sets. Disabled by default. `[path]` specifies the location of the LHAPDF installation.

- `--with-LOOPTOOLS=[path]`
  Enable the use of LoopTools in order to calculate the electroweak corrections. If this option is not specified, the electroweak corrections cannot be included. Disabled by default. `[path]` specifies the location of the LoopTools installation.

- `--with-FEYNHIGGS=[path]`
  Enable the use of FeynHiggs[8] to calculate the MSSM Higgs sector parameters. Disabled by default. `[path]` specifies the location of the FeynHiggs installation.

- `--with-root=[path]`
  Enable the use of Root. `[path]` specifies the location of the Root installation.

- `--with-hepmc=[path]`
  Enable the production of HepMC format event files. `[path]` specifies the location of the HepMC installation.

Note that, by default, both LoopTools and FeynHiggs are installed as static libraries. If this is the case, `configure` must be run with the option `--enable-shared=no`. Also note that, in order to link to an external program such as LoopTools, the external program needs to have been compiled using the same compiler (e.g. `gfortran`) as Vbfnlo. Once `configure` has finished successfully, the `make` and `make install` commands will compile and install Vbfnlo, respectively.

2.3 Source and installation directory layout

The Vbfnlo source tree contains the following subdirectories:

- `amplitudes/`: Routines to calculate matrix elements for the processes provided.

- `doc/`: The source of this manual.

- `helas/`: Helas [9] subroutines used to calculate helicity amplitudes.

- `loops/`: One-loop tensor integrals up to five-point functions [10].

- `PDFsets/`: Built-in parton distributions (CTEQ6L1 [11] for LO and CT10 [12] for NLO calculations, as well as MRST2004qed [13] and MSTW2008 [14]).

[8] Note that different versions of FeynHiggs give slightly different results as more corrections are added to the calculations. Vbfnlo has been tested with FeynHiggs versions 2.6.x, 2.7.x, 2.8.0 and 2.8.3.

- `phasespace/`: Specialized phase-space generators for the processes provided.
- `regress/`: Folder containing example results, together with input files, for all processes.
- `src/`: Source code of the main programs and input files.
- `utilities/`: Routines for administrative tasks, cuts, scale choices and interfaces.

The source does not need to be modified to change the simulation parameters. VBFNLO offers several kinematic cuts and scale choices. This is illustrated in Sec. 4. In addition, it provides a few basic histograms. Cuts, histograms and scale choices not already provided may be added in the `utilities/cuts.F`, `utilities/histograms.F` and `utilities/scales.F` files.

The installation is performed in a standard UNIX-layout, i.e. the directory specified with the `--prefix` option of the `configure` script contains the following directories:

- `bin/`: `vbfnlo` and `ggflo` executables.
- `include/VBFNLO/`: VBFNLO header files.
- `lib/VBFNLO/`: VBFNLO modules as dynamically loadable libraries. These can also be used independently from one of the main programs.
- `share/VBFNLO/`: Input files and internal PDF tables.

2.4 Running the program

Both the `vbfnlo` and `ggflo` executables contained in the `bin` directory of the installation path look for input files in their current working directory. An alternative path to input files may be specified explicitly by passing the `--input=[path]` argument to the programs, with `path` denoting the full path where input files are located. I.e. in order to run VBFNLO from the installation (`prefix`) directory, the command is

```
./bin/vbfnlo --input=[path]
```

The input files contained in the `share/VBFNLO` directory are meant to represent default settings and should not be changed. We therefore recommend that the user copies the input files to a separate directory. Here, special settings may be chosen in the input files and the program can be run in that directory without specifying further options.

VBFNLO outputs a running 'log' to the terminal, containing information about the settings used. In addition, the file `xsection.out` is produced, which contains only the LO and NLO cross sections, with the associated errors. Histograms and event files, in various forms, can be output as described later.

2.5 MacOSX

Unfortunately, owing to the library set-up, at the moment VBFNLO does not run on MacOSX. It has, however, been tested successfully on a virtual box on a MacOSX.

2.6 Bug reports

Please report any problems to

`vbfnlo@particle.uni-karlsruhe.de`

with a short report including the configure options used to build VBFNLO, as well as the versions of compilers and external libraries used.

2.7 License

VBFNLO is distributed under the GNU General Public License (GPL) version 2. This ensures that the source code will be available to users, grants them the freedom to use and modify the program and sets out the conditions under which it can be redistributed. However, it was developed as part of an academic research project and is the result of many years of work by the authors, which raises various issues that are not covered by the legal framework of the GPL. It is therefore distributed together with a set of guidelines[9], which were originally formulated and agreed on by the MCnet collaboration for event generator software.

[9] These guidelines are contained in the `GUIDELINES` file distributed with the release.

3 Processes

In the following sections, we describe all production processes and decay modes implemented in VBFNLO, together with references to more detailed discussions of the underlying calculations.

In the phase-space regions that are accessible at hadron colliders, VBF reactions are dominated by t-channel electroweak gauge boson exchange. In VBFNLO s-channel exchange contributions and kinematically suppressed fermion interference contributions [15–17] are therefore disregarded. Numerically small contributions from Pauli-interference effects for identical charged leptons are neglected. For final-state identified photons we employ the isolation criterion of Ref. [18]. This ensures that divergences from collinear emission of a photon from a final-state massless quark or anti-quark are avoided, while the cancellation of the infrared divergences between the virtual and the real part is kept intact.

3.1 VBF Higgs boson production in association with two jets

Hjj production via VBF mainly proceeds via electroweak quark-quark scattering processes such as $qq' \to qq'H$ and crossing related reactions. In VBFNLO, tree level cross sections, NLO QCD corrections and 1-loop electroweak corrections (in the Standard Model and the MSSM) to the t-channel production process are provided. The subsequent decay of the Higgs boson is simulated in the narrow width approximation (NWA). For the $H \to W^+W^-$ and the $H \to ZZ$ modes, full off-shell effects and spin correlations of the decay leptons are included. The available production process and decay modes are listed with the corresponding process IDs in Table 1. Anomalous couplings between a Higgs boson and a pair of vector bosons are implemented in the code. Details of the calculations can be found in Refs. [19–21].

ProcID	Process	BSM
100	$p\overset{(-)}{p} \to H\,jj$	anomalous HVV couplings, MSSM
101	$p\overset{(-)}{p} \to H\,jj \to \gamma\gamma\,jj$	
102	$p\overset{(-)}{p} \to H\,jj \to \mu^+\mu^-\,jj$	
103	$p\overset{(-)}{p} \to H\,jj \to \tau^+\tau^-\,jj$	
104	$p\overset{(-)}{p} \to H\,jj \to b\bar{b}\,jj$	
105	$p\overset{(-)}{p} \to H\,jj \to W^+W^-\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,jj$	
106	$p\overset{(-)}{p} \to H\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\,jj$	
107	$p\overset{(-)}{p} \to H\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\,jj$	

Table 1: *Process IDs for $p\overset{(-)}{p} \to Hjj$ production via weak boson fusion at NLO (QCD and electroweak) accuracy in the SM and MSSM. Anomalous Higgs boson couplings are implemented for all decay modes.*

ProcId	Process
110	$p\overset{(-)}{p} \to H\,jjj$
111	$p\overset{(-)}{p} \to H\,jjj \to \gamma\gamma\,jjj$
112	$p\overset{(-)}{p} \to H\,jjj \to \mu^+\mu^-\,jjj$
113	$p\overset{(-)}{p} \to H\,jjj \to \tau^+\tau^-\,jjj$
114	$p\overset{(-)}{p} \to H\,jjj \to b\bar{b}\,jjj$
115	$p\overset{(-)}{p} \to H\,jjj \to W^+W^-\,jjj \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,jjj$
116	$p\overset{(-)}{p} \to H\,jjj \to ZZ\,jjj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\,jjj$
117	$p\overset{(-)}{p} \to H\,jjj \to ZZ\,jjj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\,jjj$

Table 2: *Process IDs for $p\overset{(-)}{p} \to Hjjj$ production via VBF at NLO QCD accuracy.*

ProcId	Process
2100	$p\overset{(-)}{p} \to H\gamma\,jj$
2101	$p\overset{(-)}{p} \to H\gamma\,jj \to \gamma\gamma\gamma\,jj$
2102	$p\overset{(-)}{p} \to H\gamma\,jj \to \mu^+\mu^-\gamma\,jj$
2103	$p\overset{(-)}{p} \to H\gamma\,jj \to \tau^+\tau^-\gamma\,jj$
2104	$p\overset{(-)}{p} \to H\gamma\,jj \to b\bar{b}\gamma\,jj$
2105	$p\overset{(-)}{p} \to H\gamma\,jj \to W^+W^-\gamma\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\gamma\,jj$
2106	$p\overset{(-)}{p} \to H\gamma\,jj \to ZZ\gamma\,jj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\gamma\,jj$
2107	$p\overset{(-)}{p} \to H\gamma\,jj \to ZZ\gamma\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\gamma\,jj$

Table 3: *Process IDs for $p\overset{(-)}{p} \to H\gamma jj$ production via VBF at NLO QCD accuracy.*

3.2 VBF Higgs boson production in association with three jets

Adding an extra parton to the Higgs production processes of Sec. 3.1 gives rise to $Hjjj$ final states. The corresponding cross sections are implemented at NLO QCD accuracy (with certain approximations) in VBFNLO. A list of all available modes and corresponding process IDs is given in Table 2. Details of the calculation can be found in Ref. [22].

3.3 VBF Higgs boson production with a photon and two jets

The emission of an additional photon in VBF Higgs boson production (Sec. 3.1) results in $H\gamma jj$ final states. These are implemented at NLO QCD accuracy in VBFNLO, with process IDs as given in Table 3. Details of the calculation can be found in Ref. [23].

