VBFNLO: A parton level Monte Carlo for processes with electroweak bosons – Manual for Version 3.0

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Abstract

VBFNLO is a flexible parton level Monte Carlo program for the simulation of vector boson fusion (VBF), QCD-induced single and double vector boson production plus two jets, and double and triple vector boson production (plus jet) 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. For the new version – VERSION 3.0 – several major enhancements have been included. An interface according to the Binoth Les Houches Accord (BLHA) has been added for all VBF and di/tri-boson processes including fully leptonic decays. For all dimension-8 operators affecting vector boson scattering (VBS) processes, a modified T-matrix unitarization procedure has been implemented. Several new production processes have been added, namely the VBS $Z\gamma jj$ and $\gamma\gamma jj$ processes at NLO, $\gamma\gamma jj$, WWj and ZZj production at NLO including the loop-induced gluon-fusion contributions and the gluon-fusion one-loop induced Φjjj (Φ is a CP-even or CP-odd scalar boson) process at LO, retaining the full top-mass dependence. Finally, the code has been parallelized using OPENMPI.

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Contents

1 INTRODUCTION

The physics potential 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 parton radiation from processes with 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) [1], QCD-induced single and double vector boson production plus two jets, and double and triple vector boson (plus jet) 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 a multitude of processes. Additionally, some extra dimension models are included to simulate the production of technicolor-type vector resonances in VBF and triple vector boson production. Diboson plus two jets production via VBF can also be run in a spin-2 model and in a model with two Higgs resonances.

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, some PDFs are hard-wired into the code for checking with the results in the regress directory, which are shipped with the program for testing purpose. 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 versions [1–4] released with VBFNLO VERSION 2.0, VERSION 2.5.0, VERSION 2.6.0 and VERSION 2.7.0.
The version of VBFNLO 3.0 extends the following parts of VERSION 2.7:

- The following new processes have been added:
  WWj and ZZj production including the loop-induced gluon-fusion contributions of $\mathcal{O}(\alpha_s^3)$. VBF $\gamma\gamma jj$, QCD-induced γjj, and QCD-induced $\gamma\gamma jj$ processes.

- An interface according to the Binoth Les Houches Accord (BLHA) has been added for all VBF processes including fully leptonic decays.

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[1]The terminology VBF includes also the class of vector boson scattering processes.

- The dimension 8 operator $\mathcal{O}_{S,2}$ as well as several transverse dimension-8 operators have been added for VBS processes.

- Several unitarization procedures have been implemented for VBS processes.

- The T_u-model unitatisation procedures has been implemented for all VBF dimension-8 operators listed in sec. A.1.

- Several additional types of form factors, namely complex dipole, step and kink, have been added.

Additionally it contains the following improvements also released as VBFNLO VERSION 2.7.1:

- The following new processes have been added:
  QCD-induced $ZZjj$ and $Z\gamma jj$, $Z\gamma jj$ in VBF, $ZZ\gamma$ production.

- Higgs decays have been implemented for the VBF-HHjj process ($b\bar{b}\tau^+\tau^-$ and $b\bar{b}\gamma\gamma$ final states).

- Linking with LHAPDF v6 has been enabled.

Several bugfixes and smaller improvements have also been included. The complete list can be found in the CHANGELOG.md file included in the tarball.

The VBFNLO webpage – `https://ific.uv.es/vbfnlo/` – contains, in addition to the latest version of the code, extra information such as the explicit implementation of the electroweak parameters and couplings. To enable a simple installation test VBFNLO is shipped with a complete set of example results, together with input files, in the `regress` directory. On the webpage, users can subscribe to a low-traffic mailing list, where new versions of VBFNLO are announced.

2 INSTALLING VBFNLO

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

<div align="center">https://ific.uv.es/vbfnlo/</div>

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 FORTRAN 95 [2] and a C++ compiler. VBFNLO offers the possibility of using the LHAPDF[3] [5] library (versions 5 and 6) for parton distribution functions. In order to include the electroweak corrections to VBF Higgs production, the program LOOPTOOLS[4] [6, 7] is required. Additionally, FEYNHIGGS[5] [8–11] 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)[6] is required. VBFNLO can also be linked to ROOT[7] and HEPMC[8] 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 [9] 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]`. If not specified, VBFNLO is installed in the `root` directory.

- `--enable-processes=[list]`
  By default, the code for all available processes except those involving hexagon contributions (i.e. triboson plus jet and QCD-induced $Vjj/VVjj$ processes) is compiled[10]. Optionally, `[list]` gives a comma-separated list of selected process classes to be compiled. Possible choices are:

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[2]`gfortran` and `ifort` have been tested. Pure FORTRAN77 compilers like `g77` are no longer supported.
[3]https://lhapdf.hepforge.org/
[4]http://www.feynarts.de/looptools/
[5]http://www.feynhiggs.de/
[6]https://www.gnu.org/software/gsl/
[7]https://root.cern.ch/
[8]http://lcgapp.cern.ch/project/simu/HepMC/
[9]If the `configure` file is absent, it can be generated using the `autoreconf -i` command.
[10]This is simply due to the relatively long time required to compile the hexagon routines.

`vbf`	Vector boson fusion processes
`qcdvjj`	QCD-induced vector boson plus two jet production
`qcdvvjj`	QCD-induced vector boson pair plus two jet production
`diboson`	Double gauge boson production, including W and WH production
`triboson`	Triple gauge boson production
`dibosonjet`	Double gauge boson production with a hadronic jet, including Wj and WHj production
`tribosonjet`	Triboson production in association with a hadronic jet
`hjjj`	Higgs boson plus three jet production via vector boson fusion
`ggf`	Higgs boson plus two and three jet production via gluon fusion
`all_except_hexagons`	All the above processes except those with hexagon contributions (default)
`all`	All the above processes

- `FC=/path/to/fortran/compiler`
  With the `FC` option a specific FORTRAN 95 compiler can be requested. Otherwise a default compiler will be used, which will be most probably `gfortran`.

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

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

- `--enable-quad`
  Enable quadruple precision for difficult phase space points. Enabled by default, if QCD-induced vector boson (pair) plus two jet and Higgs plus three jet gluon-fusion-induced processes are requested, otherwise disabled by default.

- `--enable-MPI`
  Enables support for parallel runs using MPI. See Sec. 2.5 for additional requirements for using MPI. Disabled by default.

- `--with-gsl=[path]`
  Enable the use of the GNU Scientific Library. `[path]` specifies the location of the GSL installation. If the GSL is available directly from the system libraries this flag can be omitted.

- `--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[11] 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 for histograms. `[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 LHAPDF, the external program needs to have been compiled using the same compiler (e.g. `gfortran`) as VBFNLO. If no `path` is specified, VBFNLO will attempt to find the desired program in the system directories. Once `configure` has finished successfully, the `make` and `make install` commands will compile and install VBFNLO, respectively.

To test the installation against a set of typical run files, `make check` can be used. It requires `py.test` to be installed and takes a few minutes to run. Due to numerical checks it will fail if any compiler optimization beyond the default settings was used.

If at any point include files, with a file name suffix `.inc`, are changed, the command `make clean` must be run so that the changes are picked up correctly. For normal program usage, this will not be necessary, but cases where options can be altered in the file `global.inc` will be mentioned later. When changing only Fortran source code files, running `make clean` first is not mandatory. In both cases, `make all install` must be run afterwards in the main directory to recompile and reinstall the altered code.

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 [12] subroutines used to calculate helicity amplitudes.

- `loops/`: One-loop tensor integrals up to six-point functions [13].

- `PDFsets/`: Built-in parton distributions (CT18 [14], as well as MRST2004qed [17] and MSTW2008 [18]).

- `phasespace/`: Specialized phase-space generators for the processes provided.

- `regress/`: Folder containing example results, together with input files, for all processes.

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[11]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, 2.8.3 and 2.12.0

- `src/` and `lib/`: 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. 5. 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.F90` 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 executable.

- `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

The vbfnlo executables contained in the `bin` directory of the installation path looks for input files in the 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 from that directory without specifying further options.

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

The version number of VBFNLO can be obtained by appending the argument `--version`. This will print out the string `VBFNLO` followed by the release number and then exit the program.

2.4.1 Parallel jobs and optimised grids

Owing to the complexity of the calculations involved, some of the processes implemented in VBFNLO (in particular the spin-2, triboson plus jet and QCD-induced diboson plus two jets processes) require a significant amount of time in order to obtain reasonable results. There are, however, methods which can be used in order to reduce the necessary run time.

By using an optimised grid, the number of iterations needed in order to improve the efficiency of the MC integration can be reduced. Optimised grids can be easily generated

by the user (see Sec. 5.1.1). The optimised grids previously provided on the VBFNLO webpage are now no longer sustained, as they were tailored for a specific set of kinematic cuts and input parameters. Some old grids are still available on the VBFNLO webpage for all processes using standard cuts and parameter settings. The variables used to set the input grid files and number of iterations are described in Sec. 5.1.1.

Another method of improving the run time is to run several jobs in parallel and then combine the results. In order to do this, several input directories need to be set up containing all the necessary `.dat` input files for the process. The variable `SEED` in `random.dat` (Sec. 5.9) needs to be set to a different integer value in each directory. A short example of the results of a parallel run, together with their combination, is provided in the regress directory `regress/100_Hjj_parallel`. On the VBFNLO website there is a shell script which can be used to combine the cross sections and histograms from parallel runs.

2.5 MPI

MPI allows to run code in parallel. VBFNLO provides experimental support for usage with MPI. Integration as well as grid and histogram generation are available with MPI parallelization, while for event outputs only single-core runs are supported.

Compilation und running with MPI is so far only tested with GNU OpenMPI and GFortran. To use this combination load openmpi in your environment (e.g. `module load openmpi`), then configure with `--enable-MPI` and the OpenMPI wrapper `FC=mpifort`.

To run the resulting binary start `mpirun -np 8 /prefix/bin/vbfnlo`, replacing 8 with the number of requested parallel runs.

Due to the experimental nature, please test that for your configuration and choice of process the compilation with and without MPI leads to the same numerical output. For single-core usage MPI and non-MPI runs should agree up to machine precision, while for multi-core runs, numerical differences up to the stated statistical uncertainty are expected.

Use the xoroshiro random number generator (`RTYPE=3` in `random.dat`) for best performance with MPI. For details see Section 5.9.

2.6 MacOSX

Compilation of VBFNLO on MacOSX only works with static libraries. This can be requested with the configure-option `--enable-shared=no`. With this option the current version of VBFNLO has been compiled successfully on different versions of MacOSX between 10.6.8 and 10.12.3 using GFortan 5 or 6 from Homebrew. However, linking with the library LoopTools, which is only needed for the calculation of the electroweak corrections in the `Hjj` process, is known to fail.

2.7 Bug reports

Please report any problems to

    vbfnlo@ific.uv.es

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

You can also open issues in github: `https://github.com/vbfnlo/vbfnlo/issues`

2.8 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[12], which were originally formulated and agreed on by the MCnet collaboration for event generator software. In particular, the original literature on which the program is based should be cited along with the reference to VBFNLO.

Some parts of the VBFNLO matrix elements are based on automatically generated code from MADGRAPH [19, 20] and FEYNARTS/FORMCALC [6, 7, 21–26]. The routine which reads in SLHA [27] files is largely based on SLHALIB-2.2 [28]. VBFNLO ships with a copy of FF 2.0 [29] for the evaluation of one-loop integrals, and includes the file CPS_HIGGSTO.F [30, 31] for calculating the Higgs width in the CPS scheme.

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[12]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 this class of processes in VBFNLO s-channel exchange contributions and kinematically suppressed interference contributions for identical quarks [32–34] are therefore disregarded. While numerically small contributions from Pauli-interference effects for identical fermions from weak boson decays are neglected, off-shell contributions to leptonic final states are always included. For final-state identified photons we employ Frixione's smooth-cone isolation criterion [35]. This ensures that divergences from the 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. Due to the inclusion of semileptonic diboson and triboson production processes, the missing s-channel gauge boson exchanges to several VBF processes can be calculated within VBFNLO as well. This topic is described briefly in Section 5.10.

Higgs contributions (and interference effects) are included in all appropriate processes, using a fixed Higgs width. The Higgs propagator is given by

$$\frac{1}{s - M_H^2 + iM_H\Gamma_H}. \tag{1}$$

In VBFNLO external quarks are treated as massless. By default, external bottom quarks are excluded in those processes where their inclusion could lead to the presence of a top quark. For example, in WW diboson production, external bottom quarks are not allowed, as this would lead to a (massless) t-channel top quark, but in ZZ diboson production external bottom quarks are included. In the VBF processes such as $pp \to Hjj$ there are both neutral and charged current components (when the external quark lines emit Z and W bosons respectively) – by default, external bottom quarks are excluded from this class of processes. A message is printed in the log file stating whether external bottom quarks are included or excluded. In neutral current processes, bottom quarks in the final state are at present treated no differently from other final state quarks. The number of external quark flavours considered is set in the file `utilities/global.inc`. By changing the parameter `nfl` from `5` to `4`, bottom quarks will be excluded in any process. By changing the parameter `vbfNFLb` from `false` to `true`, external bottom quarks will be included in the neutral current diagrams in VBF processes if `nfl` is set to `5`[13].

VBF processes with a t-channel virtual photon produce singularities at low photon virtuality, q^2, at NLO, when the out-going quark is not tagged. To remove this photon singularity at $q^2 = 0$, VBFNLO imposes a default technical cut of $|q^2| > 4\,\mathrm{GeV}^2$ for the EW processes where the singularity occurs. This is expected to be a very good approximation for measurements at high energies.

In addition, the program can also calculate some semi-leptonic final-state processes, based on the following approximation. Starting from the above leptonic final-state processes, massless leptons are replaced by massless quarks, properly modifying color factors, couplings to Z bosons and virtual photons and including photon exchange, whenever a

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[13]Note that, if these parameters are changed, `make clean` must be run in the folders `utilities` and `amplitudes`, and then `make all install` must be run for the VBFNLO code.

neutrino is replaced by an up-quark. To distinguish them from the other quarks (e.g. tagging quarks) in the final state, we call the replacement quarks decay quarks. In this way, NLO QCD corrections to the production part can be taken over from the corresponding leptonic final state calculation. QCD corrections from gluon exchange between the other partons and decay quarks are neglected because these effects are very small, even vanishing in many cases due to color factors. Corrections from final state radiation off decay quarks (including virtual corrections) can be approximated by adding a correction factor $(1 + \alpha_s(Q^2)/\pi)$ for the decay $V \to \bar{q}q'$ with $V = W^{\pm}, Z, \gamma$, $Q = p_V$ being the four-momentum of the di-quark system. This correction factor, being about 1.04 at $Q = M_Z$, is off by default but can be turned on by using the switch `NLO_SEMILEP_DECAY` in the `vbfnlo.dat` input file (see Section 5.1). The key features of the semileptonic processes are:

- NLO QCD corrections to the production part are fully taken into account.

- Interference effects and gluon exchange between the decay quarks and the other quarks in the process are ignored.

- NLO QCD corrections involving decay quarks are not fully included. The real gluon-emission corrections cannot be resolved.

Further details can be found in [39]. Since the semileptonic processes are not fully calculated at NLO QCD as for the leptonic case, they will be marked with a star in the following process tables as a warning to the users about the limitations.

Finally, we note that realistic simulations for experimental measurements of semileptonic processes often require a sum over several VBFNLO processes. For example, the final states of semileptonic $WZjj$ and $ZZjj$ production, with a Z boson decaying leptonically, are indistinguishable. A summation of these two processes is therefore needed.

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 one-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 and can be input via the file `anom_HVV.dat`. Details of the calculations can be found in Refs. [36–38].

Furthermore, semileptonic decay modes of the vector bosons are implemented for the WW and ZZ decay modes [39].

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. [40].

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ProcId	Process	BSM
100	$p\overset{(-)}{p} \to H\,jj$	
101	$p\overset{(-)}{p} \to H\,jj \to \gamma\gamma\,jj$	
102	$p\overset{(-)}{p} \to H\,jj \to \mu^+\mu^-\,jj$	
103	$p\overset{(-)}{p} \to H\,jj \to \tau^+\tau^-\,jj$	anomalous HVV couplings, MSSM
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	$p\overset{(-)}{p} \to H\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\,jj$	
108*	$p\overset{(-)}{p} \to H\,jj \to W^+W^-\,jj \to q\bar{q}\,\ell^-\bar{\nu}_\ell\,jj$	
109*	$p\overset{(-)}{p} \to H\,jj \to W^+W^-\,jj \to \ell^+\nu_\ell\,q\bar{q}\,jj$	anomalous HVV couplings, MSSM
1010*	$p\overset{(-)}{p} \to H\,jj \to ZZ\,jj \to q\bar{q}\,\ell^+\ell^-\,jj$	

Table 1: *Process IDs for $p\overset{(-)}{p} \to Hjj$ production via vector boson fusion at NLO (QCD and electroweak) accuracy in the SM and MSSM. Anomalous couplings between the Higgs boson and vector bosons are implemented for all decay modes. Semileptonic processes are marked with a star to indicate that NLO QCD corrections are approximated as explained in the text.*

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.*

PROCID	PROCESS	BSM
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	$p\overset{(-)}{p} \to W^+\, jj \to \ell^+\nu_\ell\, jj$	anomalous couplings
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 vector boson fusion at NLO QCD accuracy.*

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. [41].

3.4 VBF production of a single 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, with the process IDs given in Table 4. Anomalous triboson couplings are input via `anomV.dat` and can be included in all processes of this class. Details of the calculations can be found in Refs. [42, 43].

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ProcId	Process	Bsm
191	$p\overset{(-)}{p} \to S_2\,jj \to \gamma\gamma\,jj$	
195	$p\overset{(-)}{p} \to S_2\,jj \to W^+W^-\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,jj$	spin-2 resonant production
196	$p\overset{(-)}{p} \to S_2\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\,jj$	
197	$p\overset{(-)}{p} \to S_2\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\,jj$	

Table 5: *Process IDs for a spin-2 particle S_2+2 jet production via vector boson fusion at NLO QCD accuracy.*

3.5   VBF production of a spin-2 particle

VBFNLO can simulate the production of a spin-2 particle via VBF, which then decays into two photons, with the process ID 191 (see Table 5). This process will only run if the switch SPIN2 in vbfnlo.dat is set to true. Furthermore, spin-2 production is also available in the WW and ZZ modes given in Table 5 if the switch SPIN2 in vbfnlo.dat is set to true. If SPIN2 is set to false, VBF Higgs production is simulated instead, similarly to the processes 105, 106 or 107 of Table 1 for a SM Higgs. The parameters of the spin-2 model are input via spin2coupl.dat. Details of the calculations can be found in Refs. [44–46].

3.6   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 (including contributions from Higgs bosons) 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 6. Anomalous gauge boson couplings, input via anomV.dat, are implemented for all processes in this class, as well as a simplified model with two Higgs resonances. This process class can also be run in the Kaluza-Klein and spin-2 models implemented in VBFNLO, with the exception of $W\gamma$, $Z\gamma$, $\gamma\gamma$ and same-sign WW production. Details of the calculations can be found in Refs. [44, 47–54].

Furthermore, semileptonic decay modes of the vector bosons are implemented for the opposite-sign WW, same-sign WW, WZ and ZZ production processes in VBF [39]. In this case only anomalous couplings are available as BSM options.

3.7   VBF production of two Higgs bosons and two jets

Higgs pair production plus two jets via VBF mainly proceeds via electroweak quark-quark scattering processes such as $qq' \to qq'HH$ and crossing-related reactions. In VBFNLO, tree level cross sections and NLO QCD corrections to the t-channel production process are

PROCID	PROCESS	BSM
200	$p\overset{(-)}{p} \to W^+W^- jj \to \ell_1^+ \nu_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2} jj$	
210	$p\overset{(-)}{p} \to ZZ jj \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^- jj$	anomalous couplings,
211	$p\overset{(-)}{p} \to ZZ jj \to \ell_1^+ \ell_1^- \nu_{\ell_2} \bar{\nu}_{\ell_2} jj$	two-Higgs model,
220	$p\overset{(-)}{p} \to W^+Z jj \to \ell_1^+ \nu_{\ell_1} \ell_2^+ \ell_2^- jj$	Kaluza-Klein models,
230	$p\overset{(-)}{p} \to W^-Z jj \to \ell_1^- \bar{\nu}_{\ell_1} \ell_2^+ \ell_2^- jj$	spin-2 models
240	$p\overset{(-)}{p} \to \gamma\gamma jj$	anomalous couplings
250	$p\overset{(-)}{p} \to W^+W^+ jj \to \ell_1^+ \nu_{\ell_1} \ell_2^+ \nu_{\ell_2} jj$	anomalous couplings, two-Higgs model
260	$p\overset{(-)}{p} \to W^-W^- jj \to \ell_1^- \bar{\nu}_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2} jj$	
270	$p\overset{(-)}{p} \to W^+\gamma jj \to \ell^+ \nu_\ell \gamma jj$	
280	$p\overset{(-)}{p} \to W^-\gamma jj \to \ell^- \bar{\nu}_\ell \gamma jj$	anomalous couplings
290	$p\overset{(-)}{p} \to Z\gamma jj \to \ell^+ \ell^- \gamma jj$	
291	$p\overset{(-)}{p} \to Z\gamma jj \to \nu_\ell \bar{\nu}_\ell \gamma jj$	
201*	$p\overset{(-)}{p} \to W^+W^- jj \to q\bar{q} \ell^- \bar{\nu}_\ell jj$	
202*	$p\overset{(-)}{p} \to W^+W^- jj \to \ell^+ \nu_\ell q\bar{q} jj$	
212*	$p\overset{(-)}{p} \to ZZ jj \to q\bar{q} \ell^+ \ell^- jj$	
221*	$p\overset{(-)}{p} \to W^+Z jj \to q\bar{q} \ell^+ \ell^- jj$	
222*	$p\overset{(-)}{p} \to W^+Z jj \to \ell^+ \nu_\ell q\bar{q} jj$	anomalous couplings,
231*	$p\overset{(-)}{p} \to W^-Z jj \to q\bar{q} \ell^+ \ell^- jj$	two-Higgs model
232*	$p\overset{(-)}{p} \to W^-Z jj \to \ell^- \bar{\nu}_\ell q\bar{q} jj$	
251*	$p\overset{(-)}{p} \to W^+W^+ jj \to q\bar{q} \ell^+ \nu_\ell jj$	
261*	$p\overset{(-)}{p} \to W^-W^- jj \to q\bar{q} \ell^- \bar{\nu}_\ell jj$	

Table 6: *Process IDs for diboson + 2 jet production via vector boson fusion at NLO QCD accuracy.*

provided in the framework of the Standard Model. Two decay modes for the subsequent decays of the Higgs bosons in the narrow-width approximation are implemented as well. The processes and corresponding process IDs are listed in Table 7. More details of the calculations can be found in Refs. [55, 56], in particular about the generation of the amplitudes of the on-shell production.