ProcId	Process
120	$p\overset{(-)}{p} \to Z\,jj \to \ell^+\ell^-\,jj$
121	$p\overset{(-)}{p} \to Z\,jj \to \nu_\ell\bar{\nu}_\ell\,jj$
130	$p\overset{(-)}{p} \to W^+\,jj \to \ell^+\nu_\ell\,jj$
140	$p\overset{(-)}{p} \to W^-\,jj \to \ell^-\bar{\nu}_\ell\,jj$
150	$p\overset{(-)}{p} \to \gamma\,jj$

Table 4: *Process IDs for vector boson + 2 jet production via weak boson fusion at NLO QCD accuracy.*

3.4 VBF production of a vector boson and two jets

Vector boson fusion processes can also produce final states with two leptons plus two jets, which are generically referred to as "VBF Zjj and $W^\pm jj$ production". These reactions and the one with a photon plus two jets in the final state are implemented to NLO QCD accuracy in VBFNLO, see Table 4. Details of the calculations can be found in Refs. [24,25].

3.5 VBF production of two vector bosons and two jets

The production of four leptons plus two jets in the final state at order $\mathcal{O}(\alpha^6)$ is dominated by VBF contributions. In VBFNLO, all resonant and non-resonant t-channel exchange contributions giving rise to a specific leptonic final state are considered. For simplicity, we refer to these reactions as "VBF diboson production". Finite width effects of the weak bosons and spin correlations of the decay leptons are fully retained. The available processes and corresponding process IDs are listed in Table 5. Anomalous gauge boson couplings are implemented for W^+W^-jj production, and this class of processes can also be run in the Higgsless models implemented in VBFNLO. Details of the calculations can be found in Refs. [26–28].

3.6 Double and triple vector boson production

The production of four- and six-lepton final states mainly proceeds via double and triple vector boson production with subsequent decays. Additionally, there are processes where one or more decaying boson is replaced by an on-shell photon, giving rise to lepton production in association with photon(s) and triple photon production. In VBFNLO, the processes listed in Table 6 are implemented to NLO QCD accuracy, including full off-shell effects and spin correlations of the final state leptons and photons. For processes with three massive gauge bosons, the Higgs boson contributions are included in the Standard Model[10]. Anomalous vector boson couplings are implemented for W^+W^-Z, $ZZW^\pm$ and

[10]This should provide a good approximation in the MSSM in the decoupling regime – i.e. where one of the Higgs bosons is SM-like.

ProcId	Process	BSM
200	$p\overset{(-)}{p} \to W^+W^- jj \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2} jj$	anomalous couplings, Kaluza-Klein models
210	$p\overset{(-)}{p} \to ZZ jj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^- jj$	Kaluza-Klein models
211	$p\overset{(-)}{p} \to ZZ jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2} jj$	
220	$p\overset{(-)}{p} \to W^+Z jj \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^- jj$	
230	$p\overset{(-)}{p} \to W^-Z jj \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^- jj$	

Table 5: *Process IDs for diboson + 2 jet production via weak boson fusion at NLO QCD accuracy.*

ProcId	Process	BSM
300	$p\overset{(-)}{p} \to W^+W^- \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}$	
400	$p\overset{(-)}{p} \to W^+W^-Z \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}{\ell_3}^+{\ell_3}^-$	anomalous couplings, Kaluza-Klein models
410	$p\overset{(-)}{p} \to ZZW^+ \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-{\ell_3}^+\nu_{\ell_3}$	
420	$p\overset{(-)}{p} \to ZZW^- \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-{\ell_3}^-\bar{\nu}_{\ell_3}$	
430	$p\overset{(-)}{p} \to W^+W^-W^+ \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}{\ell_3}^+\nu_{\ell_3}$	
440	$p\overset{(-)}{p} \to W^-W^+W^- \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\nu_{\ell_2}{\ell_3}^-\bar{\nu}_{\ell_3}$	
450	$p\overset{(-)}{p} \to ZZZ \to \ell_1^-\ell_1^+\ell_2^-\ell_2^+{\ell_3}^-{\ell_3}^+$	
460	$p\overset{(-)}{p} \to W^-W^+\gamma \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\nu_{\ell_2}\gamma$	
470	$p\overset{(-)}{p} \to ZZ\gamma \to \ell_1^-\ell_1^+\ell_2^-\ell_2^+\gamma$	
480	$p\overset{(-)}{p} \to W^+Z\gamma \to \ell_1^+\nu_{\ell_1}\ell_2^-\ell_2^+\gamma$	
490	$p\overset{(-)}{p} \to W^-Z\gamma \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^-\ell_2^+\gamma$	
500	$p\overset{(-)}{p} \to W^+\gamma\gamma \to \ell^+\nu_\ell\gamma\gamma$	
510	$p\overset{(-)}{p} \to W^-\gamma\gamma \to \ell^-\bar{\nu}_\ell\gamma\gamma$	
520	$p\overset{(-)}{p} \to Z\gamma\gamma \to \ell^-\ell^+\gamma\gamma$	
521	$p\overset{(-)}{p} \to Z\gamma\gamma \to \nu_\ell\bar{\nu}_\ell\gamma\gamma$	
530	$p\overset{(-)}{p} \to \gamma\gamma\gamma$	

Table 6: *Process IDs for the diboson and triboson production processes at NLO QCD accuracy.*

$W^\pm W^+W^-$ production. These processes can also be run in the implemented Kaluza-Klein models. Details of the calculations can be found in Refs. [29–34].

ProcId	Process	Bsm
610	$p\overset{(-)}{p} \to W^-\gamma j \to \ell^-\bar{\nu}_\ell \gamma j$	anomalous couplings
620	$p\overset{(-)}{p} \to W^+\gamma j \to \ell^+\nu_\ell \gamma j$	
630	$p\overset{(-)}{p} \to W^-Zj \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^-\ell_2^+ j$	
640	$p\overset{(-)}{p} \to W^+Zj \to \ell_1^+\nu_{\ell_1}\ell_2^-\ell_2^+ j$	

Table 7: *Process IDs for $W\gamma j$ and WZj production at NLO QCD.*

ProcId	Process	Bsm
4100	$p\overset{(-)}{p} \to H\,jj$	MSSM, general 2HDM
4101	$p\overset{(-)}{p} \to H\,jj \to \gamma\gamma\,jj$	MSSM
4102	$p\overset{(-)}{p} \to H\,jj \to \mu^+\mu^-\,jj$	
4103	$p\overset{(-)}{p} \to H\,jj \to \tau^+\tau^-\,jj$	
4104	$p\overset{(-)}{p} \to H\,jj \to b\bar{b}\,jj$	
4105	$p\overset{(-)}{p} \to H\,jj \to W^+W^-\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,jj$	
4106	$p\overset{(-)}{p} \to H\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\,jj$	
4107	$p\overset{(-)}{p} \to H\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\,jj$	

Table 8: *Process IDs for LO Higgs boson plus 2 jet production via gluon fusion.*

3.7 Double vector boson production in association with a hadronic jet

$W\gamma$ and WZ production in association with a hard hadronic jet are available in Vbfnlo at NLO QCD accuracy under the process IDs of Table 7. All off-shell and finite width effects in the fixed width scheme are included. The processes can be run with anomalous WWZ and $WW\gamma$ couplings. Details can be found in Refs. [35–38].

3.8 Higgs boson production in gluon fusion with two jets

$\mathcal{CP}$-even and $\mathcal{CP}$-odd Higgs boson production in gluon fusion, associated with two additional jets, is a process that first appears at the 1-loop level which, therefore, is counted as leading order in the strong coupling. This process is simulated with the full mass dependence of the top- and bottom-quark running in the loop in the Standard Model, in the (complex) MSSM and in a generic two-Higgs-doublet model. The relevant process IDs are given in Table 8. Details of the calculations can be found in Refs. [39–44].

4 Input files and parameters

VBFNLO is steered through the following input files:

- `vbfnlo.dat`: General parameters for a run.
- `cuts.dat`: Values for kinematic cuts.
- `ggflo.dat`: Additional parameters for the `ggflo` program.
- `susy.dat`: Parameters describing the MSSM scenario.
- `anom_HVV.dat`: Parameters for anomalous Higgs boson couplings.
- `anomV.dat`: Parameters for anomalous gauge boson couplings.
- `kk_input.dat`: Settings for the Warped Higgsless and Three-Site Higgsless Models.
- `kk_coupl_inp.dat`: Numerical values if externally calculated Kaluza-Klein couplings and masses should be used.
- `histograms.dat`: Histogram ranges.
- `random.dat`: Seed for the random number generator.

The following subsections give a detailed description of all available parameters.

4.1 `vbfnlo.dat`

`vbfnlo.dat` is the main input file for VBFNLO.

4.1.1 `vbfnlo.dat` – general parameters

- `PROCESS`: Process ID as described in Sec. 3. Default is 100: Higgs boson production via VBF.
- `LOPROCESS_PLUS_JET`: If set to `true`, the leading order process with one additional jet is generated, i.e. only the real radiation contribution is generated. This option is available for all but gluon fusion processes. Default is `false`.
- `LEPTONS`: Choice of the final state leptons (decay products of W and Z bosons) according to the MC particle numbering scheme [45]:

$$\begin{aligned} 11 &: e^- \\ 12 &: \nu_e \\ 13 &: \mu^- \\ 14 &: \nu_\mu \\ 15 &: \tau^- \\ 16 &: \nu_\tau \end{aligned}$$

  If the selected configuration is not available, the appropriate first-generation leptons (electrons and electron neutrinos) are used as default values.

- `LO_ITERATIONS`: Sets the number of iterations for the integration of LO cross sections. Usually more than one iteration is used in order to adapt the integration grid and thus improve the efficiency of the MC integration algorithm[11]. For an adapted grid file (see `LO_GRID`) this parameter can be set to 1. Default is 4.

- `NLO_ITERATIONS`: Analogous to `LO_ITERATIONS`, but for the real emission part of an NLO calculation. Since the corresponding phase-space is different from the LO configuration, a second independent MC integration has to be performed. Default is 4.

- `LO_POINTS`: Determines the number of phase-space points that are generated in each iteration. In the last iteration there are 2^N points, where $N =$ `LO_POINTS`. In each previous iteration, the number of points is half the value of the following one. Example: For 4 iterations (`LO_ITERATIONS = 4`) and `LO_POINTS = 20`, there are 2^{17} generated points in the first, 2^{18} in the second , 2^{19} in the third and $2^{20} \approx 10^6$ in the last iteration[12]. Default is $N = 20$.

- `NLO_POINTS`: Similar to `LO_POINTS`, but for the real emission part of an NLO calculation. Default is 20.

- `LO_GRID`: Sets the name of the grid files that are generated at the end of each iteration. Choosing `name` as the input parameter, in each iteration X a grid file `name.out.X` will be produced. If a grid file `name` is already present in the working directory, the program reads in this file when executed. Note that optimised grids for all processes (using standard cuts) are provided on the VBFNLO webpage.

- `NLO_GRID`: Similar to `LO_GRID`, but for the real emission part of an NLO calculation.

- `PHTN_GRID`: Similar to `NLO_GRID`, but for the real photon emission part of an NLO electroweak calculation.

- `NLO_SWITCH`: Switch for the NLO part of a process, if available. If set to `true`, cross sections and histograms are calculated to NLO QCD accuracy. Default is set to `false`.

- `EWCOR_SWITCH`: Switch for the electroweak corrections (note that this is only available for VBF Higgs boson production). If set to `true`, cross sections and histograms are calculated to NLO electroweak accuracy. This option can only be used if LoopTools was enabled at compilation. Default is set to `false`.

- `ECM`: The center-of-mass energy, $\sqrt{s}$, of the collider, measured in GeV. Default is 14000 GeV.

- `BEAM1, BEAM2`: Define the type of particle of each beam. Possible options are $+1$ for proton beams and -1 for anti-proton beams. Default is proton-proton collisions, $(+1, +1)$.

- `ID_MUF`: Choice of the factorization scale. See Table 9 for a list of available options. Default is 0.

[11] For all NLO calculations the virtual contributions are calculated using the already optimized leading order grid.

[12] The virtual contributions are calculated for 2^N points only.

ID_MUF	Factorization Scale	Process class
0	user defined constant scale set by `MUF_USER`	`all`
1	momentum transfer of exchanged W/Z boson	`vbf` (except `Hjjj`)
2	$\min(p_{\mathrm{T}}(j_i))$	`vbf`
3	invariant mass of VV system	`diboson`
4	invariant mass of VVV system	`triboson`
5	$\sqrt{p_{\mathrm{T}}(j_1) \times p_{\mathrm{T}}(j_2)}$	`ggf`
6	constant scale = Higgs boson mass	`all`
7	Minimum transverse energy of bosons	`diboson, triboson`

Table 9: *Factorization scale options.*

ID_MUR	Renormalization Scale	Process class
0	user defined constant scale set by `MUR_USER`	`all`
1	momentum transfer of exchanged W/Z boson	`vbf` (except `Hjjj`)
2	$\min(p_{\mathrm{T}}(j_i))$	`vbf`
3	invariant mass of VV system	`diboson`
4	invariant mass of VVV system	`triboson`
5	$\alpha_s^4 = \alpha_s(p_{\mathrm{T}}(j_1)) \times \alpha_s(p_{\mathrm{T}}(j_2)) \times \alpha_s^2(m_H)$	`ggf`
6	constant scale = Higgs boson mass	`all`
7	Minimum transverse energy of bosons	`diboson, triboson`

Table 10: *Renormalization scale options.*

- `ID_MUR`: Choice of the renormalization scale. See Table 10 for a list of available options. Default is 0.
- `MUF_USER`: If `ID_MUF` is set to 0, this parameter sets the user defined constant factorization scale measured in GeV. Default is 100 GeV.
- `MUR_USER`: If `ID_MUR` is set to 0, this parameter sets the user defined constant renormalization scale measured in GeV. Default is 100 GeV.
- `XIF`: Factor by which the factorization scale is multiplied. May be used to analyze the scale dependence of differential cross sections. Default is 1.
- `XIR`: Factor by which the renormalization scale is multiplied. May be used to analyze the scale dependence of differential cross sections. Default is 1.

Note that alternative scale choices can be implemented in the file `utilities/scales.F`.

4.1.2 `vbfnlo.dat` – physics parameters

- `HMASS`: Standard Model Higgs boson mass in GeV. Default value is 120 GeV.
- `HTYPE`: Type of Higgs boson produced:
  - `HTYPE = 0` : SM Higgs boson, with mass `HMASS`
  - `HTYPE = 1` : Light $\mathcal{CP}$-even MSSM Higgs boson
  - `HTYPE = 2` : Heavy $\mathcal{CP}$-even MSSM Higgs boson
  - `HTYPE = 3` : $\mathcal{CP}$-odd MSSM Higgs boson (Note: this is not produced at LO unless we are working in the MSSM with complex parameters and include Higgs-propagator effects at LO.)

  Note that for `HTYPE = 1-3`, the input `HMASS` is not used. Default value is 0 (SM Higgs boson).
- `MODEL`: This flag determines whether we are working in the SM (1) or MSSM (2). Default is SM (1). Note that if `HTYPE = 1-3` is chosen with `MODEL = 1`, the code will run in the Standard Model, but with a Higgs boson mass equal to that given by the specified MSSM parameters.
- `TOPMASS`: Top-quark mass in GeV. Default value is 172.4 GeV. If a SLHA file is being used, the SLHA value will be taken rather than the input `TOPMASS`.
- `BOTTOMMASS`: Bottom-quark pole mass in GeV, used in the calculation of the Higgs boson width and branching ratios. In the gluon fusion process, $m_b(M_H)$ is used (calculated from the input pole mass). Default value is 4.855 GeV, which corresponds to $m_b^{\overline{MS}}(m_b) = 4.204$ GeV. The explicit formula used is given on the VBFNLO webpage. If a SLHA file is being used, the SLHA value will be taken rather than the input `BOTTOMMASS`.
- `CHARMMASS`: Charm-quark pole mass in GeV used in the calculation of the Higgs boson width and branching ratios. Default value is 1.65 GeV, corresponding to $m_c^{\overline{MS}}(m_c) = 1.273$ GeV. If a SLHA file is being used, the SLHA value will be taken rather than the input `CHARMMASS`.
- `EWSCHEME`: Sets the scheme for the calculation of electroweak parameters. A summary of the six available options is given in Table 11. The implementation of `EWSCHEME` has been simplified in the current version of VBFNLO: full details of all changes and their effects, together with the explicit formulae used, are available on the VBFNLO webpage. Note that if `EWSCHEME = 4` is chosen, all variables in Table 11 are taken as inputs. As the parameters are not independent, this can lead to problems if the input values are not consistent. In this scheme, all photon couplings are set according to the input variable `INVALFA` and all other couplings are set according to `FERMI_CONST`. Note also that the choice of `EWSCHEME` can have a large effect on the relative size of the electroweak corrections, as the charge renormalization depends on the way in which the electromagnetic coupling in the LO cross section is parametrized. Default value is 3.
- `FERMI_CONST`: Fermi constant, used as input for the calculation of electroweak parameters in `EWSCHEME` = 2 and 3. Default value is 1.16637×10^{-5} GeV^{-2}. If a SLHA file is being used, the SLHA value will be taken rather than the input `FERMI_CONST`.

EWSCHEME	Parameter	Default Value	Input/Calculated
1	FERMI_CONST	1.16637×10^{-5} GeV^{-2}	Input
	INVALFA	128.944341122	Input
	SIN2W	0.230990	Calculated
	WMASS	79.9654 GeV	Calculated
	ZMASS	91.1876 GeV	Input
2	FERMI_CONST	1.16637×10^{-5} GeV^{-2}	Input
	INVALFA	132.340643024	Calculated
	SIN2W	0.222646	Input
	WMASS	80.3980 GeV	Calculated
	ZMASS	91.1876 GeV	Input
3	FERMI_CONST	1.16637×10^{-5} GeV^{-2}	Input
	INVALFA	132.340705199	Calculated
	SIN2W	0.222646	Calculated
	WMASS	80.3980 GeV	Input
	ZMASS	91.1876 GeV	Input
4	FERMI_CONST	1.16637×10^{-5} GeV^{-2}	Input
	INVALFA	137.035999679	Input
	SIN2W	0.222646	Input
	WMASS	80.3980 GeV	Input
	ZMASS	91.1876 GeV	Input
5	INVALFA(ZMASS)	128.944341122	Input
	SIN2W	0.222646	Calculated
	WMASS	80.3980 GeV	Input
	ZMASS	91.1876 GeV	Input
6	INVALFA(0)	137.035999679	Input
	SIN2W	0.222646	Calculated
	WMASS	80.398 GeV	Input
	ZMASS	91.1876 GeV	Input

Table 11: *Electroweak input parameter schemes.*

- `INVALFA`: One over the fine structure constant, used as input for `EWSCHEME` = 1, 4, 5 and 6. Within the other schemes this parameter is calculated. The default value depends on the choice of `EWSCHEME`, as given in Table 11. If `EWSCHEME = 5` is chosen, the value of α should be $\alpha(M_Z)$, whereas if `EWSCHEME = 6` is chosen, the value of α should be $\alpha(0)$. In order to ensure backwards compatibility with previous versions of VBFNLO, as an alternative `ALFA`, the fine structure constant, can be used as an input in `vbfnlo.dat`, which is read and used only if `INVALFA` is not present. If a SLHA file is being used, the SLHA value will be taken rather than the input `INVALFA` or `ALFA`.

- `DEL_ALFA`: Value of $\Delta\alpha$, where

$$\alpha(M_Z) = \frac{\alpha(0)}{1 - \Delta\alpha} \tag{1}$$

  This is used as input for `EWSCHEME` = 6. Default value is 0.059047686. Note that this is only used for the electroweak corrections during the calculation of the charge renormalization constant.