3.8 W production with up to one jet

The production of a W boson with up to one jet is implemented in VBFNLO at NLO QCD. The W boson decays leptonically and full off-shell effects and spin correlations of the final state leptons are included. The processes are listed in Table 8. Details of the calculation can be found in Ref. [57].

PROCID	PROCESS
160	$p\overset{(-)}{p} \to HH\,jj$
161	$p\overset{(-)}{p} \to HH\,jj \to b\bar{b}\tau^{+}\tau^{-}\,jj$
162	$p\overset{(-)}{p} \to HH\,jj \to b\bar{b}\gamma\gamma\,jj$

Table 7: *Process IDs for Higgs pair + 2 jet production via vector boson fusion at NLO QCD accuracy.*

PROCID	PROCESS
1330	$p\overset{(-)}{p} \to W^{+} \to \ell^{+}\nu_{\ell}$
1340	$p\overset{(-)}{p} \to W^{-} \to \ell^{-}\bar{\nu}_{\ell}$
1630	$p\overset{(-)}{p} \to W^{+}\,j \to \ell^{+}\nu_{\ell}\,j$
1640	$p\overset{(-)}{p} \to W^{-}\,j \to \ell^{-}\bar{\nu}_{\ell}\,j$

Table 8: *Process IDs for the W production processes with up to one jet at NLO QCD accuracy.*

3.9   Double vector boson production

The production of four-lepton final states mainly proceeds via double 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 a photon and double photon production. In VBFNLO, the processes listed in Table 9 are implemented to NLO QCD accuracy, including full off-shell effects and spin correlations of the final state leptons and photons. Anomalous vector boson couplings, input via `anomV.dat`, are implemented for WW, $W^{\pm}Z$ and $W^{\pm}\gamma$ production. The processes with a neutral final state (WW, ZZ, $Z\gamma$ and $\gamma\gamma$) also include the gluon-induced fermionic loop diagrams by default at NLO – both continuum production via box diagrams and the s-channel Higgs boson contributions are included, and anomalous HVV couplings (input via `anom_HVV.dat`) can be used. Details of the calculations can be found in Ref. [58].

Furthermore, semileptonic decay modes of the vector bosons are implemented for the WW, ZZ and WZ production processes [39]. Both anomalous VVV and HVV couplings are available as BSM options.

3.10   Triple vector boson production

The production of six-lepton final states mainly proceeds via triple vector boson production with subsequent decays. Additionally, there are processes where one or more decaying

PROCID	PROCESS	BSM
300	$p \overset{(-)}{p} \to W^+ W^- \to \ell_1^+ \nu_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2}$	anomalous HVV and VVV couplings
310	$p \overset{(-)}{p} \to W^+ Z \to \ell_1^+ \nu_{\ell_1} \ell_2^+ \ell_2^-$	} anomalous VVV couplings
320	$p \overset{(-)}{p} \to W^- Z \to \ell_1^- \bar{\nu}_{\ell_1} \ell_2^+ \ell_2^-$	
330	$p \overset{(-)}{p} \to ZZ \to \ell_1^- \ell_1^+ \ell_2^- \ell_2^+$	anomalous HVV couplings
340	$p \overset{(-)}{p} \to W^+ \gamma \to \ell_1^+ \nu_{\ell_1} \gamma$	} anomalous VVV couplings
350	$p \overset{(-)}{p} \to W^- \gamma \to \ell_1^- \bar{\nu}_{\ell_1} \gamma$	
360	$p \overset{(-)}{p} \to Z \gamma \to \ell_1^- \ell_1^+ \gamma$	} anomalous HVV couplings
370	$p \overset{(-)}{p} \to \gamma \gamma$	
301*	$p \overset{(-)}{p} \to W^+ W^- \to q \bar{q} \, \ell^- \bar{\nu}_\ell$	} anomalous VVV and HVV couplings
302*	$p \overset{(-)}{p} \to W^+ W^- \to \ell^+ \nu_\ell \, q \bar{q}$	
312*	$p \overset{(-)}{p} \to W^+ Z \to q \bar{q} \, \ell^+ \ell^-$	
313*	$p \overset{(-)}{p} \to W^+ Z \to \ell^+ \nu_\ell \, q \bar{q}$	anomalous VVV couplings
322*	$p \overset{(-)}{p} \to W^- Z \to q \bar{q} \, \ell^+ \ell^-$	
323*	$p \overset{(-)}{p} \to W^- Z \to \ell^- \bar{\nu}_\ell \, q \bar{q}$	
331*	$p \overset{(-)}{p} \to ZZ \to q \bar{q} \, \ell^- \ell^+$	anomalous HVV couplings

Table 9: *Process IDs for the diboson production processes at NLO QCD accuracy.*

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 Tables 10 and 11 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. Anomalous vector boson couplings[14] are implemented for all triboson processes, with the anomalous parameters input via `anomV.dat`. The processes WWZ, $ZZW^\pm$ and $W^\pm W^+ W^-$ can also be run in the implemented higgsless Kaluza-Klein models. Details of the calculations can be found in Refs. [59–64].

Furthermore, semileptonic decay modes of the vector bosons are implemented for all triple vector boson production processes with zero or one final state photon [39]. In this case only anomalous couplings are available as BSM options.

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[14]Some anomalous VVV (f_W and f_B or, equivalently, $\Delta \kappa_\gamma$ and Δg_1^Z) couplings also imply anomalous HVV couplings – these are automatically taken into account.

PROCID	PROCESS	BSM
400	$p\overset{(-)}{p} \to W^+W^-Z \to \ell_1^+ \nu_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2} \ell_3^+ \ell_3^-$	
410	$p\overset{(-)}{p} \to ZZW^+ \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^- \ell_3^+ \nu_{\ell_3}$	
420	$p\overset{(-)}{p} \to ZZW^- \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^- \ell_3^- \bar{\nu}_{\ell_3}$	anomalous couplings, Kaluza-Klein models
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	$p\overset{(-)}{p} \to W^-W^+\gamma \to \ell_1^- \bar{\nu}_{\ell_1} \ell_2^+ \nu_{\ell_2} \gamma$	anomalous couplings
470	$p\overset{(-)}{p} \to ZZ\gamma \to \ell_1^- \ell_1^+ \ell_2^- \ell_2^+ \gamma$	
472	$p\overset{(-)}{p} \to ZZ\gamma \to \ell_1^- \ell_1^+ \nu_{\ell_2} \bar{\nu}_{\ell_2} \gamma$	
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	$p\overset{(-)}{p} \to W^-\gamma\gamma \to \ell^- \bar{\nu}_\ell \gamma\gamma$	anomalous couplings
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 10: *Process IDs for the triboson production processes at NLO QCD accuracy with fully leptonic decays.*

3.11 Double vector boson production in association with a hadronic jet

Diboson production in association with a hard hadronic jet are available in VBFNLO at NLO QCD accuracy under the process IDs of Tables 12 and 13. All off-shell and finite width effects are included. The WZ and $W\gamma$ processes can be run with anomalous WWZ and $WW\gamma$ couplings, input via `anomV.dat`. Details can be found in Refs. [65–71].

Furthermore, semileptonic decay modes of the vector bosons are implemented for the W^+W^- final state in the SM.

3.12 Triple vector boson production in association with a hadronic jet

$W\gamma\gamma$ production in association with a hard hadronic jet is available in VBFNLO at NLO QCD accuracy under the process IDs of Table 14. All off-shell and finite width effects are included. Anomalous vector boson couplings are implemented, with the anomalous parameters input via `anomV.dat`. Details can be found in Ref. [72]. Note that this class of processes is not enabled by default and so, in order to run these processes, they must be enabled at compilation, using the `configure` option `--enable-processes=all`

PROCID	PROCESS	BSM
401*	$p\overset{(-)}{p} \to W^+W^-Z \to q\bar{q}\,\ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-$	
402*	$p\overset{(-)}{p} \to W^+W^-Z \to \ell_1^+\nu_{\ell_1}\,q\bar{q}\,\ell_2^+\ell_2^-$	
403*	$p\overset{(-)}{p} \to W^+W^-Z \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,q\bar{q}$	
411*	$p\overset{(-)}{p} \to ZZW^+ \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\,q\bar{q}$	
412*	$p\overset{(-)}{p} \to ZZW^+ \to q\bar{q}\,\ell_1^+\ell_1^-\ell_2^+\nu_{\ell_2}$	
421*	$p\overset{(-)}{p} \to ZZW^- \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\,q\bar{q}$	
422*	$p\overset{(-)}{p} \to ZZW^- \to q\bar{q}\,\ell_1^+\ell_1^-\ell_2^-\bar{\nu}_{\ell_2}$	
431*	$p\overset{(-)}{p} \to W^+W^-W^+ \to q\bar{q}\,\ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\nu_{\ell_2}$	anomalous couplings
432*	$p\overset{(-)}{p} \to W^+W^-W^+ \to \ell_1^+\nu_{\ell_1}\,q\bar{q}\,\ell_2^+\nu_{\ell_2}$	
441*	$p\overset{(-)}{p} \to W^-W^+W^- \to \ell_1^-\bar{\nu}_{\ell_1}\,q\bar{q}\,\ell_2^-\bar{\nu}_{\ell_2}$	
442*	$p\overset{(-)}{p} \to W^-W^+W^- \to q\bar{q}\,\ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}$	
451*	$p\overset{(-)}{p} \to ZZZ \to q\bar{q}\,\ell_1^-\ell_1^+\ell_2^-\ell_2^+$	
461*	$p\overset{(-)}{p} \to W^+W^-\gamma \to q\bar{q}\,\ell^-\bar{\nu}_\ell\gamma$	
462*	$p\overset{(-)}{p} \to W^+W^-\gamma \to \ell^+\nu_\ell\,q\bar{q}\,\gamma$	
471*	$p\overset{(-)}{p} \to ZZ\gamma \to \ell^-\ell^+\,q\bar{q}\,\gamma$	
481*	$p\overset{(-)}{p} \to W^+Z\gamma \to q\bar{q}\,\ell^-\ell^+\gamma$	
482*	$p\overset{(-)}{p} \to W^+Z\gamma \to \ell^+\nu_\ell\,q\bar{q}\,\gamma$	
491*	$p\overset{(-)}{p} \to W^-Z\gamma \to q\bar{q}\,\ell^-\ell^+\gamma$	
492*	$p\overset{(-)}{p} \to W^-Z\gamma \to \ell^-\bar{\nu}_\ell\,q\bar{q}\,\gamma$	

Table 11: *Process IDs for the triboson production processes at NLO QCD accuracy with semileptonic decays.*

or `--enable-processes=tribosonjet`.

3.13 Higgs production in association with a W

The production of a Higgs boson in association with a W boson proceeds via the production of a single off-shell W boson which radiates the Higgs boson. The W boson decays leptonically, while the Higgs boson can decay in several channels.

In VBFNLO, the processes listed in Table 15 are implemented to NLO QCD accuracy, including full off-shell effects and spin correlations of the final state leptons. Anomalous couplings can be input via `anomV.dat` and are used both in the production process as well as the decay of the Higgs boson. Details of the calculation can be found in Ref. [57].

PROCID	PROCESS	BSM
600	$p\overset{(-)}{p} \to W^+W^-j \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}j$	anomalous HVV couplings
610	$p\overset{(-)}{p} \to W^-\gamma j \to \ell^-\bar{\nu}_\ell\gamma j$	
620	$p\overset{(-)}{p} \to W^+\gamma j \to \ell^+\nu_\ell\gamma j$	
630	$p\overset{(-)}{p} \to W^-Zj \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^-\ell_2^+j$	anomalous couplings
640	$p\overset{(-)}{p} \to W^+Zj \to \ell_1^+\nu_{\ell_1}\ell_2^-\ell_2^+j$	
650	$p\overset{(-)}{p} \to ZZj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-j$	anomalous HVV couplings

Table 12: *Process IDs for diboson production in association with a hadronic jet at NLO QCD with fully leptonic decays.*

PROCID	PROCESS	BSM
601*	$p\overset{(-)}{p} \to W^+W^-j \to q\bar{q}\ell^-\bar{\nu}_\ell j$	
602*	$p\overset{(-)}{p} \to W^+W^-j \to \ell^+\nu_\ell q\bar{q}j$	

Table 13: *Process IDs for diboson production in association with a hadronic jet at NLO QCD with semileptonic decays.*

PROCID	PROCESS	BSM
800	$p\overset{(-)}{p} \to W^+\gamma\gamma j \to \ell^+\nu_\ell\gamma\gamma j$	anomalous couplings
810	$p\overset{(-)}{p} \to W^-\gamma\gamma j \to \ell^-\bar{\nu}_\ell\gamma\gamma j$	

Table 14: *Process IDs for triboson production in association with a hadronic jet at NLO QCD.*

3.14 Higgs production in association with a W and a hadronic jet

WH production in association with a hadronic jet is available at NLO QCD accuracy in VBFNLO under the process IDs of Table 16.

Full off-shell effects and spin correlations of the final state leptons are included. Anomalous couplings can be input via `anomV.dat` and are used both in the production process as well as the decay of the Higgs boson.

ProcId	Process	BSM
1300	$p\overset{(-)}{p} \to W^+H \to \ell^+\nu_\ell H$	
1301	$p\overset{(-)}{p} \to W^+H \to \ell^+\nu_\ell\gamma\gamma$	
1302	$p\overset{(-)}{p} \to W^+H \to \ell^+\nu_\ell\mu^+\mu^-$	
1303	$p\overset{(-)}{p} \to W^+H \to \ell^+\nu_\ell\tau^+\tau^-$	
1304	$p\overset{(-)}{p} \to W^+H \to \ell^+\nu_\ell b\bar{b}$	anomalous gauge couplings
1305	$p\overset{(-)}{p} \to W^+H \to W^+W^+W^- \to \ell_1^+\nu_{\ell_1}\ell_2^+\nu_{\ell_2}\ell_3^-\bar{\nu}_{\ell_3}$	
1306	$p\overset{(-)}{p} \to W^+H \to W^+ZZ \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-\ell_3^+\ell_3^-$	
1307	$p\overset{(-)}{p} \to W^+H \to W^+ZZ \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-\nu_{\ell_3}\bar{\nu}_{\ell_3}$	
1310	$p\overset{(-)}{p} \to W^-H \to \ell^-\bar{\nu}_\ell H$	
1311	$p\overset{(-)}{p} \to W^-H \to \ell^-\bar{\nu}_\ell\gamma\gamma$	
1312	$p\overset{(-)}{p} \to W^-H \to \ell^-\bar{\nu}_\ell\mu^+\mu^-$	
1313	$p\overset{(-)}{p} \to W^-H \to \ell^-\bar{\nu}_\ell\tau^+\tau^-$	
1314	$p\overset{(-)}{p} \to W^-H \to \ell^-\bar{\nu}_\ell b\bar{b}$	anomalous gauge couplings
1315	$p\overset{(-)}{p} \to W^-H \to W^-W^+W^- \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\nu_{\ell_2}\ell_3^-\bar{\nu}_{\ell_3}$	
1316	$p\overset{(-)}{p} \to W^-H \to W^-ZZ \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-\ell_3^+\ell_3^-$	
1317	$p\overset{(-)}{p} \to W^-H \to W^-ZZ \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-\nu_{\ell_3}\bar{\nu}_{\ell_3}$	

Table 15: *Process IDs for the WH production processes at NLO QCD accuracy.*

The virtual contributions of the NLO calculation include diagrams where the Higgs is radiated off a top quark loop attached to a gluon. They are calculated including the full top mass dependence. These contributions can be disabled using the flag `dotoploops` in `utilities/global.inc`[15]. Details of the calculation can be found in Refs. [57, 73].

3.15 QCD-induced production of a vector boson in association with two jets

The QCD-induced production of a vector boson in association with two jets is available in VBFNLO at NLO QCD accuracy, including leptonic decays of the vector boson. The process IDs can be found in Table 17. These processes are not included by default and they have to be enabled at compilation, using the `configure` option `--enable-processes=X` where X is one of `qcdvjj,qcdvvjj,all`. These processes use quadruple precision to handle instabilities in the virtual amplitudes. If quadruple precision is not supported by the compiler it can be disabled by adding the `configure` option `--disable-quad`. An estimate of the error due to unstable points is printed out at the end of program execution.

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[15]Note that, if this parameter is changed, `make clean` must be run in the folder `utilities`, and then `make all install` must be run for the VBFNLO code.

PROCID	PROCESS	BSM
1600	$p\overset{(-)}{p} \to W^+H\,j \to \ell^+\nu_\ell H\,j$	
1601	$p\overset{(-)}{p} \to W^+H\,j \to \ell^+\nu_\ell\gamma\gamma\,j$	
1602	$p\overset{(-)}{p} \to W^+H\,j \to \ell^+\nu_\ell\mu^+\mu^-\,j$	
1603	$p\overset{(-)}{p} \to W^+H\,j \to \ell^+\nu_\ell\tau^+\tau^-\,j$	
1604	$p\overset{(-)}{p} \to W^+H\,j \to \ell^+\nu_\ell b\bar{b}\,j$	anomalous couplings
1605	$p\overset{(-)}{p} \to W^+H\,j \to W^+W^+W^-\,j \to \ell_1^+\nu_{\ell_1}\ell_2^+\nu_{\ell_2}\ell_3^-\bar{\nu}_{\ell_3}\,j$	
1606	$p\overset{(-)}{p} \to W^+H\,j \to W^+ZZ\,j \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-\ell_3^+\ell_3^-\,j$	
1607	$p\overset{(-)}{p} \to W^+H\,j \to W^+ZZ\,j \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-\nu_{\ell_3}\bar{\nu}_{\ell_3}\,j$	
1610	$p\overset{(-)}{p} \to W^-H\,j \to \ell^-\bar{\nu}_\ell H\,j$	
1611	$p\overset{(-)}{p} \to W^-H\,j \to \ell^-\bar{\nu}_\ell\gamma\gamma\,j$	
1612	$p\overset{(-)}{p} \to W^-H\,j \to \ell^-\bar{\nu}_\ell\mu^+\mu^-\,j$	
1613	$p\overset{(-)}{p} \to W^-H\,j \to \ell^-\bar{\nu}_\ell\tau^+\tau^-\,j$	
1614	$p\overset{(-)}{p} \to W^-H\,j \to \ell^-\bar{\nu}_\ell b\bar{b}\,j$	anomalous couplings
1615	$p\overset{(-)}{p} \to W^-H\,j \to W^-W^+W^-\,j \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\nu_{\ell_2}\ell_3^-\bar{\nu}_{\ell_3}\,j$	
1616	$p\overset{(-)}{p} \to W^-H\,j \to W^-ZZ\,j \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-\ell_3^+\ell_3^-\,j$	
1617	$p\overset{(-)}{p} \to W^-H\,j \to W^-ZZ\,j \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-\nu_{\ell_3}\bar{\nu}_{\ell_3}\,j$	

Table 16: *Process IDs for the WH plus jet production processes at NLO QCD accuracy.*

PROCID	PROCESS
3120	$p\overset{(-)}{p} \to Z\,jj \to \ell^+\ell^-\,jj$
3121	$p\overset{(-)}{p} \to Z\,jj \to \nu_\ell\bar{\nu}_\ell\,jj$
3130	$p\overset{(-)}{p} \to W^+\,jj \to \ell^+\nu_\ell\,jj$
3140	$p\overset{(-)}{p} \to W^-\,jj \to \ell^-\bar{\nu}_\ell\,jj$
3150	$p\overset{(-)}{p} \to \gamma\,jj$

Table 17: *Process IDs for QCD-induced vector boson + 2 jet production at NLO QCD accuracy.*

PROCID	PROCESS
3210	$p \overset{(-)}{p} \to ZZ\,jj \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-\,jj$
3211	$p \overset{(-)}{p} \to ZZ\,jj \to \ell_1^+ \ell_1^- \nu_{\ell_2} \bar{\nu}_{\ell_2}\,jj$
3220	$p \overset{(-)}{p} \to W^+ Z\,jj \to \ell_1^+ \nu_{\ell_1} \ell_2^+ \ell_2^-\,jj$
3230	$p \overset{(-)}{p} \to W^- Z\,jj \to \ell_1^- \bar{\nu}_{\ell_1} \ell_2^+ \ell_2^-\,jj$
3240	$p \overset{(-)}{p} \to \gamma\gamma\,jj$
3250	$p \overset{(-)}{p} \to W^+ W^+\,jj \to \ell_1^+ \nu_{\ell_1} \ell_2^+ \nu_{\ell_2}\,jj$
3260	$p \overset{(-)}{p} \to W^- W^-\,jj \to \ell_1^- \bar{\nu}_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2}\,jj$
3270	$p \overset{(-)}{p} \to W^+ \gamma\,jj \to \ell^+ \nu_\ell \gamma\,jj$
3280	$p \overset{(-)}{p} \to W^- \gamma\,jj \to \ell^- \bar{\nu}_\ell \gamma\,jj$
3290	$p \overset{(-)}{p} \to Z\gamma\,jj \to \ell^+ \ell^- \gamma\,jj$
3291	$p \overset{(-)}{p} \to Z\gamma\,jj \to \nu_\ell \bar{\nu}_\ell \gamma\,jj$

Table 18: *Process IDs for QCD-induced diboson + 2 jet production at NLO QCD accuracy.*

3.16 QCD-induced diboson production in association with two jets

The QCD-induced production of two vector bosons in association with two jets is available in VBFNLO at NLO QCD accuracy for the processes listed in Table 18. All spin correlations and finite width effects are included. These processes are not included by default and they have to be enabled at compilation, using the `configure` option `--enable-processes=qcdvvjj` or `--enable-processes=all`. These processes use quadruple precision to handle instabilities in the virtual amplitudes. If quadruple precision is not supported by the compiler it can be disabled by adding the `configure` option `--disable-quad`. An estimate of the error due to unstable points is printed at the end of program execution. Details of the calculation can be found in Refs. [54, 74–79].

3.17 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, are processes that first appear at the one-loop level which, therefore, are counted as leading order in the strong coupling constant. These processes are simulated with the full mass dependence of the top- and bottom-quark[16] running in the loop in the Standard Model, in the (complex) MSSM and in a generic two-Higgs-doublet model. Anomalous HVV couplings (for decays into W or Z bosons) can be input via `anom_HVV.dat` and the input file `ggflo.dat` can be used to define additional settings for these processes. The file `susy.dat`, Sec. 5.4, can be used to specify the supersymmetric parameters when working in the MSSM. The processes are not included by default and they

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[16]The value $m_b(M_H)$ in the $\overline{\text{MS}}$ scheme is used for both the mass and the Yukawa coupling of the bottom quark, while for the top quark we use its on-shell value.