- `SIN2W`: Sinus squared of the weak mixing angle. Used as input for `EWSCHEME` = 2 and 4. Within the other schemes this parameter is calculated. Default input value is 0.222646. If a SLHA file is being used, the SLHA value will be taken rather than the input `SIN2W`.

- `WMASS`: W boson mass in GeV. This parameter is calculated in `EWSCHEME = 1` and 2. Default input value is 80.398 GeV. If a SLHA file is being used, the SLHA value will be taken rather than the input `WMASS`.

- `ZMASS`: Z boson mass in GeV. Default value is 91.1876 GeV. If a SLHA file is being used, the SLHA value will be taken rather than the input `ZMASS`.

- `ANOM_CPL`: If set to `true`, anomalous Higgs boson or gauge boson couplings are used if available for the selected process. These are available for the

  - Hjj and W^+W^-jj production processes in VBF
  - triple vector boson production processes WWZ, $W^\pm W^\mp W^\pm$ and $ZZW^\pm$
  - $W\gamma j$ and WZj production processes

  Default is set to `false`.

- `KK_MOD`: Option for the Warped Higgsless Model and Three-Site Higgsless Model. This is available for all $VVjj$ production modes in VBF and for the triboson processes $W^\pm W^+W^-$, W^+W^-Z and $W^\pm ZZ$. Default is set to `false`. Note that this needs to be enabled at compilation, using the `configure` option `--enable-kk`.

- `EW_APPROX`: Option controlling the electroweak corrections in Hjj production via VBF.

  - `EW_APPROX` = 0 : No approximations involved. This option is not available when working in the MSSM.
  - `EW_APPROX` = 1 : Only top/bottom (and stop/sbottom in the MSSM) loops are calculated.

- `EW_APPROX` = 2 : All fermion (and sfermion in the MSSM) loops are calculated.
- `EW_APPROX` = 3 : MSSM option – all SM-type (i.e. fermions, gauge and Higgs bosons) and sfermion loops are calculated.
- `EW_APPROX` = 4 : MSSM option – all MSSM corrections to the Higgs boson vertex are calculated, together with all SM-type and sfermion corrections elsewhere.
- `EW_APPROX` = 5 : MSSM option – all MSSM corrections to the Higgs boson vertex, the quark vertex and the vector boson self energies are calculated, together with all SM-type boxes and pentagons (i.e. only chargino and neutralino box and pentagon diagrams are neglected).

When working in the SM, `EW_APPROX` options 3-5 are equivalent to `EW_APPROX` = 0. Default is 5: full corrections in the SM, and the most complete available corrections in the MSSM.

4.1.3 `vbfnlo.dat` – parameters for event output

VBFNLO generates parton level events according to the most recent Les Houches Accord (LHA) format [46] and in the HEPMC format [47] for processes at leading order.

- `LHA_SWITCH`: Switch on or off output of LHA event files. Default is set to `false`. Note that LHA event file output is not yet available for diboson plus jet processes.
- `LHA_FILE`: Name of output LHA event file. Default is "`event.lhe`".
- `HEPMC_SWITCH`: Switch on or off output of HEPMC event files. Default is set to `false`. Note that HEPMC event file output is not yet available for diboson plus jet processes.
- `HEPMC_FILE`: Name of output HEPMC event file. Default is "`event.hepmc`".
- `UNWEIGHTING_SWITCH`: Option for event weights. If set to `true`, events are unweighted (event weight = +1). If set to `false`, events are weighted. Default is set to `false`.
- `PRENEVUNW`: The number of events used in the last iteration in order to calculate/estimate the premaximal weight that is needed in the first step of the unweighting procedure. Default is 1000. After all events are unweighted, the maximal weight is again calculated and a reweighting procedure is applied.
- `TAUMASS`: Option to include the mass of τ leptons in the event files. This option is only available for the `vbf` processes. Default is set to `false`.

4.1.4 `vbfnlo.dat` – PDF parameters

VBFNLO can use either built-in parton distribution functions (PDFs) or the LHAPDF library.

- `PDF_SWITCH`: Option to choose which PDFs are used. If set to `0`, built-in PDFs CTEQ6L1 [11] for LO and CT10 [12] for NLO calculations are used. If set to `2`, built-in PDFs MRST2004qed [13] are used at LO and NLO (if this option is chosen,

photon-induced processes can be included when calculating the electroweak corrections to *Hjj* production via VBF) and if set to `3` the built-in PDFs MSTW2008 [14] are used. If set to `1`, an interface to LHAPDF is provided. Default is 0.

The following options are used if LHAPDF has been selected (i.e. `PDF_SWITCH = 1`).

- `LO_PDFNAME`: Name of the LO PDF set, see `PDFsets.index` or Ref. [2]. Default is "`cteq6ll.LHpdf`" (CTEQ6L1).
- `NLO_PDFNAME`: Name of the NLO PDF set, see `PDFsets.index` or Ref. [2]. Default is "`CT10.LHgrid`" (CT10).
- `LO_PDFMEMBER`: Member PDF of the LO PDF set. Default is 0.
- `NLO_PDFMEMBER`: Member PDF of the NLO PDF set. Default is 0.

For compatibility with earlier versions of VBFNLO, the following two variables are also supported for setting the PDF sets when using LHAPDF. If both are present, `LO_PDFNAME` and `NLO_PDFNAME` take precedence over `LO_PDFSET` and `NLO_PDFSET`, respectively.

- `LO_PDFSET`: LHAGLUE number for the LO PDF set, see `PDFsets.index` or Ref. [2].
- `NLO_PDFSET`: LHAGLUE number for the NLO PDF set, see `PDFsets.index` or Ref. [2].

4.1.5 `vbfnlo.dat` – parameters for histograms

VBFNLO provides output for histograms in the following formats: TOPDRAWER[13], ROOT and GNUPLOT[14], as well as raw data tables.

- `ROOT`: Enable output of histograms in ROOT format. Default is set to `false`. Additionally, custom ROOT histograms can be defined by the user in `utilities/rootuserhisto.cpp`, which are filled with the weighted events from Monte Carlo integration. This option needs to be enabled when building VBFNLO using the option `--with-root`.
- `TOP`: Enable output of histograms in TOPDRAWER format. Default is set to `false`.
- `GNU`: Enable output of histograms in GNUPLOT format. Default is set to `true`.
- `DATA`: Enable output of raw data in a directory hierarchy. Default is set to `true`.
- `REPLACE`: Switch to overwrite existing histogram output files. Default is set to `true`.
- `ROOTFILE`: Name of the ROOT output file. Default is `histograms`.
- `TOPFILE`: Name of the TOPDRAWER output file. Default is `histograms`.
- `GNUFILE`: Name of the GNUPLOT output file. Default is `histograms`.
- `DATAFILE`: Name of the data output directory. Default is `histograms`.

[13] `http://www.pa.msu.edu/reference/topdrawer-docs/`
[14] `http://www.gnuplot.info/`

4.2 `cuts.dat` – parameters for kinematic cuts

The following general set of cuts has been implemented in VBFNLO. Alternative cuts can be added in the file `utilities/cuts.F`.

Jet-specific cuts:

- `RJJ_MIN`: Minimum separation of two identified jets, $\Delta R_{jj} = \sqrt{\Delta y_{jj}^2 + \Delta\phi_{jj}^2}$, used by the generalised $k_\perp$ jet finding algorithm [48] that combines all partons. Default is 0.8.
- `Y_P_MAX`: Maximum allowed pseudorapidity for observation of final state partons (detector edge). Default is 5.0.
- `PGENKTJET`: Exponent of the generalised $k_\perp$ algorithm. This yields the $k_\perp$ algorithm when setting the variable to 1, the Cambridge/Aachen algorithm [49] for 0 and the anti-$k_\perp$ algorithm [50] when setting it to -1. Default value of the floating-point number is 1.0.
- `PT_JET_MIN`: List of minimum transverse momenta for identified jets in descending order. The later values can be omitted if they are the same as previous values. Default is 20 GeV.
- `Y_JET_MAX`: Maximum allowed rapidity for identified jets. Default is 4.5.

Lepton specific cuts:

- `Y_L_MAX`: Maximum pseudorapidity for charged leptons. Default is 2.5.
- `PT_L_MIN`: Minimum transverse momentum for charged leptons. Default is 10 GeV.
- `MLL_MIN`: Minimum invariant mass for any combination of oppositely charged leptons. Default is 15 GeV.
- `MLL_MAX`: Maximum invariant mass for any combination of oppositely charged leptons. Default is 10^{20} GeV.
- `RLL_MIN`: Minimum separation of charged lepton pairs, $\Delta R_{\ell\ell}$. Default is 0.4.
- `RLL_MAX`: Maximum separation of charged lepton pairs, $\Delta R_{\ell\ell}$. Default is 50.

Photon specific cuts:

- `Y_G_MAX`: Maximum pseudorapidity for photons. Default is 1.5.
- `PT_G_MIN`: Minimum transverse momentum for photons. Default is 20 GeV.
- `RGG_MIN`: Minimum separation of photon pairs, $\Delta R_{\gamma\gamma}$. Default is 0.6.
- `RGG_MAX`: Maximum separation of photon pairs, $\Delta R_{\gamma\gamma}$. Default is 50.
- `PHISOLCUT`: Photon isolation cut δ_0 as defined in Ref. [18]. Default is 0.7.

- `EFISOLCUT`: Efficiency ϵ of photon isolation cut. Default is 1. The photon isolation cut is then described by:

$$\sum_i E_{T_i}\theta(\delta - R_{i\gamma}) \leq \epsilon\, p_{T_\gamma} \frac{1-\cos\delta}{1-\cos\delta_0} \text{ for all } \delta < \delta_0 \tag{2}$$

  where i is a parton with transverse energy E_{T_i} and a separation $R_{i\gamma}$ with a photon of transverse momentum $p_{T\gamma}$.

Additional cuts:

- `RJL_MIN`: Minimum separation of an identified jet and a charged lepton, $\Delta R_{j\ell}$. Default is 0.6.
- `RJG_MIN`: Minimum separation of an identified jet and a photon, $\Delta R_{j\gamma}$. Default is 0.6.
- `RLG_MIN`: Minimum separation of a charged lepton and a photon, $\Delta R_{\ell\gamma}$. Default is 0.6.

Jet veto:

- `JVETO`: If set to `true`, a jet veto is applied. For `vbf` and `ggf` processes it is applied to central jets beyond the two tagging jets. For all other processes the jet veto is applied to additional jets beyond the leading-order number, ordered by decreasing transverse momentum. Default is `false`.
- `YMAX_VETO`: Maximum pseudorapidity of the additional jet. Default is 4.5.
- `PTMIN_VETO`: Minimum transverse momentum of the additional jet. Default is 50 GeV.
- `DELY_JVETO`: Minimum rapidity separation of a central jet from the two tagging jets for `vbf` and `ggf` processes. Default is 0.

VBF specific cuts[15]:

- `ETAJJ_MIN`: Minimum required pseudorapidity gap, $\Delta\eta_{jj}$, between two tagging jets (the two leading jets in a p_{T} ordering). Default is 0.
- `YSIGN`: If set to `true`, the two tagging jets are required to be found in opposite detector hemispheres. Default is `false`.
- `LRAPIDGAP`: If set to `true` all charged leptons are required to lie between the two tagging jets in rapidity. Default is `false`.
- `DELY_JL`: Minimum rapidity distance of the charged leptons from the tagging jets, if `LRAPIDGAP` is set to `true`. Default is 0.
- `GRAPIDGAP`: If set to `true` all photons are required to lie between the two tagging jets in rapidity. Default is `false`.
- `DELY_JG`: Minimum rapidity distance of photons from tagging jets, if `GRAPIDGAP` is set to `true`. Default is 0.
- `MDIJ_MIN`: Minimum dijet invariant mass of two tagging jets. Default is 600 GeV.
- `MDIJ_MAX`: Maximum dijet invariant mass of two tagging jets. Default is 10^{20} GeV.

[15] These apply only to `vbf` and `ggf` processes.

4.3 `ggflo.dat` – general parameters for gluon fusion processes

In VBFNLO the double real-emission corrections to $gg \to \phi$, which lead to $\phi + 2$ jet events at order α_s^4, are included [44]. Here, ϕ can be set to be a Standard Model Higgs boson or any of the three neutral MSSM Higgs bosons (including mixing between h, H and A in the real or complex MSSM) by using the variables `HTYPE` and `MODEL` in `vbfnlo.dat`, or a mixture of scalar and pseudoscalar Higgs bosons as in a generic two-Higgs-doublet model (2HDM) of type II. Contributions contain top- and bottom-quark triangles, boxes and pentagon diagrams, i.e. the full mass dependence of the loop induced production. Interference effects between loops with bottom- and top-quarks as well as between $\mathcal{CP}$-even and $\mathcal{CP}$-odd couplings of the heavy quarks are fully taken into account. An option to use the large top mass approximation, which works well for intermediate Higgs boson masses (provided that the transverse momenta of the final state partons are smaller than the top-quark mass), is also implemented.

Note that these gluon fusion processes processes require the use of the `ggflo` executable rather than the `vbfnlo` one.

If Higgs boson plus two jet production via gluon fusion is selected in `vbfnlo.dat`, i.e. `PROCESS = 4100-4107.`, the following additional parameters can be adjusted in the `ggflo.dat` file:

- `Q_LOOP`: Input that sets how the Higgs boson coupling is determined.
  - `Q_LOOP = 0`: Effective theory in the large top-quark mass limit ($m_t \to \infty$).
  - `Q_LOOP = 1`: Coupling derived from top-quark loop.
  - `Q_LOOP = 2`: Coupling derived from bottom-quark loop.
  - `Q_LOOP = 3`: Coupling derived from both top- and bottom-quark loops.

  Default is set to `3`.

- `SUBPRQQ`: Switch that determines whether the subprocesses with quark-quark initial state are included. Default is set to `true`.

- `SUBPRQG`: Switch that determines whether the subprocesses with quark-gluon initial state are included. Default is set to `true`.

- `SUBPRGG`: Switch that determines whether the subprocesses with gluon-gluon initial state are included. Default is set to `true`.

- `HIGGS_MIX`: Switch for Higgs mixing. If set to 0, there is no Higgs mixing, which is the default. If set to 1, the mixing is determined via the user-input variables:
  - `CP_EVEN_MOD`: Changes the strength of the $\mathcal{CP}$-even coupling. Default is set to `1.0`.
  - `CP_ODD_MOD`: Changes the strength of the $\mathcal{CP}$-odd coupling. Default is set to `1.0`.

  using the Lagrangian

$$\mathcal{L}_{\text{Yukawa}} = \overline{q}\,(C_{\text{even}}\, y_q + \mathrm{i}\, C_{\text{odd}}\, \gamma_5\, \tilde{y}_q)\, q\, \Phi\,. \tag{3}$$

with C_{even} = `CP_EVEN_MOD` and C_{odd} = `CP_ODD_MOD` and

$$\begin{aligned} y_b &= \tilde{y_b} = \frac{1}{v} m_b \tan\beta \\ y_t &= \tilde{y_t} = \frac{1}{v} m_t \cot\beta \end{aligned} \tag{4}$$

When working in the Standard Model, $\tan\beta$ is set to 1. Note that this option is not yet available when decays of the Higgs boson are included. The option `HIGGS_MIX = 2` is only used when working in the MSSM, and incorporates mixing between all three neutral Higgs bosons according to the Z propagator matrix, as follows

$$h_i = Z_{ih}\, h_{\text{MSSM}} + Z_{iH}\, H_{\text{MSSM}} + Z_{iA}\, A_{\text{MSSM}} \tag{5}$$

where i = `HTYPE`.

4.4 `susy.dat` – parameters in the MSSM

The file `susy.dat` is used to specify the supersymmetric parameters when working in the MSSM. This file is used either if `MODEL = 2` in `vbfnlo.dat`, or if `HTYPE = 1-3` in `vbfnlo.dat`. As described earlier, if `MODEL = 2` the code will run in the MSSM, which means that the Higgs boson masses, widths and couplings will all be set to the MSSM values. If `MODEL = 1` but `HTYPE = 1-3`, the code will run in the Standard Model, and only the Higgs boson mass will be affected. Consequently, this file affects processes 101-107 (Higgs boson plus 2 jet production via VBF), processes 110-117 (Higgs boson plus 3 jet production via VBF) and processes 2100-2107 (production of a Higgs boson in association with a photon and 2 jets via VBF). In particular, the electroweak corrections to Higgs boson production via VBF are affected by the inputs of `susy.dat`. As stated in Section 3.6, the Higgs boson contributions to the production of three massive gauge bosons will be affected by `susy.dat` by fixing the Higgs boson mass and couplings, but the code will only provide a reasonable approximation to the full MSSM result in the decoupling region (i.e. when the Higgs is SM-like).

- `FEYNH_SWITCH`: Determines whether FeynHiggs is used to calculate the MSSM Higgs boson sector. Default is `false`. When working in the MSSM, especially when including electroweak corrections, it is recommended that FeynHiggs is used, as the Higgs boson mixing and the renormalization scheme used in Vbfnlo are consistent with those used by FeynHiggs. If a SLHA file is used instead of FeynHiggs, inconsistencies may occur in the calculation of parameters.

- `SLHA_SWITCH`: Determines whether the MSSM parameters are taken from a SLHA file. Default is `true`. If set to `true` the values in the SLHA input file are used instead of internal settings or calculations[16].

- `SLHA_FILE`: Name of the SLHA input file. (An example file – `sps1a.slha` – is provided, which is the default.)

- `BENCH`: Various benchmark scenarios are pre-programmed in the code, as an alternative to using a SLHA file. These are:

[16] Note that a SLHA file can also be used as the input for FeynHiggs by setting both `FEYNH_SWITCH` and `SLHA_SWITCH` to `true`.

  - `0`: User-input scenario (see below for further inputs)
  - `1`: $M_h^{\max}$ scenario [51]
  - `2`: No-mixing scenario [51]
  - `3`: Gluophobic scenario [51]
  - `4`: Small $\alpha_{\rm eff}$ scenario [51]
  - `5`: CPX scenario [52]
  - `10`: SPS1a[17] [53]
  - `11`: SPS1b
  - `12-19`: SPS 2 – 9

  Default is `1` – the $M_h^{\max}$ scenario.

- `PROPLEVEL`: Level at which Higgs propagator corrections are included:
  - `0`: Effective Higgs-mixing angle used.
  - `1`: Propagator factors included at leading order.
  - `2`: Propagator factors included at leading order and loop level.
  - `3`: Propagator factors included as an additional loop correction.

  Default is `1`. These options are discussed in more detail on the VBFNLO webpage, as well as in [21].

- `DELMB_SWITCH`: Switch determining whether or not to correct the bottom-quark Yukawa coupling. Default is `false`.

If a SLHA file is not being used, and `BENCH = 0-5`, the following inputs are also needed.

- `TANB`: Value of $\tan\beta$. Default value is 10. Note that for the SPS benchmarks (`BENCH = 10-19`), this value of $\tan\beta$ is not used.

- `MASSA0`: Mass of $\mathcal{CP}$-odd Higgs boson M_A. This should be used when working in the MSSM with real parameters. Default value is 400 GeV. Note that for the SPS benchmarks (`BENCH = 10-19`), this value of M_A is not used.

- `MASSHP`: Mass of charged Higgs boson $M_{H^\pm}$. This should be used when working in the MSSM with complex parameters. Default value is -1 GeV.

Note that it is standard to use as input the mass of the $\mathcal{CP}$-odd Higgs boson, M_A, when working in the MSSM with real parameters and the mass of the charged Higgs boson, $M_{H^\pm}$, when working in the MSSM with complex parameters[18]. The mass that is not being used as input should be set to -1 GeV.