PROCID	PROCESS	BSM
4100	$p\overset{(-)}{p} \to H\,jj$	MSSM, general 2HDM
4101	$p\overset{(-)}{p} \to H\,jj \to \gamma\gamma\,jj$	
4102	$p\overset{(-)}{p} \to H\,jj \to \mu^+\mu^-\,jj$	
4103	$p\overset{(-)}{p} \to H\,jj \to \tau^+\tau^-\,jj$	MSSM
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	$p\overset{(-)}{p} \to H\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\,jj$	MSSM, general 2HDM, anomalous HVV
4107	$p\overset{(-)}{p} \to H\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\,jj$	

Table 19: *Process IDs for LO Higgs boson plus 2 jet production via gluon fusion.*

PROCID	PROCESS	BSM
4200	$p\overset{(-)}{p} \to H\,jjj$	MSSM, general 2HDM

Table 20: *Process ID for LO Higgs boson plus 3 jet production via gluon fusion.*

have to be enabled at compilation, using the `configure` option `--enable-processes=ggf` or `--enable-processes=all`. The relevant process IDs are given in Table 19. Details of the calculations can be found in Refs. [80–85].

3.18 Higgs boson production in gluon fusion with three jets

Adding an extra parton to the Higgs production processes of Sec.3.17 gives rise Hjjj production via gluon fusion. The corresponding cross sections are implemented at LO QCD accuracy. A list of all available modes and corresponding process ID is given in Table 20. These processes are not included by default and they have to be enabled at compilation, using the `configure` option `--enable-processes=ggf` or `--enable-processes=all`. These processes use quadruple precision to handle instabilities in the virtual amplitudes. If quadruple precision is not supported by the compiler it can be disabled by adding the `configure` option `--disable-quad`. An estimate of the error due to unstable points is printed at the end of program execution. Details of the calculation can be found in Refs. [86, 87].

ProcId	Process	BSM
4300	$p\overset{(-)}{p} \to W^+W^- \to \ell_1^+ \nu_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2}$	
4330	$p\overset{(-)}{p} \to ZZ \to \ell_1^- \ell_1^+ \ell_2^- \ell_2^+$	anomalous HVV couplings
4360	$p\overset{(-)}{p} \to Z\gamma \to \ell_1^- \ell_1^+ \gamma$	
4370	$p\overset{(-)}{p} \to \gamma\gamma$	
4301	$p\overset{(-)}{p} \to W^+W^- \to q\bar{q}\,\ell^- \bar{\nu}_\ell$	
4302	$p\overset{(-)}{p} \to W^+W^- \to \ell^+ \nu_\ell\, q\bar{q}$	anomalous HVV couplings
4331	$p\overset{(-)}{p} \to ZZ \to q\bar{q}\,\ell^- \ell^+$	

Table 21: *Process IDs for the gluon-induced diboson production at LO (one-loop) QCD.*

3.19   Gluon-induced diboson production

Gluon-induced diboson production can be studied separately in VBFNLO at LO, using the process IDs in Table 21[17]. Continuum production via box diagrams as well as production via an s-channel Higgs boson resonance are included, with interference effects fully taken into account. Anomalous HVV couplings can be included, using `anom_HVV.dat`. In the loop diagrams, first and second generation quarks are taken to be massless and third generation quark masses[18] are included.

Furthermore, semileptonic decay modes of the vector bosons are implemented for the WW and ZZ production processes [39]. Anomalous HVV couplings are available.

3.20   Gluon-induced diboson production in association with a hadronic jet

Gluon-induced diboson production in association with a hadronic jet can be studied separately in VBFNLO at LO, using the process IDs in Table 22[19]. Continuum production via box and pentagon diagrams as well as production via an s-channel Higgs boson resonance are included, with interference effects fully taken into account. Anomalous HVV couplings can be included, using `anom_HVV.dat`. In the loop diagrams, first and second generation quarks are taken to be massless and third generation quark masses[20] are included. Details of the calculation can be found in Ref. [69].

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[17]These are also included by default as higher order corrections to diboson production.

[18]Again, $m_b(M_H)$ in the $\overline{\text{MS}}$scheme is used.

[19]These are also included by default as higher order corrections to diboson plus jet production.

[20]Again, $m_b(M_H)$ in the $\overline{\text{MS}}$scheme is used.

PROCID	PROCESS	BSM
4600	$p\overset{(-)}{p} \to W^+W^-j \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}j$	anomalous HVV couplings
4601	$p\overset{(-)}{p} \to W^+W^-j \to q\bar{q}\ell^-\bar{\nu}_\ell j$	
4602	$p\overset{(-)}{p} \to W^+W^-j \to \ell^+\nu_\ell q\bar{q}j$	
4650	$p\overset{(-)}{p} \to ZZj \to \ell_1^-\ell_1^+\ell_2^-\ell_2^+j$	anomalous HVV couplings

Table 22: *Process IDs for the gluon-induced diboson production in association with a hadronic jet at LO (one-loop) QCD.*

4 Interfacing and Matching to Herwig 7

VBFNLO's processes have been interfaced via the BLHA accord to the HERWIG 7 event generator [125, 126]. The MATCHBOX module of HERWIG 7 [127] is able to perform the NLO matching using the subtractive (MC NLO-type) and multiplicative (Powheg-type) matching to NLO.

Further to this, all processes can also be used for the (N)LO multi-jet merging as outlined in [128,129]. HERWIG 7 can also be used to perform fixed-order calculations with the VBFNLO matrix elements, if this eases comparison to the matched or merged simulations. Matching and merging systematics can then be addressed as *e.g.* performed in [130,131]. All VBF and VBS processes including leptonic decays, but not the semileptonic modes, have been included.

Note that all the VBF processes are computed in the VBF approximation only, i.e. s-channel contributions and interference between t- and u-channel diagrams, which both are tiny in the VBF region, are neglected. BLHAv1 [123] stipulates that all Born matrix elements are calculated by the Monte Carlo program. Therefore, to prevent inconsistencies, care must be taken that the VBF approximation is also present in the Born matrix elements. In version 2 of the interface [124] all matrix elements are provided by VBFNLO, so in that case this is ensured automatically.

We further note that the parameters such as couplings, masses and widths are supplied as set in the HERWIG input files and that cuts are applied by the MATCHBOX module, as well. Wihtout additional adjustments these different setup modes might result in small differences in between the results obtained from VBFNLO standalone as compared to those produced from HERWIG. An integrator module resembling VBFNLO's MONACO algorithm is also available for MATCHBOX.

Explicit tests of the interface, using a 'tuned' comparison for which all parameters have been made equal for the VBFNLO and HERWIG runs have been performed with HERWIG 7[21] [125]. Example input files are provided in the directory `regress/runs/BLHA` of the source code. Using the BLHA interface and a corresponding Monte Carlo program also allows one to write out VBFNLO events at NLO. The corresponding setup for Herwig is also shown in the example input files mentioned above, and further examples are provided online within the HERWIG tutorials.

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[21]`https://herwig.hepforge.org/`

LINE	DESCRIPTION
`read Matchbox/VBFNLO.in`	HERWIG will use VBFNLO as an OLP
`set PhotonIsolationCut:CutType VBFNLO`	Using the Frixione Isolation cut convention in VBFNLO
`read Matchbox/VBFDiagramsOnly.in`	Lets HERWIG know that only t-channel type diagrams contribute to the process of interest
`read Matchbox/VBFNLOPhasespace.in`	Uses the VBFNLO phasespace

Table 23: Summary of relevant lines in the HERWIG input card concerning VBFNLO with a brief description of their effect.

4.1 Usage

If HERWIG 7 is installed using the `herwig-bootstrap` [22], VBFNLO will be directly available. To use a local build of VBFNLO instead, the flag `--with-VBFNLO=PATH` can be passed to the `herwig-bootstrap` or during the configuration step in the HERWIG compilation.

HERWIG 7.3 expects VBFNLO 3.0 to have a custom BLHA interface where _VBFNLO have been appended to the standard BLHA functions. For this reason, if you compile VBFNLO from source and expect to use it with HERWIG 7.3 through the BLHA interface, the --enable-custom-blha flag has to be added to the VBFNLO configuration. Trying to compile HERWIG 7.3 with VBFNLO 3.0 without this flag will result in a compilation error.

To use VBFNLO as an amplitude provider, the line `read Matchbox/VBFNLO.in` has to be included in the HERWIG input file. The cuts for the process need to be set in HERWIG and are automatically passed to VBFNLO. If a Frixione Isolation cut has to be set, the line `set PhotonIsolationCut:CutType VBFNLO` will need to be provided. The VBF processes inside VBFNLO are calculated in the VBF approximation. Telling HERWIG to not include s-channel contributions, which are ignored in the VBF approximation, can be done with `read Matchbox/VBFDiagramsOnly.in`.

The BLHA states that the MC has to drive the process generation while the OLP has to give the amplitudes asked. In the interface between VBFNLO and HERWIG, an extension allowing the use of the VBFNLO phasespace has been implemented. To use the VBFNLO phasespace generator, which improves the convergence, we have to add `read Matchbox/VBFNLOPhasespace.in` to the HERWIG input card.

A summary of the relevant lines concerning VBFNLO with a brief description of their effect may be found in Table 23. A HERWIG input card, ready to use VBFNLO as an amplitude provider, can be found in the `share/VBFNLO` folder. It is recommended to start

---

[22]https://herwig.hepforge.org/tutorials/installation/bootstrap.html

from that input card, which can be copied to the run folder, and make the appropriate changes for the required process. For HERWIG to be able to access the libraries required and to be able to call the `Herwig` command from any folder, the pertinent environment variables must be set. If the installation was done with the `herwig-bootstrap`, it can be done with `source ${INSTALLDIR}/bin/activate`.

The process is built with the command line `Herwig build {inputcardname}`, which creates a `{runfilename}` file that is used to generate the events. Before the generation step, the phasespace grid has to be optimized with `Herwig integrate {runfilename}`. This step can be parallelized using the flag `--maxjobs={numberofjobs}` which will create integration jobs that can be integrated separately with `Herwig integrate --jobid=n {runfilename}`, where `n` is the identification number assigned to the integration job, and merged afterwards with `Herwig mergegrids`. Then, the event generation is started with `Herwig run {runfilename}`.

As an example, if our input card is named `LHC-Matchbox.in` and creates a runfile named `LHC.run`, the following commands

```
Herwig build --maxjobs=10 LHC-Matchbox.in
for i in $(seq 0 9)  do Herwig integrate --jobid=$i LHC.run & done
Herwig mergegrids
Herwig run LHC.run
```

will create 10 different integration jobs, merge the grids after the integration has finished and make an event generation run.

The comparison with VBFNLO standalone can be performed by turning off the parton shower, hadronization and MPI in HERWIG, and using the same cuts and parameters in both programs. To help with the possible difficulties with the last step, curated input cards for VBFNLO and HERWIG can be found inside `VBFNLO/regress/runs` and `VBFNLO/regress/runs/BLHA` respectively.

5 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 gluon-fusion induced processes.

- `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.

- `spin2coupl.dat`: Settings for the spin-two models.

- `histograms.dat`: Histogram options.

- `random.dat`: Seed for the random number generator.

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

5.1 `vbfnlo.dat`

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

5.1.1 `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-induced 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 [88]:

$$
\begin{array}{rcl}
11 & : & e^- \\
12 & : & \nu_e \\
13 & : & \mu^- \\
14 & : & \nu_\mu \\
15 & : & \tau^- \\
16 & : & \nu_\tau \\
98 & : & \text{leptons are either generation 1 or generation 2} \\
99 & : & \text{any lepton}
\end{array}
$$

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The ordering of particles is not important. If the selected configuration is not available, the appropriate first-generation leptons are used as default values. If 99(98) is set, results are output summed over all possible lepton combinations (all possible lepton combinations of generation 1 or 2) – for individual events (in the cuts, histograms and Les Houches event output) the specific leptons for that particular event are generated randomly.

- DECAY_QUARKS: Choice of the final state quarks from hadronic vector boson decays (decay products of W and Z bosons) according to the MC particle numbering scheme [88]:

$$
\begin{array}{rcl}
1 & : & d \\
2 & : & u \\
3 & : & s \\
4 & : & c \\
5 & : & b \\
93 & : & \text{all possible combinations of } u, \bar{u}, d, \bar{d}, s, \bar{s}, c, \bar{c} \\
94 & : & \text{all possible combinations of } u, \bar{u}, d, \bar{d}, s, \bar{s}, c, \bar{c}, b, \bar{b}
\end{array}
$$

If 93 is set, results are output summed over all possible quark / anti-quark combinations of the first and second generation. For DECAY_QUARKS = 94 additionally b and $\bar{b}$ are considered. For individual events in the Les Houches event output, the specific quarks for that particular event are generated randomly, weighted by the contribution of that specific quark combination. If the selected configuration is not available, all possible combinations of first and second generation quarks are used as default values (DECAY_QUARKS = 93).

- 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[23]. 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[24]. Default is $N = 20$.

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

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

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

- **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 in the working directory. If a grid file `name` is already present in the input directory (specified by `--input=INPUT`), the program reads in this file when executed. Note that some optimised grids for several processes (using the standard cuts given in the `regress` files) are provided on the VBFNLO webpage.

- **FLOOP_GRID:** Similar to `LO_GRID`, but for the gluon-induced fermion loop contributions (the kinematics of which can differ significantly from the LO kinematics). The number of iterations used is given by `LO_ITERATIONS` and the number of points used is `LO_POINTS-8`.

- **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 LOOP-TOOLS was enabled at compilation. Default is set to `false`.

- **FERMIONLOOP:** Flag for the gluon-induced fermionic loop processes, such as $gg \rightarrow WW$ (currently only available for neutral diboson processes in the ranges 300-370 and 4300-4370). The options are:

  - `0` switches off these processes
  - `1` includes only the box contribution
  - `2` includes only diagrams via an s-channel Higgs resonance
  - `3` includes both contributions including interference effects.

  The default value is `3` (all contributions included).

- **NLO_SEMILEP_DECAY:** This flag defines how the hadronic decay in processes with semileptonic vector boson decay should be calculated:

  - `0` the hadronic decay $V \rightarrow q\bar{q}$ is calculated at leading order QCD
  - `1` the hadronic decay $V \rightarrow q\bar{q}$ is calculated including approximate next-to leading order QCD effects: A factor of [89]

  $$1 + \frac{\alpha_s(Q^2)}{\pi}$$

  is applied to the full cross section (including off-shell and singly or non-resonant contributions), which reproduces the NLO corrections for the on-shell $V \rightarrow q\bar{q}$ decay. The real emission of a gluon is not resolved.

  The default value is `0` (leading order calculation for the decay).

- **ECM:** The center-of-mass energy, $\sqrt{s}$, of the collider, measured in GeV. Default is 13000 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 24 for a list of available options. Default is 0.
  For the QCD-induced processes, the following definitions are used (the momentum of the gauge boson system is reconstructed from the momenta of the corresponding fermions in the final state):

$$H_T = \sum_{i \in \text{partons}} p_{T,i} + E_T(V_1) + E_T(V_2), \tag{2}$$

$$H_T' = \sum_{i \in \text{jets}} p_{T,i} e^{|y_i - y_{12}|} + E_T(V_1) + E_T(V_2), \tag{3}$$

with

$$E_T = \sqrt{p_T^2 + m^2}, \quad \text{and} \quad y_{12} = \frac{1}{2}(y_1 + y_2).$$

- **ID_MUR:** Choice of the renormalization scale. See Table 25 for a list of available options. Default is 0.
  For the QCD-induced processes the definitions of Eqs. (2) and (3) are used.

- **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.F90`.

5.1.2 vbfnlo.dat − **physics parameters**

- **HMASS:** Standard Model Higgs boson mass in GeV. Default value is 126 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.)

ID_MUF	Factorization Scale	Process class
0	user defined constant scale set by MUF_USER	all
1	momentum transfer of exchanged gauge boson	vbf (except Hjjj)
2	$\min(p_{\mathrm{T}}(j_i))$	vbf, tribosonjet
3 or 4	invariant mass of the electroweak system $(V \ / \ VV \ / \ VH \ / \ VVV)$	diboson, dibosonjet, triboson, tribosonjet
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 the "primary" bosons	diboson (except W), dibosonjet, triboson, tribosonjet
8	$\frac{1}{2} H_T$ as defined in Eq. (2)	vbf,qcdvjj,qcdvvjj
9	$\frac{1}{2} H'_T$ as defined in Eq. (3)	vbf,qcdvjj,qcdvvjj
10	$\frac{1}{2} \left(E_T(j_1 j_2) + E_T(V/VV) \right)$	vbf,qcdvjj,qcdvvjj
11	$E_T(V/VV)$	vbf,qcdvjj,qcdvvjj
12	$\sqrt{p_{\mathrm{T}}(j_1) \times p_{\mathrm{T}}(j_2)}$	vbf,qcdvjj,qcdvvjj

Table 24: *Factorization scale options. The definition of the process classes can be found in Section 2.2.*

Note that for HTYPE = 1-3, the input HMASS is not used. Default value is 0 (SM Higgs boson).

- HSCHEME: Distribution of Higgs boson produced (VBF-H only, process IDs 100-117,1010).

  - HSCHEME = 0 : on-shell
  - HSCHEME = 1 : Breit-Wigner distribution
  - HSCHEME = 2 : Passarino CPS scheme [30, 31]

  Default value is 0 (on-shell).

- HWIDTH: Although VBFNLO can calculate the Higgs total and partial widths, it is also possible to set the Higgs boson width with this input parameter. Default is

ID_MUR	RENORMALIZATION SCALE	PROCESS CLASS
0	user defined constant scale set by MUR_USER	all
1	momentum transfer of exchanged gauge boson	vbf (except Hjjj)
2	$\min(p_{\mathrm{T}}(j_i))$	vbf, tribosonjet
3 or 4	invariant mass of the electroweak system $(V \; / \; VV \; / \; VH \; / \; VVV)$	diboson, dibosonjet, triboson, tribosonjet
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 the "primary" bosons	diboson (except W), dibosonjet, triboson, tribosonjet
8	$\frac{1}{2}H_T$ as defined in Eq. (2)	vbf,qcdvjj,qcdvvjj
9	$\frac{1}{2}H_T'$ as defined in Eq. (3)	vbf,qcdvjj,qcdvvjj
10	$\frac{1}{2}\left(E_T(j_1j_2) + E_T(V/VV)\right)$	vbf,qcdvjj,qcdvvjj
11	$E_T(V/VV)$	vbf,qcdvjj,qcdvvjj
12	$\sqrt{p_{\mathrm{T}}(j_1) \times p_{\mathrm{T}}(j_2)}$	vbf,qcdvjj,qcdvvjj

Table 25: *Renormalization scale options. The definition of the process classes can be found in Section 2.2.*

-999 GeV, which means that the internally calculated value of the width is used. A value of -998 GeV uses the value by the LHC HXSWG [90]. If a SLHA file is being used, the SLHA value will be taken rather than the input HWIDTH.

- MODEL: This flag determines whether we are working in the SM (1), the MSSM (2) or the Two-Higgs model (3). 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.

- H2MASS: Mass of the second Higgs boson for MODEL = 3. Default value is 126 GeV.

- H2WIDTH: Width of the second Higgs boson for MODEL = 3. Default is -999 GeV, which means that an internally calculated value of the width is used.

- `SIN2BA`: Multiplicative factor for the squared HVV-coupling of the first Higgs boson for `MODEL = 3`. Default value is 1.

- `COS2BA`: Multiplicative factor for the squared HVV-coupling of the second Higgs boson for `MODEL = 3`. Note that unitarity requires that `SIN2BA + COS2BA = 1`. Default value is -999, which means that the value which fulfills the unitarity relation is chosen.

- `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 processes and gluon-induced contributions to diboson production, $m_b(M_H)$ in the $\overline{\text{MS}}$scheme is used (which is calculated internally from the input pole mass). Default value is 4.855 GeV, which corresponds to $m_b^{\overline{\text{MS}}}(m_b) = 4.204$ 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 $m_c^{\overline{\text{MS}}}(m_c) = 1.273$ GeV. If a SLHA file is being used, the SLHA value will be taken rather than the input `CHARMMASS`.

- `TAU_MASS`: Tau mass in GeV used in the calculation of the Higgs boson width and branching ratios. Default value is 1.77684 GeV. If a SLHA file is being used, the SLHA value will be taken rather than the input `TAU_MASS`.

- `EWSCHEME`: Sets the scheme for the calculation of electroweak parameters. A summary of the six available options is given in Table 26. Note that if `EWSCHEME = 4` is chosen, all variables in Table 26 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. Full details of all changes and their effects, together with the explicit formulae used, are available on the VBFNLO webpage. Default value is 3.

- `FERMI_CONST`: Fermi constant, used as input for the calculation of electroweak parameters in `EWSCHEME` = 1-4. 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`.

- `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 26. 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.

EWSCHEME	PARAMETER	DEFAULT VALUE	INPUT/CALCULATED
1	FERMI_CONST INVALFA SIN2W WMASS ZMASS	1.16637×10^{-5} GeV^{-2} 128.944341122 0.230990 79.9654 GeV 91.1876 GeV	INPUT INPUT CALCULATED CALCULATED INPUT
2	FERMI_CONST INVALFA SIN2W WMASS ZMASS	1.16637×10^{-5} GeV^{-2} 132.340643024 0.222646 80.3980 GeV 91.1876 GeV	INPUT CALCULATED INPUT CALCULATED INPUT
3	FERMI_CONST INVALFA SIN2W WMASS ZMASS	1.16637×10^{-5} GeV^{-2} 132.340705199 0.222646 80.3980 GeV 91.1876 GeV	INPUT CALCULATED CALCULATED INPUT INPUT
4	FERMI_CONST INVALFA SIN2W WMASS ZMASS	1.16637×10^{-5} GeV^{-2} 137.035999679 0.222646 80.3980 GeV 91.1876 GeV	INPUT INPUT INPUT INPUT INPUT
5	INVALFA(ZMASS) SIN2W WMASS ZMASS	128.944341122 0.222646 80.3980 GeV 91.1876 GeV	INPUT CALCULATED INPUT INPUT
6	INVALFA(0) SIN2W WMASS ZMASS	137.035999679 0.222646 80.398 GeV 91.1876 GeV	INPUT CALCULATED INPUT INPUT

Table 26: *Electroweak input parameter schemes.*

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

$$\alpha(M_Z) = \frac{\alpha(0)}{1 - \Delta\alpha} \tag{4}$$

  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. Anomalous coupling parameters are set via the files `anom_HVV.dat` and `anomV.dat`. These are available for

  - Hjj, single and double vector production processes in VBF
  - diboson production processes, including WH
  - diboson + jet production processes, including WHj
  - triple vector boson production processes
  - triboson + jet production processes
  - $Hjj \to VVjj$ production via gluon fusion
  - gluon-induced (contributions to) diboson production

  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 except $W\gamma$ and same sign $W^\pm W^\pm$ production 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`. Kaluza-Klein parameters are specified via the files `kk_input.dat` or `kk_coupl_inp.dat`.