If desired, the SUSY breaking parameters that define the scenario can be input by the user, by selecting `BENCH = 0`. Default values are those for SPS1a. These parameters are (in the notation used by FEYNHIGGS):

[17] The SPS points are defined with low-energy parameters, as given at `http://www.ippp.dur.ac.uk/~georg/sps/`).

[18] This is because, when working with complex parameters, there is mixing between all three neutral Higgs bosons, and thus all neutral Higgs boson masses receive loop corrections.

- `M3SQ` etc.: The soft SUSY breaking parameters for the sfermion section.
- `AT` etc.: Third generation trilinear coupling parameters.
- `MUE`: Higgs boson mixing parameter.
- `M_1` etc.: Gaugino mass parameters.

4.5 Parameters for anomalous couplings

VBFNLO supports anomalous HVV couplings, where $V = W, Z, \gamma$, in both the production and the decay of a Higgs boson in VBF-type reactions, i.e. for process IDs 100-107. The anomalous HVV couplings can be specified in the `anom_HVV.dat` input file.

Anomalous triple and quartic gauge boson couplings are available for the VBF process $p\overset{(-)}{p} \to W^+W^-jj(j)$ [54], the triple vector boson production processes WWZ, $ZZW^\pm$ and $W^+W^-W^\pm$ (process IDs 400-440) [55] and for $W\gamma j$ and WZj production [35,36]. The respective parameters are set in the input file `anomV.dat`[19]. Note, however, that not all parameters in `anomV.dat` affect all processes.

4.5.1 `anom_HVV.dat` – anomalous HVV couplings

The file `anom_HVV.dat` controls the anomalous Higgs boson coupling parameters. It is used if the input `ANOM_CPL` in `vbfnlo.dat` is set to `true`. Among the anomalous coupling input parameters, the user can choose between three different parameterizations.

The anomalous HVV couplings can be described by the following effective Lagrangian involving the dimension five operators

$$\begin{aligned}\mathcal{L} \;=\; & \frac{g_{5e}^{HZZ}}{2\Lambda_5} H Z_{\mu\nu} Z^{\mu\nu} + \frac{g_{5o}^{HZZ}}{2\Lambda_5} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \frac{g_{5e}^{HWW}}{\Lambda_5} H W^+_{\mu\nu} W^{\mu\nu}_- + \frac{g_{5o}^{HWW}}{\Lambda_5} H \tilde{W}^+_{\mu\nu} W^{\mu\nu}_- + \\ & \frac{g_{5e}^{HZ\gamma}}{\Lambda_5} H Z_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{HZ\gamma}}{\Lambda_5} H \tilde{Z}_{\mu\nu} A^{\mu\nu} + \frac{g_{5e}^{H\gamma\gamma}}{2\Lambda_5} H A_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{H\gamma\gamma}}{2\Lambda_5} H \tilde{A}_{\mu\nu} A^{\mu\nu}\end{aligned} \tag{6}$$

where the subscript e or o refers to the $\mathcal{CP}$-even or $\mathcal{CP}$-odd nature of the individual operators [56].

An alternative approach is to write the effective Lagrangian in terms of the operators $\mathcal{O}_{WW}$, $\mathcal{O}_{BB}$, $\mathcal{O}_W$ and $\mathcal{O}_B$ and their corresponding $\mathcal{CP}$-odd operators according to Refs. [57, 58]:

$$\mathcal{L}_{\text{eff}} \;=\; \frac{f_W}{\Lambda_6^2}\mathcal{O}_W + \frac{f_B}{\Lambda_6^2}\mathcal{O}_B + \frac{f_{WW}}{\Lambda_6^2}\mathcal{O}_{WW} + \frac{f_{BB}}{\Lambda_6^2}\mathcal{O}_{BB} + \text{ CP-odd part} \tag{7}$$

[19] In previous versions of VBFNLO, anomalous gauge boson couplings for WW production via VBF were input via the file `anom_WW.dat`. To ensure backwards compatibility, these old files can still be used (for this process only) by re-naming `anom_WW.dat` to `anomV.dat`.

The explicit form of the operators is[20]

$$\begin{aligned}
\mathcal{O}_W &= (D_\mu\phi^\dagger)\hat{W}^{\mu\nu}(D_\nu\phi) \\
\mathcal{O}_B &= (D_\mu\phi^\dagger)\hat{B}^{\mu\nu}(D_\nu\phi) \\
\mathcal{O}_{WW} &= \phi^\dagger\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\phi \\
\mathcal{O}_{BB} &= \phi^\dagger\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\phi \\
\mathcal{O}_{WWW} &= Tr\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}_\rho{}^\mu\right],
\end{aligned} \tag{8}$$

with

$$\begin{aligned}
\hat{W}_{\mu\nu} &= igT^aW^a_{\mu\nu} \\
\hat{B}_{\mu\nu} &= ig'YB_{\mu\nu},
\end{aligned} \tag{9}$$

where g and g' are the SU(2) and U(1) gauge couplings, T^a are the SU(2) generators and $W_{\mu\nu}$ and $B_{\mu\nu}$ are the field strength tensors. The $\mathcal{CP}$-odd part of the Lagrangian has the same form, although only three parameters (denoted with a tilde) are needed.

The different parameterizations, and the relationships between them, are discussed in more detail on the VBFNLO webpage, where the explicit forms of the HVV couplings are given.

1. A parameterization in terms of couplings in the effective Lagrangian approach given by Eq. 6.

   - `PARAMETR1`: Parameter that switches on the effective Lagrangian parameterization of Eq. (6). The default value is `false`.
   - `LAMBDA5`: Mass scale Λ_5 in units of GeV with 480 GeV chosen as default.
   - `G5E_HWW, G5E_HZZ, G5E_HGG, G5E_HGZ`: Parameters that determine the couplings g_{5e}^{HVV} of the $\mathcal{CP}$-even dimension five operators. Their default values are set to 0.
   - `G5O_HWW, G5O_HZZ, G5O_HGG, G5O_HGZ`: Parameters that determine the couplings g_{5o}^{HVV} of the $\mathcal{CP}$-odd dimension five operators. Their default values are set to 0.

2. The parameterization of the anomalous couplings by the L3 Collaboration as given in Ref. [59]. The parameters are d, d_B, Δg_1^Z and $\Delta\kappa_\gamma$, which are related to the coefficients f_i/Λ^2 of the effective Lagrangian of Eq. 7 in the following manner [60]:

$$\begin{aligned}
d &= -\frac{m_W^2}{\Lambda^2}\, f_{WW}\,, & \tilde{d} &= -\frac{m_W^2}{\Lambda^2}\, f_{\tilde{W}W}\,, \\
d_B &= -\frac{m_W^2}{\Lambda^2}\,\frac{\sin^2\theta_w}{\cos^2\theta_w}\, f_{BB}\,, & \tilde{d}_B &= -\frac{m_W^2}{\Lambda^2}\,\frac{\sin^2\theta_w}{\cos^2\theta_w}\, f_{\tilde{B}B}\,, \\
\Delta\kappa_\gamma &= \kappa_\gamma - 1 = \frac{m_W^2}{2\Lambda^2}\,(f_B + f_W)\,, & \tilde{\kappa}_\gamma &= \frac{m_W^2}{2\Lambda^2}\, f_{\tilde{B}}\,, \\
\Delta g_1^Z &= g_1^Z - 1 = \frac{m_Z^2}{\Lambda^2}\,\frac{f_W}{2}\,.
\end{aligned} \tag{10}$$

[20] Note that $\mathcal{O}_{WWW}$ is used only in the anomalous gauge boson couplings.

- `PARAMETR2`: Parameter that switches on the above mentioned parameterization of Eqs. 10. The default value is `false`.
- `D_EVEN, DB_EVEN, DKGAM_EVEN, DG1Z_EVEN`: Parameters that are the $\mathcal{CP}$-even couplings in this parameterization with default 0.
- `D_ODD, DB_ODD, KGAM_ODD`: Parameters that are the $\mathcal{CP}$-odd couplings in this parameterization with default values equal to 0.
- `HVV1`: Parameter that determines which anomalous HVV couplings are used for the run. For `HVV1` $= 0$, only the $HZ\gamma$ coupling, for `HVV1` $= 1$, only the $H\gamma\gamma$ coupling, for `HVV1` $= 2$, only the HZZ coupling and for `HVV1` $= 3$, only the HWW coupling is used. If `HVV1` is set to 4, all possible anomalous couplings are used. This is also the default value.

3. The parameterization of the anomalous couplings in terms of coefficients f_i/Λ^2 of the effective Lagrangian in Eq. 7.

   - `PARAMETR3`: Parameter that switches on the parameterization stated above. The default value is `false`.
   - `FWW_EVEN, FBB_EVEN, FW_EVEN, FB_EVEN`: Parameters that represent the coefficients of the $\mathcal{CP}$-even operators – i.e. f_i/Λ^2 – with default values equal to 0 GeV^{-2}.
   - `FWW_ODD, FBB_ODD, FB_ODD`: Parameters that are the coefficients of the $\mathcal{CP}$-odd operators – i.e. f_i/Λ^2 – with default values 0 GeV^{-2}.
   - `HVV2`: Parameter that allows the user to choose which anomalous HVV couplings are used. For `HVV2` $= 0$, only the $HZ\gamma$ coupling, for `HVV2` $= 1$, only the $H\gamma\gamma$ coupling, for `HVV2` $= 2$, only the HZZ coupling and for `HVV2` $= 3$, only the HWW coupling is used. If set to 4 all possible anomalous couplings are used. The default value is 4.

Moreover, for all parameterizations, two different form factors can be chosen as described in Refs. [56, 60]. They model effective, momentum dependent HVV vertices, motivated by new physics entering with a large scale Λ at the loop level.

$$F_1 = \frac{\Lambda^2}{q_1^2 - \Lambda^2} \frac{\Lambda^2}{q_2^2 - \Lambda^2}, \tag{11}$$

$$F_2 = -2\,\Lambda^2\, C_0\big(q_1^2, q_2^2, (q_1+q_2)^2, \Lambda^2\big). \tag{12}$$

Here the q_i are the momenta of the vector bosons and C_0 is the scalar one-loop three point function in the notation of Ref. [61].

- `FORMFACTOR`: Parameter that switches on the above form factor. The default value is set to `false`.
- `MASS_SCALE`: Characteristic mass scale, Λ, of new physics in units of GeV. The default value is 200 GeV.
- `FFAC`: Parameter that is used to select one particular form factor out of Eqs. (11) and (12). If `FFAC` $= 1$, the form factor F_1 is used for the parameterization. `FFAC` $= 2$ selects F_2, which is also the default value.

Finally, the following two parameters can be used to rescale the SM HVV couplings.

- `TREEFAC`: Parameter that multiplies the HVV tensor present in the SM Lagrangian. Default is 1.
- `LOOPFAC`: Parameter that multiplies the $HZ\gamma$ and $H\gamma\gamma$ vertices induced by SM loops. The default is chosen to be 1.

4.5.2 `anomV.dat` – anomalous triple and quartic gauge boson couplings

The anomalous triple and quartic gauge boson couplings can be set in the file `anomV.dat`. They are parameterized using an effective Lagrangian, as described in Refs. [58, 62, 63]

$$\mathcal{L}_{\text{eff}} = \frac{f_i}{\Lambda^n}\mathcal{O}_i^{n+4}, \tag{13}$$

where $n+4$ signifies the dimension of the operator $\mathcal{O}_i$. VBFNLO defines the anomalous gauge couplings in terms of the coefficients f_i/Λ^n of the dimension 6 and (for triboson production) dimension 8 operators (a full list of implemented operators for triboson production can be found in Ref. [55]).

A common alternative parameterization (which VBFNLO can also use as input) of the trilinear couplings $WW\gamma$ and WWZ uses the following effective Lagrangians:

$$\mathcal{L}_{WW\gamma} = -ie\left[W^\dagger_{\mu\nu}W^\mu A^\nu - W^\dagger_\mu A_\nu W^{\mu\nu} + \kappa_\gamma W^\dagger_\mu W_\nu F^{\mu\nu} + \frac{\lambda_\gamma}{m_W^2}W^\dagger_{\sigma\mu}W^\mu_\nu F^{\nu\sigma}\right] \tag{14}$$

for the anomalous $WW\gamma$ vertex, and

$$\mathcal{L}_{WWZ} = -ie\cot\theta_w\left[g_1^Z\left(W^\dagger_{\mu\nu}W^\mu Z^\nu - W^\dagger_\mu Z_\nu W^{\mu\nu}\right) + \kappa_Z W^\dagger_\mu W_\nu Z^{\mu\nu} + \frac{\lambda_Z}{m_W^2}W^\dagger_{\sigma\mu}W^\mu_\nu Z^{\nu\sigma}\right] \tag{15}$$

for the anomalous WWZ vertex. It is customary to rephrase the electroweak modifications around the SM Lagrangian in terms of new quantities,

$$(\Delta g_1^Z, \Delta\kappa_Z, \Delta\kappa_\gamma) = (g_1^Z, \kappa_Z, \kappa_\gamma) - 1. \tag{16}$$

These quantities are related to the coefficients of the dimension 6 operators $\mathcal{O}_W$, $\mathcal{O}_B$ and $\mathcal{O}_{WWW}$ in the following fashion.

$$\begin{aligned}
\Delta g_1^Z &= \frac{f_W}{\Lambda^2}\frac{M_Z^2}{2}, \\
\Delta\kappa_Z &= \left(\cos^2\theta_W\frac{f_W}{\Lambda^2} - \sin^2\theta_W\frac{f_B}{\Lambda^2}\right)\frac{M_Z^2}{2}, \\
\Delta\kappa_\gamma &= \left(\frac{f_W}{\Lambda^2} + \frac{f_B}{\Lambda^2}\right)\frac{M_W^2}{2}, \\
\lambda_Z &= \lambda_\gamma = \frac{3M_W^2e^2}{2\sin^2\theta_W}\frac{f_{WWW}}{\Lambda^2}.
\end{aligned} \tag{17}$$

In order to include anomalous vector boson couplings, the parameter `ANOM_CPL` must be switched to `true` in `vbfnlo.dat`. The parameters described above are input via the file `anomV.dat`:

- `TRIANOM`: Switches between parameterizations of the anomalous $WW\gamma$ and WWZ couplings. `TRIANOM = 1` uses the coefficients of the dimension 6 operators[21] as input:
  - `FWWW`: Coefficient of the operator $\mathcal{O}_{WWW}$, i.e. f_{WWW}/Λ^2. Default is set to 9.19×10^{-6} GeV^{-2}.
  - `FW`: Coefficient of the operator $\mathcal{O}_W$, i.e. f_W/Λ^2. Default is set to -1.44×10^{-5} GeV^{-2}.
  - `FB`: Coefficient of the operator $\mathcal{O}_B$, i.e. f_B/Λ^2. Default is set to 3.83×10^{-5} GeV^{-2}.

  `TRIANOM = 2` uses the alternative parameterization of Eqs. 14 and 15 as input:
  - `LAMBDA0`: The quantity $\lambda_\gamma (= \lambda_Z)$. Default is set to 0.038.
  - `ZDELTAKAPPA0`: The quantity $\Delta\kappa_Z$. Default is set to -0.082.
  - `ZDELTAG0`: The quantity Δg_1^Z. Default is set to -0.060.
  - `ADELTAKAPPA0`: The quantity $\Delta\kappa_\gamma$. Default is set to 0.077.
  - Note that, as can be seen from Eqs. 17, the quantities $\Delta\kappa_Z$, $\Delta\kappa_\gamma$ and Δg_1^Z are not independent, but obey the relation

$$\Delta\kappa_Z = \Delta g_1^Z - \frac{\sin^2\theta_W}{\cos^2\theta_W}\Delta\kappa_\gamma. \tag{18}$$

    If one of these quantities is zero, it will be set by VBFNLO to be consistent with the other values. If the input values are inconsistent, $\Delta\kappa_\gamma$ will be reset to give the correct relation.

  Default is `TRIANOM = 1`, and the default values are approximately the central values in the three-parameter fit given in Ref. [64].

- `FBW, FDW, FWW, FBB`: The coefficients of the remaining $\mathcal{CP}$-even dimension-6 operators, i.e. f_i/Λ^2. Note that these are only implemented for W pair production via vector boson fusion. Default value is 0 GeV^{-2}.

- `FWWWt, FWt, FBt, FBWt, FDWt, FWWt, FBBt`: The coefficients of the $\mathcal{CP}$-odd dimension-6 operators, i.e. f_i/Λ^2. Note that these are only implemented for W pair production via vector boson fusion. Default value is 0 GeV^{-2}.

- `FS0, FS1, FM0 - FM7, FT0 - FT2, FT5 - FT7`: Parameters that give the values of the coefficients of the dimension-8 operators, i.e. f_i/Λ^4. The default values for these parameters are 0 GeV^{-4}. Note that these are only relevant for triboson production.

In addition, a form factor can be applied:

$$F = \left(1 + \frac{s}{\Lambda^2}\right)^{-p}, \tag{19}$$

where Λ is the scale of new physics.

[21] The explicit form of the operators is given in Eq. 8.

- `FORMFAC`: Switch determining whether the above form factor F is included. Default is set to `false`.
- `FFMASSSCALE`: Mass scale Λ. Default is set to 2000 GeV.
- `FFEXP`: The exponent p. Default is set to 2.

Individual form factor mass scales and exponents can be set for the trilinear WWZ and $WW\gamma$ couplings, using either of the parametrizations above. If chosen, these values overwrite the "universal" mass scale and exponent (`FFMASSSCALE` and `FFEXP`) set above for the selected parameters.

- `FORMFAC_IND`: Switch determining whether individual or universal form factors are used. Default is set to `false` – universal form factors are used.

If `TRIANOM = 1` then

- `MASS_SCALE_FWWW`: Mass scale Λ for coefficient f_{WWW}. Default is 2000 GeV.
- `FFEXP_FWWW`: Exponent p for coefficient f_{WWW}. Default is 2.
- `MASS_SCALE_FW`: Mass scale Λ for coefficient f_W. Default is 2000 GeV.
- `FFEXP_FW`: Exponent p for coefficient f_W. Default is 2.
- `MASS_SCALE_FB`: Mass scale Λ for coefficient f_B. Default is 2000 GeV.
- `FFEXP_FB`: Exponent p for coefficient f_B. Default is 2.

If `TRIANOM = 2` then

- `MASS_SCALE_KAPPA`: Mass scale Λ for parameter $\Delta\kappa$. Default is 2000 GeV.
- `FFEXP_KAPPA`: Exponent p for parameter $\Delta\kappa$. Default is 2.
- `MASS_SCALE_LAMBDA`: Mass scale Λ for parameter λ. Default is 2000 GeV.
- `FFEXP_LAMBDA`: Exponent p for parameter λ. Default is 2.
- `MASS_SCALE_G`: Mass scale Λ for parameter Δg. Default is 2000 GeV.
- `FFEXP_G`: Exponent p for parameter Δg. Default is 2.

Finally, an overall factor scheme [54] can be employed for W^+W^- production via VBF, using the switch:

- `OVS`: Switch for overall factor scheme. Default is `false`.