- `SPIN2`: Option for the spin-2 models. This is available for the $VVjj$ production modes in VBF except same sign $W^\pm W^\pm$ production. Default is set to `false`. Spin-2 parameters are set via the file `spin2coupl.dat`.

- `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.

5.1.3 `vbfnlo.dat` − parameters for event output

VBFNLO generates parton level events according to the most recent Les Houches Accord (LHA) format [91] and in the HEPMC format [92] for all processes at leading order, except for $W\gamma j$, WZj and $W\gamma\gamma j$ production. For $WH(j)$ production the event output is only available in the case of a non-decaying Higgs boson.

- **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 or triboson 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 or triboson 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 `true`.

- **DESIRED_EVENT_COUNT**: With `UNWEIGHTING_SWITCH = true`, the number of unweighted events written out to disk can be specified. For multi-channel processes (for example diboson / triboson production with a final-state photon) this can be time-consuming.
  `DESIRED_EVENT_COUNT = 0` stands for collecting all events generated during the normal integration (behaviour of VBFNLO up to version 2.7 beta 2).
  Default is `DESIRED_EVENT_COUNT = 0`.

- **PARTIAL_UNWEIGHTING:** For some processes or parameter settings it may not be possible to get the desired number of unweighted events: Single events with large weights in some problematic phase space regions can spoil the unweighting efficiency. For this case `PARTIAL_UNWEIGHTING = true` will give the desired number of events with weight 1 and additionally a few events with weight > 1 which occured during the event generation.
  Default is `PARTIAL_UNWEIGHTING = false`.

- **TAUMASS:** Option to include the mass of τ leptons in the event files. Default is set to `false`.
  All calculations (except for branching ratios) are done with massless τ leptons. However, as subsequent programs need the non-zero mass for the τ decay, VBFNLO can include the τ mass in the output and rescale the momentum consistently. The τ leptons in the events have to fulfill $m_{\tau\tau} > 2 \cdot m_\tau$ and $m_{\tau\nu_\tau} > m_\tau$, otherwise the inclusion of m_τ is not possible. All events where this requirement is not fulfilled will be dismissed. Usually this criterium should be always met when using reasonable cuts. To ensure that no events are thrown away please use a cut on the invariant lepton pair mass of at least $m_{\ell\ell} > 2\, m_\tau$.

Important note for processes with more than one phase space (usually processes involving a final state photon):
VBFNLO writes the events of different phase spaces block-wise into the event file. Therefore the event file should always be used completely, otherwise some parts of phase space are underrepresented. Using only parts of the event file gives only correct results if the events are taken randomly from the whole file. This note is put out at the end of the VBFNLO run for the relevant processes if event output is requested.

5.1.4 `vbfnlo.dat` − **PDF parameters**

VBFNLO can use either built-in parton distribution functions (PDFs) or the LHAPDF [5] library, either in version 5 or 6.

- **PDF_SWITCH:** Flag to choose which PDFs are used. The options are

  - `0` : built-in PDFs CT18 [14]
  - `1` : an interface to LHAPDF is provided
  - `2` : built-in PDFs MRST2004qed [17] 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)
  - `3` : the built-in PDFs MSTW2008 [18] are used

  Default is 0.

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

- **LO_PDFNAME:** Name of the LO PDF set.

- **NLO_PDFNAME:** Name of the NLO PDF set.

- **LO_PDFMEMBER:** Member PDF of the LO PDF set. Default is 0.

- `NLO_PDFMEMBER`: Member PDF of the NLO PDF set. Default is 0.

The names of the PDF sets can be found on the LHAPDF website[25]. In case of LHAPDF 6 the file ending (`.LHgrid`/`.LHpdf`) is no longer needed, but using the LHAPDF 5 naming scheme is still supported. The list of PDF sets which are already available in LHAPDF 6 can be obtained from the LHAPDF website as well[26]. The PDF name can also be obtained from the file `PDFsets.index`, which is located in the LHAPDF 5 subfolder `share/lhapdf`[27].

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.

- `NLO_PDFSET`: LHAGLUE number for the NLO PDF set.

The LHAGLUE numbers can be found on the LHAPDF website[25] or in the file `PDFsets.index`, which is located in the LHAPDF 5 subfolder `share/lhapdf`[27].

5.1.5 `vbfnlo.dat` − parameters for output and histograms

VBFNLO provides output for histograms in the following formats: GNUPLOT[28], ROOT[29] and TOPDRAWER[30], as well as raw data tables. Options controlling the histogram ranges and smearing are defined in `histograms.dat`. Additional histograms can be defined by the user in the file `utilities/histograms.F`.

- `XSECFILE`: Name of output file containing LO and NLO cross sections with the associated errors. Default is `xsection`.

- `ROOT`: Enable output of histograms in ROOT format. Default is set to `false`. Additionally, custom ROOT histograms can be defined by the user with the file `utilities/rootuserhists.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. Additionally, a GNUPLOT command file is written into the data output directory. 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`.

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[25]https://lhapdf.hepforge.org/pdfsets
[26]https://www.hepforge.org/archive/lhapdf/pdfsets/6.0/
[27]When using LHAPDF 6 this file is located at `<LHAPDF-PATH>/share/LHAPDF/pdfsets.index` .
[28]http://www.gnuplot.info/
[29]https://root.cern.ch/
[30]https://www.pa.msu.edu/reference/topdrawer-docs/

5.2 `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`.

A brief documentation on how to implement additional cuts into the file `cuts.F` can be found on the VBFNLO webpage, `https://ific.uv.es/vbfnlo/` .

5.2.1 `cuts.dat` − 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 [93] that combines all partons. Default is 0.8.

- `Y_P_MAX`: Maximum allowed (pseudo)rapidity[31] 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 [94] for 0 and the anti-$k_\perp$ algorithm [95] 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.

5.2.2 `cuts.dat` − lepton specific cuts

- `Y_L_MAX`: Maximum (pseudo)rapidity for charged leptons. Default is 2.5.

- `PT_L_MIN`: List of minimum transverse momenta for charged leptons in descending order. The later values can be omitted if they are the same as previous values. Default is 10 GeV.

- `MLL_MIN`: Minimum invariant mass for pairs of charged leptons. Whether this applies only to opposite-sign leptons or to all pairs is chosen by the variable `MLL_OSONLY`. Default is 15 GeV.

- `MLL_MAX`: Maximum invariant mass for pairs of charged leptons. Whether this applies only to opposite-sign leptons or to all pairs is chosen by the variable `MLL_OSONLY`. Default is 10^{20} GeV.

- `MLL_OSONLY`: If set to `true`, the variables `MLL_MIN` and `MLL_MAX` only apply to pairs of oppositely signed leptons, otherwise to all pairs of charged leptons. Default is `true`.

- `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.

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[31]As all quarks and leptons are considered massless in VBFNLO, pseudorapidity and rapidity coincide for almost all final state particles, with one exception: Jets which consist of more than one parton have a non-vanishing mass and therefore rapidity $\neq$ pseudorapidity.

5.2.3 `cuts.dat` − photon specific cuts

- `Y_G_MAX`: Maximum (pseudo)rapidity for photons. Default is 1.5.

- `PT_G_MIN`: List of minimum transverse momenta for photons in descending order. The later values can be omitted if they are the same as previous values. 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.

VBFNLO has a photon isolation cut implemented as defined in Ref. [35],

$$\sum_i E_{T_i} \theta(\delta - R_{i\gamma}) \leq \epsilon \, p_{T_\gamma} \left(\frac{1 - \cos\delta}{1 - \cos\delta_0} \right)^n \quad \text{for all } \delta < \delta_0 \,, \tag{5}$$

where i is a parton with transverse energy E_{T_i} and a separation $R_{i\gamma}$ with a photon of transverse momentum $p_{T\gamma}$. The parameters δ_0 and ϵ can be adjusted:

- `PHISOLCUT`: Photon isolation δ_0. Default is 0.7.

- `EFISOLCUT`: Efficiency ϵ of photon isolation cut. Default is 1.

- `EXISOLCUT`: Exponent n of the photon isolation cut. Default is 1.

5.2.4 `cuts.dat` − 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.

- `MLG_MIN`: Minimum invariant mass for any combination of a charged lepton and a photon. Default is 0 GeV.

- `MLG_MAX`: Maximum invariant mass for any combination of a charged lepton and a photon. Default is 14 TeV.

- `PTMISS_MIN`: Minimum missing transverse momentum of the event

$$p_T^{miss} = -\sum_i p_{T,i} \,,$$

summing over all visible jets, leptons and photons. Default is 0 GeV.

- `MJ_WINDOWV`: To exclude jet/dijet/trijet masses with $|m_{\text{jets}} - (M_W + M_Z)/2|$ smaller than this cut value. Default is 0 GeV. M_W and M_Z are the physical masses here.

5.2.5 `cuts.dat` − jet veto

- `JVETO`: If set to `true`, a jet veto is applied. For processes with fully leptonic decays of the vector bosons the following criteria apply:

  - For `vbf` and `ggf` processes it is applied to central jets beyond the two tagging jets, where the central region is bounded by the rapidities of 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.

  For processes with one hadronically decaying vector boson, one or two additional jets are allowed, depending on the value of `SINGLE_DECAYJET` (one jet for `SINGLE_DECAYJET = 2`, else two jets).
  Default is `false`.

- `YMAX_VETO`: Maximum rapidity 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.

5.2.6 `cuts.dat` − VBF specific cuts

These cuts apply only to `vbf`, `qcdv(v)jj` and `ggf` processes. Furthermore, they apply to the processes with semileptonic decays if `VBFCUTS_ALWAYS = true`.

- `ETAJJ_MIN`: Minimum required rapidity gap, $\Delta\eta_{jj}$, between two tagging jets, which are the two leading jets in a p_T ordering for fully leptonically decaying vector bosons. For tagging jet definition in semileptonic decay processes see `DEF_TAGJET`. 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 0 GeV.

- `MDIJ_MAX`: Maximum dijet invariant mass of two tagging jets. Default is 10^{20} GeV.

5.2.7 `cuts.dat` – special cuts for semileptonic decays

These cuts apply only to processes with one hadronically decaying vector boson.

- `DEF_TAGJET`: Switch for different tagging jet definitions.

  - `DEF_TAGJET = 1`: two jets with largest p_T
  - `DEF_TAGJET = 2`: two jets with largest p_T and $|y| >$ `ETA_CENTRAL`. Furthermore both jets have to lie in opposite detector hemispheres.
  - `DEF_TAGJET = 3`: two jets with largest separation in rapidity
  - `DEF_TAGJET = 4`: two jets with largest p_T, except for the two jets (or one jet if `SINGLE_DECAYJET > 0` and the mass of a single jet is closer to m_V than any two-jet combination) with an invariant mass closest to m_V.

  Default is 1.

- `ETA_CENTRAL`: Defines the outer limit of the "central region" if `DEF_TAGJET = 2`. For other values of `DEF_TAGJET` the "central region" is defined by the rapidity values of the two tagging jets. Default is 2.

- `PTMIN_TAG_1`: Minimum transverse momentum for the harder tagging jet. Default is 20 GeV.

- `PTMIN_TAG_2`: Minimum transverse momentum for the softer tagging jet. Default is 20 GeV.

- `HARD_CENTRAL`: If set to `true` an additional jet is required within the central region. Default is `false`.

- `PTMIN_CENTRAL`: Minimum transverse momentum for the additional hard jet in the central region if `PTMIN_CENTRAL = true`. Default is 20 GeV.

- `VBFCUTS_ALWAYS`: Usually the VBF cuts are only applied for VBF processes. With `VBFCUTS_ALWAYS = true`, the VBF cuts are applied to the semileptonic diboson and triboson production processes as well, as they supplement the s-channel part of the electroweak $V(V)jj$ production to the VBF processes.
  Default is `false`.

- `RECONST_HAD_V`: Choose between different options for a cut on the reconstructed invariant mass of the hadronically decaying vector boson. All possible jet combinations are taken into account, the one which gives an invariant mass closest to the vector boson mass is used to apply the cut.

  - `RECONST_HAD_V = 0`: No cut on the reconstructed invariant vector boson mass.
  - `RECONST_HAD_V = 1`: Use two-jet invariant mass, tagging jets are not considered.
  - `RECONST_HAD_V = 2`: Use invariant mass of a single jet, tagging jets are not considered ("subjet-analysis", only needed when `SINGLE_DECAYJET > 0`).
  - `RECONST_HAD_V = 3`: Use one- or two-jet invariant mass, tagging jets are not considered.

Default is 0.

- **V_MASS_RANGE:** Mass range for the cut on the reconstructed invariant vector boson mass: `|m_V - m_reconst| < V_MASS_RANGE`. Default is 20 GeV.

- **SINGLE_DECAYJET:** This switch controls the number of additional jets which is required for processes with semileptonic decay of the vector bosons with respect to the fully leptonic process:

  - **SINGLE_DECAYJET = 0:** two jets are required from the hadronic decay (plus two tagging jets for the VBF processes).
  - **SINGLE_DECAYJET = 1:** a single jet is allowed if both quarks from the hadronic decay are collimated into one jet.
  - **SINGLE_DECAYJET = 2:** a single jet is allowed for all phase space points.

  `SINGLE_DECAYJET = 2` can only be used with `LOPROCESS_PLUS_JET` set to `false` in `vbfnlo.dat`.
  Default is 0.

- **QSQAMIN_ZDEC:** Minimal photon virtuality of hadronically decaying Z/γ^*.
  Default is 0 GeV^2. However, any values below the Q^2 threshold (see Section 5.2.8) for u/d-quarks of $(0.373\,\text{GeV})^2$ have no effect.
  As the Higgs boson does not couple directly to photons, no special treatment or cut is needed for process 1010. Therefore `QSQAMIN_ZDEC` is not evaluated there.

5.2.8 Treatment of hadronic decays of low-virtuality photons

As the hadronic decay of a Z boson also includes the hadronic decay of photons, a divergence in $\gamma^* \to q\bar{q}$ occurs, when the final state quarks are treated massless and no cuts are applied. In the case of the semileptonic decays within VBFNLO, this can lead to problems in two cases:

- In the real emission case with one additional visible jet from QCD radiation both decay quarks are allowed to form a single jet.

- This can also happen already at leading order, when `SINGLE_DECAYJET` is set to `true`.

Therefore we apply a cut on the minimal photon virtuality, which is estimated from $e^+e^- \to$ hadrons individually for each final state quark flavour. The threshold for each quark is chosen such that the NLO approximation for $\sigma(e^+e^- \to$ hadrons$)$ gives the same contribution as the experimental continuum data plus the contribution from the sharp resonances of the respective quark flavours [96].
This procedure approximates the correct rates from low-q^2 photons. The kinematics of the quarks in this region are not modeled correctly, but this is of minor importance as the low-q^2 region is only relevant for semileptonic decays when the decay products form a single jet.
Unfortunately, this procedure can cause problems when interfacing VBFNLO with a parton shower Monte Carlo program by using the Les Houches event output without jet cuts or with `SINGLE_DECAYJET = true`. Events which involve $q\bar{q}$ pairs with an invariant mass

below 1 GeV or below $2 \cdot m_q$ may be dismissed by the parton shower Monte Carlo. This can be avoided by using the option `QSQAMIN_ZDEC`.

5.3 `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 [85]. 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[32]. 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.

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 a quark-quark initial state are included. Default is set to `true`.

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

- `SUBPRGG`: Switch that determines whether the subprocesses with a 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 1d0.
    - `CP_ODD_MOD`: Changes the strength of the $\mathcal{CP}$-odd coupling. Default is set to 1d0.

---

[32]The bottom quark mass is taken as $m_b(M_H)$ in the $\overline{\text{MS}}$scheme.

using the Lagrangian

$$\mathcal{L}_{\text{Yukawa}} = \overline{q} \left(C_{\text{even}} \, y_q + \mathrm{i} \, C_{\text{odd}} \, \gamma_5 \, \tilde{y}_q \right) q \, \Phi \tag{6}$$

with $C_{\text{even}} = \texttt{CP\_EVEN\_MOD}$ and $C_{\text{odd}} = \texttt{CP\_ODD\_MOD}$ and

$$
\begin{aligned}
y_b &= \tilde{y}_b = \frac{1}{v} m_b \tan \beta \\
y_t &= \tilde{y}_t = \frac{1}{v} m_t \cot \beta \, .
\end{aligned}
\tag{7}
$$

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 to fermions or photons are included. The option $\texttt{HIGGS\_MIX = 2}$ 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

$$h_i = Z_{ih} \, h_{\text{MSSM}} + Z_{iH} \, H_{\text{MSSM}} + Z_{iA} \, A_{\text{MSSM}} \, , \tag{8}$$

where $i = \texttt{HTYPE}$.

5.4 `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 100-107 (Higgs boson plus 2 jet production via VBF), processes 110-117 (Higgs boson plus 3 jet production via VBF), processes 2100-2107 (production of a Higgs boson in association with a photon and 2 jets via VBF) and gluon fusion processes 4100-4107. In particular, the electroweak corrections to Higgs boson production via VBF are affected by the inputs of `susy.dat`. As stated earlier, the Higgs boson contributions to the production of 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[33].

---

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

- `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:

  - `0`: User-input scenario (see below for further inputs)
  - `1`: M_h^{max} scenario [97]
  - `2`: No-mixing scenario [97]
  - `3`: Gluophobic scenario [97]
  - `4`: Small α_{eff} scenario [97]
  - `5`: CPX scenario [98]
  - `10`: SPS1a[34] [99]
  - `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 [38].

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

- `MH_LOOPS`: Flag determining the value of the internal Higgs masses used in the electroweak loops:

  - `0`: Tree level Higgs masses used in loops.
  - `1`: Corrected Higgs masses used in loops.

- `LOOPSQR_SWITCH`: Flag determining whether the squared contributions of the electroweak corrections from the (s)fermion sector will be included – i.e. if set to `true` the amplitude is given by:

$$|\mathcal{M}_{\mathrm{Born}}|^2 + 2\Re\left[\mathcal{M}_{\mathrm{Born}}^* \mathcal{M}_{loop}\right] + |\mathcal{M}_{\mathrm{(s)fermion\ loop}}|^2 \tag{9}$$

  Note that the loop squared component is only added if $|\mathcal{M}_{\mathrm{(s)fermion\ loop}}|$ is greater than 10% of $|\mathcal{M}_{\mathrm{Born}}|$. Default is set to `true`.

---

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

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[35]. 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):

- `M3SQ` etc.: The soft SUSY breaking parameters for the sfermion section.

- `AT` etc.: Trilinear coupling parameters.

- `MUE`: Higgs boson mixing parameter.

- `M_1` etc.: Gaugino mass parameters.

By default, lower generation parameters are set to the corresponding higher generation parameters – e.g. `Ac = At`.

5.5 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. Anomalous HVV couplings are also included in gluon-induced diboson (plus jet) production (processes 430x, 433x, 4360, 4370, 4600, 4650 and processes 30x, 33x, 360, 370, 600 and 650), as well as in gluon fusion processes $Hjj \to VVjj$ (IDs 4105-7). The anomalous HVV couplings can be specified in the `anom_HVV.dat` input file.

Anomalous triple and quartic gauge boson couplings are available for single and double vector boson production via VBF (process IDs 120-150, 200-291) [100,101], all triple vector boson production processes (process IDs 400-530, 800, 810) [101,102], diboson production WW, $W^\pm\gamma$, $W^\pm Z$ and WH (process IDs 300-323, 340-350, 1300-1317) [57,58] and for diboson plus jet processes $W^\pm\gamma j$ [66], $W^\pm Zj$ [65] and WHj [57] (IDs 610-640, 1600-1617). The respective parameters are set in the input file `anomV.dat`. Note, however, that not all parameters in `anomV.dat` affect all processes and no neutral triple gauge boson couplings are included. By altering the triple gauge boson couplings (in `anomV.dat`), the couplings between a Higgs and a pair of gauge bosons are also affected – these changes are taken into account automatically for internal and external Higgs bosons occurring in these processes (and during the Higgs width calculations).

---

[35]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.

5.5.1 `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 parametrizations.

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

$$
\begin{aligned}
\mathcal{L} = & \frac{g_{5e}^{HZZ}}{2\Lambda_5} H Z_{\mu\nu} Z^{\mu\nu} + \frac{g_{5o}^{HZZ}}{2\Lambda_5} H \widetilde{Z}_{\mu\nu} Z^{\mu\nu} + \frac{g_{5e}^{HWW}}{\Lambda_5} H W_{\mu\nu}^{+} W_{-}^{\mu\nu} + \frac{g_{5o}^{HWW}}{\Lambda_5} H \widetilde{W}_{\mu\nu}^{+} W_{-}^{\mu\nu} + \\
& \frac{g_{5e}^{HZ\gamma}}{\Lambda_5} H Z_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{HZ\gamma}}{\Lambda_5} H \widetilde{Z}_{\mu\nu} A^{\mu\nu} + \frac{g_{5e}^{H\gamma\gamma}}{2\Lambda_5} H A_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{H\gamma\gamma}}{2\Lambda_5} H \widetilde{A}_{\mu\nu} A^{\mu\nu}
\end{aligned}
\tag{10}
$$

where the subscript e or o refers to the $\mathcal{CP}$-even or $\mathcal{CP}$-odd nature of the individual operators [103], $V^{\mu\nu}$ is the field strength tensor of the gauge boson V and $\widetilde{V}^{\mu\nu}$ is the dual field strength.

An alternative approach is to write the effective Lagrangian in terms of the dimension-6 operators $\mathcal{O}_{WW}$, $\mathcal{O}_{BB}$, $\mathcal{O}_W$ and $\mathcal{O}_B$ and their corresponding $\mathcal{CP}$-odd operators according to Refs. [104, 105]:

$$
\mathcal{L}_{\text{eff}} = \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \text{ CP-odd part}
\tag{11}
$$

The explicit form of the operators is

$$
\begin{aligned}
\mathcal{O}_W &= (D_\mu \phi^\dagger) \widehat{W}^{\mu\nu} (D_\nu \phi) \\
\mathcal{O}_B &= (D_\mu \phi^\dagger) \widehat{B}^{\mu\nu} (D_\nu \phi) \\
\mathcal{O}_{WW} &= \phi^\dagger \widehat{W}_{\mu\nu} \widehat{W}^{\mu\nu} \phi \\
\mathcal{O}_{BB} &= \phi^\dagger \widehat{B}_{\mu\nu} \widehat{B}^{\mu\nu} \phi \,,
\end{aligned}
\tag{12}
$$

with

$$
\begin{aligned}
\widehat{W}_{\mu\nu} &= i g T^a W_{\mu\nu}^a \\
\widehat{B}_{\mu\nu} &= i g' Y B_{\mu\nu},
\end{aligned}
\tag{13}
$$

where g and g' are the SU(2) and U(1) gauge couplings, and T^a are the SU(2) generators. The $\mathcal{CP}$-odd part of the Lagrangian has the same form, although only three parameters (they are denoted with a tilde, see Appendix A.1) are needed.

The different parametrizations, 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 parametrization in terms of couplings in the effective Lagrangian approach given by Eq. (10).

    - `PARAMETR1`: Parameter that switches on the effective Lagrangian parameterization of Eq. (10). The default value is `true`.
    - `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. [106]. 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. (11) in the following manner [107]:

$$
\begin{aligned}
d &= -\frac{m_W^2}{\Lambda^2}\, f_{WW}\,, & \widetilde{d} &= -\frac{m_W^2}{\Lambda^2}\, f_{\widetilde{W}W}\,, \\
d_B &= -\frac{m_W^2}{\Lambda^2}\, \frac{\sin^2\theta_w}{\cos^2\theta_w}\, f_{BB}\,, & \widetilde{d}_B &= -\frac{m_W^2}{\Lambda^2}\, \frac{\sin^2\theta_w}{\cos^2\theta_w}\, f_{\widetilde{B}B}\,, \\
\Delta\kappa_\gamma &= \kappa_\gamma - 1 = \frac{m_W^2}{2\Lambda^2}\, (f_B + f_W)\,, & \widetilde{\kappa}_\gamma &= \frac{m_W^2}{2\Lambda^2}\, f_{\widetilde{B}}\,, \\
\Delta g_1^Z &= g_1^Z - 1 = \frac{m_Z^2}{\Lambda^2}\, \frac{f_W}{2}\,. &
\end{aligned}
\tag{14}
$$

- `PARAMETR2:` Parameter that switches on the above mentioned parameterization of Eqs. (14). The default value is `false`.

- `D_EVEN, DB_EVEN, DKGAM_EVEN, DG1Z_EVEN:` Parameters that are the $\mathcal{CP}$-even couplings in this parameterization. Default values are set to zero.

- `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 parametrization of the anomalous couplings in terms of coefficients f_i/Λ^2 of the effective Lagrangian in Eq. (11).

- `PARAMETR3:` Parameter that switches on the parametrization 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 set to zero.

- `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 parametrizations, two different form factors can be chosen as described in Refs. [103, 107]. They model effective, momentum dependent HVV vertices, motivated by new physics entering with a large scale Λ at the loop level.

$$F_1 = \frac{\Lambda^2}{q_1^2 - \Lambda^2} \frac{\Lambda^2}{q_2^2 - \Lambda^2}, \tag{15}$$

$$F_2 = -2\,\Lambda^2\,C_0\big(q_1^2, q_2^2, (q_1 + q_2)^2, \Lambda^2\big). \tag{16}$$

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. [108].

- `FORMFACTOR:` Flag 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. (15) and (16). If `FFAC = 1`, the form factor F_1 is used for the parametrization. `FFAC = 2` selects F_2, which is also the default value.

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

- `TREEFACW:` Parameter that multiplies the HWW tensor present in the SM Lagrangian. Default is 1.

- `TREEFACZ:` Parameter that multiplies the HZZ 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.

In order to comply with previous versions of VBFNLO, an input `TREEFAC` can be used, and both `TREEFACW` and `TREEFACZ` are set to this input.

Note that, when working in the SM, the loop-induced couplings $HZ\gamma$ and $H\gamma\gamma$ are used only in the calculation of the Higgs width and decays, not in the production amplitude. For the case of anomalous Higgs couplings (`ANOM_CPL = .true.` and one of the processes 10x, (4)300, (4)330, (4)360, (4)370 has been selected), these contributions are included in the production as well as in the decay of the Higgs boson.

5.5.2 `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. [105, 109–111]

$$\mathcal{L}_{\text{eff}} = \frac{f_i}{\Lambda^n} \mathcal{O}_i^{n+4}, \tag{17}$$

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 dimension-8 operators. The full list of implemented operators can be found in Appendix A.1.

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

$$\mathcal{L}_{WW\gamma} = -ie \left[W_{\mu\nu}^\dagger W^\mu A^\nu - W_\mu^\dagger A_\nu W^{\mu\nu} + \kappa_\gamma W_\mu^\dagger W_\nu F^{\mu\nu} + \frac{\lambda_\gamma}{m_W^2} W_{\sigma\mu}^\dagger W_\nu^\mu F^{\nu\sigma} \right] \qquad (18)$$

for the anomalous $WW\gamma$ vertex, and

$$\mathcal{L}_{WWZ} = -ie\cot\theta_w \left[g_1^Z \left(W_{\mu\nu}^\dagger W^\mu Z^\nu - W_\mu^\dagger Z_\nu W^{\mu\nu} \right) + \kappa_Z W_\mu^\dagger W_\nu Z^{\mu\nu} + \frac{\lambda_Z}{m_W^2} W_{\sigma\mu}^\dagger W_\nu^\mu Z^{\nu\sigma} \right] \qquad (19)$$

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

$$(\Delta g_1^Z, \Delta\kappa_Z, \Delta\kappa_\gamma) = (g_1^Z, \kappa_Z, \kappa_\gamma) - 1. \qquad (20)$$

These quantities are related to the coefficients of the dimension-6 operators $\mathcal{O}_W$, $\mathcal{O}_B$ and $\mathcal{O}_{WWW}$ as shown in Eqs. (14) for $\Delta\kappa_\gamma$ and Δg_1^Z. The corresponding relations for $\Delta\kappa_Z$ and $\Delta\lambda_\gamma$, $\Delta\lambda_Z$ are

$$\Delta\kappa_Z = \frac{m_Z^2}{2\Lambda^2} \left(f_W \cos^2\theta_W - f_B \sin^2\theta_W \right),$$
$$\Delta\lambda_\gamma = \Delta\lambda_Z = \frac{3g^2 m_W^2}{2\Lambda^2} \, f_{WWW}\,. \qquad (21)$$

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 as input:

  - `FWWW`: Coefficient of the operator $\mathcal{O}_{WWW}$, i.e. f_{WWW}/Λ^2. Default is set to 0 GeV^{-2}.
  - `FW`: Coefficient of the operator $\mathcal{O}_W$, i.e. f_W/Λ^2. Default is set to 0 GeV^{-2}.
  - `FB`: Coefficient of the operator $\mathcal{O}_B$, i.e. f_B/Λ^2. Default is set to 0 GeV^{-2}.

  `TRIANOM = 2` uses the alternative parameterization of Eqs. (18) and (19) as input:

  - `LAMBDA0`: The quantity $\lambda_\gamma(=\lambda_Z)$. Default is set to 0.0.
  - `ZDELTAKAPPA0`: The quantity $\Delta\kappa_Z$. Default is set to 0.0.
  - `ZDELTAG0`: The quantity Δg_1^Z. Default is set to 0.0.
  - `ADELTAKAPPA0`: The quantity $\Delta\kappa_\gamma$. Default is set to 0.0.
  - Note that, as can be seen from Eqs. (14) and (21), the quantities $\Delta\kappa_Z$, $\Delta\kappa_\gamma$ and Δg_1^Z are not independent, but obey the relation

  $$\Delta\kappa_Z = \Delta g_1^Z - \frac{\sin^2\theta_W}{\cos^2\theta_W}\Delta\kappa_\gamma. \qquad (22)$$

  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`. The LEP limits on those couplings can be found in [112]. Note that Vjj and VVj processes (process IDs 120-150 and 610-640) only take account of the above anomalous coupling parameters and not the following parameters.

- `FWW, FBB:` The coefficients of the remaining $\mathcal{CP}$-even dimension-6 operators, i.e. f_i/Λ^2. Note that these are not implemented for Vjj production via VBF (process IDs 120-150) and VVj processes (IDs 610-640). 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 not implemented for Vjj production via VBF (process IDs 120-150) and VVj processes (IDs 610-640). Default value is 0 GeV^{-2}.

- `FS0 - FS2, FM0 - FM7, FM5hc, FT0 - FT9:` 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 and $VVjj$ production via VBF.

In addition, a form factor can be applied. Several choices are available. One option is to use a dipole form factor, which takes the form

$$F = \left(1 + \frac{s}{\Lambda^2}\right)^{-p}, \tag{23}$$

for all processes except γjj production in VBF (process ID 150), where Λ is the characteristic scale where the form factor effect becomes relevant. s is a universal scale (the invariant mass squared of the produced bosons) for each phase-space point. A complex version of the dipole form factor [115],

$$F = \left(1 + i\left(\frac{s}{\Lambda^2}\right)^p\right)^{-1}, \tag{24}$$

is available as well. The second possibility is to use a step function of the form

$$F = \Theta\left(\Lambda^2 - s\right) \tag{25}$$

such that the effect of the anomalous coupling is switched off beyond the characteristic scale Λ. The third possibility uses a kink form factor [113],

$$F = \begin{cases} 1 & \text{for } s \leq \Lambda^2, \\ \left(\frac{\Lambda^2}{s}\right)^p & \text{for } s > \Lambda^2, \end{cases} \tag{26}$$

where the effect of the damping sets in exactly at the characteristic scale.
Moreover, for the two operators $\mathcal{O}_{S,1}$ and the isospin-conserving combination $\mathcal{O}_{S,0} \equiv \mathcal{O}_{S,2}$ the so called K-matrix unitarisation procedure is available. For this unitarisation method no additional input parameters need to be set.

- `FORMFAC:` Switch determining whether the above form factor F is included. Default is set to `false`.

- `FORMFACTYPE:` Parameter that is used to select one particular type of form factor. Possible choices are denoted in Table 27. Default is set to 1 (dipole formfactor).

FORMFACTYPE	FORM FACTOR TYPE	DEFINITION
1	dipole form factor	Eqs. (23), (27)
2	complex dipole form factor	Eqs. (24)
3	step form factor	Eq. (25)
4	kink form factor	Eq. (26)

Table 27: *Form factor types.*

- FFMASSSCALE: Mass scale Λ. Default is set to 2000 GeV.

- FFEXP: The exponent p. Default is set to 2.

- KMATRIX: Switch determining whether to use K-matrix unitarisation for $\mathcal{O}_{S,1}$ and $\mathcal{O}_{S,0} \equiv \mathcal{O}_{S,2}$ as described in section 5.5.3. Default is set to `false`.

- TMATRIX: Switch determining whether to use the T_u-model unitarisation procedure for the dimension-8 operators as described in section 5.5.4. Default is set to `false`.

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_AKAPPA: Mass scale Λ for parameter $\Delta\kappa_\gamma$. Default is 2000 GeV.

- FFEXP_AKAPPA: Exponent p for parameter $\Delta\kappa_\gamma$. Default is 2.

- MASS_SCALE_ZKAPPA: Mass scale Λ for parameter $\Delta\kappa_Z$. Default is 2000 GeV.

- FFEXP_ZKAPPA: Exponent p for parameter $\Delta\kappa_Z$. 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_1^Z. Default is 2000 GeV.

- `FFEXP_G:` Exponent p for parameter Δg_1^Z. Default is 2.

- As with the anomalous parameters themselves, the formfactors in the parameterization of `TRIANOM = 2` are not independent (see Eq. (22)). If one mass scale is set to zero, it will be set by VBFNLO to be consistent with the other values. If the input values are inconsistent, they will be reset to give the correct relation.

For γjj production in VBF (process ID 150), the dipole form factor takes the form

$$F = \left(1 + \frac{q_1^2}{\Lambda^2} + \frac{q_2^2}{\Lambda^2} + \frac{q_3^2}{\Lambda^2}\right)^{-p}, \tag{27}$$

with Λ and p set by `FFMASSSCALE` and `FFEXP`, respectively. q_1^2, q_2^2 and q_3^2 are the invariant masses squared of the three vector bosons involved in the VVV vertex. For this process only the universal form factor can be applied.

5.5.3 K-Matrix unitarisation

The K-matrix unitarisation procedure has been implemented for the dimension-8 operators $\mathcal{O}_{S,1}$ and the isospin-conserving combination $\mathcal{O}_{S,0} \equiv \mathcal{O}_{S,2}$ by using the relations [113] to the operators $\mathcal{O}_4$ and $\mathcal{O}_5$ of the electroweak chiral Lagrangian and the procedure worked out there [114]. This method guarantees the preservation of unitarity when either of these operators is used in the study of anomalous quartic gauge couplings. In contrast to using form factors, no additional input parameters need to be set. The anomalous contributions are automatically suppressed at the energy scale where unitarity would be violated without unitarisation. After this energy scale is reached, the anomalous contributions are kept at a finite value, representing the maximally possible anomalous contribution. See Refs. [111, 113–116] for details of the K-matrix unitarisation procedure and its implementation.

5.5.4 T_u-model

Similarly to the K-matrix, the T_u-model guarantees the preservation of unitarity when studying anomalous quartic gauge couplings without needing any additional ad hoc input parameters. Furthermore the T_u-model preserves unitarity not only at large energy scales but also for large virtualities of the incoming vector bosons in the vector boson scattering process by suppressing the anomalous contribution sufficiently. Finally the T_u-model works for all dimension-8 operators listed in sec. A.1. It can therefore be seen as an improvement of the K-matrix unitarisation and should be used instead. See Refs. [158,159] for details of the T_u-model and its implementation.

5.5.5 Using `anom_HVV.dat` and `anomV.dat` simultaneously

Some of the anomalous coupling parameters affect both the VVV and HVV couplings. These parameters (f_W and f_B or, equivalently, Δg_1^Z and $\Delta \kappa_\gamma$) are consequently inputs in

both `anom_HVV.dat` and `anomV.dat`. As stated previously, when working with anomalous VVV couplings with a process that contains internal Higgs bosons (e.g. WWZ triboson production), the anomalous HVV couplings resulting from f_W and f_B (input via `anomV.dat`) are calculated and used.

In diboson WW production (process ID 300), however, `anomV.dat` and `anom_HVV.dat` can be used simultaneously. The anomalous VVV couplings are taken directly from `anomV.dat`. The values of f_W and f_B for the HVV couplings are also taken from `anomV.dat`, but the additional parameters (f_{BB}, f_{WW} etc.) are taken from `anom_HVV.dat` using the appropriate parametrisation[36]. Alternatively, the HVV couplings can be specified directly via g_5^{HXY} by setting `PARAMETR1=true` in `anom_HVV.dat`. In this case, the values g_5^{HXY} are used if they are consistent with the `anomV.dat` inputs – if they are inconsistent, a warning message is printed and HVV parametrisation 2 or 3 is used instead.

5.6 `kk_input.dat` − parameters for Higgsless models

VBFNLO allows the calculation of the vector boson fusion processes $WWjj$, $WZjj$ and $ZZjj$ in the Warped Higgsless scenario [117, 118] at LO and NLO QCD level (see, for example, Ref. [119] for a phenomenological application). This feature is used if the switch `KK_MOD` in `vbfnlo.dat` is switched to `true` and must be enabled at compilation using the `configure` option `--enable-kk`.

The triple vector-boson processes WWW, WWZ and WZZ can be calculated in both this model and a Three-Site Higgsless Model [120]. The model parameters (masses and couplings) 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`. Alternatively, the user can input their own model parameters (masses and couplings) as described below.

- `MHLM_SWITCH`: Switch that determines whether the Three-Site Higgsless Model [120] (`true`) or the Warped Higgsless Model [117] (`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.

---

[36]`TRIANOM=1` in `anomV.dat` corresponds to `PARAMETR3=true` in `anom_HVV.dat`, and `TRIANOM=2` corresponds to `PARAMETR2=true`.

– `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. [121], 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 [122] 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 $W_x^\pm - W_y^\pm - Z_{\text{KKMAXZ}}$.
  – `CPL_W`x`-W`y`-GX`: List of couplings between Kaluza-Klein states: $W_x^\pm - W_y^\pm - Z'_0$ to $W_x^\pm - W_y^\pm - Z'_{\text{KKMAXG}}$.
  – `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 $W_x^\pm - W_y^\pm - W_z^\pm - W_{\text{KKMAXW}}^\pm$.
  – `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 $W_x^\pm - W_y^\pm - Z_z - Z_{\text{KKMAXZ}}$.
  – `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 $W_x^\pm - W_y^\pm - Z'_z - Z'_{\text{KKMAXG}}$.
  – `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 $W_x^\pm - W_y^\pm - Z'_z - Z_{\text{KKMAXZ}}$.

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.

5.7 `spin2coupl.dat` − parameters for spin-2 models

The file `spin2coupl.dat` is used to set the parameters for the spin-2 models. It is read if the switch SPIN2 in `vbfnlo.dat` is set to `true`.

VBFNLO uses an effective model to describe the interactions of spin-2 particles with electroweak gauge bosons for two cases: an isospin singlet spin-2 state and a spin-2 triplet in the adjoint representation, as described in Refs. [44–46]. For the singlet spin-2 field, $T^{\mu\nu}$, the effective Lagrangian is

$$\mathcal{L}_{\text{singlet}} = \frac{1}{\Lambda} T_{\mu\nu} \left(f_1 B^{\alpha\nu} B^{\mu}_{\alpha} + f_2 W_i^{\alpha\nu} W^{i,\mu}_{\alpha} + f_3 \widetilde{B}^{\alpha\nu} B^{\mu}_{\alpha} + f_4 \widetilde{W}_i^{\alpha\nu} W^{i,\mu}_{\alpha} \right. $$
$$\left. +2 f_5 (D^{\mu}\Phi)^{\dagger}(D^{\nu}\Phi) + f_9\, G_a^{\alpha\nu} G^{a,\mu}_{\alpha} \right), \tag{28}$$

and for the spin-2 triplet field, $T^{\mu\nu}_j$, the effective Lagrangian is given by

$$\mathcal{L}_{\text{triplet}} = \frac{1}{\Lambda} T_{\mu\nu j} \left(f_6 (D^{\mu}\Phi)^{\dagger}\sigma^j (D^{\nu}\Phi) + f_7 W^{j,\mu}_{\alpha} B^{\alpha\nu} \right), \tag{29}$$

where W, B and G are the usual field strength tensors of the SM gauge fields, $\widetilde{W}$ and $\widetilde{B}$ the dual field strength tensors, Φ is the Higgs field and D^{μ} is the covariant derivative. f_i are variable coupling parameters and Λ is the characteristic energy scale of the new physics.

In order to preserve unitarity, a formfactor is introduced to multiply the amplitudes. The formfactor has the form:

$$f(q_1^2, q_2^2, p_{\text{sp2}}^2) = \left(\frac{\Lambda_{ff}^2}{|q_1^2| + \Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|q_2^2| + \Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|p_{\text{sp2}}^2| + \Lambda_{ff}^2} \right)^{n_{ff}}. \tag{30}$$

Here p_{sp2}^2 is the invariant mass of a virtual s-channel spin-2 particle and $q_{1,2}^2$ are the invariant masses of the electroweak bosons. The energy scale Λ_{ff} and the exponent n_{ff} describe the scale of the cutoff and the suppression power.

The input parameters used by VBFNLO are:

- `F1,F2,F3,F4,F5,F9`: Coupling parameters for the spin-2 singlet field.

- `F6,F7`: Coupling parameters for the spin-2 triplet field.

- `LAMBDA`: Energy scale of the couplings in GeV.

- `LAMBDAFF`: Energy scale of the formfactor in GeV.

- `NFF`: Exponent of the formfactor.

The gluon coupling `F9` only affects the implemented VBF processes via the total width of the spin-2 particle. Note that the electroweak part of the graviton scenario corresponds to `F1=F2=F5=1` and `F3=F4=F6=F7=F9=0`.

VBFNLO also needs the masses and branching ratios of the spin-2 particles into SM gauge bosons.

- `SP2MASS:` Mass of the spin-2 singlet particle in GeV.

- `MSP2TRIPPM:` Mass of charged spin-2 triplet particles in GeV.

- `MSP2TRIPN:` Mass of neutral spin-2 triplet particle in GeV.

- `BRRAT:` Branching ratio for spin-2 singlet particle into SM gauge bosons. Default value is `1`.

- `BRRATTRIPPM:` Branching ratio for charged spin-2 triplet particles into SM gauge bosons. Default value is `1`.

- `BRRATTRIPN:` Branching ratio for neutral spin-2 triplet particle into SM gauge bosons. Default value is `1`.

Default values for different processes and scenarios can be found in Refs. [44–46][37].

5.8   `histograms.dat` − parameters for histogram options

VBFNLO can output histogram data in a variety of different formats (ROOT, GNUPLOT, TOPDRAWER, raw data tables), as described in Sec.5.1.5.

The file `histograms.dat` allows the user to set the x-axis range, enable a bin smearing, and enable the calculation of the Monte Carlo error per bin[38].

VBFNLO can calculate the Monte Carlo error for each bin and output this to the root and the raw histogram data output for 1D and 2D histograms. For the gnuplot histogram output only the 1D histograms can display the error bars.

- `CALC_ERROR_GNUPLOT:` Enable or disable y-error bars in 1D GNUPLOT histograms. Default is `false`.

- `CALC_ERROR_ROOT:` Enable or disable y/z-error bars in 1D/2D ROOT histograms. Please note: only the histograms defined in the FORTRAN file `histograms.F` can be generated with error bars. Default is `false`.

- `CALC_ERROR_1D:` Enable or disable y-error bars in raw 1D histogram output. Default is `true`.

- `CALC_ERROR_2D:` Enable or disable z-error bars in raw 2D histogram output. Default is `false`.

Furthermore, VBFNLO uses a smearing between adjacent bins to avoid artefacts at NLO when the real emission kinematics and the corresponding subtraction term fall into different bins. As this can lead to remnants at the sharp edges caused by cuts, the smearing can be switched off.

- `SMEARING:` Enable or disable smearing. Default is `true`.

- `SMEAR_VALUE:` Set the bin fraction where the bin smearing is active. The part that is put to the next bin becomes larger when the x-value is closer to a bin border. Default is `0.1`.