4.6 `kk_input.dat` – parameters for Higgsless models

VBFNLO allows the calculation of the weak boson fusion processes $WWjj$, $WZjj$ and $ZZjj$ in the Warped Higgsless scenario [65, 66] at LO and NLO QCD level (see, for example, Ref. [67] for a phenomenological application). The triple vector-boson processes WWW, WWZ and WZZ can be calculated in both this model and a Three-Site Higgsless Model [68]. The model parameters can be generated by VBFNLO via the input file `kk_input.dat` for a choice of the relevant five dimensional gauge parameters. The input parameters are:

- `VBFCALC_SWITCH`: Switch that determines whether VBFNLO should calculate the parameters needed by the model. Default is `true`.
- `MHLM_SWITCH`: Switch that determines whether the Three-Site Higgsless Model [68] (`true`) or the Warped Higgsless Model [65] (`false`) should be used. Default is `false` (Warped Higgsless Model).
- The following parameters are used only when working in the Warped Higgsless Model (`MHLM_SWITCH = false`):
  - `RDWN`: Location of the UV brane for the generation of the model parameters in the Warped Higgsless Model. Default is $R = 9.75 \times 10^{-9}$, which amounts to the Kaluza-Klein excitations having masses of $m_{W_1} = 700$ GeV, $m_{Z_1} = 695$ GeV, and $m_{Z_1'} = 718$ GeV. Smaller values of R result in a heavier Kaluza-Klein spectrum.
  - `KKMAXW`: The maximum number of Kaluza-Klein $W_k^\pm$ states to be included on top of the Standard Model $W^\pm$ bosons, which correspond to $W_{k=0}^\pm$. All states $k \geq 3$ are phenomenologically irrelevant. Default is 1.
  - `KKMAXZ`: The maximum number of Kaluza-Klein Z_k states to be included on top of the Standard Model Z boson, which corresponds to $Z_{k=0}$. All states $k \geq 3$ are phenomenologically irrelevant. Default is 1.
  - `KKMAXG`: The maximum number of Kaluza-Klein Z_k' bosons that are excitations of the Standard Model photon $Z_{k=0}'$. States $k \geq 2$ are phenomenologically irrelevant. Default is 1.
- `WPMASS`: $W_{k=1}$ mass in the Three-Site Higgsless Model (`MHLM_SWITCH = true`). Default is 500 GeV.

The explicit breaking of higher dimensional gauge invariance is balanced according to the description of Ref. [69], where more details regarding the model and its implementation can be found. Information on the widths and the sum rules relating the various gauge boson couplings [70] are written to the file `kkcheck.dat`.

VBFNLO generates the text file `kk_coupl_inp.dat`, which documents the calculated model parameters, i.e. Kaluza-Klein gauge boson masses and couplings of the specified input parameters. This file can also be used as an input file for advanced users who want to run the code with their own set of parameters – e.g. for simulation of more general technicolor-type scenarios. To that end, select `VBFCALC_SWITCH = false` in the file `kk_input.dat`. VBFNLO will then calculate the gauge boson widths on the basis of these parameters by the decay to the lower lying states. The inputs in `kk_coupl_inp.dat` are as follows:

- `KKMAXW`: The maximum number of Kaluza-Klein $W_k^\pm$ states included on top of the Standard Model $W^\pm$ bosons.
- `KKMAXZ`: The maximum number of Kaluza-Klein Z_k states included on top of the Standard Model Z boson.
- `KKMAXG`: The maximum number of Kaluza-Klein Z'_k bosons that are excitations of the Standard Model photon $Z'_{k=0}$.
- Kaluza-Klein masses:
  - `KKMASSW`: List of masses of the Kaluza-Klein $W_k^\pm$ states.
  - `KKMASSZ`: List of masses of the Kaluza-Klein Z_k states.
  - `KKMASSG`: List of masses of the Kaluza-Klein Z'_k states.
- Couplings
  - `CPL_W`x`-W`y`-ZX`: List of couplings between Kaluza-Klein states: $W_x^\pm - W_y^\pm - Z_0$ to $W_x^\pm - W_y^\pm - Z_{\texttt{KKMAXZ}}$.
  - `CPL_W`x`-W`y`-GX`: List of couplings between Kaluza-Klein states: $W_x^\pm - W_y^\pm - Z'_0$ to $W_x^\pm - W_y^\pm - Z'_{\texttt{KKMAXG}}$.
  - `CPL_W`x`-W`y`-W`z`-WX`: List of couplings between Kaluza-Klein states: $W_x^\pm - W_y^\pm - W_z^\pm - W_0^\pm$ to $W_x^\pm - W_y^\pm - W_z^\pm - W_{\texttt{KKMAXW}}^\pm$.
  - `CPL_W`x`-W`y`-Z`z`-ZX`: List of couplings between Kaluza-Klein states: $W_x^\pm - W_y^\pm - Z_z - Z_0$ to $W_x^\pm - W_y^\pm - Z_z - Z_{\texttt{KKMAXZ}}$.
  - `CPL_W`x`-W`y`-G`z`-GX`: List of couplings between Kaluza-Klein states: $W_x^\pm - W_y^\pm - Z'_z - Z'_0$ to $W_x^\pm - W_y^\pm - Z'_z - Z'_{\texttt{KKMAXG}}$.
  - `CPL_W`x`-W`y`-G`z`-ZX`: List of couplings between Kaluza-Klein states: $W_x^\pm - W_y^\pm - Z'_z - Z_0$ to $W_x^\pm - W_y^\pm - Z'_z - Z_{\texttt{KKMAXZ}}$.

The default values in `kk_coupl_inp.dat` are those produced when VBFNLO is used to calculate the couplings and masses using the default values of `kk_input.dat` as described above.

4.7 `histograms.dat` – parameters for histogram ranges

The file `histograms.dat` allows the user to set the range of the x-axis of the produced histograms. The range is input in the format: `xmin xmax`. The following describes those histograms which are already implemented in VBFNLO. By altering the file `utilities/histograms.F`, however, it should be easy for the user to add new histograms – VBFNLO will automatically read-in the range of each created histogram.

- `HIST_ID1`: Range for p_T of tagging jets. Default range is 0 to 250 GeV.
- `HIST_ID2`: Range for p_T of tagging jet with higher p_T. Default range is 0 to 500 GeV.
- `HIST_ID3`: Range for p_T of tagging jet with lower p_T. Default range is 0 to 200 GeV.
- `HIST_ID4`: Range for pseudorapidity of tagging jets. Default range is -5 to 5.

- `HIST_ID5`: Range for pseudorapidity of tagging jet with higher p_T. Default range is -5 to 5.
- `HIST_ID6`: Range for pseudorapidity of tagging jet with lower p_T. Default range is -5 to 5.
- `HIST_ID7`: Range for $p_T^{\max}$ of leptons. Default range is 0 to 500 GeV.
- `HIST_ID8`: Range for $p_T^{\min}$ of leptons. Default range is 0 to 500 GeV.
- `HIST_ID9`: Range for $\eta_{\max}$ of leptons. Default range is 0 to 5.
- `HIST_ID10`: Range for $\eta_{\min}$ of leptons. Default range is 0 to 5.
- `HIST_ID11`: Range for azimuthal angle of tagging jets. Default range is -180 to 180.

VBFNLO can also produce 2D histograms. In this case, both the x and y ranges can be set using `histograms.dat` in the format `xmin xmax ymin ymax`.

- `2DHIST_ID1`: Range for 2D histogram of $d^2S/(d\eta_{jj}dm_{jj})$. Default ranges are 0 to 6 for the η (x) axis and 0 to 800 GeV for the m_{jj} (y) axis.

5 Changes

The current version of VBFNLO – 2.5.0 – has been altered in such a way that some results will differ from previous versions. These changes are described briefly here, and in more detail on the VBFNLO website, `http://www-itp.particle.uni-karlsruhe.de/vbfnlo/`.

5.1 `EWSCHEME`

The implementation of options `EWSCHEME = 1` and `4`, which are described in Section 4.1.2, has been altered. The new implementation is hopefully more transparent, and is described in this manual.

5.2 Gluon fusion

In the current version of VBFNLO, the gluon fusion cross section has also been affected by changes to the code. In the new version, the bottom-quark mass $M_b(M_H)$ is used throughout the calculation. New, more stable, tensor routines for the boxes and pentagons have been implemented, reducing the number of omitted points with bad Gram Determinants.

6 Checks

Extensive checks for the LO and the real emission amplitudes as well as for the total LO cross sections have been performed for all processes implemented in VBFNLO. Born amplitudes and real emission diagrams have been compared with the fully automatically generated results provided by MadGraph [71]. Complete agreement has been found in each case. Moreover, total LO cross sections with a minimal set of cuts agree with the respective results obtained by MadEvent[22] [72, 73], Sherpa[23] [74] and/or Helac-Phegas[24] [75–77], a completely automatic parton level event generator based on Dyson-Schwinger recursive equations.

LHA event files for the LO processes have been tested with Herwig++[25] [78], a general purpose Monte Carlo event generator for the simulation of hard lepton-lepton and hadron-hadron collisions.

As a final and very important test, comparisons with already published results have been made. The NLO results for Higgs boson production via VBF agree with those produced by the code Hawk[26]. In Ref. [79], a tuned comparison of LO and NLO QCD results for Higgs boson production via vector boson fusion at the LHC has been performed. Three different calculations have been cross checked: VBFNLO, the results of Refs. [80,81], and the VV2H program[27]. For the dominant t- and u-channel contributions which are implemented in VBFNLO, good agreement has been found. For the triboson processes a comparison for the production of on-shell gauge bosons without leptonic decays has been performed with the results presented in Ref. [82]. Additionally, the tree-level results for $W^{\pm}\gamma\gamma$ have been compared to the results with an on-shell W boson of Ref. [83]. Again, in both cases good agreement has been found. Triple photon production has been tested against FeynArts, FormCalc and HadCalc [3, 4, 84]. Results for the $\mathcal{CP}$-odd and $\mathcal{CP}$-even Higgs boson production via gluon fusion have been tested against FeynArts and FormCalc [85,86].

[22] http://madgraph.hep.uiuc.edu/
[23] http://www.sherpa-mc.de/
[24] http://helac-phegas.web.cern.ch/helac-phegas/
[25] http://projects.hepforge.org/herwig/
[26] http://omnibus.uni-freiburg.de/~sd565/programs/hawk/hawk.html
[27] http://people.web.psi.ch/spira/vv2h/

7 Outlook

Additional processes will become available in the near future and will be included in the code version on the VBFNLO website.

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