---

[37]Note that in Ref. [44], process 191 ($pp \to \text{spin-2}\, jj \to \gamma\gamma\, jj$) is referred to as process 240.

[38]By default 100 bins are used. This number can be altered in `utilities/histograms.F`.

The range of the x-axis of the produced histograms 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 rapidity of tagging jets. Default range is -5 to 5.

- `HIST_ID5`: Range for rapidity of tagging jet with higher p_T. Default range is -5 to 5.

- `HIST_ID6`: Range for rapidity 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 (in degrees) 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 $d^2\sigma/(d\eta_{jj}dm_{jj})$. Default ranges are 0 to 6 for the η (x) axis and 0 to 800 GeV for the m_{jj} (y) axis.

If the x-axis and y-axis ranges are not provided in the file `histograms.dat` the default values, which are set in `utilities/histograms.F`, are used.

A brief documentation on how to implement additional histograms into the file `histograms.F` can be found on the VBFNLO webpage, `https://ific.uv.es/vbfnlo/`.

5.9 `random.dat` − parameters for the random number generator

For the Monte Carlo integration different random number generators can be used by setting `RTYPE` in `random.dat` to one of the following.

0 ranmar based on [155]. This is the default.

1 Sobol sequences as introduced in [156] and based on the implementation in [157].

2 Internal random number generator of the compiler, availability and performance depend on the used compiler. Might not work with MPI.

3 xoroshiro128+ as provided at `http://vigna.di.unimi.it/xorshift/`. This generator is faster than the other choices. It also allows quick skipping of random numbers and thus significantly improves the performance in combination with MPI.

For all those generators (except Sobol) an initialization seed is needed. This allows reproducible random number generation.

To run with different seeds, set the variable `SEED` to a different integer value for each run.

5.10 Calculating the s-channel vector boson exchange contributions for the VBF processes

The VVV processes with semileptonic decays can be used to calculate the s-channel vector boson exchange contributions which are neglected in the $VVjj$ processes with fully leptonic decays in VBF. The same holds for semileptonic VV production and Vjj production in VBF.

Using the available processes with semileptonic decays it is possible to calculate the s-channel contributions to the processes Zjj, $W^\pm jj$, $W^+W^- jj$, $W^\pm Zjj$, $W^\pm \gamma jj$, $Z\gamma jj$ and $ZZjj$ in VBF with fully leptonic decays. In order to achieve this, the corresponding processes with semileptonic decay should be run with the same settings as the VBF process, except for the scale choice in case a dynamical scale has been used in the VBF processes. Additionally, the following settings should be made in `cuts.dat`:

- `DEF_TAGJET = 1`

- `PTMIN_TAG_1 = 0` and `PTMIN_TAG_2 = 0`

- `HARD_CENTRAL = false`

- `VBFCUTS_ALWAYS = true`

- `RECONST_HAD_V = 0`

- `SINGLE_DECAYJET = 0`

- `RECONST_HAD_V = 0`

The option `DECAY_QUARKS` in the file `vbfnlo.dat` has to be set to the value 93 (or 94 if initial and final-state b-quarks should be included). The list of corresponding s- and t-channel contributions in VBFNLO can be found in Table 28.

With this prescription a few simplifications are in place: interferences between s- and t-channel contributions are still neglected. Additionally, the NLO QCD corrections of the hadronic vector boson decay can be included only in an approximation (see Section 5.1).

5.11 Implementation of new cuts

New cuts can be implemented easily in VBFNLO by modifying the file `utilities/cuts.F` (called `cuts.F` for short) and related files as follows.

PROCESS	PROCID of t-channel	PROCIDs of s-channel
$p\overset{(-)}{p} \to Z\,jj \to \ell^+\ell^-\,jj$	120	312, 331
$p\overset{(-)}{p} \to W^+\,jj \to \ell^+\nu_\ell\,jj$	130	302, 313
$p\overset{(-)}{p} \to W^-\,jj \to \ell^-\bar{\nu}_\ell\,jj$	140	301, 323
$p\overset{(-)}{p} \to W^+W^-\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,jj$	200	403, 431, 442
$p\overset{(-)}{p} \to W^+Z\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-\,jj$	220	402, 412
$p\overset{(-)}{p} \to W^-Z\,jj \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-\,jj$	230	401, 422
$p\overset{(-)}{p} \to ZZ\,jj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\,jj$	210	411, 421, 451
$p\overset{(-)}{p} \to W^+\gamma\,jj \to \ell^+\nu_\ell\gamma\,jj$	270	462, 482
$p\overset{(-)}{p} \to W^-\gamma\,jj \to \ell^-\bar{\nu}_\ell\gamma\,jj$	280	461, 492
$p\overset{(-)}{p} \to Z\gamma\,jj \to \ell^+\ell^-\gamma\,jj$	290	471, 481, 491

Table 28: *Corresponding s- and t-channel vector boson exchange contributions of electroweak $V(V)jj$ production in VBFNLO.*

1. In the subroutine `InitCuts` in `cuts.F` read the value of the cut from the input file `cuts.dat` using

   `call read_real("CUTNAME",CutValue,DefaultValue)`

   where `CUTNAME` is the name of the cut (e.g. `MTW_MIN`), as written in the input file `cuts.dat`; `CutValue` is the internal variable storing the value of the cut (e.g. `MtwMin`); `DefaultValue` is the default value of the cut, in case the input value is not specified in the `cuts.dat` (e.g. `50d0`). The new variable `CutValue` must be declared in the file `utilities/cuts.inc` and added to the common block `basiccuts` there. If the value of the cut is not a real number, the call to `read_real` should be replaced by `read_logical` (for logical value) or `read_int` (for integer value) etc. Note that this step is not strictly necessary, but it will make setting and changing the value of the cut much simpler. It is possible to skip this step and use a hardwired cut value in the `BASIC_CUTS` function as instructed in the next steps.

2. In the function `BASIC_CUTS` in the file `cuts.F` calculate the value of the quantity, named `ObsValue`, on which to cut (e.g. `Mtw`). The new variable `ObsValue` must be declared locally. One then adds the cut condition to the logical value `pass_cuts` as follows

   `pass_cuts = pass_cuts .and.  (ObsValue .gt.  CutValue)`

   Of course, if the cut specifies the maximum value of a quantity, `.gt.` should be replaced by `.lt.` etc. The `CutValue` is read in from the `cuts.dat` as explained in

the above step. It can be replaced by a hardwired value here.

3. The `utilities` directory must be cleaned by using the `make clean` command before VBFNLO is remade and installed using the `make` and `make install` commands from the program directory.

Information about the final state particles is stored in the arrays `jets`, `leptons`, `invisible` (neutrinos) and `photons`. The entries are as follows

- `jets(i,j)`: information about the jets is stored here, entries are p_T-ordered

  - j = jet number
  - i = 0-3 = 4-momentum
  - i = 4 = mass
  - i = 5 = transverse momentum p_T
  - i = 6 = rapidity y
  - i = 7 = azimuthal angle ϕ

- `leptons(i,j)`: information about the charged leptons is stored here

  - j = lepton number
  - i = 0-3 = 4-momentum
  - i = 4 = mass (all leptons are treated as massless, i.e. this entry is always equal to zero)
  - i = 5 = transverse momentum p_T
  - i = 6 = rapidity y
  - i = 7 = azimuthal angle ϕ
  - i = 8 = lepton ID (i.e. PDG particle number)

- `invisible(i,j)`: information about the invisible particles (i.e. neutrinos) is stored here

  - j = neutrino number
  - i = 0-3 = 4-momentum
  - i = 4 = mass (all neutrinos are treated as massless, i.e. this entry is always equal to zero)
  - i = 5 = transverse momentum p_T
  - i = 6 = rapidity y
  - i = 7 = azimuthal angle ϕ
  - i = 8 = neutrino ID (i.e. PDG particle number)

- `photons(i,j)`: information about the photons is stored here

  - j = photon number
  - i = 0-3 = 4-momentum
  - i = 4 = mass (all photons are massless, i.e. this entry is always equal to zero)
  - i = 5 = transverse momentum p_T
  - i = 6 = rapidity y
  - i = 7 = azimuthal angle ϕ

5.12 Implementation of new histograms

VBFNLO offers two kinds of histograms, 1D and 2D. Additional histograms can be created easily in VBFNLO by modifying the file `utilities/histograms.F` as follows.

1. In the subroutine `InitHistograms` create a new histogram template with the following command, for the 1D case:

   `call CreateHist(HIST_ID, "title", nobins, xmin, xmax)`,

   where `HIST_ID` is the integer identification of the histogram (make sure to use a different number for each histogram); `title` the title of the histogram (will be used as plot title – e.g. `dS/dmjj:  dijet mass`); `nobins` the number of histogram bins; `xmin` the lower bound of the histogram; `xmax` the upper bound of histogram. Similarly, for the 2D case:

   `call Create2dHist(HIST_ID, "title", "x-axis label", "y-axis label", nobins_x, nobins_y, xmin, xmax, ymin, ymax)`,

   where the number of bins and the bounds must be specified separately for the two axes. The axis labels `"x-axis label"` and `"y-axis label"` can read e.g. `"eta_jj"` and `"m_jj"`, respectively.

2. In the subroutine `HistogramEvent`, for 1D case, calculate the desired distribution (or observable) value, named `ObsValue` - e.g. dijet mass `mjj`, then fill the new histogram using the command:

   `call FillHist(HIST_ID, ObsValue, dw, NLO)`,

   where `HIST_ID` is the integer identification of the histogram, same number as in `CreateHist`; `dw` is the variable `dw` (this is already calculated by the code, being the weight*cross section); `NLO` the variable `NLO` (this is already filled by the code – flag determining the order of the calculation). Similarly, for a 2D histogram, the command reads

   `call FillHist2d(HIST_ID, ObsValue_x, ObsValue_y, dw, NLO)`,

   where `ObsValue_x` and `ObsValue_y` are the x-axis and y-axis observables, respectively. They can be, e.g. `etajj` and `mjj`, which must be calculated from the external-state momenta.

3. The `utilities` directory must be cleaned by using the `make clean` command before VBFNLO is remade and installed using the `make` and `make install` commands from the program directory.

Information about the final state particles is stored in the arrays `jets`, `leptons`, `invisible` (neutrinos) and `photons` as in the previous section.

5.13 Implementation of new dynamical scales

A number of popular dynamical scale choices have been implemented and explained in Section 5.1. They can be used as templates for implementing a new scale. If the desired factorization or renormalization scale is not in this list, the user can easily add it as follows.

1. One first looks into the interface subroutine `Scales` in the file `utilities/scales.F90` to find out where to implement the new scales of the process at hand. For example, for the class of VBF or VBS processes (Hjj, Vjj, $VVjj$), the scales are calculated in the subroutine `calcVBFscales`, while it is `calcVXjScales` for diboson and triboson processes.

2. One then implements the factorization and renormalization scales separately, e.g. in `calcVBFscales`. The new identification numbers for `ID_MUF` and `ID_MUR` must be different from the ones already used. A good practice is to use the same value for both scales. The factorization-scale implementation reads

   ```
   case(ID_MUF_NEW)
   do L=1,Lmax
   ...
   mufsq(1,L) = ...
   mufsq(2,L) = ...
   enddo
   ```

   where `Lmax` (already calculated by the program) is the number of different kinematic configurations, which is greater than unity when calculating the dipole-subtraction term at NLO; `mufsq(1,L)` is the square of the factorization scale for the first hadron, `mufsq(2,L)` is for the second hadron. Similarly, for the renormalization scale, we have

   ```
   case(ID_MUR_NEW)
   do L=1,Lmax
   ...
   mursq(1,L) = ...
   als(1,L) = ...
   als(2,L) = ...
   ...
   enddo
   ```

   where `mursq(1,L)` is the square of the renormalization scale, the calculation of the strong coupling constants `als(i,L)` is the same as for the already implemented cases. The values of `mufsq(i,L)`, `mursq(i,L)` and `als(i,L)` are then transfered to other routines via the common block `cscales` in `scales.inc`.

3. The `utilities` directory must be cleaned by using the `make clean` command before VBFNLO is remade and installed using the `make` and `make install` commands from the program directory. The new scales are then ready to be used by specifying the values of the identification numbers in `vbfnlo.dat`.

Dynamical scales are calculated from the momenta of the external-state particles. The following momenta are available and ready to be used

- `p(i,j,L)`: 4-momenta of the partons.

- `v(i,j,L)`: 4-momenta of all other particles (charged leptons, neutrinos, photons, ...). The `particle_IDs(j)` can be used to select the desired momentum, as it returns the particle identification code according to the Monte Carlo particle numbering scheme.

- `jets(i,j,L)`: array with the jet information (4-momenta, mass, p_T, rapidity y, azimuthal angle ϕ).

- `leptons(i,j,L)`: array with the charged lepton information (4-momenta, mass, p_T, rapidity y, azimuthal angle ϕ).

- `photons(i,j,L)`: array with the photon information (4-momenta, mass, p_T, rapidity y, azimuthal angle ϕ).

Differently from the momenta in Section 5.11, the momenta here depend additionally on the index `L` marking the kinematic configurations. It is always a good practice to print out the value of an unknown variable to get more information about it.

6 Changes

The release VERSION 3.0 includes some changes that alter previous results:

6.1 NLO calculation of VBF-Hjj

A bug has been found in the virtual and real-emission parts of VBF-Hjj production, which leads to a decrease of the NLO cross section of roughly 10%.

6.2 NLO calculation of VBF-$Z\gamma jj$ with anomalous couplings

A bug has been found in the real-emission part of VBF-$Z\gamma jj$ production when anomalous couplings were switched on.

6.3 K-matrix unitarisation

Following the introduction of the dimension 8 operator $\mathcal{O}_{S,2}$, the K-matrix unitarisation procedure for $\mathcal{O}_{S,0}$ has been reworked. The relation to the parameters α_4 and α_5 of the electroweak chiral Lagrangian is now process-universal. To account for the isospin-conservation of these operators, which is used in the K-matrix procedure, only the combination $\mathcal{O}_{S,0} \equiv \mathcal{O}_{S,2}$ can be unitarised, as well as $\mathcal{O}_{S,1}$.

6.4 Calculation of histogram-bin errors

A bug has been found in the calculation of the statistical errors of histogram bins, which leads to an increase of the errors. The mean value of the cross section (bin-wise) is unchanged. The statistical error of the total cross section was correctly calculated, hence not affected by this change.

6.5 Previous changes – version 2.7.1

The release VERSION 2.7.1 includes some changes that alter previous results:

6.5.1 NLO calculations of W^-jj, W^-Zjj, $W^-\gamma jj$ production

A bug in the PDF convolution of the QCD-induced production processes W^-jj, W^-Zjj and $W^-\gamma jj$ has been fixed. The size of the effect, which can be observed both in the real-emission part of the NLO calculation and the corresponding LO+jet processes, can reach several percent, depending on the parameter settings.

6.5.2 VBF cuts for $HHjj$

VBF cuts now also apply to VBF production of a Higgs pair.

6.6 Previous changes – version 2.7.0

The release VERSION 2.7.0 includes some changes that alter previous results:

6.6.1 Running scales in NLO calculations

In release 2.7.0 a problem with certain dynamical renormalization and factorization scales has been fixed, which lead to wrong results at NLO QCD in the subtraction part of the real emission calculation. In particular, the scale choices "$\min(p_T(j_i))$" (ID=2) and "minimal transverse energy of the bosons" (ID=7) did not give correct results in previous releases.

6.6.2 Jet cuts in VBF/gluon fusion Higgs boson production with $H \to b\bar{b}$

Starting with VBFNLO 2.7.0 the jet cuts will be applied to the b-quarks from Higgs boson decay.

6.6.3 NLO calculation of W^+W^-Z production

A bug in the calculation of the virtual contributions for WWZ production has been fixed while comparing with the results of Ref. [132]. The new results are roughly one per cent smaller, and agree between both codes for squared amplitudes at the level of the machine precision and for integrated cross sections at the per mill level.

6.6.4 LO and NLO calculation of W^+jj / Zjj production in VBF

The particle–anti-particle–assignment in W^+jj, Zjj has been fixed. In case of W^+jj production this leads to an increase in cross section of roughly one per cent with basic cuts.

6.6.5 Event output

Several bugs have been fixed concerning the event output to Les Houches or HepMC files:

- The color information in the event output for W^-W^-jj in VBF has been fixed.

- The momenta assignment in the event output for $W^-W^+W^-$ has been corrected.

6.7 Previous changes – version 2.6.3

The release VERSION 2.6.3 includes some changes that alter previous results:

6.7.1 Event output

Several bugs have been fixed concerning the event output to Les Houches or HepMC files:

- Fixed bugs in output of particle IDs for processes 191 and 43xx: In previous versions some particles had the particle ID 0.

- Parton and beam particle IDs have been fixed for process 260.

- The tau mass can now be included in the event output of all processes. Furthermore, several bugs have been fixed in the existing implementation of tau mass inclusion.

- Several bugs have been fixed in the helicity output.

6.7.2 Calculation of the $H \to gg$ partial width

Higher-order corrections to the $H \to gg$ partial width have been included which lead to slightly smaller branching ratios for all other decay channels. Therefore cross sections of processes involving Higgs bosons can be up to a few per cent smaller.

6.7.3 Electroweak corrections in the VBF Hjj processes

Some bugs have been fixed in the calculation of electroweak corrections for the processes 10x.

6.8 Previous changes – version 2.6.2

The release VERSION 2.6.2 included some changes that altered previous results:

6.8.1 Distributions and cross section for $H \to WW$ in VBF and gluon fusion

Due to a bug which has been fixed in the lepton assignment for $H \to WW/ZZ \to 4\ell$ distributions (and cross sections after the $m_{\ell\ell}$ cut) were off for the 1x5 and 4105 processes in the previous versions. This bug has been fixed in v.2.6.2.

6.8.2 Les Houches event output for processes with more than one phase space

The fraction of events coming from the different phase spaces was not sampled correctly in previous versions. Processes affected are $W\gamma$, $Z\gamma$, $W\gamma j$, $Z\gamma j$, ZZZ, $WW\gamma$, $WZ\gamma$, $W\gamma\gamma$, $Z\gamma\gamma$, $\gamma\gamma\gamma$ and $W\gamma\gamma j$.

6.8.3 ZZZ production

The QCD real emission part of the NLO computation gave no reliable result in previous versions due to a bug in the dipole subtraction. This bug has been fixed in v.2.6.2.

6.8.4 Form factor in γjj production with anomalous couplings

For the γjj production in VBF (procID 150) a different form factor is used.

6.9 Previous changes – version 2.6.1

The release VERSION 2.6.1 included some changes that altered previous results:

6.9.1 Anomalous Higgs couplings

A bug was found and fixed in the implementation of the `TREEFACZ` and `TREEFACW`, the factors which multiply the SM HZZ and HWW couplings. Note that this bug was only present in VERSION 2.6.0, not in earlier versions. Additionally, a small bug was found and fixed in the coefficient of the input `FB_ODD` in the a_3^{HZZ} coupling.

6.9.2 Symmetry factor $ZZ \to \ell^+\ell^-\ell^+\ell^-$

In the processes $pp \to H\gamma jj \to ZZ\gamma jj \to \ell^+\ell^-\ell^+\ell^-\gamma jj$ (ID 2106) and gluon fusion $pp \to Hjj \to ZZjj \to \ell^+\ell^-\ell^+\ell^- jj$ (ID 4106) a symmetry factor was missing when identical final-state leptons were chosen.

6.10 Previous changes – version 2.6.0

The release VERSION 2.6.0 included some changes that alter results (events, cross sections and distributions) from earlier versions.

6.10.1 Allowed width of virtuality

In the phase-space generators, the allowed range of the virtuality of a resonance of intermediate vector bosons has been increased. This mainly affects processes where an intermediate Z boson decays into a pair of neutrinos – i.e.

- $pp \to Hjj \to ZZjj \to \ell^+\ell^-\nu\bar{\nu}jj$ via vector boson fusion (process ID 107) and gluon fusion (process ID 4107)

- $pp \to Hjjj \to ZZjjj \to \ell^+\ell^-\nu\bar{\nu}jjj$ (process ID 117)

- $pp \to H\gamma jj \to ZZ\gamma jj \to \ell^+\ell^-\nu\bar{\nu}\gamma jj$ (process ID 2107)

- $pp \to ZZjj \to \ell^+\ell^-\nu\bar{\nu}jj$ (process ID 211)

This not only affects the cross sections for these processes, but also means that the events produced by VBFNLO-2.6.0 will differ from those produced by VBFNLO-2.5, even if the same random numbers are used.

6.10.2 Matrix element $H \to ZZ \to 4\ell$

A bug was found and fixed in the implementation of the matrix element calculating the decay $H \to ZZ \to 4\ell$.

6.10.3 Anomalous couplings

Several changes have been made to the implementation of the anomalous couplings. For Higgs production via vector boson fusion (process IDs 100-107) the variable `TREEFAC`, which multiplies the Standard Model contribution to the tree-level HVV couplings, has been corrected and altered – now, separate factors for HZZ and HWW are input (`TREEFACZ` and `TREEFACW` respectively).

When working with anomalous HVV couplings two types of formfactor can be applied which model effective, momentum dependent HVV vertices, motivated by new physics entering with a large scale Λ at loop level. Corrections to the HVV formfactor F_2 (see Eq. 16) have been made. The implementation of the parameterization described by `PARAMETR3` – where the input determining the anomalous couplings is in terms of the dimension-6 operators ($\mathcal{O}_W$, $\mathcal{O}_B$, $\mathcal{O}_{WW}$ and $\mathcal{O}_{BB}$) have also been altered.

If anomalous triple (and quartic) gauge boson couplings are being studied, a formfactor given by

$$F = \left(1 + \frac{s}{\Lambda^2}\right)^{-p}, \tag{31}$$

can be applied in order to preserve unitarity, where Λ is the scale of new physics. The momentum dependence of the applied formfactor (i.e. s) is now universal for each phase-space point, with the invariant mass of the produced bosons as the scale. This ensures the proper cancellations for anomalous contributions. The values of the formfactor scales Λ and p can be set to different values for each input describing the triboson couplings.

In the parameterization `TRIANOM = 2`, the formfactor scales for $\Delta\kappa_\gamma$ and $\Delta\kappa_Z$ are now separately set, and the consistency of related parameters (i.e. Δg_1^Z, $\Delta\kappa_\gamma$ and $\Delta\kappa_Z$) is enforced when formfactors are applied.

When processes involving resonant Higgs diagrams (e.g. WWW production) are studied with anomalous couplings, the Higgs width is now calculated with the appropriate anomalous HVV couplings (the anomalous HVV couplings in the production amplitudes were taken into account in previous versions of VBFNLO). Various corrections have also been made to the anomalous triboson couplings in diboson plus jet processes (these were incorporated into the intermediate release VBFNLO 2.5.3).

6.10.4 VBF Higgs boson production in association with three jets

A small bug was found and fixed in the calculation of the processes $pp \rightarrow Hjjj$, with process IDs 110-117.

6.11 Previous changes – version 2.5.0

The previous version of VBFNLO – 2.5.0 – was altered in such a way that some results differ from VBFNLO-2.0 and below. These changes are described briefly here, and in more detail on the VBFNLO website, `https://ific.uv.es/vbfnlo/`.

6.11.1 EWSCHEME

The implementation of options `EWSCHEME = 1` and `4`, which are described in Section 5.1.2, was altered. The new implementation is hopefully more transparent, and is described in this manual.

6.11.2 Gluon fusion

Since version 2.5.0, in gluon fusion processes the bottom-quark mass $M_b(M_H)$ is used throughout the calculation. New, more stable, tensor routines for the boxes and pentagons were implemented, reducing the number of omitted points with bad numerical accuracy.

7 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 [19]. 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[39] [20, 133], SHERPA[40] [134] and/or HELAC-PHEGAS[41] [135–137].

LHA event files for the LO processes have been tested with HERWIG++[42] [138], 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[43]. In Ref. [139], 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. [140, 141], and the VV2H program[44]. For the dominant t- and u-channel contributions which are implemented in VBFNLO, good agreement has been found. Diboson processes, including WH, as well as W and Wj production have been checked against MCFM[45] [142–144]. The results for WH+jet production have been compared with Ref. [145]. 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. [146]. Additionally, the tree-level results for $W^{\pm}\gamma\gamma$ have been compared to the results with an on-shell W boson of Ref. [147]. Again, in all cases good agreement has been found. Triple photon production has been tested against FEYNARTS, FORMCALC and HADCALC [6, 7, 148]. QCD-induced γjj production has been compared to MADGRAPH5_AMC@NLO [149] using the model `sm-no_b_mass` and agreement at the 0.1% level was found. Processes with anomalous quartic gauge couplings have been compared with MADGRAPH/MADEVENT and WHIZARD[46] [150] in Ref. [111]. Results for the $\mathcal{CP}$-odd and $\mathcal{CP}$-even Higgs boson production via gluon fusion have been tested against FEYNARTS and FORMCALC [24, 25].

All fermion loops have been checked against results obtained with FEYNARTS, FORMCALC and LOOPTOOLS. and the gluon-gluon loops have also been checked against GG2VV[47] [151, 152].

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[39]http://madgraph.physics.illinois.edu

[40]https://sherpa.hepforge.org/

[41]https://helac-phegas.web.cern.ch/helac-phegas/

[42]https://herwig.hepforge.org/

[43]http://omnibus.uni-freiburg.de/~sd565/programs/hawk/hawk.html

[44]http://tiger.web.psi.ch/vv2h/

[45]https://mcfm.fnal.gov/

[46]https://whizard.hepforge.org/

[47]https://gg2VV.hepforge.org/

8 Outlook

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

Acknowledgments

A OPERATORS FOR ANOMALOUS GAUGE BOSON COUPLINGS

A.1 List of operators implemented in VBFNLO

This is a list of the full set of operators included the effective Lagrangian which is used for calculations with anomalous gauge boson couplings. The full set can be used in the diboson, triboson and $VVjj$ in VBF production processes.

The dimension-6 operators are constructed according to Refs. [104, 105] and the dimension-8 operators are taken from [110, 153]. The operators $\mathcal{O}_{T,3}$, $\mathcal{O}_{T,4}$ and $\mathcal{O}_{M,5hc}$ are constructed accordingly to complete the sets of $\mathcal{O}_T$ and $\mathcal{O}_M$ operators as presented in Refs. [160, 161]. See also Refs. [111, 113] for relations between different sets of definitions. More details on the implementation of these operators can be found in Refs. [100–102].

With the building blocks (following the notation of [104, 105])

$$
\begin{aligned}
\widehat{W}_{\mu\nu} &= igT^a W^a_{\mu\nu} \\
\widehat{B}_{\mu\nu} &= ig'Y B_{\mu\nu} \\
D_\mu &= \partial_\mu + igT^a W^a_\mu + ig'Y B_\mu,
\end{aligned}
\tag{32}
$$

we can construct the following operators, where g and g' are the SU(2) and U(1) gauge couplings, and T^a are the SU(2) generators. We obtain slightly different expressions for the dimension-8 operators compared to [110], as they use different field strength tensor expressions ($\widehat{W}_{\mu\nu} = T^a W^a_{\mu\nu}$ and $\widehat{B}_{\mu\nu} = B_{\mu\nu}$). The conversion factors for the coupling strengths f_i between [110] and our implementation can be found in Appendix A.2.

The explicit form of the $\mathcal{CP}$-even operators is

$$
\begin{aligned}
\mathcal{O}_W &= (D_\mu\Phi)^\dagger \widehat{W}^{\mu\nu}(D_\nu\Phi) \\
\mathcal{O}_B &= (D_\mu\Phi)^\dagger \widehat{B}^{\mu\nu}(D_\nu\Phi) \\
\mathcal{O}_{WWW} &= Tr\left[\widehat{W}_{\mu\nu}\widehat{W}^{\nu\rho}\widehat{W}_\rho{}^\mu\right] \\
\mathcal{O}_{WW} &= \Phi^\dagger \widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\Phi \\
\mathcal{O}_{BB} &= \Phi^\dagger \widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\Phi.
\end{aligned}
\tag{33}
$$

If we replace one field strength tensor with the corresponding dual field strength tensor, we obtain the $\mathcal{CP}$-odd part of the Lagrangian

$$
\begin{aligned}
\mathcal{O}_{\widetilde{W}} &= (D_\mu\Phi)^\dagger \widetilde{\widehat{W}}^{\mu\nu}(D_\nu\Phi) \\
\mathcal{O}_{\widetilde{B}} &= (D_\mu\Phi)^\dagger \widetilde{\widehat{B}}^{\mu\nu}(D_\nu\Phi) \\
\mathcal{O}_{\widetilde{W}WW} &= Tr\left[\widetilde{\widehat{W}}_{\mu\nu}\widehat{W}^{\nu\rho}\widehat{W}_\rho{}^\mu\right] \\
\mathcal{O}_{\widetilde{W}W} &= \Phi^\dagger \widetilde{\widehat{W}}_{\mu\nu}\widehat{W}^{\mu\nu}\Phi \\
\mathcal{O}_{\widetilde{B}B} &= \Phi^\dagger \widetilde{\widehat{B}}_{\mu\nu}\widehat{B}^{\mu\nu}\Phi \\
\mathcal{O}_{D\widetilde{W}} &= Tr\left([D_\mu, \widetilde{\widehat{W}}_{\nu\rho}][D^\mu, \widehat{W}^{\nu\rho}]\right) \\
\mathcal{O}_{B\widetilde{W}} &= \Phi^\dagger \widehat{B}_{\mu\nu}\widetilde{\widehat{W}}^{\mu\nu}\Phi.
\end{aligned}
\tag{34}
$$

The operators $\mathcal{O}_{B\widetilde{W}}$ and $\mathcal{O}_{D\widetilde{W}}$ are included only in their $\mathcal{CP}$-odd version, as their $\mathcal{CP}$-even counterparts affect the gauge boson two-point functions and are already extremely constrained by electroweak precision tests. Furthermore, only 4 of these 7 operators are linearly independent. For example $\mathcal{O}_{\widetilde{W}}$, $\mathcal{O}_{B\widetilde{W}}$ and $\mathcal{O}_{D\widetilde{W}}$ can be written as

$$
\begin{aligned}
\mathcal{O}_{\widetilde{W}} &= \mathcal{O}_{\widetilde{B}} - \frac{1}{2}\mathcal{O}_{\widetilde{W}W} + \frac{1}{2}\mathcal{O}_{\widetilde{B}B} \\
\mathcal{O}_{B\widetilde{W}} &= -2\,\mathcal{O}_{\widetilde{B}} - \mathcal{O}_{\widetilde{B}B} \\
\mathcal{O}_{D\widetilde{W}} &= -4\,\mathcal{O}_{\widetilde{W}WW}\,.
\end{aligned}
\tag{35}
$$

The dimension-8 operators can be split into three categories:

1. Operators using $D_\mu\Phi$:

$$
\begin{aligned}
\mathcal{O}_{S,0} &= \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \\
\mathcal{O}_{S,1} &= \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right] \\
\mathcal{O}_{S,2} &= \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\nu\Phi)^\dagger D^\mu\Phi\right]
\end{aligned}
\tag{36}
$$

2. Operators using $D_\mu\Phi$, $\hat{W}_{\mu\nu}$ and $\hat{B}_{\mu\nu}$:

$$
\begin{aligned}
\mathcal{O}_{M,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{O}_{M,1} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{O}_{M,2} &= \left[\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{O}_{M,3} &= \left[\hat{B}_{\mu\nu}\hat{B}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{O}_{M,4} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times \hat{B}^{\beta\nu} \\
\mathcal{O}_{M,5} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times \hat{B}^{\beta\mu} \\
\mathcal{O}_{M,5hc} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\mu} D^\nu\Phi\right] \times \hat{B}^{\beta\nu} \\
\mathcal{O}_{M,6} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right] \\
\mathcal{O}_{M,7} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]
\end{aligned}
\tag{37}
$$

3. Operators using $\hat{W}_{\mu\nu}$ and $\hat{B}_{\mu\nu}$:

$$
\begin{aligned}
\mathcal{O}_{T,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right] \\
\mathcal{O}_{T,1} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right] \\
\mathcal{O}_{T,2} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right] \\
\mathcal{O}_{T,3} &= \mathrm{Tr}\left[\hat{W}^{\mu\nu}\hat{W}^{\alpha\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\nu\alpha}\hat{W}^{\beta\mu}\right] \\
\mathcal{O}_{T,4} &= \mathrm{Tr}\left[\hat{W}^{\mu\nu}\hat{W}^{\alpha\beta}\right] \times \mathrm{Tr}\left[\hat{B}_{\nu\alpha}\hat{B}^{\beta\mu}\right] \\
\mathcal{O}_{T,5} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \hat{B}_{\alpha\beta}\hat{B}^{\alpha\beta} \\
\mathcal{O}_{T,6} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \hat{B}_{\mu\beta}\hat{B}^{\alpha\nu} \\
\mathcal{O}_{T,7} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \hat{B}_{\beta\nu}\hat{B}^{\nu\alpha} \\
\mathcal{O}_{T,8} &= \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\hat{B}_{\alpha\beta}\hat{B}^{\alpha\beta} \\
\mathcal{O}_{T,9} &= \hat{B}_{\alpha\mu}\hat{B}^{\mu\beta}\hat{B}_{\beta\nu}\hat{B}^{\nu\alpha}
\end{aligned}
\tag{38}
$$

Each new operator introduces a new coupling strength f_i, so the complete effective Lagrangian containing effects from dimension six and eight operators is

$$
\begin{aligned}
\mathcal{L}_{eff} \;=\; & \mathcal{L}_{SM} \\
& + \; \frac{f_W}{\Lambda^2}\mathcal{O}_W + \frac{f_B}{\Lambda^2}\mathcal{O}_B + \frac{f_{WWW}}{\Lambda^2}\mathcal{O}_{WWW} + \frac{f_{WW}}{\Lambda^2}\mathcal{O}_{WW} + \frac{f_{BB}}{\Lambda^2}\mathcal{O}_{BB} \\
& + \; \frac{f_{Wt}}{\Lambda^2}\mathcal{O}_{\widetilde{W}} + \frac{f_{Bt}}{\Lambda^2}\mathcal{O}_{\widetilde{B}} + \frac{f_{WWWt}}{\Lambda^2}\mathcal{O}_{\widetilde{W}WW} + \frac{f_{WWt}}{\Lambda^2}\mathcal{O}_{\widetilde{W}W} + \frac{f_{BBt}}{\Lambda^2}\mathcal{O}_{\widetilde{B}B} \\
& + \; \frac{f_{DWt}}{\Lambda^2}\mathcal{O}_{D\widetilde{W}} + \frac{f_{BWt}}{\Lambda^2}\mathcal{O}_{B\widetilde{W}} \\
& + \; \frac{f_{S0}}{\Lambda^4}\mathcal{O}_{S,0} + \frac{f_{S1}}{\Lambda^4}\mathcal{O}_{S,1} + \frac{f_{S2}}{\Lambda^4}\mathcal{O}_{S,2} \\
& + \; \frac{f_{M0}}{\Lambda^4}\mathcal{O}_{M,0} + \frac{f_{M1}}{\Lambda^4}\mathcal{O}_{M,1} + \frac{f_{M2}}{\Lambda^4}\mathcal{O}_{M,2} + \frac{f_{M3}}{\Lambda^4}\mathcal{O}_{M,3} \\
& + \; \frac{f_{M4}}{\Lambda^4}\mathcal{O}_{M,4} + \frac{f_{M5}}{\Lambda^4}\mathcal{O}_{M,5} + \frac{f_{M5hc}}{\Lambda^4}\mathcal{O}_{M,5hc} + \frac{f_{M6}}{\Lambda^4}\mathcal{O}_{M,6} + \frac{f_{M7}}{\Lambda^4}\mathcal{O}_{M,7} \\
& + \; \frac{f_{T0}}{\Lambda^4}\mathcal{O}_{T,0} + \frac{f_{T1}}{\Lambda^4}\mathcal{O}_{T,1} + \frac{f_{T2}}{\Lambda^4}\mathcal{O}_{T,2} + \frac{f_{T3}}{\Lambda^4}\mathcal{O}_{T,3} \\
& + \; \frac{f_{T4}}{\Lambda^4}\mathcal{O}_{T,4} + \frac{f_{T5}}{\Lambda^4}\mathcal{O}_{T,5} + \frac{f_{T6}}{\Lambda^4}\mathcal{O}_{T,6} + \frac{f_{T7}}{\Lambda^4}\mathcal{O}_{T,7} + \frac{f_{T8}}{\Lambda^4}\mathcal{O}_{T,8} + \frac{f_{T9}}{\Lambda^4}\mathcal{O}_{T,9}\,. \quad (39)
\end{aligned}
$$

A.2 Conventions for anomalous gauge boson coupling parameters in VBFNLO

As mentioned in Appendix A.1, our definition of the field strengths is slightly different than the one of [110]. For comparisons with programs that use the definition from [110] (for example MadGraph5 [154] with the UFO file written by Éboli et al.[48]), you should rescale the coupling strengths by

$$ f_{S,0,1} \;=\; f_{S,0,1}^{\text{Éboli}} \tag{40} $$

$$ f_{M,0,1} \;=\; -\frac{1}{g^2}\cdot f_{M,0,1}^{\text{Éboli}} \tag{41} $$

$$ f_{M,2,3} \;=\; -\frac{4}{g'^2}\cdot f_{M,2,3}^{\text{Éboli}} \tag{42} $$

$$ f_{M,4,5} \;=\; -\frac{2}{gg'}\cdot f_{M,4,5}^{\text{Éboli}} \tag{43} $$

$$ f_{M,6,7} \;=\; -\frac{1}{g^2}\cdot f_{M,6,7}^{\text{Éboli}} \tag{44} $$

$$ f_{T,0,1,2} \;=\; \frac{1}{g^4}\cdot f_{T,0,1,2}^{\text{Éboli}} \tag{45} $$

$$ f_{T,5,6,7} \;=\; \frac{4}{g^2 g'^2}\cdot f_{T,5,6,7}^{\text{Éboli}} \tag{46} $$

$$ f_{T,8,9} \;=\; \frac{16}{g'^4}\cdot f_{T,8,9}^{\text{Éboli}} \tag{47} $$

---

[48]available from https://feynrules.irmp.ucl.ac.be/wiki/AnomalousGaugeCoupling

where g and g' are the SU(2) and U(1) gauge couplings. The numerical values of g, g used in the calculation are printed out at the beginning of the VBFNLO run.

B   Process list

The following is a complete list of all processes available in VBFNLO, including any Beyond the Standard Model (BSM) effects that are implemented.

PROCID	PROCESS	BLHA	semi-leptonic decay	VBF process	anom. gauge couplings	anom. Higgs couplings	Two-Higgs model	Kaluza-Klein model	Spin-2 model	MSSM
100	$p\overset{(-)}{p} \to H\,jj$	✓	–	✓	–	✓	–	–	–	✓
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	$p\overset{(-)}{p} \to H\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\,jj$	–	–	✓	–	✓	–	–	–	✓
108	$p\overset{(-)}{p} \to H\,jj \to W^+W^-\,jj \to q\bar{q}\,\ell^-\bar{\nu}_\ell\,jj$	–	✓	✓	–	✓	–	–	–	✓
109	$p\overset{(-)}{p} \to H\,jj \to W^+W^-\,jj \to \ell^+\nu_\ell\,q\bar{q}\,jj$	–	✓	✓	–	✓	–	–	–	✓
1010	$p\overset{(-)}{p} \to H\,jj \to ZZ\,jj \to q\bar{q}\,\ell^+\ell^-\,jj$	–	✓	✓	–	✓	–	–	–	✓
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	$p\overset{(-)}{p} \to H\,jjj \to ZZ\,jjj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\,jjj$	–	–	✓	–	–	–	–	–	–
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	$p\overset{(-)}{p} \to \gamma\,jj$	✓	–	✓	✓	–	–	–	–	–
191	$p\overset{(-)}{p} \to S_2\,jj \to \gamma\gamma\,jj$	–	–	✓	–	–	–	–	✓	–
195	$p\overset{(-)}{p} \to S_2\,jj \to W^+W^-\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,jj$	–	–	✓	–	–	–	–	✓	–
196	$p\overset{(-)}{p} \to S_2\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\,jj$	–	–	✓	–	–	–	–	✓	–
197	$p\overset{(-)}{p} \to S_2\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\,jj$	–	–	✓	–	–	–	–	✓	–

PROCID	PROCESS	BLHA	semi-leptonic decay	VBF process	anom. gauge couplings	anom. Higgs couplings	Two-Higgs model	Kaluza-Klein model	Spin-2 model	MSSM
160	$p\overset{(-)}{p} \to HH\,jj$	–	–	✓	–	–	–	–	–	–
161	$p\overset{(-)}{p} \to HH\,jj \to b\bar{b}\tau^+\tau^-\,jj$	–	–	✓	–	–	–	–	–	–
162	$p\overset{(-)}{p} \to HH\,jj \to b\bar{b}\gamma\gamma\,jj$	–	–	✓	–	–	–	–	–	–
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	$p\overset{(-)}{p} \to H\gamma\,jj \to ZZ\gamma\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\gamma\,jj$	–	–	✓	–	–	–	–	–	–
200	$p\overset{(-)}{p} \to W^+W^-\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,jj$	✓	–	✓	✓	–	✓	✓	✓	–
201	$p\overset{(-)}{p} \to W^+W^-\,jj \to q\bar{q}\,\ell^-\bar{\nu}_\ell\,jj$	–	✓	✓	✓	–	✓	–	–	–
202	$p\overset{(-)}{p} \to W^+W^-\,jj \to \ell^+\nu_\ell\,q\bar{q}\,jj$	–	✓	✓	✓	–	✓	–	–	–
210	$p\overset{(-)}{p} \to ZZ\,jj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\,jj$	✓	–	✓	✓	–	✓	✓	✓	–
211	$p\overset{(-)}{p} \to ZZ\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\,jj$	✓	–	✓	✓	–	✓	✓	✓	–
212	$p\overset{(-)}{p} \to ZZ\,jj \to q\bar{q}\,\ell^+\ell^-\,jj$	–	✓	✓	✓	–	✓	–	–	–
220	$p\overset{(-)}{p} \to W^+Z\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-\,jj$	✓	–	✓	✓	–	✓	✓	✓	–
221	$p\overset{(-)}{p} \to W^+Z\,jj \to q\bar{q}\,\ell^+\ell^-\,jj$	–	✓	✓	✓	–	✓	–	–	–
222	$p\overset{(-)}{p} \to W^+Z\,jj \to \ell^+\nu_\ell\,q\bar{q}\,jj$	–	✓	✓	✓	–	✓	–	–	–
230	$p\overset{(-)}{p} \to W^-Z\,jj \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-\,jj$	✓	–	✓	✓	–	✓	✓	✓	–
231	$p\overset{(-)}{p} \to W^-Z\,jj \to q\bar{q}\,\ell^+\ell^-\,jj$	–	✓	✓	✓	–	✓	–	–	–
232	$p\overset{(-)}{p} \to W^-Z\,jj \to \ell^-\bar{\nu}_\ell\,q\bar{q}\,jj$	–	✓	✓	✓	–	✓	–	–	–
240	$p\overset{(-)}{p} \to \gamma\gamma\,jj$	✓	–	✓	✓	–	–	–	–	–
250	$p\overset{(-)}{p} \to W^+W^+\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^+\nu_{\ell_2}\,jj$	✓	–	✓	✓	–	✓	–	–	–
251	$p\overset{(-)}{p} \to W^+W^+\,jj \to q\bar{q}\,\ell^+\nu_\ell\,jj$	–	✓	✓	✓	–	✓	–	–	–
260	$p\overset{(-)}{p} \to W^-W^-\,jj \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,jj$	✓	–	✓	✓	–	✓	–	–	–
261	$p\overset{(-)}{p} \to W^-W^-\,jj \to q\bar{q}\,\ell^-\bar{\nu}_\ell\,jj$	–	✓	✓	✓	–	✓	–	–	–
270	$p\overset{(-)}{p} \to W^+\gamma\,jj \to \ell^+\nu_\ell\gamma\,jj$	✓	–	✓	✓	–	–	–	–	–
280	$p\overset{(-)}{p} \to W^-\gamma\,jj \to \ell^-\bar{\nu}_\ell\gamma\,jj$	✓	–	✓	✓	–	–	–	–	–
290	$p\overset{(-)}{p} \to Z\gamma\,jj \to \ell^+\ell^-\gamma\,jj$	✓	–	✓	✓	–	–	–	–	–
291	$p\overset{(-)}{p} \to Z\gamma\,jj \to \nu_\ell\bar{\nu}_\ell\gamma\,jj$	✓	–	✓	✓	–	–	–	–	–

PROCID	PROCESS	BLHA	semi-leptonic decay	VBF process	anom. gauge couplings	anom. Higgs couplings	Two-Higgs model	Kaluza-Klein model	Spin-2 model	MSSM
3120	$p\overset{(-)}{p} \to Z\,jj \to \ell^+\ell^-\,jj$	–	–	–	–	–	–	–	–	–
3121	$p\overset{(-)}{p} \to Z\,jj \to \nu_\ell\bar\nu_\ell\,jj$	–	–	–	–	–	–	–	–	–
3130	$p\overset{(-)}{p} \to W^+\,jj \to \ell^+\nu_\ell\,jj$	–	–	–	–	–	–	–	–	–
3140	$p\overset{(-)}{p} \to W^-\,jj \to \ell^-\bar\nu_\ell\,jj$	–	–	–	–	–	–	–	–	–
3210	$p\overset{(-)}{p} \to ZZ\,jj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\,jj$	–	–	–	–	–	–	–	–	–
3211	$p\overset{(-)}{p} \to ZZ\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar\nu_{\ell_2}\,jj$	–	–	–	–	–	–	–	–	–
3220	$p\overset{(-)}{p} \to W^+Z\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-\,jj$	–	–	–	–	–	–	–	–	–
3230	$p\overset{(-)}{p} \to W^-Z\,jj \to \ell_1^-\bar\nu_{\ell_1}\ell_2^+\ell_2^-\,jj$	–	–	–	–	–	–	–	–	–
3240	$p\overset{(-)}{p} \to \gamma\gamma\,jj$	–	–	–	–	–	–	–	–	–
3250	$p\overset{(-)}{p} \to W^+W^+\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^+\nu_{\ell_2}\,jj$	–	–	–	–	–	–	–	–	–
3260	$p\overset{(-)}{p} \to W^-W^-\,jj \to \ell_1^-\bar\nu_{\ell_1}\ell_2^-\bar\nu_{\ell_2}\,jj$	–	–	–	–	–	–	–	–	–
3270	$p\overset{(-)}{p} \to W^+\gamma\,jj \to \ell^+\nu_\ell\gamma\,jj$	–	–	–	–	–	–	–	–	–
3280	$p\overset{(-)}{p} \to W^-\gamma\,jj \to \ell^-\bar\nu_\ell\gamma\,jj$	–	–	–	–	–	–	–	–	–
3290	$p\overset{(-)}{p} \to Z\gamma\,jj \to \ell^+\ell^-\gamma\,jj$	–	–	–	–	–	–	–	–	–
3291	$p\overset{(-)}{p} \to Z\gamma\,jj \to \nu_\ell\bar\nu_\ell\gamma\,jj$	–	–	–	–	–	–	–	–	–
1330	$p\overset{(-)}{p} \to W^+ \to \ell^+\nu_\ell$	–	–	–	–	–	–	–	–	–
1340	$p\overset{(-)}{p} \to W^- \to \ell^-\bar\nu_\ell$	–	–	–	–	–	–	–	–	–
1630	$p\overset{(-)}{p} \to W^+j \to \ell^+\nu_\ell\,j$	–	–	–	–	–	–	–	–	–
1640	$p\overset{(-)}{p} \to W^-j \to \ell^-\bar\nu_\ell\,j$	–	–	–	–	–	–	–	–	–

PROCID	PROCESS	BLHA	semi-leptonic decay	VBF process	anom. gauge couplings	anom. Higgs couplings	Two-Higgs model	Kaluza-Klein model	Spin-2 model	MSSM
300	$p\overset{(-)}{p} \to W^+W^- \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}$	✓	–	–	✓	✓	–	–	–	–
301	$p\overset{(-)}{p} \to W^+W^- \to q\bar{q}\,\ell^-\bar{\nu}_\ell$	–	✓	–	✓	✓	–	–	–	–
302	$p\overset{(-)}{p} \to W^+W^- \to \ell^+\nu_\ell\,q\bar{q}$	–	✓	–	✓	✓	–	–	–	–
310	$p\overset{(-)}{p} \to W^+Z \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-$	✓	–	–	✓	–	–	–	–	–
312	$p\overset{(-)}{p} \to W^+Z \to q\bar{q}\,\ell^+\ell^-$	–	✓	–	✓	–	–	–	–	–
313	$p\overset{(-)}{p} \to W^+Z \to \ell^+\nu_\ell\,q\bar{q}$	–	✓	–	✓	–	–	–	–	–
320	$p\overset{(-)}{p} \to W^-Z \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-$	✓	–	–	✓	–	–	–	–	–
322	$p\overset{(-)}{p} \to W^-Z \to q\bar{q}\,\ell^+\ell^-$	–	✓	–	✓	–	–	–	–	–
323	$p\overset{(-)}{p} \to W^-Z \to \ell^-\bar{\nu}_\ell\,q\bar{q}$	–	✓	–	✓	–	–	–	–	–
330	$p\overset{(-)}{p} \to ZZ \to \ell_1^-\ell_1^+\ell_2^-\ell_2^+$	✓	–	–	–	✓	–	–	–	–
331	$p\overset{(-)}{p} \to ZZ \to q\bar{q}\,\ell^-\ell^+$	–	✓	–	–	✓	–	–	–	–
340	$p\overset{(-)}{p} \to W^+\gamma \to \ell_1^+\nu_{\ell_1}\gamma$	✓	–	–	✓	–	–	–	–	–
350	$p\overset{(-)}{p} \to W^-\gamma \to \ell_1^-\bar{\nu}_{\ell_1}\gamma$	✓	–	–	✓	–	–	–	–	–
360	$p\overset{(-)}{p} \to Z\gamma \to \ell_1^-\ell_1^+\gamma$	✓	–	–	–	✓	–	–	–	–
370	$p\overset{(-)}{p} \to \gamma\gamma$	✓	–	–	–	✓	–	–	–	–
1300	$p\overset{(-)}{p} \to W^+H \to \ell^+\nu_\ell H$	–	–	–	✓	–	–	–	–	–
1301	$p\overset{(-)}{p} \to W^+H \to \ell^+\nu_\ell\gamma\gamma$	–	–	–	✓	–	–	–	–	–
1302	$p\overset{(-)}{p} \to W^+H \to \ell^+\nu_\ell\mu^+\mu^-$	–	–	–	✓	–	–	–	–	–
1303	$p\overset{(-)}{p} \to W^+H \to \ell^+\nu_\ell\tau^+\tau^-$	–	–	–	✓	–	–	–	–	–
1304	$p\overset{(-)}{p} \to W^+H \to \ell^+\nu_\ell b\bar{b}$	–	–	–	✓	–	–	–	–	–
1305	$p\overset{(-)}{p} \to W^+H \to W^+W^+W^- \to \ell_1^+\nu_{\ell_1}\ell_2^+\nu_{\ell_2}\ell_3^-\bar{\nu}_{\ell_3}$	–	–	–	✓	–	–	–	–	–
1306	$p\overset{(-)}{p} \to W^+H \to W^+ZZ \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-\ell_3^+\ell_3^-$	–	–	–	✓	–	–	–	–	–
1307	$p\overset{(-)}{p} \to W^+H \to W^+ZZ \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-\nu_{\ell_3}\bar{\nu}_{\ell_3}$	–	–	–	✓	–	–	–	–	–
1310	$p\overset{(-)}{p} \to W^-H \to \ell^-\bar{\nu}_\ell H$	–	–	–	✓	–	–	–	–	–
1311	$p\overset{(-)}{p} \to W^-H \to \ell^-\bar{\nu}_\ell\gamma\gamma$	–	–	–	✓	–	–	–	–	–
1312	$p\overset{(-)}{p} \to W^-H \to \ell^-\bar{\nu}_\ell\mu^+\mu^-$	–	–	–	✓	–	–	–	–	–
1313	$p\overset{(-)}{p} \to W^-H \to \ell^-\bar{\nu}_\ell\tau^+\tau^-$	–	–	–	✓	–	–	–	–	–
1314	$p\overset{(-)}{p} \to W^-H \to \ell^-\bar{\nu}_\ell b\bar{b}$	–	–	–	✓	–	–	–	–	–
1315	$p\overset{(-)}{p} \to W^-H \to W^-W^+W^- \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\nu_{\ell_2}\ell_3^-\bar{\nu}_{\ell_3}$	–	–	–	✓	–	–	–	–	–
1316	$p\overset{(-)}{p} \to W^-H \to W^-ZZ \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-\ell_3^+\ell_3^-$	–	–	–	✓	–	–	–	–	–
1317	$p\overset{(-)}{p} \to W^-H \to W^-ZZ \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-\nu_{\ell_3}\bar{\nu}_{\ell_3}$	–	–	–	✓	–	–	–	–	–

ProcId	Process	BLHA	semi-leptonic decay	VBF process	anom. gauge couplings	anom. Higgs couplings	Two-Higgs model	Kaluza-Klein model	Spin-2 model	MSSM
600	$p\overset{(-)}{p} \to W^+W^-j \to \ell_1^+ \nu_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2} j$	–	–	–	–	✓	–	–	–	–
601	$p\overset{(-)}{p} \to W^+W^-j \to q\bar{q}\ell^- \bar{\nu}_\ell j$	–	✓	–	–	–	–	–	–	–
602	$p\overset{(-)}{p} \to W^+W^-j \to \ell^+ \nu_\ell q\bar{q} j$	–	✓	–	–	–	–	–	–	–
610	$p\overset{(-)}{p} \to W^-\gamma j \to \ell^- \bar{\nu}_\ell \gamma j$	–	–	–	✓	–	–	–	–	–
620	$p\overset{(-)}{p} \to W^+\gamma j \to \ell^+ \nu_\ell \gamma j$	–	–	–	✓	–	–	–	–	–
630	$p\overset{(-)}{p} \to W^-Z j \to \ell_1^- \bar{\nu}_{\ell_1} \ell_2^- \ell_2^+ j$	–	–	–	✓	–	–	–	–	–
640	$p\overset{(-)}{p} \to W^+Z j \to \ell_1^+ \nu_{\ell_1} \ell_2^- \ell_2^+ j$	–	–	–	✓	–	–	–	–	–
650	$p\overset{(-)}{p} \to ZZ j \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^- j$	–	–	–	–	✓	–	–	–	–
1600	$p\overset{(-)}{p} \to W^+H\,j \to \ell^+ \nu_\ell H\,j$	–	–	–	✓	–	–	–	–	–
1601	$p\overset{(-)}{p} \to W^+H\,j \to \ell^+ \nu_\ell \gamma\gamma\,j$	–	–	–	✓	–	–	–	–	–
1602	$p\overset{(-)}{p} \to W^+H\,j \to \ell^+ \nu_\ell \mu^+\mu^-\,j$	–	–	–	✓	–	–	–	–	–
1603	$p\overset{(-)}{p} \to W^+H\,j \to \ell^+ \nu_\ell \tau^+\tau^-\,j$	–	–	–	✓	–	–	–	–	–
1604	$p\overset{(-)}{p} \to W^+H\,j \to \ell^+ \nu_\ell b\bar{b}\,j$	–	–	–	✓	–	–	–	–	–
1605	$p\overset{(-)}{p} \to W^+H\,j \to W^+W^+W^-\,j \to \ell_1^+ \nu_{\ell_1} \ell_2^+ \nu_{\ell_2} \ell_3^- \bar{\nu}_{\ell_3}\,j$	–	–	–	✓	–	–	–	–	–
1606	$p\overset{(-)}{p} \to W^+H\,j \to W^+ZZ\,j \to \ell_1^+ \nu_{\ell_1} \ell_2^+ \ell_2^- \ell_3^+ \ell_3^-\,j$	–	–	–	✓	–	–	–	–	–
1607	$p\overset{(-)}{p} \to W^+H\,j \to W^+ZZ\,j \to \ell_1^+ \nu_{\ell_1} \ell_2^+ \ell_2^- \nu_{\ell_3} \bar{\nu}_{\ell_3}\,j$	–	–	–	✓	–	–	–	–	–
1610	$p\overset{(-)}{p} \to W^-H\,j \to \ell^- \bar{\nu}_\ell H\,j$	–	–	–	✓	–	–	–	–	–
1611	$p\overset{(-)}{p} \to W^-H\,j \to \ell^- \bar{\nu}_\ell \gamma\gamma\,j$	–	–	–	✓	–	–	–	–	–
1612	$p\overset{(-)}{p} \to W^-H\,j \to \ell^- \bar{\nu}_\ell \mu^+\mu^-\,j$	–	–	–	✓	–	–	–	–	–
1613	$p\overset{(-)}{p} \to W^-H\,j \to \ell^- \bar{\nu}_\ell \tau^+\tau^-\,j$	–	–	–	✓	–	–	–	–	–
1614	$p\overset{(-)}{p} \to W^-H\,j \to \ell^- \bar{\nu}_\ell b\bar{b}\,j$	–	–	–	✓	–	–	–	–	–
1615	$p\overset{(-)}{p} \to W^-H\,j \to W^-W^+W^-\,j \to \ell_1^- \bar{\nu}_{\ell_1} \ell_2^+ \nu_{\ell_2} \ell_3^- \bar{\nu}_{\ell_3}\,j$	–	–	–	✓	–	–	–	–	–
1616	$p\overset{(-)}{p} \to W^-H\,j \to W^-ZZ\,j \to \ell_1^- \bar{\nu}_{\ell_1} \ell_2^+ \ell_2^- \ell_3^+ \ell_3^-\,j$	–	–	–	✓	–	–	–	–	–
1617	$p\overset{(-)}{p} \to W^-H\,j \to W^-ZZ\,j \to \ell_1^- \bar{\nu}_{\ell_1} \ell_2^+ \ell_2^- \nu_{\ell_3} \bar{\nu}_{\ell_3}\,j$	–	–	–	✓	–	–	–	–	–

ProcId	Process	BLHA	semi-leptonic decay	VBF process	anom. gauge couplings	anom. Higgs couplings	Two-Higgs model	Kaluza-Klein model	Spin-2 model	MSSM
400	$p\overset{(-)}{p} \to W^+W^-Z \to \ell_1^+ \nu_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2} \ell_3^+ \ell_3^-$	✓	−	−	✓	−	−	✓	−	−
401	$p\overset{(-)}{p} \to W^+W^-Z \to q\bar{q}\,\ell_1^- \bar{\nu}_{\ell_1} \ell_2^+ \ell_2^-$	−	✓	−	✓	−	−	−	−	−
402	$p\overset{(-)}{p} \to W^+W^-Z \to \ell_1^+ \nu_{\ell_1}\, q\bar{q}\, \ell_2^+ \ell_2^-$	−	✓	−	✓	−	−	−	−	−
403	$p\overset{(-)}{p} \to W^+W^-Z \to \ell_1^+ \nu_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2}\, q\bar{q}$	−	✓	−	✓	−	−	−	−	−
410	$p\overset{(-)}{p} \to ZZW^+ \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^- \ell_3^+ \nu_{\ell_3}$	✓	−	−	✓	−	−	✓	−	−
411	$p\overset{(-)}{p} \to ZZW^+ \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-\, q\bar{q}$	−	✓	−	✓	−	−	−	−	−
412	$p\overset{(-)}{p} \to ZZW^+ \to q\bar{q}\,\ell_1^+ \ell_1^- \ell_2^+ \nu_{\ell_2}$	−	✓	−	✓	−	−	−	−	−
420	$p\overset{(-)}{p} \to ZZW^- \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^- \ell_3^- \bar{\nu}_{\ell_3}$	✓	−	−	✓	−	−	✓	−	−
421	$p\overset{(-)}{p} \to ZZW^- \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-\, q\bar{q}$	−	✓	−	✓	−	−	−	−	−
422	$p\overset{(-)}{p} \to ZZW^- \to q\bar{q}\,\ell_1^+ \ell_1^- \ell_2^- \bar{\nu}_{\ell_2}$	−	✓	−	✓	−	−	−	−	−
430	$p\overset{(-)}{p} \to W^+W^-W^+ \to \ell_1^+ \nu_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2} \ell_3^+ \nu_{\ell_3}$	✓	−	−	✓	−	−	✓	−	−
431	$p\overset{(-)}{p} \to W^+W^-W^+ \to q\bar{q}\,\ell_1^- \bar{\nu}_{\ell_1} \ell_2^+ \nu_{\ell_2}$	−	✓	−	✓	−	−	−	−	−
432	$p\overset{(-)}{p} \to W^+W^-W^+ \to \ell_1^+ \nu_{\ell_1}\, q\bar{q}\, \ell_2^+ \nu_{\ell_2}$	−	✓	−	✓	−	−	−	−	−
440	$p\overset{(-)}{p} \to W^-W^+W^- \to \ell_1^- \bar{\nu}_{\ell_1} \ell_2^+ \nu_{\ell_2} \ell_3^- \bar{\nu}_{\ell_3}$	✓	−	−	✓	−	−	✓	−	−
441	$p\overset{(-)}{p} \to W^-W^+W^- \to \ell_1^- \bar{\nu}_{\ell_1}\, q\bar{q}\, \ell_2^+ \bar{\nu}_{\ell_2}$	−	✓	−	✓	−	−	−	−	−
442	$p\overset{(-)}{p} \to W^-W^+W^- \to q\bar{q}\,\ell_1^+ \nu_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2}$	−	✓	−	✓	−	−	−	−	−
450	$p\overset{(-)}{p} \to ZZZ \to \ell_1^- \ell_1^+ \ell_2^- \ell_2^+ \ell_3^- \ell_3^+$	✓	−	−	✓	−	−	−	−	−
451	$p\overset{(-)}{p} \to ZZZ \to q\bar{q}\,\ell_1^- \ell_1^+ \ell_2^- \ell_2^+$	−	✓	−	✓	−	−	−	−	−
460	$p\overset{(-)}{p} \to W^-W^+\gamma \to \ell_1^- \bar{\nu}_{\ell_1} \ell_2^+ \nu_{\ell_2} \gamma$	✓	−	−	✓	−	−	−	−	−
461	$p\overset{(-)}{p} \to W^+W^-\gamma \to q\bar{q}\,\ell^- \bar{\nu}_\ell \gamma$	−	✓	−	✓	−	−	−	−	−
462	$p\overset{(-)}{p} \to W^+W^-\gamma \to \ell^+ \nu_\ell\, q\bar{q}\, \gamma$	−	✓	−	✓	−	−	−	−	−
470	$p\overset{(-)}{p} \to ZZ\gamma \to \ell_1^- \ell_1^+ \ell_2^- \ell_2^+ \gamma$	✓	−	−	✓	−	−	−	−	−
471	$p\overset{(-)}{p} \to ZZ\gamma \to \ell^- \ell^+\, q\bar{q}\, \gamma$	−	✓	−	✓	−	−	−	−	−
472	$p\overset{(-)}{p} \to ZZ\gamma \to \ell_1^- \ell_1^+ \nu_{\ell_2} \bar{\nu}_{\ell_2} \gamma$	✓	−	−	−	−	−	−	−	−
480	$p\overset{(-)}{p} \to W^+Z\gamma \to \ell_1^+ \nu_{\ell_1} \ell_2^- \ell_2^+ \gamma$	✓	−	−	✓	−	−	−	−	−
481	$p\overset{(-)}{p} \to W^+Z\gamma \to q\bar{q}\,\ell^- \ell^+ \gamma$	−	✓	−	✓	−	−	−	−	−
482	$p\overset{(-)}{p} \to W^+Z\gamma \to \ell^+ \nu_\ell\, q\bar{q}\, \gamma$	−	✓	−	✓	−	−	−	−	−
490	$p\overset{(-)}{p} \to W^-Z\gamma \to \ell_1^- \bar{\nu}_{\ell_1} \ell_2^- \ell_2^+ \gamma$	✓	−	−	✓	−	−	−	−	−
491	$p\overset{(-)}{p} \to W^-Z\gamma \to q\bar{q}\,\ell^- \ell^+ \gamma$	−	✓	−	✓	−	−	−	−	−
492	$p\overset{(-)}{p} \to W^-Z\gamma \to \ell^- \bar{\nu}_\ell\, q\bar{q}\, \gamma$	−	✓	−	✓	−	−	−	−	−
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	$p\overset{(-)}{p} \to \gamma\gamma\gamma$	✓	−	−	−	−	−	−	−	−

PROCID	PROCESS	BLHA	semi-leptonic decay	VBF process	anom. gauge couplings	anom. Higgs couplings	Two-Higgs model	Kaluza-Klein model	Spin-2 model	MSSM
800	$p\overset{(-)}{p} \to W^+\gamma\gamma j \to \ell^+\nu_\ell\gamma\gamma j$	–	–	–	✓	–	–	–	–	–
810	$p\overset{(-)}{p} \to W^-\gamma\gamma j \to \ell^-\bar{\nu}_\ell\gamma\gamma j$	–	–	–	✓	–	–	–	–	–

The gluon-fusion processes are given below.

ProcId	Process	BLHA	gluon-fusion process	semi-leptonic decay	anom. Higgs couplings	general 2HDM	MSSM
4100	$p\overset{(-)}{p} \to H\,jj$	–	✓	–	–	✓	✓
4101	$p\overset{(-)}{p} \to H\,jj \to \gamma\gamma\,jj$	–	✓	–	–	–	✓
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	$p\overset{(-)}{p} \to H\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\,jj$	–	✓	–	✓	✓	✓
4200	$p\overset{(-)}{p} \to H\,jjj$	–	✓	–	–	✓	✓
4300	$p\overset{(-)}{p} \to W^+W^- \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}$	–	✓	–	✓	–	–
4301	$p\overset{(-)}{p} \to W^+W^- \to q\bar{q}\,\ell^-\bar{\nu}_\ell$	–	✓	✓	✓	–	–
4302	$p\overset{(-)}{p} \to W^+W^- \to \ell^+\nu_\ell\,q\bar{q}$	✓	✓	✓	✓	–	–
4330	$p\overset{(-)}{p} \to ZZ \to \ell_1^-\ell_1^+\ell_2^-\ell_2^+$	–	✓	–	✓	–	–
4331	$p\overset{(-)}{p} \to ZZ \to q\bar{q}\,\ell^-\ell^+$	–	✓	✓	✓	–	–
4360	$p\overset{(-)}{p} \to Z\gamma \to \ell_1^-\ell_1^+\gamma$	–	✓	–	✓	–	–
4370	$p\overset{(-)}{p} \to \gamma\gamma$	–	✓	–	✓	–	–
4600	$p\overset{(-)}{p} \to W^+W^-j \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}j$	–	✓	–	✓	–	–
4601	$p\overset{(-)}{p} \to W^+W^-j \to q\bar{q}\ell^-\bar{\nu}_\ell j$	–	✓	✓	–	–	–
4602	$p\overset{(-)}{p} \to W^+W^-j \to \ell^+\nu_\ell q\bar{q}j$	✓	✓	✓	–	–	–
4650	$p\overset{(-)}{p} \to ZZj \to \ell_1^-\ell_1^+\ell_2^-\ell_2^+j$	–	✓	–	✓	–	–

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